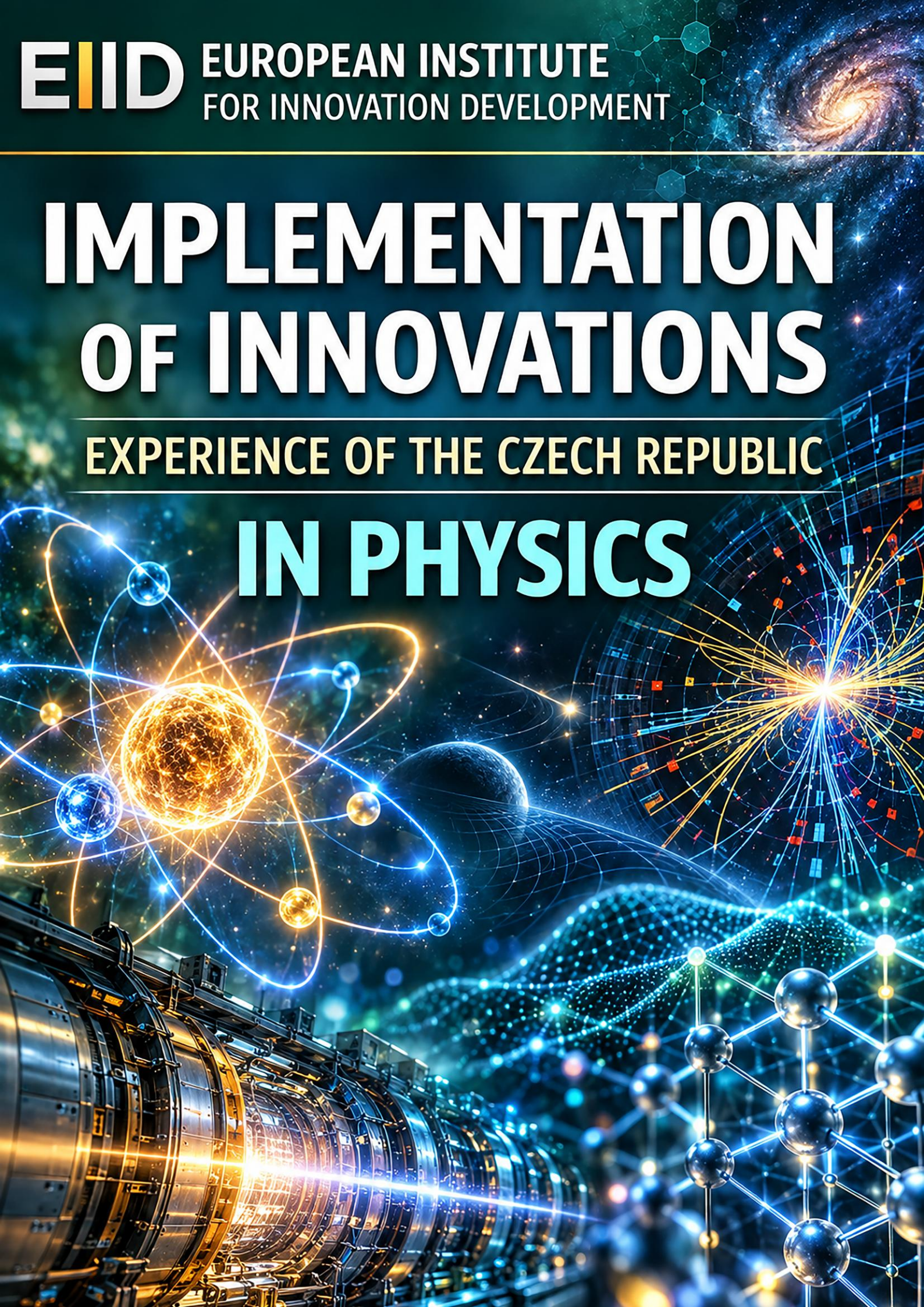
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IMPLEMENTATION OF INNOVATIONS

EXPERIENCE OF THE CZECH REPUBLIC

IN PHYSICS



EUROPEAN INSTITUTE FOR INNOVATION DEVELOPMENT



Implementation of Innovations in Physics

Experience of the Czech Republic

Dr. Alexander Buychik

Ostrava–Opava, Czech Republic

2026

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Introduction

Physics in Contemporary Czechia: Scientific Continuity, European Integration, and Innovation between 1993 and 2025

The history of physics in contemporary Czechia between 1993 and 2025 is a history of continuity transformed by profound institutional, technological, and international change. The establishment of the independent Czech Republic in 1993 created a new political and administrative framework for scientific research, but it did not create Czech physics anew. Czech physicists entered the period with established scientific schools, specialised institutes, university departments, experimental facilities, and professional traditions inherited from Czechoslovakia and from much older Central European intellectual networks. During the following three decades, these inherited capacities were reorganised within a competitive research environment increasingly connected with European and global science. Physics became one of the fields in which this transformation was particularly visible because contemporary physical research depends heavily on costly instruments, sophisticated laboratories, international collaborations, and long-term research infrastructures. The development of Czech physics consequently reflected not only changes within individual scientific disciplines but also the broader modernisation of the national research system. By 2025, Czech researchers were participating in some of the largest scientific collaborations in the world while the country itself hosted research facilities of European significance. The trajectory from inherited national scientific capacity towards an internationally integrated research ecosystem therefore provides the central historical framework for understanding Czech physics after 1993. This introduction examines that trajectory through the interaction of scientific continuity, European integration, infrastructural development, disciplinary diversification, and innovation.

The scientific foundations upon which independent Czechia built after 1993 had been established over a much longer period. Physics in the Czech lands had developed through universities, technical schools, observatories, industrial laboratories, Academy institutes, and specialised research organisations whose histories often extended well into the nineteenth or early twentieth century. During the Czechoslovak period, important research traditions emerged in nuclear physics, solid-state physics, optics, plasma physics, astronomy, low-temperature physics, theoretical physics, materials research, and scientific instrumentation. The post-war creation of the Czechoslovak Academy of Sciences strengthened institutional support for fundamental research and concentrated substantial scientific expertise in specialised institutes. The Nuclear Physics Institute, for example, traces its origins to the establishment of a major nuclear research centre at Řež in 1955, while other institutes developed specialised programmes in condensed matter, plasma, astronomy, and instrumentation. Universities simultaneously maintained essential roles in education and research, particularly Charles University and the Czech Technical University in Prague, together with important centres in Brno and other regions. These structures were affected by the political conditions of state socialism, but they nevertheless accumulated laboratories, equipment, theoretical traditions, research schools, and highly trained personnel. The political transformation after 1989 therefore released Czech physics into a much more open scientific

environment rather than replacing an intellectually empty or institutionally undeveloped system. What changed after 1993 was primarily the framework within which existing expertise could be evaluated, financed, renewed, and internationally connected. The long historical depth of Czech physics is thus essential for explaining why the country was able to participate relatively rapidly in advanced European scientific networks after independence.

The year 1993 nevertheless represents a decisive chronological watershed because it established the sovereign institutional setting within which Czech science would subsequently develop. The Czech Academy of Sciences (CAS) began operating within the legal and organisational framework created during the dissolution of Czechoslovakia, preserving a substantial part of the former Academy research system while adapting it to new expectations. Physical research institutes entered an environment in which scientific quality, international publication, external evaluation, project competition, and cooperation with foreign partners became increasingly important measures of performance. The change did not eliminate established research areas, but it altered the mechanisms through which those areas were supported and justified. The Nuclear Physics Institute became an institute of the new Czech Academy of Sciences, illustrating how institutional continuity was combined with a different national and legal framework. Similar transformations affected the Institute of Physics, the Institute of Plasma Physics, the Astronomical Institute, and other organisations concerned with physical and related sciences. Consequently, 1993 should be understood less as the beginning of Czech physics than as the beginning of a new phase in its organisation, governance, and international positioning. The subsequent thirty-two years would reveal how effectively this inherited scientific structure could respond to increasingly demanding European and global standards.

The reorganisation of the Academy system was particularly important because the Academy remained one of the principal institutional pillars of Czech physical research. The contemporary structure of the Czech Academy of Sciences demonstrates the breadth of physics-related activity distributed across institutes concerned with fundamental physics, nuclear science, astronomy, photonics, materials, plasma, scientific instruments, thermomechanics, atmospheric physics, and neighbouring fields. Fundamental research ranges from the constituents of matter and accelerator experiments to condensed matter, non-linear optics, nuclear processes, and astrophysics. Applied-physics institutes investigate materials, plasma, optical systems, instrumentation, and other problems that connect fundamental principles with technological applications. This architecture is significant because Czech physics did not develop after 1993 around a single dominant institution or a narrowly defined disciplinary model. Instead, different institutes cultivated complementary forms of expertise while increasingly cooperating with universities and international partners. The Institute of Physics of the Czech Academy of Sciences became especially important as a large multidisciplinary centre encompassing condensed-matter physics, particle physics, optics, materials research, and later major laser infrastructures. The Nuclear Physics Institute at Řež maintained a specialised position in nuclear and accelerator research, while the Institute of Plasma Physics became increasingly embedded in European fusion research. The Astronomical Institute connected Czech astrophysical traditions with international observational infrastructures, and institutes devoted to photonics, materials, and scientific instruments expanded the technological dimension of the national physics system. This institutional diversity gave Czechia a broader physical-science base than the size of the

country alone might suggest. It also provided the organisational foundation from which later large-scale projects could emerge.

Universities underwent an equally important transformation because the relationship between research and higher education became progressively closer after the end of the socialist system. Charles University preserved and expanded strong programmes in theoretical, nuclear, particle, condensed-matter, optical, and astrophysical physics, while the Czech Technical University strengthened the connection between fundamental physics, nuclear engineering, instrumentation, and technological applications. Masaryk University and Brno University of Technology contributed to the growth of condensed-matter physics, materials science, optics, nanotechnology, and interdisciplinary research in Brno. University laboratories increasingly participated in competitive projects and international collaborations rather than functioning primarily as teaching environments. Doctoral education became more closely integrated with active research teams, advanced instrumentation, and mobility across European institutions. The presence of university researchers within international experiments also allowed students to enter scientific collaborations whose scale would have been impossible to reproduce nationally. The Czech group participating in the ATLAS experiment at the European Organization for Nuclear Research (CERN), for example, combines scientific analysis with detector development and upgrades, exposing younger researchers to frontier experimental physics. By the twenty-first century, the distinction between Academy-based and university-based physics had therefore become increasingly permeable, although the two institutional sectors retained different traditions and organisational roles. This interaction between education and research became one of the principal mechanisms through which scientific generations were renewed after 1993.

International integration began almost immediately and was particularly visible in high-energy physics. Czechoslovakia had become a CERN Member State in 1992, shortly before the federation ceased to exist. Following independence, both successor states applied for membership, and the Czech Republic and Slovakia were admitted as CERN Member States from 1 July 1993. This chronology meant that Czech particle physics entered the independent-state period with direct institutional access to one of the world's leading centres of fundamental research. CERN membership was more than a symbolic confirmation of European scientific belonging because it allowed Czech institutions to participate continuously in experiments, technical development, governance, and scientific training. Czech groups subsequently became involved in major collider programmes and in the construction, operation, and improvement of particle detectors. At Charles University, researchers working on the ATLAS experiment have contributed to studies of Higgs-boson production, top- and beauty-quark physics, heavy-ion collisions, forward physics, and searches extending beyond the Standard Model of particle physics. They have also contributed to detector components and later upgrades, illustrating how international participation encompasses engineering and instrumentation as well as data analysis. Similar forms of collaboration connected Czech researchers with other major experimental programmes at CERN and elsewhere. For a medium-sized national research system, membership in such organisations offered access to facilities that no individual country of comparable scale could reasonably construct alone. It also placed Czech physicists within large multinational teams where scientific competitiveness depended upon specialised expertise rather than national size. The CERN relationship therefore became an early model for the increasingly infrastructure-based internationalisation of Czech physics.

The accession of the Czech Republic to the European Union (EU) on 1 May 2004 created a second major framework for scientific internationalisation. European integration expanded access to collaborative programmes, mobility schemes, infrastructure investments, and institutional partnerships that increasingly shaped research strategy across the country. The importance of this development extended beyond the acquisition of individual grants because European programmes encouraged organisations to plan research in larger international consortia and to adopt shared standards of scientific management. Physics was particularly suited to this model because many of its frontier areas already depended upon expensive facilities and transnational collaboration. European structural funding also supported the construction and modernisation of research infrastructures within Czechia itself, altering the physical geography of advanced science in the country. The 2004 enlargement thus contributed to a gradual movement from post-socialist institutional adaptation towards active participation in the European Research Area. The European Research Area (ERA) aims to create a more integrated environment for research, innovation, researchers, and knowledge across participating European states. Czech research policy increasingly developed within this wider context, even though domestic funding arrangements and national institutional structures continued to retain their importance. By the 2010s, participation in European scientific networks had become an ordinary rather than exceptional component of professional physics.

One of the most consequential results of this integration was the growing importance of large research infrastructures. Czech scientific policy increasingly recognised that competitiveness in modern physics depends not merely on individual laboratories but on sustained access to complex experimental systems, shared technological platforms, data resources, and international user facilities. National roadmaps consequently identified both Czech-hosted facilities and Czech participation in infrastructures located abroad as strategic components of the research system. Physics-related entries included the Extreme Light Infrastructure Beamlines facility, the HiLASE laser centre, participation in the European Spallation Source, the Facility for Antiproton and Ion Research, the Institut Laue-Langevin, and other projects. This approach effectively connected domestic investment with European scientific specialisation. Instead of attempting to reproduce every advanced experimental capability within national borders, Czech institutions could develop selected areas of particular strength while securing access to complementary facilities elsewhere. The result was a networked model of scientific capacity in which national laboratories and multinational infrastructures became mutually dependent. By 2025, this model was one of the defining structural characteristics of Czech physical science.

The most visible example of the transformation from infrastructure participant to infrastructure host was the development of the Extreme Light Infrastructure (ELI) in Dolní Břežany near Prague. ELI emerged as a European initiative to construct a new generation of powerful laser research facilities capable of opening experimental regimes inaccessible to conventional laboratories. Czechia was selected to host ELI Beamlines, which became one of the principal pillars of this distributed European infrastructure. The first implementation phase culminated in the formal opening of the centre in October 2015, following major investment in specialised buildings, laser systems, secondary sources, and experimental stations. Its scientific mission encompasses high-field and ultra-intense laser physics together with applications in materials science, nuclear and particle-related research, chemistry, biology, and medicine. The importance of the project lies partly in the extraordinary physical parameters of the laser systems, but its institutional significance is equally substantial. On 30 April 2021, the European

Commission granted the Extreme Light Infrastructure the legal status of a European Research Infrastructure Consortium (ERIC). The Czech Republic became a founding member and hosts the statutory seat of ELI ERIC at the ELI Beamlines facility in Dolní Břežany. This development placed Czechia in the relatively small group of European states hosting major internationally governed scientific infrastructures. ELI therefore symbolises a historical shift from the predominantly outward-looking internationalisation of the 1990s towards the capacity to attract international users to facilities located inside the country. It also demonstrates how European integration could reshape national scientific capabilities through concentrated infrastructural investment.

The neighbouring HiLASE Centre provides a complementary example of how advanced physical research became connected with technological innovation. HiLASE is an acronym for High average power pulsed LASErs and was established within the Institute of Physics of the Czech Academy of Sciences in 2011. Its focus differs from the ultra-intense short-pulse emphasis of ELI Beamlines by concentrating on high-average-power diode-pumped solid-state laser technologies with strong scientific and industrial relevance. Construction began in 2012, the centre was inaugurated in 2014, and full operation followed as specialised laser systems became available. The BIVOJ laser subsequently achieved internationally recognised performance records, including a 2016 result in which a Czech-British team demonstrated a kilowatt-class high-energy laser source operating at 100 joules and 10 hertz. HiLASE research also developed applications in areas such as laser shock peening, micromachining, optical-component testing, and advanced manufacturing. This combination of fundamental laser development and industrial application illustrates an important evolution within Czech physics after 1993. Experimental physics increasingly became embedded in environments where new instruments themselves were both research achievements and platforms for external users. The development of the Dolní Břežany laser cluster consequently strengthened the position of Czechia within European photonics and high-power laser science.

Plasma physics and controlled thermonuclear fusion underwent a similarly revealing transformation. Czech plasma research possessed an established experimental tradition centred on the Institute of Plasma Physics and the CASTOR tokamak. A crucial institutional step occurred in 1999 when the Czech Republic became associated with the European Atomic Energy Community fusion programme, creating a deeper framework for participation in European research. The decision to transfer the COMPASS-D tokamak from the United Kingdom Atomic Energy Authority to Prague was taken in 2005, and the machine arrived in the Czech capital in 2007. The first plasma was generated in December 2008, followed by formal commissioning and a scientific operating programme that became increasingly relevant to research supporting the International Thermonuclear Experimental Reactor (ITER). COMPASS enabled investigations of plasma confinement, edge phenomena, instabilities, diagnostics, and plasma-wall interactions under configurations relevant to larger fusion devices. Its scientific operation also trained researchers and engineers in the complex experimental culture required by modern magnetic-confinement fusion. The final experimental discharge occurred in 2021, but this closure represented transition rather than termination. Development of the much more powerful COMPASS Upgrade began as a strategic successor intended to operate at a magnetic field of approximately five tesla and plasma current of up to two megaamperes. By 2025, the new tokamak was under construction in Prague and was attracting attention within the wider European fusion community. German plasma-physics institutions, including the Max Planck Institute for Plasma Physics, treated the project as a technologically

significant high-field tokamak development. Czech fusion research therefore progressed from participation in European programmes towards the construction of a specialised device intended to contribute knowledge relevant to ITER and future fusion power systems.

Nuclear physics followed a related pattern of preserving specialised national facilities while expanding international connectivity. The Nuclear Physics Institute of the Czech Academy of Sciences at Řež entered the post-1993 period with a lineage extending to the principal Czechoslovak nuclear research institutions of the 1950s. Its fundamental-research component remained within the Academy system after earlier institutional divisions had separated basic and applied nuclear activities. In 1994, the former Institute of Radiation Dosimetry was incorporated into the Nuclear Physics Institute, broadening the institutional base for research involving radiation and its measurement. During subsequent decades, accelerator systems, neutron sources, analytical techniques, and nuclear-physics laboratories supported investigations ranging from nuclear structure and reactions to materials analysis and isotope applications. Such facilities also became components of larger national research infrastructures rather than isolated instruments serving only internal research groups. Czech nuclear physicists simultaneously increased participation in multinational facilities and collaborations requiring specialised detector, accelerator, and data-analysis expertise. The national infrastructure roadmap recorded Czech involvement in projects including the European Spallation Source and the Facility for Antiproton and Ion Research. This pattern illustrates the dual character of modern Czech nuclear physics: a stable experimental base at home combined with systematic access to facilities beyond the country. Nuclear techniques also connected fundamental physics with medicine, materials research, environmental studies, radiation protection, and industrial applications. These links prevented nuclear physics from becoming narrowly separated from other domains of science and technology. By 2025, the field therefore represented both a continuation of a long Czech scientific tradition and an example of the increasingly distributed geography of contemporary experimental science.

Astronomy and astrophysics experienced another major international opening when Czechia joined the European Southern Observatory (ESO). The accession agreement was signed in December 2006, and the country formally became an ESO Member State in 2007. Czechia was the first member from Central and Eastern Europe, giving the accession particular symbolic significance within the post-1989 integration of European science. Membership provided Czech astronomers with access to major observing facilities and to the competitive scientific environment associated with some of the world's most advanced ground-based telescopes. It also opened possibilities for engineers and companies to participate in instrument development and technological procurement. Czech astronomical research continued to draw upon domestic centres such as the Astronomical Institute and university groups, but their observational opportunities became increasingly international. Access to facilities associated with the Very Large Telescope, the Atacama Large Millimeter/submillimeter Array, and later the Extremely Large Telescope programme substantially enlarged the technical scale at which Czech astrophysicists could operate. The transition demonstrates once again that national scientific capability increasingly depended upon membership in shared international infrastructures. By 2025, Czech astronomy combined long-standing domestic observational traditions with participation in a global system of precision astrophysics.

Condensed-matter physics remained one of the most important areas in which continuity with established Czech strengths was combined with rapid methodological renewal. Research on

solids, electronic structures, magnetism, semiconductors, surfaces, phase transitions, low-temperature phenomena, and functional materials had deep institutional roots before 1993. During the following decades, however, these subjects increasingly converged with nanoscience, materials engineering, quantum physics, and advanced computational methods. The Institute of Physics of the Czech Academy of Sciences became a major centre for this transition, while university groups in Prague and Brno contributed substantial complementary expertise. The expansion of sophisticated microscopy, spectroscopy, nanofabrication, structural analysis, and high-performance computing allowed researchers to address phenomena at increasingly fine spatial and energetic scales. In Brno, condensed-matter research became closely linked with the Central European Institute of Technology and with interdisciplinary materials research. At the national level, infrastructure development also encouraged the sharing of expensive equipment among researchers from different institutional backgrounds. The scientific significance of condensed-matter physics extended beyond academic questions because modern electronics, sensing, data storage, energy conversion, and photonic technologies all depend upon the control of material properties. The field therefore became one of the clearest meeting points between fundamental research and technological innovation. Czech achievements in spintronics and magnetic materials later emerged from this broader environment rather than from an isolated research programme. By the 2020s, condensed-matter physics had become one of the areas in which Czech researchers could contribute not only to established international topics but also to the formulation of new physical concepts.

The development of altermagnetism provides perhaps the most striking example of such conceptual contribution during the final years covered by this book. In 2022, Libor Šmejkal, Jairo Sinova, and Tomáš Jungwirth published a systematic description of an emerging magnetic phase that they termed altermagnetism. The work addressed systems whose magnetic organisation combines zero net magnetisation with electronic spin-splitting behaviour not captured adequately by the conventional distinction between ferromagnets and antiferromagnets. A related theoretical article in *Physical Review X* demonstrated how symmetry could support a distinct magnetic phase with implications for condensed-matter physics and spintronics. The concept rapidly attracted international attention because it suggested a broad new class of magnetic materials and phenomena. The research was rooted in a long programme of work on antiferromagnetic spintronics associated with the Institute of Physics of the Czech Academy of Sciences and international collaborators. Subsequent experimental research strengthened the evidence that altermagnetic behaviour could be observed in real materials, turning an initially theoretical classification into a rapidly expanding field. Czech scientific participation in this development is historically significant because it differs from the model of contributing to an externally created international infrastructure. Here, researchers associated with Czech institutions participated directly in defining a new conceptual research landscape. Altermagnetism therefore offers an especially powerful illustration of the maturation of Czech physics from international integration towards internationally influential scientific agenda-setting.

High-energy particle physics demonstrates the complementary importance of sustained participation in international experimental systems. The Large Hadron Collider and its detectors require technical, computational, and organisational capacities far beyond those of individual national laboratories. Czech scientists have nevertheless been able to make identifiable contributions because large collaborations depend upon specialised groups

responsible for particular detector systems, analyses, software, and upgrades. Researchers from Charles University participating in ATLAS have worked on the Higgs boson, heavy-ion collisions, top and beauty physics, and searches for phenomena beyond established theory. Czech teams have also contributed hardware to the detector and remained involved in modernisation programmes intended to extend its scientific capabilities. Such work shows that international participation does not reduce smaller countries to passive users of facilities constructed elsewhere. On the contrary, membership in CERN requires sustained technical competence and the ability to contribute reliably to a collective experimental system. The resulting knowledge circulates back into Czech universities through doctoral supervision, instrumentation expertise, computing skills, and international mobility. Participation in large experiments also reinforces connections between particle physics, electronics, detector development, cryogenics, software, and data science. The history of Czech particle physics after 1993 is therefore simultaneously a history of fundamental inquiry and of integration into a highly specialised technological ecosystem.

The growing interaction between physics and neighbouring disciplines became another defining feature of the post-1993 period. Materials science increasingly combined physical characterisation with chemistry and engineering, while nanoscience required cooperation among physicists, chemists, materials specialists, and device engineers. Laser facilities supported experiments extending from plasma and nuclear physics to structural biology and medicine. Nuclear techniques were applied not only to fundamental questions but also to radiopharmaceutical development, materials analysis, environmental measurements, and dosimetry. Photonics expanded towards communication, sensing, manufacturing, and advanced microscopy. Plasma research developed technological branches alongside fusion science, including surface modification and specialised industrial processes. Astrophysics increasingly relied on sophisticated detectors, high-performance computation, statistical analysis, and complex international data infrastructures. The same trend was visible in condensed matter, where quantum materials, spintronics, and nanoscale devices blurred older boundaries between fundamental and applied research. These connections changed the professional identity of physicists because expertise in one subfield increasingly had to be combined with knowledge of computation, instrumentation, materials, or data analysis. Czech research institutions responded by creating shared facilities and interdisciplinary centres rather than organising all work exclusively within traditional departmental boundaries. This development paralleled the wider international transformation of physics into a discipline whose most productive frontiers often lie between established categories. The increasing permeability of disciplinary boundaries therefore became an essential component of Czech scientific innovation.

Computational methods likewise altered both theoretical and experimental physics during the three decades covered by this study. Numerical modelling had long been important, but the rapid increase in computing power fundamentally expanded the range and complexity of systems that could be investigated. Condensed-matter researchers increasingly relied on electronic-structure calculations and atomistic simulations to interpret or predict material properties. Plasma physicists used modelling to understand confinement, instabilities, turbulence, and interaction between plasma and surrounding structures. Astrophysicists depended upon increasingly elaborate simulations and data-processing pipelines capable of handling observations from large international facilities. Particle physics became inseparable from distributed computing because collider experiments generate datasets that require

sophisticated reconstruction, simulation, and statistical analysis. The development of machine learning and other data-driven techniques during the 2010s and 2020s extended these changes further, particularly in pattern recognition, optimisation, and experimental control. Computation did not displace experimental physics but increasingly influenced how experiments were designed, interpreted, and connected with theory. The digital transformation of physics was therefore methodological rather than merely administrative, and Czech institutions became progressively integrated into this broader international shift.

Education and the reproduction of scientific expertise remained indispensable throughout these transformations. Advanced physical research cannot be sustained by infrastructure alone because sophisticated instruments require researchers, engineers, technicians, programmers, and students capable of understanding and improving them. Czech universities consequently became increasingly important as entry points into international scientific careers. Students could gain experience through research projects linked with CERN, European observatories, laser facilities, nuclear laboratories, and domestic Academy institutes. Doctoral programmes became more international, while postdoctoral mobility exposed younger scientists to research cultures in Germany, France, the United Kingdom, Switzerland, and other countries. At the same time, the development of major facilities within Czechia itself helped reverse the earlier assumption that internationally ambitious young physicists necessarily had to leave the country to gain access to frontier instrumentation. ELI Beamlines, HiLASE, advanced materials laboratories, fusion research, and other infrastructures created new domestic opportunities for internationally competitive work. Foreign researchers also became a more visible component of Czech scientific teams, particularly in large centres operating in English-language international environments. The circulation of researchers therefore became bidirectional rather than simply outward. Teaching likewise had to incorporate emerging topics such as quantum information, nanotechnology, computational physics, and advanced photonics alongside classical foundations. This combination of disciplinary depth and international mobility became essential for maintaining scientific continuity across generations. The human-resource dimension is therefore as important to the history of Czech physics as the history of its instruments and institutions.

The geography of Czech physics also changed substantially after 1993. Prague remained the country's largest concentration of institutions because it brought together the Czech Academy of Sciences, Charles University, the Czech Technical University, and numerous specialised laboratories. The broader Prague region later gained the major laser cluster at Dolní Břežany, strengthening an already dense scientific environment. Řež retained its distinctive position in nuclear and accelerator research close to the capital. Brno developed into a powerful second centre through Masaryk University, Brno University of Technology, the Central European Institute of Technology, and specialised materials and instrumentation research. Other cities, including Olomouc, Opava, Plzeň, Liberec, and Ostrava, contributed through university departments and specialised programmes in optics, astrophysics, materials, engineering physics, and related fields. The resulting system cannot be described accurately as entirely decentralised, because Prague continues to possess exceptional institutional weight. Nevertheless, it is substantially more polycentric than a simple capital-centred model would suggest. Regional centres often developed distinctive research profiles rather than merely reproducing disciplines already established in Prague. This geographical differentiation enhanced the diversity and resilience of the national physics ecosystem.

The relationship between physics and technological application also became more explicit during the period under consideration. Fundamental physics remained essential because many major technological developments emerge from knowledge whose practical significance is initially uncertain. At the same time, public investment increasingly encouraged research institutions to demonstrate pathways towards innovation, industrial cooperation, or broader societal benefit. Laser science provided an especially visible example through applications in advanced manufacturing, materials treatment, metrology, and optical technologies. HiLASE developed industrially relevant techniques alongside its work on new laser architectures, while the wider Dolní Břežany environment brought fundamental and application-oriented laser research into unusually close proximity. Solid-state physics and materials research contributed to semiconductor technologies, photovoltaics, sensors, magnetic devices, and emerging spintronic concepts. Nuclear methods supported medicine and materials analysis, while optics and photonics increasingly connected with communications and high-precision instrumentation. This did not transform Czech physics into an exclusively applied discipline, nor would such a transformation have been compatible with the requirements of long-term scientific excellence. Instead, the period was characterised by increasing interaction between basic research and technological development. The ability to move knowledge, instruments, and specialised expertise across this boundary became an important measure of the maturity of the research system.

The early 2020s brought several global scientific and technological pressures into sharper focus. Research institutions had to respond to the disruptions created by the coronavirus pandemic while preserving experiments, collaborations, teaching, and access to specialised facilities. At the same time, European science increasingly emphasised energy security, low-carbon technologies, digitalisation, strategic materials, advanced semiconductor research, and quantum technologies. Physics was central to many of these priorities because the relevant technologies depend on precise understanding of matter, energy, information, and complex physical systems. Fusion research acquired renewed strategic visibility as European programmes continued to prepare for ITER and longer-term power-generation concepts. Laser science developed connections with compact accelerators, secondary radiation sources, advanced materials, and high-field physics. Quantum materials and spintronics gained additional importance in the search for new information-processing technologies. Quantum communication, sensing, and computation also moved from specialised theoretical subjects towards more organised research and educational agendas. Artificial intelligence increasingly entered experimental analysis, instrumentation, simulation, and scientific data processing. These shifts did not make older disciplines obsolete, but they altered the questions asked within them and the technologies through which answers could be obtained. Czech physics responded from a position considerably stronger than that of the early 1990s because it now possessed modern infrastructures and much denser international networks. The period 2020–2025 can therefore be understood as a phase in which earlier institutional modernisation began to support participation in emerging strategic fields of twenty-first-century physics.

The scale of the national research system nevertheless places Czech achievements within important structural constraints. According to the Czech Statistical Office, total expenditure on research and development reached approximately 146.9 billion Czech crowns in 2024. This represented around 1.82 per cent of gross domestic product, below the average level reported for the European Union and substantially below the shares recorded in neighbouring Germany and Austria. Physics therefore developed within a national system that could not compete with

the largest European research economies simply through expenditure volume. Its international position depended instead on selective specialisation, collaboration, and efficient use of shared infrastructure. Membership in organisations such as CERN and ESO provided access to extremely costly facilities without requiring Czechia to reproduce them nationally. Conversely, investments in ELI Beamlines, HiLASE, fusion research, nuclear infrastructure, and advanced materials laboratories concentrated domestic resources in areas where the country could develop distinctive competence. This combination of external access and internal specialisation became one of the most characteristic features of Czech science policy. It also helps explain why international cooperation is not an optional supplement to Czech physics but one of its structural foundations.

A relatively modest national scale can in fact create certain advantages when institutions develop complementary rather than duplicative specialisations. Researchers working in Prague, Řež, Dolní Břežany, Brno, and other centres often operate within professional networks that connect Academy institutes, universities, technological organisations, and international facilities. The resulting scientific environment can support rapid interdisciplinary contact when administrative and funding conditions permit it. Czechia also occupies a geographically favourable position in Central Europe, close to major German, Austrian, Polish, Slovak, and broader European research centres. Cross-border mobility therefore reinforces participation in projects whose intellectual geography extends well beyond national borders. Nevertheless, several persistent challenges accompany this model. Expensive infrastructure requires reliable long-term operating budgets after construction funding has ended. International competitiveness depends upon the ability to attract and retain highly qualified researchers in a labour market where richer scientific systems can offer greater salaries and resources. Doctoral and early-career conditions influence whether new generations remain within research, while administrative complexity can reduce the flexibility required for international projects. Dependence on competitive funding may also create tension between long-term fundamental research and shorter project cycles. These structural limitations must be considered alongside visible successes if the historical development of Czech physics is to be understood realistically. By 2025, the system had achieved substantial international integration, but continued competitiveness required sustained institutional rather than merely episodic support.

The interaction between continuity and innovation provides the most useful conceptual framework for interpreting the entire period. Czech physics did not progress by discarding its inherited disciplines and replacing them with fashionable new subjects. Nuclear research, condensed matter, optics, astronomy, plasma physics, and theoretical physics remained important because accumulated expertise provided the intellectual basis for later innovations. What changed was the environment in which these traditions operated and the technologies available to develop them further. Solid-state research expanded into quantum materials and spintronics, while established magnetic studies contributed to the emergence of altermagnetism. Classical optics and laser research evolved towards high-average-power and ultra-intense laser facilities. Plasma experiments developed from CASTOR through COMPASS towards the technologically more ambitious COMPASS Upgrade. Domestic astronomy was connected to ESO observatories of a scale inaccessible to Czech institutions alone. Particle physics became deeply embedded in CERN collaborations and the data-intensive research culture of the Large Hadron Collider. Innovation therefore resulted from the reconfiguration of

established expertise within new infrastructures, collaborations, and scientific questions rather than from discontinuity with the past.

By 2025, Czech physics had consequently acquired several different forms of international visibility. One form derived from membership and active participation in large multinational organisations such as CERN and ESO. A second came from specialised national facilities and research groups whose expertise made them valuable partners in wider European collaborations. A third emerged from hosting internationally significant infrastructure, most prominently ELI Beamlines and the statutory seat of ELI ERIC. A fourth was associated with scientific concepts and results generated by researchers working in Czech institutions, with altermagnetism providing a particularly prominent contemporary example. These forms of visibility should not be conflated because they represent different kinds of scientific achievement. Building a detector component, operating a laser user facility, developing a fusion device, and proposing a new magnetic classification demand different institutional and intellectual capabilities. Together, however, they demonstrate that Czech physics had moved well beyond the transitional concerns that dominated the early 1990s. The national system was increasingly capable of contributing to international physics through infrastructure, specialised experimental expertise, theoretical work, instrumentation, and technological development.

This development also altered the meaning of scientific sovereignty for a medium-sized European country. In contemporary physics, autonomy cannot realistically mean possessing every type of accelerator, telescope, laser, reactor, computing system, and specialised laboratory within national territory. Scientific sovereignty instead depends increasingly upon the capacity to contribute meaningfully to shared infrastructures while retaining sufficient domestic expertise to formulate independent research questions. Czechia's experience illustrates this shift particularly clearly. CERN membership gives Czech physicists access to frontier particle physics, but participation remains scientifically valuable only because domestic institutions sustain trained groups capable of contributing to experiments. ESO membership provides access to world-class telescopes, but Czech astronomy still requires national research communities able to compete successfully for observing time and interpret the resulting data. ELI Beamlines reverses the direction of access by bringing international users to a facility located in Czechia. COMPASS Upgrade similarly seeks to create specialised knowledge that can feed into European fusion research rather than duplicate the largest devices elsewhere. The strength of the system therefore lies in reciprocal dependence between national competence and international infrastructure. This pattern is one of the defining characteristics of modern European science and one of the central themes of Czech physics after 1993.

Another important feature of the period was the gradual convergence of scientific excellence with research infrastructure policy. In the 1990s, the central challenge was to preserve strong research groups while adapting institutions to new forms of funding and evaluation. By the 2000s, competitiveness increasingly depended upon modern equipment and stable international connections. During the 2010s, the construction of large centres made infrastructure itself a strategic instrument of national scientific development. The Czech roadmap system formalised this change by identifying major facilities and international memberships as long-term components of the national research landscape. Such investments require a different temporal logic from ordinary project funding because complex facilities may take many years to design, build, commission, and operate. Their value cannot be measured

solely by the number of publications produced immediately after construction. They generate technical skills, international networks, user communities, training opportunities, industrial contracts, and capabilities that accumulate gradually. ELI Beamlines, HiLASE, COMPASS and its successor, nuclear facilities, and participation in overseas observatories and accelerators all illustrate this longer infrastructural horizon. The transition towards infrastructure-centred science therefore changed not only what Czech physicists could investigate but also how scientific institutions had to plan their future.

The internationalisation of physics also transformed scientific culture within Czech institutions. English became the normal working language of many research collaborations and an increasingly important language of doctoral training and publication. Recruitment became more international, particularly in centres dependent upon multinational scientific teams. Evaluation increasingly relied on standards that compared Czech research directly with work produced in major European, American, and Asian institutions. Scientific careers became less nationally bounded as researchers moved repeatedly between Czech laboratories and foreign universities or facilities. These processes increased competition but also exposed research groups to a wider range of methods, technical practices, and theoretical approaches. They encouraged younger researchers to regard mobility and international collaboration as ordinary components of scientific work rather than exceptional opportunities. Large infrastructures reinforced this culture because their operation requires continuous communication among engineers, technicians, data specialists, and scientists of many nationalities. At the same time, internationalisation created pressure on institutions to provide working conditions capable of attracting researchers into Czechia rather than merely training them for careers elsewhere. The changing social organisation of research thus became as significant as the development of particular scientific topics.

Public understanding of physics also acquired greater importance as research became more expensive and technologically visible. Facilities such as ELI Beamlines and COMPASS require substantial public investment and therefore operate within a social environment in which scientists must explain the value of long-term fundamental research. The same challenge affects participation in CERN, ESO, and other international organisations financed through national contributions. Communication is particularly difficult when the immediate practical outcome of an experiment cannot be predicted in advance. Yet the history of physics repeatedly demonstrates that fundamental investigations can generate technologies whose later applications were unforeseen at the time of discovery. Czech research organisations increasingly responded through public events, educational programmes, media communication, exhibitions, and outreach activities. Such engagement also serves recruitment by exposing school pupils and university students to contemporary research rather than presenting physics only as a classical textbook discipline. Modern facilities have become visible symbols of the scientific and technological capacities of the country. Their public role therefore extends beyond laboratory output into education, national scientific culture, and the social legitimacy of research investment. By 2025, communication with society had become an increasingly normal component of institutional scientific activity.

The development of Czech physics between 1993 and 2025 should consequently not be reduced to a catalogue of discoveries or a sequence of new buildings. Its deeper significance lies in the formation of an ecosystem capable of connecting different scales of scientific activity. Individual theoretical researchers, university departments, specialised laboratories, national infrastructures, and multinational organisations all became components of the same

increasingly interconnected system. Fundamental and applied research interacted without becoming identical. Domestic scientific traditions continued while international mobility changed their intellectual environment. European integration opened access to shared resources while simultaneously enabling Czechia to host facilities serving researchers from abroad. Large investments produced new experimental possibilities, but their effectiveness continued to depend upon education, technical competence, and stable institutional communities. Emerging topics such as quantum technologies and altermagnetism developed alongside, rather than instead of, established strengths in nuclear, optical, plasma, and condensed-matter physics. This layered structure is one reason why the Czech experience offers a valuable case study in the transformation of science in Central Europe after the end of the Cold War. It demonstrates how a country with strong inherited scientific traditions but limited national scale can pursue frontier research through strategic internationalisation and selective infrastructural concentration.

At the same time, the history of the period contains important asymmetries that should not be obscured by a narrative centred exclusively on success. Some areas benefited from large infrastructure investment more directly than others, and access to international networks varied among institutions and disciplines. The scientific prominence of Prague and its surrounding region remained much greater than that of most other parts of the country. Major centres could attract international personnel and equipment more easily than smaller university departments. Dependence upon European and national project cycles sometimes complicated long-term planning, especially for infrastructures requiring continuous technical maintenance. The cost of operating sophisticated facilities could become as important as the original construction investment. International collaboration also meant that some of the most visible scientific results were collective achievements for which national contributions cannot always be isolated neatly. Assessment therefore requires attention to institutional capacity and sustained participation rather than simple claims of national ownership over discoveries. These qualifications do not diminish the transformation of Czech physics, but they make its achievements historically intelligible. A mature account must distinguish between hosting an infrastructure, participating in an international experiment, originating a theoretical concept, and translating physical knowledge into technology.

The period from 1993 to 2025 nevertheless reveals a clear long-term movement from adaptation towards greater scientific agency. During the 1990s, Czech institutions primarily had to stabilise themselves within a new political economy of research and reconnect with unrestricted international science. In the 2000s, European Union membership and expanding institutional partnerships strengthened the foundations for deeper participation in multinational research. The 2010s brought the most visible expansion of advanced research infrastructure, particularly in lasers, materials, nanoscience, and fusion-related physics. By the early 2020s, Czechia was not merely sending researchers to foreign facilities but hosting an internationally governed laser infrastructure and constructing advanced experimental systems of its own. Research associated with Czech institutions was simultaneously contributing to emerging conceptual areas such as altermagnetism. This sequence does not represent a simple linear progression because different branches of physics developed at different speeds and under different institutional conditions. It does, however, indicate a substantial increase in the range of ways through which Czech physics could influence international science. The concept of innovation used in this book therefore includes

institutional, infrastructural, methodological, technological, and conceptual change rather than only commercially applicable invention.

By the endpoint of this study, Czech physics had become firmly embedded within the European scientific landscape while retaining recognisable national centres of expertise. Its researchers worked on questions ranging from the fundamental constituents of matter to the behaviour of plasmas, quantum and magnetic materials, nanoscale structures, stellar systems, and extreme electromagnetic fields. They operated instruments ranging from laboratory microscopes and accelerator systems to petawatt-class lasers, fusion devices, and detectors located within international facilities. The country possessed research institutions capable of educating specialists, maintaining technologically demanding facilities, and participating in large collaborations over long periods. Its strongest achievements emerged when historical expertise was combined with international openness and sustained infrastructure. The transformation was therefore cumulative rather than revolutionary. Each new stage depended heavily on scientific communities, instruments, and institutional knowledge created during previous decades. At the same time, the research environment of 2025 differed fundamentally from that of 1993 in its degree of international integration, technological sophistication, interdisciplinarity, and organisational scale. Understanding this combination of continuity and transformation is essential for assessing the actual meaning of innovation in contemporary Czech physics.

This book examines that transformation through three interconnected perspectives. The first traces the historical evolution of Czech physics from the institutional reorganisation of 1993 through European integration and the infrastructure expansion of the 2010s to the emerging priorities of the mid-2020s. The second investigates major scientific fields and achievements, including particle and nuclear physics, condensed matter, magnetism, optics and laser science, plasma and fusion physics, astronomy and astrophysics, nanophysics, quantum research, and computational approaches. The third considers the institutions and scientific centres through which these developments were organised, with particular attention to Prague, Řež, Dolní Břežany, Brno, and other regional centres. International infrastructures are treated not as external additions to Czech science but as integral components of the national research environment. Particular attention is also given to moments when Czech researchers or institutions moved beyond participation and contributed distinctive technologies, facilities, or scientific concepts. The resulting history is therefore neither purely institutional nor simply disciplinary. It is a history of how scientific knowledge, research organisations, infrastructures, people, and international networks interacted over more than three decades. Between 1993 and 2025, Czech physics evolved from a strong inherited research tradition operating within a newly independent state into a mature component of European and global physical science. That development provides a revealing example of how continuity can become a resource for innovation when scientific institutions remain open to organisational change, international cooperation, and new intellectual challenges.

Part One

Historical Evolution of Physics in Contemporary Czechia, 1993–2025

1993 as a Watershed: Continuity and Reorganisation of Czech Physical Science

The year 1993 constitutes a natural watershed in the history of modern Czech physics, but it should not be interpreted as the point at which an entirely new national physical science suddenly came into existence. The establishment of the independent Czech Republic on 1 January 1993 created a sovereign political, administrative, and financial framework within which universities, Academy institutes, research laboratories, and scientific communities would henceforth operate. Physics nevertheless entered this new period with a dense institutional landscape and with scientific traditions accumulated during many decades of Czechoslovak and earlier Czech development. Laboratories, university departments, observatories, accelerator facilities, specialist institutes, and professional communities did not disappear when the federal state was dissolved. Czech physicists already possessed recognised expertise in fields including condensed-matter physics, nuclear science, theoretical physics, astronomy, optics, plasma research, materials physics, physical engineering, and scientific instrumentation. The democratic transformation beginning in 1989 had already removed many political restrictions affecting academic communication and institutional autonomy before Czech independence was established. What changed decisively in 1993 was the national framework within which inherited scientific resources were governed, financed, evaluated, and represented internationally. For this reason, the development of Czech physics after independence must be understood through the simultaneous operation of continuity and reorganisation rather than through a simple narrative of rupture. The importance of 1993 lies precisely in the transformation of the conditions under which an already mature physical-science community could pursue research in an increasingly competitive European and global environment.

The historical foundations of this community reached far beyond the final decades of Czechoslovakia. Charles University possessed a much older tradition of physical research, while its modern Faculty of Mathematics and Physics was established in 1952 as a separate faculty created from the former Faculty of Science. The institution subsequently developed specialised departments and research institutes reflecting the increasing differentiation of twentieth-century mathematics and physics. The Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague had similarly originated in 1955, initially within Charles University, as part of the expanding Czechoslovak nuclear programme. It was transferred to the Czech Technical University in 1959 and gradually broadened from nuclear specialisation towards physical engineering, materials, mathematical methods, electronics, and related technological disciplines. Within the Academy system, the Nuclear Physics Institute at Řež traced its institutional origin to 1955 and became one of the country's principal centres for nuclear research. The Astronomical Institute also possessed a substantial pre-1993 history, having emerged in its post-war institutional form during the early 1950s and

maintaining the important observatory at Ondřejov. Other institutes accumulated expertise in plasma physics, physical metallurgy, atmospheric physics, instrumentation, electronics, mechanics, and related fields. These organisations carried into the independent Czech Republic not merely buildings and equipment but also research traditions, methodological knowledge, professional networks, and accumulated experimental experience. The institutional depth of Czech physics therefore gave the new state a substantial scientific inheritance upon which the post-1993 system could be constructed.

The political changes of 1989 and the establishment of the Czech Republic in 1993 performed different historical functions in this process. The Velvet Revolution initiated the more fundamental political and intellectual opening by dismantling the structures through which the communist regime had controlled academic institutions and scientific careers. The Czech Academy's own historical account notes that the reconstruction of the former Czechoslovak Academy of Sciences had already begun during the 1990–1992 presidency of Otto Wichterle. Political barriers limiting contact with foreign scientific communities diminished rapidly, creating new possibilities for mobility, collaboration, access to information, and institutional reform. Independence in 1993 therefore did not introduce academic freedom into a system that had remained unchanged until the final day of Czechoslovakia. It instead gave the reforms begun after 1989 a new sovereign institutional setting and required the scientific system to be organised specifically for the Czech state. In intellectual terms, 1989 was thus the deeper political rupture, whereas 1993 became the decisive legal and organisational watershed. Distinguishing these two moments is essential for understanding why Czech physics could preserve substantial disciplinary continuity while simultaneously undergoing far-reaching structural change.

The clearest institutional expression of the 1993 watershed was the replacement of the Czechoslovak Academy of Sciences (CSAS) by the Czech Academy of Sciences (CAS). The former Czechoslovak Academy ceased to exist on 31 December 1992, while the Czech successor institution was established under Act No. 283/1992 Coll. The legislation did not require the Czech scientific system to reconstruct Academy research from the beginning. Instead, institutes transferred to the Czech Republic from the former federal Academy became institutes of the new Academy, providing explicit legal continuity across the dissolution of the state. Existing directors and scientific councils were likewise carried into the transitional arrangements until the new governing procedures could be completed. The law defined the Academy as an organisation conducting research through its institutes and provided a separate relationship with the Czech state budget. It also established self-governing bodies through which scientists and institutional representatives could participate in Academy governance. International scientific cooperation was explicitly recognised as one of the activities that the Academy and its institutes could undertake. For physics, these provisions were crucial because expensive experimental programmes could not have tolerated the abrupt disappearance of their institutional and legal foundations. Laboratories, research teams, equipment, scientific archives, and ongoing programmes could therefore continue while the new governance structure was being formed. The creation of the Czech Academy consequently represented considerably more than a change of name, because it combined preservation of research capacity with a new model of institutional authority and accountability.

The constituting meeting of the Academy Assembly on 24 and 25 February 1993 made the intended character of the new institution unusually explicit. The Assembly described the Academy as a modern system of autonomous research workplaces intended to contribute

through high-level research and strong international cooperation to scientific knowledge, education, and culture. It also emphasised close relations with universities and organisations engaged in applied research rather than proposing that Academy institutes should develop as an isolated sector. Interdisciplinarity and thematic specialisation were identified as important principles for the newly organised research system. The Assembly linked future support increasingly to competition among research programmes and projects and to evaluation of scientific results. These principles were especially important for physics because modern physical research typically combines specialised knowledge with expensive instrumentation and cooperation across institutional boundaries. The Assembly simultaneously acknowledged that intellectual autonomy would be ineffective without adequate financial and legislative support from the state. Its resolutions therefore reveal both the ambition and the vulnerability of the new system during its first year. The transformation agenda of 1993 was already centred on concepts that would shape Czech physics for the following decades: autonomy, evaluation, competition, university cooperation, internationalisation, and selective specialisation.

The organisational structure adopted later in 1993 demonstrates how prominent physical science remained within the reformed Academy. By 1 November, the Section of Mathematics, Physics and Informatics included the Astronomical Institute, the Institute of Physics, the Nuclear Physics Institute, the Mathematical Institute, the Institute of Computer Science, and the Institute of Information Theory and Automation. A separate Section of Applied Physics contained the Institute of Physical Metallurgy, the Institute of Plasma Physics, the Institute of Electrical Engineering, the Institute of Hydrodynamics, the Institute of Scientific Instruments, the Institute of Radio Engineering and Electronics, the Institute of Theoretical and Applied Mechanics, and the Institute of Thermomechanics. Physics-related research also extended into the Section of Earth Sciences through the Institute of Atmospheric Physics, the Geophysical Institute, and radiation-dosimetry activities. The resulting map was much broader than a conventional definition of physics centred exclusively on theoretical or laboratory investigation of fundamental phenomena. It included areas ranging from nuclear and astronomical research to materials, instrumentation, electronics, mechanics, plasma, and atmospheric processes. Such breadth reflected the institutional differentiation accumulated under the Czechoslovak Academy rather than an entirely new disciplinary classification invented in 1993. At the same time, placing these institutes within the restructured Czech Academy created new opportunities to reconsider their relationships and scientific priorities. The physical sciences therefore occupied a substantial portion of the Academy system at the very moment when that system was being subjected to major institutional change. This broad institutional base would later prove important when Czech physics entered increasingly interdisciplinary fields and large European research infrastructures.

The Institute of Physics provides a particularly useful illustration of institutional continuity combined with new governance. It remained a central Academy institution after the dissolution of the federal scientific system rather than being reconstructed as an entirely new organisation. During the transitional administration in February 1993, the existing director, Svatopluk Krupička, was formally confirmed in office under the procedures established by the new Academy legislation. Later that year, Vladimír Dvořák was appointed director for a four-year term with effect from 1 October 1993. These apparently administrative details reveal an important change in institutional culture because scientific councils, formal appointments, and defined terms of office were becoming components of the post-communist governance model. Leadership legitimacy was no longer expected to derive simply from continuity with

structures inherited from the former Academy. The new procedures sought to connect institutional autonomy with explicit scientific and managerial responsibility. In this sense, the Institute of Physics entered the Czech Republic as an old research institution functioning within a substantially altered governance environment.

The Nuclear Physics Institute at Řež reveals an even more complex relationship between continuity, state transformation, and the changing boundary between fundamental and applied research. Its institutional ancestry began with the creation of the Czechoslovak nuclear research centre in 1955, when nuclear science and technology were being developed as strategically important fields. In 1972 the original organisation was divided, with the larger part concerned mainly with applied nuclear research transferred outside the Academy structure. The part concentrating principally on fundamental nuclear research remained within the Czechoslovak Academy of Sciences under the name Nuclear Physics Institute. The applied Nuclear Research Institute was subsequently privatised in 1992 during the economic transformation preceding the dissolution of Czechoslovakia. The fundamental-research institute, by contrast, entered 1993 as part of the new Czech Academy of Sciences. This institutional divergence provides a particularly clear example of how the transition to a market economy affected different forms of scientific activity in different ways. Fundamental nuclear physics continued to require long-term public support and specialised infrastructure that could not readily be organised according to ordinary commercial logic. At the same time, applied nuclear activities were exposed much more directly to new ownership and economic structures. The former Institute of Radiation Dosimetry was later incorporated into the Nuclear Physics Institute in 1994, showing that institutional consolidation continued beyond the first year of independence. The Řež case therefore demonstrates that the post-1993 transformation was selective: some scientific capacities were commercialised, some were consolidated, and others were preserved within the public research system.

Astronomy followed a different institutional trajectory while displaying the same fundamental principle of continuity through reorganisation. The Astronomical Institute had developed from earlier observatory traditions and acquired its consolidated Academy form in the 1950s. By the end of 1992 it had become a workplace of the newly established Czech Academy of Sciences. The following year brought a significant geographical and organisational adjustment when the Institute's headquarters were transferred to Ondřejov. Its Prague workplace was simultaneously moved from Vinohrady to Spořilov, where it occupied facilities associated with the Geophysical Institute. These changes did not constitute the creation of a new Czech astronomical discipline, because the observational programmes, specialist personnel, and scientific traditions had much deeper origins. They instead represented the practical reorganisation of an inherited research institution within the administrative geography of the new Academy. Ondřejov's long-established observational infrastructure consequently became even more central to the institutional identity of Czech astronomy. The 1993 changes in astronomy therefore illustrate how physical-science institutions could be reorganised materially and administratively without disrupting the continuity of their scientific purpose.

Plasma physics and the broader applied-physics sector demonstrate another important feature of the system inherited in 1993. The Czech Academy retained a dedicated Institute of Plasma Physics within a section that also contained physical metallurgy, scientific instrumentation, electronics, hydrodynamics, mechanics, and thermomechanics. This arrangement shows that Czech physical science had already developed extensive connections with engineering and technological research before the independent state was created. The

distinction between fundamental and applied physics was consequently institutional but never absolute. Plasma research required sophisticated experimental devices, materials knowledge, diagnostics, vacuum technology, electrical engineering, and theoretical analysis. Scientific instrumentation likewise depended upon fundamental understanding of physical processes while producing technologies useful far beyond academic laboratories. The continuation of these specialised institutes prevented the transition from reducing physics to a narrow collection of university disciplines. It also preserved technical workshops, experimental competence, and professional knowledge that would be difficult to recreate after institutional closure. Later Czech achievements in high-power lasers, fusion-oriented plasma research, precision instruments, and advanced materials would draw upon capacities whose institutional origins pre-dated 1993. The structure established during the first year of the Czech Academy therefore preserved a broad conception of physical science that linked explanation of natural phenomena with the construction of advanced experimental technologies.

The Academy was only one pillar of the Czech physics system that entered independence. The Faculty of Mathematics and Physics at Charles University, founded in 1952, had already developed into a major centre for education and research across numerous branches of physics and mathematics. The Faculty of Nuclear Sciences and Physical Engineering at the Czech Technical University in Prague had likewise evolved from the nuclear ambitions of the 1950s into an institution combining physical science with technological applications. By 1993 these faculties represented established mechanisms for training physicists, engineers, doctoral researchers, and future scientific staff. Their continued existence meant that the new Czech Republic inherited an educational structure capable of reproducing specialised scientific communities across generations. Independence did not require new universities to be created in order to sustain fundamental physics. The principal challenge was instead to redefine the relationship between university research and the specialised Academy institutes under conditions of greater institutional autonomy and international openness. The founding declaration of the Czech Academy explicitly identified close university cooperation as a central objective, making this relationship part of the new scientific architecture from the outset.

A second fundamental transformation concerned the way research was financed and selected. Act No. 300/1992 Coll., which became effective on 1 July 1992, had already created a new statutory framework for state support of scientific activity and technological development before the Czech Republic formally became independent. The legislation distinguished institutional support from project-oriented funding and established mechanisms through which research proposals could compete for dedicated public resources. It also provided for public competition in the allocation of project funding rather than assuming that research resources would flow automatically through inherited organisational hierarchies. A Government Council for Research and Development was created as an expert and advisory body involved in the distribution and coordination of state research support. The same law established the Grant Agency of the Czech Republic as a new mechanism for allocating competitive funding. These changes introduced a logic fundamentally different from that of a system in which research programmes were determined primarily through institutional plans and administrative allocation. Physicists increasingly had to formulate discrete research projects, define objectives, justify requested resources, and expose proposals to comparative evaluation. This transformation was especially consequential for experimental physics because access to equipment, materials, computing resources, and specialist staff often depends directly on project funding. Institutional finance remained indispensable for

maintaining laboratories and long-term research capacity, but it was now supplemented by a competitive layer capable of rewarding particular scientific initiatives. The funding reforms surrounding 1993 therefore altered not only the quantity of resources available to physics but also the procedures through which scientific priorities were selected.

The Grant Agency of the Czech Republic began operating in 1993 and quickly became one of the clearest institutional symbols of the new research order. Standard grant projects have been supported since the Agency's creation and were designed for fundamental research across disciplinary fields. Investigators could propose their own research topics rather than working exclusively within centrally predetermined scientific programmes. Projects were selected through competitive procedures that developed around expert assessment and peer review. For physics, this model encouraged research groups to articulate specific problems that could be compared with proposals submitted elsewhere in the national scientific system. Competition also created stronger incentives to define originality, methodological feasibility, and scientific significance in forms intelligible beyond the immediate institutional hierarchy of a laboratory. The new system did not eliminate institutional funding, nor could project grants alone sustain capital-intensive physical research. It nevertheless introduced an additional mechanism through which individual researchers and teams could obtain resources independently of their institute's ordinary budget. The beginning of Grant Agency activity in 1993 consequently reinforced the significance of that year as a transition from inherited organisational allocation towards a mixed system combining institutional stability with competitive project finance.

Competitive grant funding formed only one part of a wider movement towards evaluation and accountability. At its October 1993 meeting, the Academy Assembly reviewed the progress of transformation and required institutes to undertake an initial assessment of university-educated research staff by February 1994. The Assembly also regarded a shift of many scientific and professional employees towards fixed-term contracts of no more than five years as appropriate within this evaluation process. It instructed the Academy's governing bodies to complete a system for evaluating the scientific activity of institutes and to establish independent evaluation panels so that assessment could begin during 1994. Such measures indicate that institutional autonomy was intended to operate together with systematic scrutiny of scientific performance. This represented a substantial cultural change from reliance upon inherited institutional status as a sufficient justification for continued support. Researchers and institutes increasingly had to demonstrate the quality and relevance of their work within formalised evaluative procedures. For physics, the new principle contained an inherent tension because long experimental programmes and highly specialised laboratories require continuity even when personnel and projects are periodically assessed. The post-1993 system therefore had to reconcile scientific competition with the preservation of accumulated technical competence. That tension between evaluation and continuity would remain a recurrent feature of Czech research policy long after the immediate transformation period had ended.

These reforms were implemented under severe financial pressure rather than during a period of uncomplicated scientific expansion. The constituting Academy Assembly explicitly acknowledged that reductions in the number of institutes and employees formed part of the intended transformation. It also warned, however, that the actual extent and speed of contraction were being driven by a sharp reduction in the Academy's 1993 budget. The Assembly stated that the financial situation risked causing irreversible damage to scientific

capacity. A number of Academy workplaces were closed with effect from 30 June 1993 as the institutional system was reduced and reorganised. The list included organisations from several disciplines, showing that restructuring was not confined to one area of scholarship. Physics-related and adjacent fields were therefore operating within an environment in which institutional survival could not simply be taken for granted. Decisions about laboratories, research programmes, staffing, and equipment acquired unusual significance because knowledge-intensive capacities can be difficult or impossible to rebuild once specialised teams have dispersed. The transformation of 1993 must consequently be understood as a period of opportunity accompanied by genuine institutional vulnerability rather than as a straightforward story of liberalisation and growth.

Despite these pressures, the physical sciences retained a remarkably broad institutional presence within the reorganised Academy by the end of 1993. Fundamental physics remained represented through the Institute of Physics, the Nuclear Physics Institute, and the Astronomical Institute, alongside mathematically and computationally oriented organisations. Applied physics retained a dedicated section containing institutes concerned with plasma, materials, electronics, instruments, mechanics, thermomechanics, and fluid processes. Atmospheric and geophysical research provided additional domains in which physical methods remained central. The preservation of this range suggests that physics continued to be treated as a core component of the national research system during institutional reduction. Preservation, however, did not mean that these institutes could continue operating according to unchanged organisational assumptions. Their leadership was being reconsidered, budgets were redistributed, evaluation mechanisms were introduced, and competitive project funding was beginning to influence research planning. The new Academy also expected substantially stronger international cooperation and closer relationships with universities. The combination of organisational continuity with new incentives gradually altered the way scientific groups defined success and institutional relevance. Research traditions therefore survived, but the conditions under which they could reproduce themselves were changing. The physical-science system that emerged from 1993 was consequently neither the old Czechoslovak system under a new national label nor an entirely reconstructed network of institutions. It was a selectively transformed structure in which inherited capabilities were required to function within new mechanisms of governance, evaluation, finance, and international competition.

Physicists themselves were directly represented in the governance of the new Academy during this transitional year. From 1 January until the constituting Academy Assembly in February, the Committee responsible for managing former Czechoslovak Academy workplaces temporarily performed the functions of the new Academy Council. Its membership included Jiří Niederle from the Institute of Physics, Ladislav Půst from the Institute of Thermomechanics, and Ladislav Sehnal from the Astronomical Institute. After the new governance structure was constituted, scientists connected with physical research continued to participate in Academy leadership. Jiří Niederle became a member of the Presidium of the Academy Council, while Karel Jungwirth from the Institute of Plasma Physics and Bedřich Velický from the Faculty of Mathematics and Physics were also represented in the new governing structure. Their presence should not be interpreted as evidence that physics dominated the Academy, which encompassed natural sciences, technical disciplines, life sciences, social sciences, and the humanities. It does, however, show that the physical-science community participated directly in decisions concerning institutional transformation rather than merely receiving reforms designed elsewhere. The emerging Czech research system was therefore shaped partly

through forms of scientific self-government in which practising researchers occupied important administrative and strategic roles. This relationship between disciplinary expertise and institutional governance became one of the defining features of the Academy model established in 1993.

The international significance of 1993 becomes particularly clear in the history of Czech participation in the European Organization for Nuclear Research (CERN). The Czech and Slovak Federal Republic had become a CERN Member State on 1 January 1992, only one year before the federation ceased to exist. Its membership formally ended when Czechoslovakia was dissolved on 31 December 1992. Both successor republics subsequently submitted applications for membership in their own right. CERN's Council delegates unanimously supported the accession of the Czech Republic and the Slovak Republic as separate Member States. Their membership became effective on 1 July 1993. This decision ensured that political separation did not interrupt the institutional connection between Czech high-energy physics and one of the most important centres of fundamental research in the world. CERN documentation preparing the Czech accession referred to the high level of scientific activity in the country and to its long-standing involvement in CERN's experimental programme. Membership carried financial obligations, representation in CERN governance, and opportunities for Czech researchers to participate systematically in experimental programmes and technological development. The 1993 accession therefore provided Czech physics with an immediate institutional anchor in European big science at the very beginning of independent statehood.

CERN membership also demonstrates that internationalisation had to be adapted to the economic realities of post-socialist transition. The arrangements negotiated for the new Czech Member State included a transitional contribution regime rather than immediately imposing the full financial burden associated with mature Western European research economies. CERN documents explicitly connected these arrangements with the country's transition from a centrally planned to a market economy. A later Council resolution extending the contribution schedule stated that savings generated by the transitional arrangement should help strengthen the Czech domestic infrastructure for high-energy physics. This point is important because membership in an international laboratory cannot substitute entirely for national scientific capacity. Researchers still require domestic departments, detector laboratories, computing facilities, technical expertise, doctoral training, and stable institutional support if they are to contribute meaningfully to large experiments. International access and national infrastructure therefore had to develop together. The CERN relationship already embodied in 1993 a model that would later become characteristic of Czech physics: selective domestic specialisation combined with participation in facilities whose scale exceeded national possibilities.

The opening of Czech physics to international science consequently involved more than the formal acquisition of memberships and agreements. Researchers gained much wider opportunities to attend conferences, work in foreign laboratories, establish collaborative projects, and participate in scientific networks that had previously been restricted by political circumstances. Physics benefited particularly from this opening because advanced experimental work often depends upon instruments, accelerators, observatories, and specialist techniques distributed across different countries. At the same time, the end of political isolation exposed technological gaps that could not be closed immediately. The 1993 Academy budget crisis made rapid modernisation more difficult precisely when international comparison was becoming more direct. Membership in CERN offered access to shared

infrastructure, but Czech groups still needed adequate domestic equipment and computing capacity to participate effectively. Laboratories also had to adapt to new standards of project preparation, reporting, publication, and international communication. These changes transformed the daily organisation of research even when the underlying scientific questions remained familiar. The growing use of computers, electronic communication, and international databases further altered the practical conditions under which physicists exchanged information and analysed results. Czech researchers were therefore entering a scientific environment that was becoming simultaneously more open and more technologically demanding. The early 1990s marked the beginning of this transition rather than its completion, and 1993 concentrated many of its institutional consequences into a single formative year.

The transformation of scientific communication can be observed even in the history of the principal Czech professional physics journal. The *Czechoslovak Journal of Physics* and related Czech-language professional publishing traditions had long helped connect national physicists across institutions and specialisations. A historical account of Czech physics publishing notes that the early 1990s brought major technological changes in typesetting, printing, computing, electronic mail, and later internet-based communication. The 1992 volume was the last to be produced through the older classical letterpress process used by the previous publishing system. From 1993 the Czech physics journal returned to the larger A4 format after several decades and entered a period of increasingly modern production. Such editorial details may appear peripheral to the history of research, but they reveal how rapidly the infrastructure of scholarly communication was changing. Scientific communities depend upon the circulation of articles, conference information, data, correspondence, and professional debate as much as upon the physical equipment inside laboratories. The technological modernisation of publication therefore formed part of the broader transformation through which Czech physics entered the information environment of the 1990s. It also symbolised the movement from an institutional culture dominated by older centralised production mechanisms towards a more flexible and increasingly digital scientific world.

The economic transformation simultaneously required a reconsideration of the relationship between fundamental physics and technological application. The history of nuclear research provides a particularly clear illustration because the applied Nuclear Research Institute had been privatised in 1992 while the Nuclear Physics Institute devoted mainly to basic research remained within the Academy. The new Academy did not interpret this differentiation as a reason to separate fundamental science completely from technological practice. Its constituting Assembly explicitly called for close cooperation with organisations engaged in applied research and for stronger links between research institutions and universities. This objective corresponded well with the historical character of Czech physical engineering, in which scientific investigation and technical application had long overlapped. The Faculty of Nuclear Sciences and Physical Engineering, for example, had been designed from its early decades to integrate mathematics, physics, nuclear science, materials, and engineering applications. The post-socialist economy nevertheless changed the mechanisms through which applied research could be organised and financed. Some activities increasingly had to interact with private enterprises and market demand, whereas long-term fundamental research remained dependent upon public institutional support. Physics occupied both sides of this evolving boundary because discoveries in materials, optics, electronics, plasma, and

nuclear processes could generate technological applications while still requiring non-commercial fundamental investigation. The arrangements emerging around 1993 therefore encouraged a dual model in which scientific autonomy and public support coexisted with growing expectations of technological relevance and external cooperation.

The dissolution of Czechoslovakia also demonstrates how political sovereignty and scientific continuity could coexist. The federal state disappeared, but the professional knowledge produced within it could not be divided neatly according to the new international border. Czech and Slovak physicists had been educated in common institutional systems and had worked within overlapping scientific networks for decades. CERN's response provides an especially revealing example because both successor states applied separately and were admitted as members on the same date in 1993. Their new national representation therefore emerged within an international organisation to which the common federation had already belonged. Czech institutes simultaneously inherited scientific traditions whose development had often involved researchers, institutions, and facilities from both parts of the former country. The political separation thus changed administration, budgetary responsibility, and international representation more rapidly than it changed the intellectual geography of physical science. Czech physics acquired a sovereign national institutional identity without becoming detached from the broader Central European and post-Czechoslovak scientific environment. In this respect, 1993 represents state separation accompanied by substantial continuity of scientific culture and professional relationships.

The geographical distribution of Czech physics further illustrates why independence involved reorganisation rather than creation. Prague contained the greatest concentration of research organisations, including the Institute of Physics, major university faculties, the Institute of Plasma Physics, and numerous laboratories concerned with instruments, electronics, mechanics, and related fields. The nuclear complex at Řež provided a specialised research environment outside the central city while remaining closely connected with Prague's scientific community. Ondřejov supplied a distinctive observational centre for astronomy and became the headquarters of the Astronomical Institute in 1993. The Czech Technical University and Charles University maintained several specialised facilities and departments whose research programmes interacted with Academy institutes. Physics-related institutions also existed beyond Prague, particularly in disciplines such as materials research, technical physics, instrumentation, and university-based science. This distributed structure meant that the new state inherited not a single metropolitan laboratory but a network of research sites with different historical functions. Coordination therefore required both national policy and institutional autonomy. The transformation of Academy sections in 1993 attempted to impose a coherent organisational framework without eliminating the specialised character of individual institutes. Geographical and disciplinary diversity could consequently become an advantage if institutions developed complementary rather than duplicative capabilities. The later emergence of major regional and specialised research centres was built upon this already differentiated physical-science landscape.

The first year of independence also changed the meaning of professional success for Czech physicists. Under the emerging system, an institute's historical prestige could no longer provide sufficient justification for its scientific programme. Competitive grants required proposals that could withstand expert assessment, while Academy reforms introduced more explicit evaluation of staff and institutional performance. International collaboration increasingly exposed research results to comparison with laboratories operating under

different methodological and technological conditions. Publication beyond the domestic scientific environment became correspondingly more important as researchers sought recognition within specialised international communities. At the same time, maintaining experimental continuity required protecting expertise that could not simply be replaced through short-term competition. A specialist responsible for an accelerator subsystem, precision instrument, observatory programme, or advanced materials technique represented accumulated knowledge as well as an individual employee. The emerging Czech system therefore had to distinguish between productive evaluation and destabilising loss of irreplaceable competence. This difficulty was particularly acute during a period when budget reductions and economic uncertainty already encouraged institutional contraction. Reform was consequently not a purely managerial matter, because decisions concerning staffing and finance could reshape the scientific possibilities available to the country for many years. The experience of 1993 established the basic problem that Czech research policy would repeatedly confront: how to combine openness and competition with the long-term continuity required by complex physical science.

Scientific autonomy acquired a similarly complex meaning during the creation of the new Academy. The founding resolutions emphasised the intention to build autonomous institutes rather than restore central administrative control over scientific questions. Autonomy allowed research communities to define programmes, elect or propose scientific leadership, and develop international connections with greater freedom than under the previous political system. Yet the Academy remained publicly financed and therefore accountable for the use of limited national resources. The introduction of evaluation, competitive grants, and fixed-term appointments represented mechanisms intended to reconcile scientific freedom with such accountability. Physics was an especially revealing field in this respect because researchers required freedom to pursue long-term theoretical and experimental questions whose eventual outcomes could not always be predicted. At the same time, particle detectors, accelerators, cryogenic systems, telescopes, lasers, and plasma devices demanded expenditure that inevitably attracted institutional scrutiny. Scientific autonomy therefore could not mean independence from evaluation or public responsibility. Instead, the post-1993 settlement gradually defined autonomy as the capacity to make scientific choices within transparent organisational and financial structures. This understanding differed both from centrally prescribed research planning and from a purely commercial model in which immediate economic return determined value. The new Czech Academy attempted to institutionalise precisely this intermediate position.

The changes of 1993 also reinforced the importance of cooperation between research and education. The Academy possessed specialised institutes and equipment, whereas universities provided systematic degree education and direct access to successive generations of students. The constituting Assembly explicitly envisaged universities, Academy institutes, and applied research as interconnected components of a wider scientific system. For physics, such cooperation was particularly logical because advanced students could participate in experimental or theoretical work that exceeded the resources of an ordinary teaching department. Academy researchers could contribute specialised expertise to university teaching, while university departments could provide doctoral candidates and young researchers to research institutes. This relationship also helped prevent the inherited Academy model from becoming separated from the educational mission of higher education. Although the institutional balance between universities and the Academy would continue to evolve, the

principle of cooperation was embedded in the new system from its first year. It later became essential to Czech participation in international research projects, where doctoral education and advanced research increasingly overlapped. The 1993 framework therefore strengthened the possibility of building integrated scientific communities across formal institutional boundaries.

The physical sciences were also well placed to benefit from the increasing emphasis on interdisciplinarity announced during the reorganisation. The Academy's 1993 institutional map already placed physics in contact with mathematics, informatics, materials research, engineering, atmospheric science, and scientific instrumentation. Nuclear physics relied upon chemistry, electronics, computing, materials, and radiation measurement, while plasma physics combined theoretical analysis with electrical and mechanical engineering. Astronomy increasingly depended upon sophisticated detectors, optics, signal processing, and computational techniques. Condensed-matter research occupied an equally porous boundary between fundamental physics, chemistry, materials engineering, and technological application. Such connections had existed before independence, but the new Academy explicitly presented interdisciplinarity as part of its modernising programme. This orientation made it easier to conceptualise physical science as a network of related research problems rather than a set of rigidly separated institutes. It also prepared the institutional culture for later fields such as nanoscience, photonics, advanced materials, computational physics, and quantum technologies. The importance of 1993 therefore extended beyond administrative reform because the new organisational discourse anticipated a more integrated understanding of scientific research.

In methodological terms, the year 1993 is best interpreted as a watershed precisely because neither the language of complete rupture nor that of simple continuity is adequate. Legal discontinuity was unmistakable: Czechoslovakia disappeared, the Czech Republic became sovereign, and the former federal Academy ceased to exist. Institutional continuity was equally evident because major physics institutes, university faculties, laboratories, observatories, scientific personnel, and research programmes remained active. What changed most profoundly were the rules under which these inherited resources had to operate. Funding increasingly combined institutional allocations with competitive projects, staff and institutes faced more formal evaluation, and scientific leadership operated within new self-governing structures. International organisations now dealt with the Czech Republic as an independent scientific state, as demonstrated dramatically by CERN membership in July 1993. Universities and Academy institutes were encouraged to cooperate more closely, while interdisciplinary work and international collaboration acquired greater strategic importance. Interpreting the period only as continuity would therefore obscure the powerful new incentives and constraints that were reshaping scientific behaviour. Interpreting it only as rupture would be equally misleading because the scientific capacities enabling later Czech achievements had been accumulated over many previous decades. The subsequent development of Czech physics emerged from the interaction of these two historical forces.

By the end of 1993, the fundamental institutional conditions for the next phase of Czech physical science had therefore been established. The Czech Academy of Sciences was operating as the successor to the former Czechoslovak Academy and had defined a new internal structure for its institutes. Major organisations in physics, nuclear science, astronomy, plasma research, materials, instrumentation, and related technical disciplines had survived the initial restructuring. Universities continued to provide the educational and research

foundations necessary for training new physicists and engineers. The national research-funding system had acquired a competitive component through the Grant Agency of the Czech Republic. Evaluation, fixed-term appointments, and institutional accountability were becoming normal parts of the reform agenda. Internationally, independent Czech membership of CERN secured immediate continuity with European high-energy physics and demonstrated that political separation need not produce scientific isolation. At the same time, budgetary contraction, technological modernisation, career uncertainty, and the need to compete internationally remained formidable unresolved problems. The remainder of the 1990s and the early 2000s would therefore be devoted less to establishing the legal existence of Czech physics than to testing whether its institutions could adapt successfully to this new environment. The watershed of 1993 created the framework; the following decade would determine how effectively inherited scientific strength could be converted into modern research competitiveness.

The First Post-Czechoslovak Stage: The 1990s and Early 2000s as a Period of Institutional Adaptation and International Reconnection

The decade following the establishment of the independent Czech Republic was a period in which the institutional settlement created in 1993 had to prove that it could sustain internationally competitive physical science. Czech physics did not begin this stage from an institutional vacuum, because the country inherited specialised Academy institutes, strong university departments, accelerator facilities, observatories, plasma devices, materials laboratories, and experienced research communities. The immediate problem was therefore not reconstruction from nothing but adaptation of inherited capacity to a radically different system of governance, funding, evaluation, and international exchange. During the 1990s, research organisations had to function under tighter financial constraints while simultaneously modernising equipment, rebuilding foreign contacts, and learning to compete for project-based support. Universities were expected to strengthen the research component of doctoral education, while Academy institutes were required to justify their programmes through increasingly explicit evaluation. For experimental physics, these pressures were unusually demanding because scientific continuity depended on maintaining costly instruments and teams with highly specialised technical knowledge. The opening of borders and access to Western laboratories created opportunities that had been restricted before 1989, but it also made differences in equipment and research resources much more visible. Czech physicists consequently entered the decade with considerable intellectual strengths but with an urgent need to reconnect those strengths to contemporary European research practices. By the early 2000s, the essential mechanisms of this adaptation were increasingly visible in competitive grants, international memberships, European programme participation, joint laboratories, and modernised research facilities. The first post-Czechoslovak stage can therefore be understood as the period in which scientific continuity was converted into a new capacity for international participation rather than merely preserved in institutional form.

The Czech Academy of Sciences (CAS) remained one of the principal anchors of physical research throughout this transition, but its internal culture changed substantially after the institutional reforms of 1993. The Academy combined baseline institutional financing with a

growing use of targeted project funding, thereby requiring institutes to maintain long-term research programmes while also competing for specific resources. This mixed model was particularly important for physics because accelerator operations, observatories, plasma devices, and advanced materials laboratories could not be supported through short grants alone. At the same time, competitive mechanisms created incentives for research groups to formulate clearly defined projects and demonstrate scientific relevance beyond their own institutions. The Academy's emphasis on international projects and exchanges also encouraged institutes to treat foreign collaboration as a normal component of research rather than an exceptional privilege. Physical-science institutes responded by widening partnerships, hosting foreign visitors, sending researchers abroad, and participating more intensively in multinational experiments. The transition was uneven, because financially constrained laboratories could not modernise at the same speed as better connected groups. Nevertheless, the institutional framework increasingly rewarded scientific quality, international visibility, and the ability to secure external support. By the end of the 1990s, the Academy system had moved significantly away from the organisational assumptions inherited from centrally planned science, even though its core physics institutes and research traditions remained recognisably continuous.

The creation and consolidation of the Grant Agency of the Czech Republic (GA CR) was one of the most important structural changes affecting basic physics during this period. The Agency began operating in 1993 and introduced an annual competitive mechanism through which investigators could propose projects from any field of fundamental research. Standard projects were generally designed for two or three years, and their topics were selected by applicants rather than prescribed centrally. This model increased the importance of peer review, comparative assessment, and clearly formulated scientific objectives. For physicists, the new system provided an additional route for financing specialised experiments, theoretical work, computing, equipment upgrades, and collaborative teams. It also allowed researchers from different institutions to cooperate within the same project, thereby weakening some of the barriers between university and Academy environments. The practical effects can be seen in projects at the Nuclear Physics Institute and the Institute of Plasma Physics, where Grant Agency funding supported accelerator improvements, turbulence studies, plasma modelling, and other programmes during the 1990s and early 2000s. Competitive funding did not remove the need for institutional support, because large devices still required stable technical staff and continuous maintenance. It did, however, change the intellectual economy of research by making the formulation of project-level novelty increasingly important. Younger researchers also entered a system in which securing competitive grants became part of professional advancement. By the early 2000s, the coexistence of institutional and project financing had become a normal feature of Czech physical science.

University physics underwent a parallel adjustment as research became more tightly connected with graduate education and international cooperation. The Faculty of Mathematics and Physics at Charles University retained its strong disciplinary breadth, while the Faculty of Nuclear Sciences and Physical Engineering at the Czech Technical University in Prague continued to combine mathematics, physics, nuclear science, materials, and engineering. Both institutions increasingly operated in an environment where participation in external research collaborations influenced teaching, doctoral supervision, and access to modern instrumentation. The Czech Technical University's training reactor, commissioned in 1990, provided a distinctive educational and experimental resource for nuclear and reactor physics.

At Charles University, research groups became deeply involved in international particle-physics projects at the European Organization for Nuclear Research (CERN), Deutsches Elektronen-Synchrotron (DESY), and other laboratories. International mobility gradually became more attainable for students and staff, and formal agreements with foreign universities expanded during the late 1990s and early 2000s. These developments strengthened the connection between domestic degree programmes and frontier research environments abroad. The university sector therefore became an increasingly active component of national research rather than a system concerned primarily with teaching.

High-energy physics provides one of the clearest examples of successful international reconnection during the first post-Czechoslovak stage. Czech researchers did not have to build their participation in major European experiments from the beginning, because groups from the Institute of Physics and Charles University had already joined large collaborations before 1989. Two especially important commitments were the DELPHI (Detector with Lepton, Photon and Hadron Identification) experiment at CERN and the H1 experiment at DESY in Hamburg. Czech groups participated in the preparation and operation of DELPHI and, from 1992, worked as regular member laboratories rather than through the earlier framework of the Joint Institute for Nuclear Research in Dubna. The first phase of the Large Electron-Positron Collider programme provided precision measurements of the Z boson and tests of the Standard Model, while the higher-energy phase from 1996 to 2000 extended studies to W-boson production and searches for new phenomena. Participation exposed Czech teams to detector construction, electronics, software, data analysis, and the organisational culture of very large collaborations. H1 provided a complementary connection with deep-inelastic electron-proton scattering and the internal structure of the proton. These programmes gave the post-1993 generation of Czech particle physicists a direct route into the central experimental questions of international high-energy physics. They also created professional networks that later facilitated the transition towards experiments at the Large Hadron Collider. The importance of this continuity was institutional as well as scientific, because it demonstrated that Czech groups could function as reliable partners in collaborations whose technical and organisational standards were set internationally.

Independent Czech membership of CERN from 1 July 1993 transformed this participation into a stable state-level relationship rather than a collection of individual laboratory contacts. Membership meant that the Czech Republic contributed to CERN's budget, held representation in the Council, and secured long-term institutional access to the Organisation's scientific programmes. The arrangement was especially significant because it followed immediately after the dissolution of Czechoslovakia, whose CERN membership had begun only in 1992. Transitional financial arrangements acknowledged the economic conditions of the new Czech state while preserving full scientific membership. CERN documents explicitly connected part of this transition with the need to strengthen domestic high-energy physics infrastructure, showing that international access was understood to require a viable national base. Czech groups continued to participate in experimental programmes while training students and engineers who could work with detectors, computing systems, and complex collaborative procedures. Membership also offered a powerful model of scientific internationalisation in which a medium-sized country could contribute specialised expertise to facilities it could never reproduce nationally. This model became increasingly influential in other branches of Czech physics during the following decade. CERN therefore served not only

as a research site but also as an institutional school for the broader Europeanisation of Czech science.

By the turn of the millennium, particle physics had become sufficiently consolidated for Czech institutions to develop more structured domestic cooperation around their international commitments. A Centre for Particle Physics operated from July 2000 to the end of 2004 and brought together much of the related research activity associated with the Institute of Physics and collaborating university groups. The centre emerged from a community whose experience included DELPHI at CERN, H1 at DESY, and other international projects. Its existence illustrates how foreign collaboration could stimulate organisational consolidation within Czechia rather than simply draw researchers outward. Experimental particle physics required shared expertise in detector technology, computing, phenomenology, and data analysis, making cooperation across institutional boundaries particularly valuable. The domestic research environment also provided continuity for students who spent only part of their training at international laboratories. By this stage, Czech physicists were no longer merely re-establishing contacts severed or constrained during the Cold War. They were beginning to organise national research structures around sustained participation in multinational scientific programmes. This transition would become decisive when preparations for Large Hadron Collider experiments intensified in the early 2000s. It also reinforced the idea that internationalisation could strengthen national scientific capacity when external collaboration and domestic institution-building developed together. The particle-physics experience thus became one of the clearest early examples of successful post-Czechoslovak adaptation.

Nuclear physics followed a less visible but equally important path of technical modernisation at the Nuclear Physics Institute in Řež. The U-120M isochronous cyclotron, originally commissioned in 1977, remained a central experimental instrument and underwent substantial upgrades during the 1990s. An axial injection system was developed and implemented during the first half of the decade, while a project for accelerating negative ions was pursued from 1992 to 1996. A new computerised control system based on a local-area network was introduced in 1995–1996. The key conversion enabling negative-ion acceleration was completed in 1996–1998 and increased extracted beam currents by approximately an order of magnitude. These improvements extended the usefulness of an inherited Czechoslovak machine rather than replacing it with an entirely new accelerator. The cyclotron thereby continued to support both fundamental nuclear experiments and applied irradiation work. This pattern of incremental modernisation was characteristic of the financially constrained but technically ambitious research environment of the decade.

The modernisation of the U-120M also shows how project funding and institutional engineering capacity interacted in practice. Accelerator specialists at Řež did not treat the machine as a static legacy device, but continually redesigned injection, extraction, control, cooling, and target systems. A Grant Agency project supported the magnetostatic axial injector during the 1990–1995 period, providing a direct example of new competitive funding contributing to infrastructure renewal. The accelerator's flexibility allowed proton, deuteron, helium, and later negative-ion beams to support a wide range of measurements and applications. Development of high-intensity fast-neutron sources further broadened the experimental possibilities available at the institute. Such work required physicists, engineers, electronics specialists, vacuum experts, and technicians to cooperate over many years. The resulting competence could not be separated neatly into fundamental and applied categories because improved accelerator performance benefited nuclear-data measurements, materials irradiation,

radionuclide production, and method development simultaneously. Modernisation therefore preserved the value of older infrastructure while aligning it more closely with contemporary experimental requirements. The Řež experience demonstrates that post-1993 scientific adaptation often depended less on spectacular new construction than on sustained technical renewal of inherited facilities. By the end of the 1990s, the upgraded cyclotron had become a stronger platform for both domestic research and international collaboration.

The vulnerability of this infrastructure became dramatically visible during the severe floods of 2002. The U-120M cyclotron and associated systems at Řež were affected, forcing an extensive programme of repair, replacement, and technical reconstruction. The institute subsequently modernised flooded subsystems rather than abandoning the accelerator. A new cooling system was introduced in 2002 as part of the recovery and improvement programme. The episode demonstrated the importance of maintaining domestic engineering knowledge around specialised research devices. External procurement alone could not substitute for staff who understood the history, configuration, and operational behaviour of the machine. The recovery also showed that research infrastructure is a long-term institutional commitment rather than a one-time capital purchase. By restoring the facility, the Nuclear Physics Institute preserved experimental continuity at a moment when the Czech research system was preparing for deeper European integration. The 2002 floods thus became an unintended test of the resilience developed during the first decade of the independent republic.

Plasma physics underwent one of the most extensive internal restructurings among Czech physical-science institutes. Between 1990 and 1992, the Institute of Plasma Physics reduced its workforce by roughly half, simplified management, and placed greater emphasis on scientific outputs. This contraction preceded formal Czech independence but shaped the conditions under which the institute entered the post-Czechoslovak period. Research nevertheless continued on the CASTOR (Czech Academy of Sciences TORus) tokamak, plasma turbulence, wave-particle interactions, discharges, X-ray diagnostics, and technological applications of plasma. During 1994, a four-channel X-ray spectrometer built at the institute was installed on the TCV (Tokamak à Configuration Variable) tokamak at the École Polytechnique Fédérale de Lausanne in Switzerland. Czech researchers also pursued numerical studies of anomalous ion diffusion and other problems relevant to tokamak physics throughout the second half of the decade. In 1996, a fast capillary-discharge experimental facility began operation and supported work connected with compact X-ray laser physics. These activities indicate that organisational contraction did not lead to scientific withdrawal from advanced plasma research. On the contrary, the institute increasingly combined domestic experiments with contributions to foreign devices and international projects. The restructuring therefore produced a smaller but more externally connected research environment. This evolution prepared the Institute of Plasma Physics for the decisive European integration that followed at the end of the decade.

The signing of the association agreement between the European Atomic Energy Community (EURATOM) and the Institute of Plasma Physics in December 1999 marked a major turning point. The agreement was explicitly intended to integrate the Czech Republic into European controlled-fusion research. It created a formal EURATOM–Institute of Plasma Physics association and connected Czech researchers with the coordinated fusion programmes operating across Europe. Subsequent arrangements opened participation in the Joint European Torus programme, researcher mobility schemes, coordinated technology development, and shared high-performance computing resources. The agreement

transformed fusion research from an international interest pursued through individual contacts into an organised national contribution to a common European programme. It also imposed expectations concerning work programmes, reporting, coordination, and strategic alignment with broader European objectives. For Czech plasma physicists, this framework greatly expanded access to expertise and facilities while preserving CASTOR as a domestic experimental platform. The association therefore became one of the earliest examples of a Czech physics field being institutionally integrated into a European research architecture before the country's accession to the European Union.

International reconnection in plasma physics was visible not only through formal agreements but also through the ability to convene large scientific meetings in Prague. The Institute of Plasma Physics hosted an international steering committee meeting of a United Nations Educational, Scientific and Cultural Organization project on dense magnetised plasma in 1995. In 1996 it organised the eleventh International Conference on High Power Particle Beams with worldwide participation. Two years later Prague hosted the International Congress on Plasma Physics together with the twenty-fifth European Physical Society Conference on Controlled Fusion and Plasma Physics. The 1998 meeting attracted nearly one thousand specialists from around the world. In 1999 the Institute organised the fourteenth International Symposium on Plasma Chemistry for approximately five hundred participants. These events were significant because scientific internationalisation involves the capacity to host global networks as well as to send researchers abroad. Conferences brought foreign expertise into direct contact with Czech students, laboratories, and research programmes. They also helped position Prague as a recognised meeting place for plasma and fusion science. The dense sequence of international events during the second half of the 1990s therefore provides a useful indicator of how quickly Czech plasma physics re-entered mainstream professional circulation. This visibility also strengthened the case for deeper participation in coordinated European fusion research.

Laser physics became another field in which international cooperation produced a transformative piece of domestic infrastructure. Czech laser research retained expertise from the PERUN and PERUN II iodine-laser systems developed before independence, but the scale of experimentation remained limited by available equipment. In June 1997, an agreement was signed for the transfer of the ASTERIX IV high-power laser from the Max Planck Institute for Quantum Optics in Garching to Czech institutions. The Czech Academy of Sciences became the operator, and the project was organised jointly by the Institute of Physics and the Institute of Plasma Physics. Funding for the Prague Asterix Laser System (PALS) facility was approved in December 1997. Construction of the building was completed in March 1999, followed by installation and commissioning of the laser and target systems later that year. Operational testing continued from November 1999 to May 2000. The completed system was formally launched on 8 June 2000. The transfer illustrates a particularly productive form of post-Cold War scientific circulation in which advanced equipment from a Western European laboratory was not merely donated but integrated into a new research centre with its experimental programme. PALS therefore became both a symbol and a practical instrument of Czech reintegration into European high-energy-density and laser-plasma physics.

The early operation of PALS quickly moved beyond national use and adopted the model of an international research infrastructure. Under the Fifth Framework Programme, the European Commission supported the Prague Asterix Laser System as a joint research centre and transnational-access facility. The system delivered roughly kilojoule-class pulses on the sub-

nanosecond timescale and generated hot dense plasmas, intense X-ray radiation, highly charged ions, and extreme pressures. These capabilities made it relevant to laser-plasma physics, radiation physics, laboratory astrophysics, and related high-energy-density research. European funding also supported training stays for doctoral researchers from European Community and associated countries. The training programme combined experiments, computer modelling, and theoretical analysis, illustrating how infrastructure and human-resource development were deliberately linked. PALS consequently helped reverse the earlier one-way pattern in which Czech researchers primarily travelled abroad to gain access to advanced equipment. Foreign scientists could now come to Prague for experiments that required a specialised laser unavailable in many of their home institutions. This user-oriented model anticipated the much larger European laser infrastructures later developed in Czechia and made PALS a crucial bridge between the scientific reconnection of the 1990s and the infrastructure expansion of the following decade.

The Europeanisation of Czech research policy accelerated sharply around the same time. In 1999 the Czech Republic became fully associated with the European Union's Fifth Framework Programme (FP5) for research and technological development. Association allowed Czech universities, research institutes, and companies to participate in projects under essentially the same conditions as organisations from European Union Member States. Czechia also participated in the corresponding EURATOM research programme, which was particularly relevant to nuclear and fusion science. This pre-accession arrangement was explicitly intended to accelerate integration of candidate countries into the European scientific and technological community. For physicists, FP5 created additional opportunities to join multinational consortia, access research infrastructures, organise workshops, and support mobility. The PALS project provides a concrete example of Czech physics benefiting from this new framework. European records also document Czech-led activities in fusion technology and materials-related research during the same period. The significance of FP5 therefore lay not only in additional finance but in the normalisation of competitive multinational project work before Czech membership of the European Union. It trained institutions in the administrative, collaborative, and evaluative practices that would become even more important after 2004. The programme thus became a practical rehearsal for full participation in the European Research Area.

This European opening interacted with older bilateral and regional networks rather than replacing them. Czech physicists continued close scientific relations with Slovak colleagues despite the political separation of 1993. Archival records of the Slovak Academy of Sciences show that CERN cooperation remained an organised concern before and after the division of the federation, with separate Czech and Slovak arrangements growing out of a shared Czechoslovak framework. University agreements also demonstrate continued Czech-Slovak exchange during the early 2000s. The Faculty of Mathematics and Physics at Charles University, for example, concluded cooperation agreements with Slovak institutions that included staff and student exchange, joint research, doctoral supervision, conferences, and international grant applications. Such links were facilitated by linguistic proximity and by professional networks created during decades of common statehood. German, Austrian, Swiss, French, Italian, and other Western European connections expanded at the same time. Czech scientific internationalisation was therefore geographically plural rather than a simple movement from an eastern to a western orientation.

Optics offers a particularly clear example of regional institutional adaptation within Czechia itself. The Joint Laboratory of Optics in Olomouc had been established before independence as a shared workplace linking Palacký University and the Institute of Physics. Political and organisational changes around 1989–1990 altered its leadership and ended the earlier system of centrally planned scientific research. During the 1990s, the laboratory was strengthened by younger researchers and gradually concentrated theoretical, experimental, and technical activities in improved facilities. A modern building was completed in 1996 after a prolonged construction process constrained by the financial limitations of both the former Academy system and Palacký University. Research in Olomouc connected applied optics with quantum and nonlinear optics, optical technologies, and later experimental particle and astroparticle physics. In 1997, local researchers built an early quantum-cryptographic system, and an original protocol for quantum mutual identification was implemented two years later. These developments show that modernisation was not confined to the Prague metropolitan research environment. They also demonstrate how a joint university–Academy laboratory could preserve institutional continuity while adapting its scientific profile to new technological and conceptual fields. The Olomouc case therefore broadened the geographical and disciplinary map of post-1993 Czech physics.

The Olomouc experience is important because it reveals the emergence of a more polycentric national physics system during the transition years. Prague retained the country's greatest concentration of institutes and universities, but significant capabilities existed in regional centres with distinctive profiles. Palacký University combined optics with laboratory development and international contacts, while other universities strengthened specialised work in materials, astrophysics, and engineering physics. Regional laboratories often benefited from closer links between teaching, research, and locally relevant technical expertise. Their survival also reduced the danger that the restructuring of Czech science would concentrate nearly all advanced physics in the capital. At the same time, regional institutions remained dependent on national grant competitions and on access to international partners for equipment and specialist knowledge. The post-1993 model therefore produced neither complete decentralisation nor rigid metropolitan dominance. Instead, it encouraged a differentiated research geography in which smaller centres could become internationally visible through specialised fields. This pattern would later become much more pronounced as European structural funds supported major research centres outside Prague.

Condensed-matter and materials physics also changed substantially as Czech laboratories reoriented towards internationally competitive research problems and methods. Existing strengths in solid-state physics, semiconductors, metals, magnetism, defects, and structural characterisation provided a strong platform inherited from the Czechoslovak period. The transition economy simultaneously exposed materials research to new industrial conditions and to the restructuring of traditional manufacturing sectors. Research groups therefore had to balance fundamental investigation with a changing landscape of technological demand. The Faculty of Nuclear Sciences and Physical Engineering retained a distinctive tradition of combining the physics of materials with mechanics and engineering applications. Academy institutes likewise preserved expertise in solid-state and materials research while expanding international collaboration and publication. Improved computing enabled more extensive theoretical modelling, while advances in microscopy and spectroscopy increasingly shaped experimental practice. These changes were gradual rather than dramatic, but they were crucial to the later emergence of Czech strengths in nanophysics, functional materials, spintronics,

and quantum materials. The 1990s were therefore a period in which older materials traditions were progressively reframed within the conceptual language of modern condensed-matter science. This reframing illustrates the broader pattern of the decade: inherited expertise was rarely abandoned, but its scientific questions and international reference points changed substantially. The field thus became a foundation for later innovation rather than a remnant of the earlier research system.

Scientific instrumentation formed an equally important but sometimes less visible component of this adaptation. Czech physics had long depended on institutes and technical groups capable of designing detectors, optical systems, vacuum equipment, electronics, control systems, and precision measurement devices. The transition to international collaboration increased the value of such engineering competence because large experiments require partners able to deliver technically reliable components rather than only analyse data. Upgrades of the U-120M cyclotron, construction of plasma diagnostics, participation in DELPHI and H1, and development of PALS all depended upon domestic technical expertise. In many cases, the most durable contribution of Czech groups to an international project was embodied in instrumentation and software rather than in a single headline scientific result. This technical culture also supported knowledge transfer into industry and other scientific disciplines. Maintaining it during years of institutional contraction was therefore strategically important. The survival of workshops, engineering teams, and experimental know-how enabled Czech physics to enter later European infrastructure projects from a position of practical competence.

A further transformation concerned the social organisation of scientific careers. The competitive environment encouraged researchers to obtain external grants, publish internationally, and spend periods in foreign laboratories, creating career expectations different from those prevailing under late socialism. Doctoral students were increasingly incorporated into active research projects with international partners rather than being trained only within nationally bounded programmes. English became progressively more important as the language of publication, conferences, collaborative meetings, and technical documentation. International mobility widened intellectual horizons but also intensified concerns about the loss of talented researchers to wealthier scientific systems. Czech institutions therefore faced the dual task of encouraging outward experience while retaining or attracting researchers capable of sustaining domestic laboratories. By the early 2000s, the Czech Academy had begun to introduce measures specifically intended to support promising young scientists. The Otto Wichterle Award, established in 2002, symbolised this growing awareness of early-career development within the Academy system. Although such measures could not resolve all structural career problems, they indicated that generational renewal had become an explicit institutional priority. The human dimension of internationalisation was consequently inseparable from questions of salaries, career stability, mobility, and access to competitive research environments.

Research legislation also continued to evolve as the provisional arrangements of the early transition matured. In 2002, the Czech Republic adopted Act No. 130/2002 Coll. on the support of research and development from public funds. European Commission assessments of the accession process treated the law as an important step in the development of the Czech research system. It clarified mechanisms for allocating public support, established responsibilities for research providers and recipients, and strengthened the formal framework for evaluation. The law therefore consolidated principles that had emerged during the previous

decade rather than introducing them for the first time. Competitive funding, institutional support, public calls, and assessment were increasingly embedded in a coherent legal architecture. For physics institutes, the significance of the reform lay in greater procedural stability at a moment when participation in European programmes was expanding. The legislation also helped align Czech research governance more closely with practices expected within the European Union. By the early 2000s, the institutional experimentation of the 1990s was thus giving way to a more codified system of research administration. This transition from improvisation to formalisation was one of the clearest signs that the post-Czechoslovak adaptation phase was approaching completion. The law also provided a durable legal basis for the mixed funding model on which many physics institutions increasingly depended.

Financial conditions nonetheless remained a persistent constraint. European Commission reporting recorded a gradual increase in Czech public research support around the turn of the millennium, but the system still operated with substantially fewer resources than the largest Western European research economies. Physics was especially sensitive to this gap because experimental competitiveness often depends on capital equipment, maintenance, computing, and highly specialised technical staff. International participation partly mitigated the problem by giving Czech researchers access to facilities such as CERN, DESY, and European fusion laboratories. However, access abroad could not replace domestic laboratories capable of preparing experiments, training students, and developing instruments. The most successful fields therefore combined international facility access with selective national investment. PALS, the modernised U-120M cyclotron, CASTOR, and university laboratories illustrate this hybrid strategy. The policy challenge was to avoid spreading limited resources so thinly that no field could maintain internationally credible capability. This pressure encouraged increasing differentiation among institutes and the gradual concentration of effort around areas with established expertise.

The broader accession process to the European Union supplied an external timetable for this institutional maturation. European Commission reports during the late 1990s and early 2000s generally assessed Czech progress in research and technological development positively. Full association with FP5 in 1999 was followed by deeper participation in European research networks, while the 2002 legislation strengthened the national funding framework. By 2003, the Commission judged that Czechia would be able to implement the relevant research acquis from the moment of accession. For physicists, this political process mattered less because European law directly prescribed scientific questions than because it normalised access to common programmes, funding rules, mobility schemes, and evaluation cultures. Institutes learned to build international consortia and to present projects within European thematic priorities. Administrators acquired experience with contractual and reporting practices that differed from purely national grant management. Researchers became accustomed to competition across borders rather than only within Czech disciplinary communities. The scientific significance of European integration was therefore cumulative and organisational before it became infrastructural on the much larger scale seen after 2004. By the eve of accession, European cooperation had already become embedded in the routine operation of many Czech physics groups. The accession process thus closed the experimental phase of international reconnection and opened a period of deeper structural integration.

The period also changed Czech perceptions of what counted as a successful research institution. Survival after the financial contraction of the early 1990s was no longer sufficient evidence of scientific strength. Institutes increasingly sought external grants, international

publications, foreign partners, competitive doctoral candidates, and recognised experimental capabilities. Universities likewise came to regard research cooperation as central to institutional prestige rather than as a secondary activity alongside teaching. Large international collaborations provided benchmarks against which technical reliability and scientific productivity could be judged. Domestic centres such as PALS demonstrated that Czech institutions could themselves become destinations for foreign researchers. Regional laboratories such as the Joint Laboratory of Optics showed that international relevance did not require location in Prague if a specialised competence could be developed. The emerging standard of excellence was therefore relational: a strong Czech laboratory was one that could occupy a meaningful position within wider scientific networks. This shift in expectations helped move the national system away from inherited institutional status towards more dynamic forms of scientific legitimacy.

By the early 2000s, the scientific map of Czech physics had thus become more connected, competitive, and technologically differentiated than it had been at the beginning of the independent state. Particle physicists were embedded in CERN and DESY collaborations, nuclear physicists had modernised the Řež accelerator complex, and plasma researchers were incorporated into the European fusion programme. Laser physicists had transformed the transfer of ASTERIX IV into the PALS user facility, while optics researchers in Olomouc were developing quantum and applied optical technologies. University departments increasingly linked doctoral education with active research networks abroad. Competitive grants and revised legislation supplied a more stable framework for selecting and financing projects. International conferences held in Prague indicated that Czech institutions could again function as conveners within European and global scientific communities. At the same time, material constraints, uneven infrastructure, and career pressures remained significant weaknesses. The first post-Czechoslovak stage therefore produced neither complete convergence with Western European science nor a simple continuation of inherited structures. Its central achievement was the creation of institutional mechanisms through which Czech physicists could participate continuously and credibly in international research while retaining domestic scientific capacity. This combination of openness and continuity prepared the system for a more ambitious phase of consolidation after 2004.

In historical perspective, the years from the mid-1990s to the early 2000s formed a bridge between the institutional rupture of 1993 and the infrastructure-centred expansion that followed European Union accession. The period stabilised competitive grant funding, normalised external evaluation, strengthened university–Academy cooperation, and re-established international mobility as an ordinary feature of scientific life. It also demonstrated that inherited Czechoslovak facilities could remain valuable when they were technically renewed and linked to international programmes. The U-120M, CASTOR, and the established university laboratories survived not because they were protected from change but because their scientific roles were repeatedly redefined. At the same time, PALS showed that Czech institutions could acquire and successfully operate advanced equipment transferred from a leading Western European centre. CERN membership and EURATOM association provided two distinct models of participation in large international scientific structures. Full association with FP5 then extended this logic across the wider European research system before formal European Union membership. By 2003, the Czech physics community had acquired the organisational experience necessary to compete for larger collaborative projects and infrastructures. The major expansion of the following decade would therefore rest on

foundations constructed during this quieter but decisive period of adaptation. The first post-Czechoslovak stage should consequently be regarded as the moment when international reconnection ceased to be a corrective to past isolation and became a permanent structural principle of Czech physical science. This was the institutional legacy carried into the next stage of consolidation.

European Integration and Scientific Consolidation: The 2000s as the Formation of a Modern Physics Research Architecture

The first decade of the twenty-first century represented a decisive stage in the transformation of Czech physics from a post-transition research system into an increasingly consolidated component of European science. By 2000, the basic institutional structures created after the dissolution of Czechoslovakia had stabilised, and the principal challenge was no longer simply to preserve laboratories and research schools. Czech institutions now had to improve scientific quality, renew equipment, strengthen doctoral training, and participate more effectively in competitive international programmes. This task coincided with the Czech Republic's political preparation for membership of the European Union and with the wider European effort to construct a common research area. Physics was especially sensitive to these developments because many of its leading fields depended on expensive infrastructures, distributed computing, highly specialised instrumentation, and multinational collaboration. During the decade, Czech researchers deepened their participation in particle and nuclear physics, fusion science, astronomy, laser physics, condensed matter, and materials research. They also began to move from international reconnection towards more systematic institutional integration, in which participation abroad was matched by the development of stronger facilities at home. The accession of the Czech Republic to the European Union in 2004 accelerated this process by widening access to common programmes, structural funding, and research networks. By the end of the decade, projects such as COMPASS, the preparation of the Extreme Light Infrastructure, and the emerging Central European Institute of Technology demonstrated that the country was beginning to plan research architecture on a scale that would have been difficult to imagine in the early 1990s. The 2000s should therefore be understood as the decade in which Czech physics acquired the institutional, legal, financial, and international foundations for the infrastructure expansion of the 2010s.

One of the most important elements of consolidation was the gradual codification of the national research system. Act No. 130/2002 Coll. established a more comprehensive legal framework for public support of research and development and clarified the distinction between institutional and targeted funding. The law formalised procedures for public competitions, research programmes, evaluation, and the responsibilities of funding bodies and recipients. For physics institutes, this mattered because long-term institutional support could be combined with competitive project resources rather than treated as mutually exclusive alternatives. The resulting framework created greater predictability for organisations maintaining costly laboratories, while preserving incentives for teams to compete for specific research objectives. It also brought Czech procedures into closer alignment with the standards increasingly expected within the European research environment. The law did not resolve

persistent funding limitations, but it reduced some of the legal uncertainty associated with the transformation period. By the middle of the decade, research governance had therefore become more rule-based and less dependent on provisional arrangements inherited from the 1990s. This legal consolidation was an essential prerequisite for larger investments that required stable institutions capable of assuming long-term financial and technical obligations.

A second institutional reform concerned the legal status of the research institutes of the Czech Academy of Sciences. During 2004 and 2005, the Academy prepared a structural transformation linked to the creation of public research institutions under Act No. 341/2005 Coll. The Academy Assembly explicitly connected the transformation with previous evaluation results, the quality of research programmes, the strength of scientific teams, and the ability of institutes to obtain competitive resources. From 1 January 2007, Academy workplaces selected under this process became public research institutions with their own legal personality. The new status gave institutes a clearer framework for managing property, contractual relations, cooperation, and supplementary activities while preserving the Academy as their founder. The statutes adopted in this period also emphasised research evaluation, international cooperation, postgraduate education, and the provision of research infrastructure. For physics, the change was highly consequential because major experimental institutes routinely entered complex contracts, maintained expensive equipment, and cooperated with foreign organisations over long periods. Greater organisational autonomy therefore improved their ability to operate as partners in multinational projects. At the same time, supervisory boards, scientific councils, and regular evaluation created mechanisms intended to maintain public accountability. The reform consequently strengthened the institutional capacity of Academy physics without converting its institutes into private or commercially driven organisations. It provided a durable legal architecture that would later support large infrastructure projects and more extensive international partnerships.

The Czech Republic's accession to the European Union on 1 May 2004 transformed the external environment in which this consolidated research system operated. Czech researchers had already participated in European programmes before accession, but membership made their involvement part of the ordinary institutional life of the Union. The European Research Area became an increasingly important framework for mobility, collaborative projects, infrastructure planning, and research policy. Physics benefited because many frontier questions required resources and expertise distributed across several countries. Czech institutions could now approach European programmes not primarily as organisations from a candidate country seeking integration, but as partners from a Member State sharing responsibility for common research objectives. This altered both the scale of opportunity and the expectations placed upon research management. European integration therefore became a structural condition of Czech physical science rather than an external supplement to national policy. It also reinforced the view that international competitiveness depended on institutional quality at home as much as on access to laboratories abroad. The political event of accession thus had direct organisational consequences for the practice of science.

The Sixth Framework Programme for Research and Technological Development (FP6) provided an early arena in which Czech institutions could operate within this enlarged European setting. FP6 ran from 2002 to 2006 and placed strong emphasis on networks of excellence, integrated projects, researcher mobility, and the development of the European Research Area. Czech universities and Academy institutes participated in projects and scientific events that connected domestic research directly with European disciplinary communities. A visible

example occurred in 2004, when Charles University coordinated the twentieth General Conference of the Condensed Matter Division of the European Physical Society in Prague together with the Czech Physical Society and the Institute of Physics. The conference covered the breadth of condensed-matter physics and materials science and was supported as an FP6 activity. Its organisation in Prague during the year of European Union accession was symbolically appropriate, but its importance was more than ceremonial. It demonstrated that Czech physicists could convene a major European disciplinary meeting rather than participate only as visitors to events elsewhere. Similar project-based cooperation expanded professional networks and familiarised institutions with the financial and administrative rules of European research. The increasing presence of Czech groups in multinational consortia also encouraged more systematic project management within universities and Academy institutes. These practices gradually became part of the normal organisational competence required for competitive physics. European programmes were thus contributing to institutional modernisation at the same time as they financed specific scientific activities.

The Seventh Framework Programme (FP7) began in 2007 and extended the European logic of collaborative research, investigator-driven excellence, mobility, and infrastructure access. Its scale was much larger than that of previous Framework Programmes and its structure included programmes devoted to cooperation, ideas, people, and research capacities. For Czech physicists, FP7 coincided with a period when domestic institutions were legally more autonomous and increasingly capable of entering complex international projects. The programme also strengthened links between research policy and the emerging European Strategy Forum on Research Infrastructures agenda. Participation required groups to compete not only on scientific merit but also on consortium design, management capacity, and the ability to define European added value. This favoured laboratories with established international contacts and clear areas of specialisation. It also encouraged researchers to think in terms of shared platforms and distributed infrastructures rather than isolated national facilities. By the end of the decade, European project culture had become deeply embedded in the planning of many Czech research organisations. The effects were especially visible in fields such as lasers, fusion, particle physics, materials, and astronomy, where transnational access and infrastructure coordination were intrinsic to the research itself.

The financial environment supporting this consolidation improved in absolute terms, although Czech research intensity remained below the level of the leading Western and Nordic European states. Czech Statistical Office data show that gross domestic expenditure on research and development rose from 1.23 per cent of gross domestic product in 2000 to 1.28 per cent in 2004, with further growth before the financial crisis. Government budget appropriations for research and development increased from about 12.3 billion Czech koruna (CZK) in 2002 to roughly CZK 20.5 billion in 2007. This expansion provided a broader resource base for universities and public research institutions, even though the system continued to face shortages in salaries and advanced equipment. The global financial crisis interrupted the earlier upward trajectory, and research intensity fell in 2007 and 2008 before recovering. In 2009, public sources accounted for about 44 per cent of total Czech research and development expenditure, while foreign funding had risen to more than nine per cent. The growing foreign component reflected the increasing importance of European programmes and international investment within the national research system. Physics did not receive all of these resources, but the general financial environment influenced its capacity to maintain laboratories and prepare larger projects. The decade therefore combined genuine growth with

persistent recognition that Czech research expenditure remained lower than the European Union average. This constraint encouraged selective investment in fields where existing expertise could produce the greatest international leverage. Financial consolidation was consequently important not because Czechia could match the largest scientific economies, but because it enabled a more strategic combination of national and European resources.

The changing financial model was accompanied by a gradual move towards infrastructure-oriented research policy. Across Europe, the European Strategy Forum on Research Infrastructures created a framework for identifying facilities whose scientific importance and cost exceeded the logic of ordinary project grants. Its first roadmap, published in 2006, helped make large research infrastructures a central element of European science policy. Czech policymakers and research organisations increasingly adopted the same vocabulary when discussing accelerators, laser systems, fusion devices, observatories, computing resources, and advanced materials facilities. This was a significant conceptual shift because infrastructure was no longer understood simply as equipment owned by an individual institute. Instead, major facilities were increasingly expected to serve wider research communities, provide structured access, and participate in international networks. Physics was among the disciplines most strongly affected by this change because its experimental frontier often depends directly on instrument scale. The new infrastructure logic encouraged Czech institutions to identify specialised areas in which the country could become either a significant host or a strategically important partner. It also created a bridge between national scientific planning and the priorities defined at European level.

Particle physics entered the 2000s during a generational transition from the experiments of the Large Electron-Positron Collider and the HERA electron-proton collider towards the Large Hadron Collider. Czech groups had accumulated substantial experience through DELPHI (Detector with Lepton, Photon and Hadron Identification) at the European Organization for Nuclear Research (CERN) and H1 at the Deutsches Elektronen-Synchrotron (DESY) in Germany. This experience provided detector, electronics, computing, and analysis skills that could be transferred to the construction of the next generation of experiments. During the early 2000s, Czech researchers from the Institute of Physics, Charles University, and faculties of the Czech Technical University participated in preparations for ATLAS (A Toroidal LHC Apparatus, with LHC standing for Large Hadron Collider), one of the principal collider experiments. Contemporary Czech accounts described a community of roughly sixty physicists, students, engineers, and technicians involved in detector preparation, particularly calorimetry and silicon tracking. The work required years of component testing and integration before the accelerator could deliver physics data. It also reinforced cooperation among Czech institutions because no single domestic organisation possessed all the required expertise. This long preparatory period illustrates the changing temporal scale of modern physics, in which a scientific result may depend on infrastructure developed over a decade or more. By 2008, when the Large Hadron Collider circulated its first beam, Czech groups were already deeply embedded in the technical and scientific culture of the experiment. Their participation demonstrated that the consolidation of national physics was inseparable from the capacity to sustain long commitments to multinational projects.

Computing became an equally important component of this particle-physics architecture. The volume of data anticipated from Large Hadron Collider experiments exceeded the capacity of a single central computing centre and led to the development of distributed grid infrastructures. Czech institutions contributed to this emerging system by building regional

computing capacity linked to international data processing. The Institute of Physics developed a centre intended to support Large Hadron Collider experiments and to provide Czech researchers with direct access to large-scale distributed analysis. This investment changed the meaning of experimental infrastructure because participation in high-energy physics now required networks, storage, software, and processing power as well as detector hardware. It also connected particle physics with developments in computer science and high-performance data management. Students trained in the field consequently acquired skills extending beyond traditional detector physics. The emergence of distributed computing in the 2000s was therefore one of the clearest examples of how digital infrastructure became inseparable from physical experimentation. It also strengthened Czech participation by ensuring that access to international datasets could be matched by domestic computational capability.

Heavy-ion physics developed along a related but distinct international pathway. The Nuclear Physics Institute had joined the CERES experiment at CERN in 1997 and had participated since the mid-1990s in preparations for ALICE (A Large Ion Collider Experiment). During the 2000s, this work intensified as the Large Hadron Collider moved towards operation. Czech teams contributed both to the physics programme and to detector-related tasks associated with the Inner Tracking System. In parallel, researchers from the institute became involved in the STAR (Solenoidal Tracker at the Relativistic Heavy Ion Collider) experiment at Brookhaven National Laboratory in the United States from 2000. This dual participation allowed Czech nuclear physicists to study strongly interacting matter across complementary accelerator environments. It also expanded the international geography of Czech physics beyond European institutions while preserving CERN as a central reference point. Preparations for ALICE required long-term investments in detector expertise, software, data processing, and young researchers well before the first Large Hadron Collider collisions. When the collider delivered its first colliding beams in 2009, the Czech group entered the operational phase with more than a decade of preparatory experience. The transition therefore exemplified the broader consolidation of Czech nuclear and subnuclear physics into durable international collaborations rather than short-term bilateral projects. It also strengthened the interface between nuclear physics, particle physics, computing, and detector technology.

Domestic nuclear infrastructure was modernised at the same time. The Nuclear Physics Institute installed a Tandetron 4130 MC electrostatic accelerator in 2005, adding a major new capability for nuclear analytical methods and ion-beam research. The instrument complemented the older U-120M cyclotron, whose earlier upgrades had already extended its useful scientific life. The institute also maintained access to neutron diffraction and scattering facilities associated with the LVR-15 research reactor at Řež. Together, these resources supported nuclear physics, materials research, elemental analysis, radiation studies, and interdisciplinary applications. The coexistence of national facilities and participation in large experiments abroad became a defining institutional principle. Czech researchers could develop methods and train students locally while pursuing questions requiring much larger accelerators through international collaborations. This architecture reduced the risk that membership in foreign facilities would erode domestic experimental competence. Instead, external participation and internal capability became mutually reinforcing components of the same research strategy.

Laser science entered the decade with the Prague Asterix Laser System (PALS) already operating as an important international facility. The system had been transferred from

Germany and formally launched in Prague in 2000 through cooperation between the Institute of Physics and the Institute of Plasma Physics. Its kilojoule-class pulses enabled research on laser-produced plasmas, X-ray generation, high-energy-density matter, and related phenomena. European support under the Fifth Framework Programme established PALS as a transnational-access facility, bringing foreign teams to Prague for experiments. During the 2000s, this user model strengthened Czech expertise in operating complex laser infrastructure for an international scientific community. It also created a generation of researchers familiar with the organisational requirements of shared experimental facilities, including scheduling, diagnostics, safety, technical support, and external peer selection. PALS therefore had an importance beyond the individual experiments carried out with the laser. It provided practical experience that later became highly relevant when Czech physicists became involved in the much more ambitious Extreme Light Infrastructure project. The continuity between PALS and later laser developments illustrates how modern research architecture often grows through accumulated operational knowledge rather than through isolated construction projects. The facility also reinforced cooperation between laser and plasma physics, two communities that would remain closely connected in subsequent infrastructure planning.

Fusion research achieved an equally important infrastructural advance through the transfer of the COMPASS (Compact Assembly) tokamak to Prague. The device had originally operated in the United Kingdom, and in 2004 the United Kingdom Atomic Energy Authority formally offered COMPASS-D to the Czech Institute of Plasma Physics. The Czech side decided to accept the tokamak in November 2005 with governmental support. In 2006 the project moved into implementation, including construction planning, new power supplies, and dismantling of the device at Culham. The older CASTOR (Czech Academy of Sciences TORus) tokamak was subsequently moved to the Czech Technical University, preserving its value for education and smaller-scale experiments. COMPASS was installed at the Institute of Plasma Physics, where the first plasma was generated on 9 December 2008. Test operation began in February 2009, followed by further commissioning of diagnostics, control systems, and power infrastructure. The project represented a qualitative increase in the experimental scale of Czech magnetic-confinement research. It also showed how European scientific integration could produce the physical relocation of advanced research infrastructure into Czechia rather than only provide access to equipment abroad. COMPASS therefore became one of the clearest symbols of the transition from international reconnection to European scientific consolidation. The relocation also preserved a chain of expertise from CASTOR while creating a substantially more capable platform for the next stage of Czech fusion research.

The success of the COMPASS transfer depended on the European framework created by the Czech association with the European Atomic Energy Community fusion programme. Through this association, the Institute of Plasma Physics coordinated Czech participation in common European fusion research and gained access to expertise, mobility schemes, and shared facilities. Czech scientists could contribute to work related to the Joint European Torus, which remained the principal European magnetic-confinement experiment of the period. The European programme also connected national research with the long-term development of the International Thermonuclear Experimental Reactor and future fusion technology. COMPASS was valuable precisely because its configuration allowed investigation of plasma shapes and edge phenomena relevant to larger devices. The project therefore linked a domestic tokamak directly to questions defined within a multinational research strategy. European support did not remove the need for national investment, because the Czech state had to provide

buildings, power systems, personnel, and long-term operational resources. The fusion case thus demonstrates how successful integration required complementary commitments from both European and national institutions. By the end of the decade, Prague had become a more significant experimental node within the European fusion landscape.

Astronomy experienced perhaps the clearest transformation in access to frontier observational infrastructure. On 22 December 2006, the Czech Republic signed an accession agreement with the European Southern Observatory (ESO). Following ratification, Czechia formally became ESO's thirteenth Member State on 30 April 2007 and the first member from Central and Eastern Europe. Membership gave Czech astronomers access to the organisation's major facilities through the same competitive procedures available to researchers from other member states. These facilities included the Very Large Telescope in Chile and participation in the developing Atacama Large Millimeter/submillimeter Array, while planning for the Extremely Large Telescope was also advancing. The significance of accession was scientific, technological, and institutional at the same time. Czech astronomers could propose observations at facilities whose scale could never have been reproduced nationally. Czech engineers and companies also gained opportunities to contribute to high-technology instrumentation and procurement. Membership placed national astronomy within the governance and strategic planning of one of the world's leading astronomical organisations. It consequently marked a transition from international cooperation based largely on bilateral contacts towards durable participation in shared European infrastructure. For a relatively small astronomical community, this access substantially enlarged the range of observational questions that could be pursued.

ESO membership did not diminish the importance of domestic astronomy, because access to major telescopes is scientifically useful only when national institutions maintain researchers capable of designing competitive projects and interpreting complex observations. The Astronomical Institute of the Czech Academy of Sciences remained a central national institution, with Ondřejov providing long-term observational programmes and specialised instruments. University groups in Prague, Brno, and later Opava contributed theoretical and observational expertise in astrophysics and cosmology. The new European framework therefore supplemented rather than replaced national capabilities. International observing time could be combined with local spectroscopy, solar observations, theoretical modelling, and archival analysis. The 2006 General Assembly of the International Astronomical Union in Prague also demonstrated the visibility of the Czech astronomical community immediately before ESO accession. This combination of domestic continuity and international access closely resembled the architecture already emerging in particle and fusion physics. It confirmed that modern Czech science increasingly depended on an intelligent division of labour between national research bases and shared international facilities. Astronomy thus became another field in which European integration fundamentally changed the scale of possible research without erasing local scientific traditions.

Condensed-matter physics remained one of the broadest and most institutionally distributed areas of Czech research during the decade. The field encompassed magnetism, semiconductors, superconductivity, surfaces, thin films, structural physics, low-temperature phenomena, and the theoretical description of many-body systems. Czech groups at the Institute of Physics, Charles University, Masaryk University, Brno University of Technology, and other centres increasingly worked within international networks rather than primarily national disciplinary structures. The twentieth General Conference of the Condensed Matter Division of

the European Physical Society, held in Prague in July 2004, reflected this integration at an especially visible moment. It brought together research across condensed matter and materials science and included a tutorial programme designed for students. The meeting also highlighted the growing overlap between classical solid-state physics and emerging nanoscale approaches. Advanced characterisation, improved computation, and the ability to control surfaces and structures at progressively smaller scales were changing both experimental methods and research questions. Czech laboratories responded by linking long-standing materials expertise with nanophysics, spin-dependent phenomena, and semiconductor research. The consolidation of condensed-matter physics during the 2000s therefore occurred through methodological renewal rather than abandonment of established schools. This continuity would become particularly important in the following decade, when Czech research in magnetism and spintronics gained wider international prominence.

Nanoscience emerged during the same period as a powerful organising concept connecting physics, materials science, chemistry, and engineering. Czech researchers investigated thin films, surfaces, nanostructures, semiconductor systems, magnetic materials, and nanoscale measurement techniques in several institutional settings. The international summer school on physics at the nanoscale held in the Czech Republic in 2008 attracted participants from nineteen countries and was supported by Czech academic institutes, universities, professional societies, and industry. Such events indicate that nanoscale research was already developing a coherent professional community before the construction of the large nanotechnology centres of the next decade. Brno was particularly well positioned because Masaryk University, Brno University of Technology, and Academy materials institutes possessed complementary expertise. By 2009, seven Brno institutions had agreed the final form of the Central European Institute of Technology (CEITEC) project. The planned centre combined research programmes in advanced materials and technologies with biomedical and life-science fields and sought support from the European Operational Programme Research and Development for Innovation. Although the European Commission approved CEITEC only in 2011, its scientific architecture was substantially prepared during the final years of the 2000s. The project therefore belongs intellectually to the consolidation period even though its physical construction belongs to the infrastructure expansion that followed. It exemplified a new model in which regional universities and Academy institutes would share sophisticated equipment within large interdisciplinary centres. In this sense, CEITEC planning already anticipated the shared-platform model that would become characteristic of Czech research infrastructure after 2010.

The Operational Programme Research and Development for Innovation became the financial mechanism that translated many such ambitions into realistic infrastructure plans. Created for the 2007–2013 programming period, it channelled European structural resources towards centres of excellence, regional research centres, infrastructure, and research-oriented higher education. Later government documents recorded that the programme ultimately supported eight European centres of excellence and forty regional research and development centres. Its design was especially important for Czechia because decades of underinvestment had left significant technological gaps between many domestic laboratories and leading Western European facilities. Physics and materials research were among the fields able to formulate projects requiring expensive buildings and instruments rather than only personnel funding. The programme also had a strong regional dimension because European structural-fund rules limited the eligibility of Prague for some categories of investment. This encouraged the

development of major facilities in Central Bohemia, Brno, Olomouc, Ostrava, and other regions. The geography of Czech research consequently began to change alongside its institutional architecture. The planning initiated in the late 2000s would produce many of the most visible research centres of the following decade. European integration thus influenced not only who funded Czech science but also where advanced physical research would increasingly be located.

No project illustrated this transition more dramatically than the Extreme Light Infrastructure (ELI). The concept emerged at European level as a proposed next-generation laser infrastructure capable of reaching unprecedented electromagnetic intensities. ELI was included in the roadmap of the European Strategy Forum on Research Infrastructures and entered a formal preparatory phase involving partners from numerous European countries. Czech physicists, led institutionally by the Institute of Physics of the Czech Academy of Sciences, developed a national proposal to host part of the distributed facility. The bid was supported by the Ministry of Education, Youth and Sports, the Academy, Czech universities, and an ELI-CZ consortium of scientific institutions. On 1 October 2009, the international steering committee of the preparatory phase granted the Czech Republic, together with Hungary and Romania, a mandate to proceed with implementation of the distributed infrastructure. The Czech proposal envisaged a major laser centre at Dolní Břežany near Prague. In November 2009, the Institute of Physics submitted the project application for support through the Operational Programme Research and Development for Innovation. The decision represented a qualitative change in national ambition because Czechia was no longer seeking only participation in a large European facility located abroad. It was preparing to become one of the host countries of a pan-European research infrastructure, with responsibility for construction, operation, and international user access. The ELI decision of 2009 therefore formed a natural endpoint to the consolidation decade and a starting point for the infrastructure-driven phase of the 2010s.

The emergence of ELI was possible partly because Czech laser science had already demonstrated competence through PALS and through long-standing work in optics and laser-plasma interaction. Infrastructure planning therefore built on an existing scientific community rather than selecting a field without domestic roots. Czech researchers could point to operational experience with a transnational-access laser facility, collaboration between the Institute of Physics and the Institute of Plasma Physics, and international links created over the previous decade. The European ELI process also required a national consortium capable of representing universities and research institutes beyond a single host organisation. This broadened the political and scientific constituency supporting the project. The planned centre promised to connect high-field physics with materials, particle acceleration, X-ray sources, chemistry, biology, and technological applications. Its interdisciplinary scope reflected the wider transformation of physics towards large platforms serving multiple research communities. The project also posed significant organisational risks because operating a facility of European importance required governance, recruitment, procurement, and user policies on a scale new to Czech physical science. Precisely for that reason, the selection of Czechia in 2009 can be interpreted as evidence that the institutional consolidation of the preceding decade had achieved international credibility. The country was increasingly regarded as capable not only of producing research but also of sustaining complex European scientific infrastructure.

The global financial crisis of 2008 and 2009 tested this emerging architecture at a sensitive moment. Czech research and development expenditure as a share of gross domestic product declined during 2007 and 2008, reflecting a combination of national trends and the wider economic slowdown. Business expenditure was particularly vulnerable, while public funding provided a degree of stabilisation. In 2009, state-budget resources used for research and development increased even as the economy experienced recession. Foreign sources also continued to rise, illustrating the growing importance of European and other international funding in cushioning national fluctuations. For physics, the crisis underlined the advantage of having multiple funding channels rather than depending on a single institutional budget. It also demonstrated the vulnerability of long-term experimental commitments to short-term economic pressures. Projects such as COMPASS and ELI required confidence that support would continue beyond one fiscal cycle. The ability to maintain these plans through the crisis suggested that large research infrastructure had acquired a more strategic position within national policy than it possessed a decade earlier.

Institutional evaluation became increasingly prominent alongside infrastructure investment. The Academy's transition to public research institutions had been preceded by assessments of institutes and research plans, and the new statutes retained regular evaluation as a formal responsibility. Government research policy also placed growing emphasis on measurable outputs and the distribution of institutional resources according to assessed performance. These developments were intended to strengthen quality and accountability, but they generated debates about how different forms of scientific contribution should be compared. Physics illustrated the difficulty particularly clearly because a theoretical paper, a detector component, operation of a national facility, and participation in a thousand-person experiment cannot be evaluated through identical indicators. Large infrastructures also produce benefits in training, technical expertise, and international access that may appear only indirectly in publication statistics. The 2000s therefore saw the beginnings of a tension between increasingly quantitative assessment and the complex organisational realities of modern science. This tension would become more visible in subsequent Czech research-policy debates. Even so, systematic evaluation contributed to a culture in which institutions were expected to articulate strategies and demonstrate scientific performance. Consolidation thus involved not only more resources and better facilities but also more explicit scrutiny of how those resources were used.

Human capital became another increasingly visible component of the modern research architecture. Larger European projects required scientists who could work fluently in international teams, prepare competitive proposals, manage technical work packages, and move between institutions. Doctoral students in particle physics, nuclear physics, plasma research, astronomy, and condensed matter increasingly participated directly in multinational experiments and conferences. Mobility programmes under European frameworks expanded opportunities for young Czech researchers to spend extended periods abroad. Conversely, improved domestic facilities made it more plausible to attract foreign researchers or Czech scientists returning from overseas positions. The Academy's Otto Wichterle Award, established in 2002 for promising young scientists, reflected the growing institutional concern with generational renewal. Such measures remained modest compared with the salary and career advantages offered by richer research systems, but they signalled a change in priorities. Research organisations increasingly understood that equipment alone could not create scientific excellence without stable teams capable of exploiting it. The decade therefore linked

infrastructure policy with a gradual professionalisation of doctoral and early-career research. The movement of people became as important to European integration as the movement of money or instruments. In practical terms, internationalisation therefore became a career structure as well as an institutional strategy.

The growth of international collaboration also strengthened the relationship between scientific research and advanced instrumentation. Czech groups contributed detector components, electronics, optical systems, plasma diagnostics, accelerator technology, and specialised software to domestic and international projects. This technical expertise allowed the country to participate in collaborations in ways that extended beyond providing individual researchers for data analysis. It also created potential links with Czech engineering companies capable of manufacturing precision components or supporting complex installations. ESO membership explicitly opened procurement and instrumentation opportunities to Czech industry, while CERN participation had already exposed firms and laboratories to demanding technological standards. PALS, COMPASS, and nuclear accelerators similarly required cooperation among physicists, engineers, technicians, and external suppliers. The resulting ecosystem blurred the boundary between fundamental research infrastructure and high-technology innovation. Although technology transfer remained less developed than in some Western European systems, the 2000s created stronger institutional conditions for it. Czech physics was therefore becoming not only more international but also more technologically integrated with the wider innovation system.

By the end of the 2000s, Czech physical science had acquired a research architecture with several interconnected layers. The first layer consisted of established domestic institutes and university departments providing disciplinary continuity, education, and specialised laboratories. A second layer comprised national facilities such as PALS, COMPASS, the Řež accelerators, and advanced materials laboratories. A third consisted of Czech participation in external organisations and experiments such as CERN, ESO, the Joint European Torus, DESY, and Brookhaven National Laboratory. A fourth emerging layer involved European infrastructure projects in which Czechia intended to act as a host rather than only a user, most visibly ELI and the planned CEITEC centre. These layers were connected by competitive grants, European programmes, mobility, doctoral training, and increasingly professional research management. The architecture was therefore networked rather than hierarchical, with different institutions contributing complementary capabilities. Prague remained dominant, but regional centres were preparing for substantial expansion through structural-fund investment. This configuration gave Czech physics greater resilience because no single funding mechanism or institution carried the entire burden of scientific development. It also allowed a medium-sized national system to combine domestic specialisation with access to experimental capabilities distributed across Europe and beyond.

The deeper historical significance of the decade lies in the change from adaptation to strategic positioning. During the 1990s, Czech institutions had concentrated on stabilising themselves, reopening international contacts, and adjusting to competitive funding. During the 2000s, those same institutions increasingly began to decide where Czech physics could occupy durable positions within the European division of scientific labour. CERN participation was converted into long-term involvement in Large Hadron Collider experiments and distributed computing. European Atomic Energy Community cooperation led to the transfer and reconstruction of COMPASS as a significant domestic fusion device. ESO membership gave Czech astronomy permanent access to world-class observational infrastructure. PALS

demonstrated the viability of international user access to a major Czech laser facility. The preparation of CEITEC and the 2009 decision on ELI showed that European funds could be used to create entirely new concentrations of scientific capacity inside the country. None of these developments represented simple convergence with a single Western European model. Instead, Czechia constructed a hybrid architecture that combined inherited institutes, reformed public institutions, strong universities, international memberships, and selective large-scale infrastructure. This model provided the platform from which Czech physics would enter the 2010s not merely as an integrated participant in European science but increasingly as a host of major facilities and a contributor to globally visible research programmes.

The Stage of Internationalisation and Major Research Infrastructures: Czech Physics in European and Global Science, 2010–2020

Between 2010 and 2020, Czech physics entered a qualitatively different phase from the institutional adaptation and European reconnection that had characterised the preceding two decades. By 2010, the principal scientific institutes, university departments, competitive funding mechanisms, and international memberships of the Czech Republic were already sufficiently stable to support considerably more ambitious forms of research development. The central feature of the new decade was therefore not the restoration of international contacts, but the systematic embedding of Czech physics within European and global networks of large research infrastructures. Czech institutions increasingly participated in scientific projects whose scale exceeded the possibilities of any individual university or national laboratory. Internationalisation became closely associated with shared accelerators, astronomical observatories, laser facilities, fusion devices, supercomputers, neutron sources, and distributed computing networks. Large domestic investments simultaneously allowed Czechia to move from being predominantly a user of research infrastructures located abroad towards becoming a host of facilities serving international scientific communities. This shift was accompanied by a growing emphasis on open access, external users, international advisory structures, and competitive allocation of experimental time. The period also witnessed important scientific results in particle physics, plasma physics, condensed matter, astrophysics, laser science, and emerging spintronics. It can consequently be regarded as the decade in which Czech physics became fully established within the infrastructure-based organisation of twenty-first-century European science.

An important policy instrument behind this transformation was the national Roadmap of Large Infrastructures for Research, Experimental Development and Innovation, which provided a systematic framework for identifying strategically important facilities and Czech participation in international infrastructures. The roadmap approach brought the Czech research system closer to the infrastructure planning developed through the European Strategy Forum on Research Infrastructures (ESFRI). Physics occupied a particularly prominent position because the national portfolio included both domestic facilities and Czech participation in major installations abroad. The 2010s portfolio eventually encompassed the Extreme Light Infrastructure Beamlines, HiLASE, the Prague Asterix Laser System, COMPASS, the Centre of Accelerators and Nuclear Analytical Methods, CEITEC Nano, and several specialised materials and nanotechnology facilities. It also included Czech participation in the European

Organization for Nuclear Research (CERN), the European Southern Observatory (ESO), the European Spallation Source (ESS), the Facility for Antiproton and Ion Research (FAIR), the Pierre Auger Observatory, the Cherenkov Telescope Array (CTA), the Institut Laue-Langevin, and other international projects. This arrangement institutionalised a strategic principle that had already emerged during the 1990s: Czechia could remain competitive by concentrating national resources in selected areas while securing access to complementary facilities abroad. The roadmap further provided more predictable public support for infrastructures whose operating timescales were much longer than those of ordinary research grants. It encouraged facilities to develop user policies, governance procedures, and evaluation mechanisms appropriate to wider scientific communities. The result was an increasingly coherent national architecture in which infrastructure was treated as a long-term component of research policy rather than simply as expensive scientific equipment. By the middle of the decade, this architecture had become one of the principal organisational foundations of Czech physical science.

European structural funding was another decisive element in the transformation. The Operational Programme Research and Development for Innovation enabled Czech institutions to construct research centres whose capital requirements would have been difficult to meet from ordinary national science budgets. Physics, materials science, nanotechnology, laser science, and high-performance computing were among the fields that benefited particularly strongly from this investment cycle. Structural-fund rules also encouraged the development of large centres outside Prague, contributing to a more geographically differentiated national research landscape. Dolní Břežany in Central Bohemia, Brno in South Moravia, and Ostrava in Moravia-Silesia acquired major new scientific facilities during the decade. These investments altered not only the technological level of Czech laboratories but also their organisational model, because many new centres were designed as shared platforms for multiple research teams. Open access and external scientific use increasingly became expectations built into infrastructure funding. By the end of the decade, the geographical map of Czech physics therefore contained several research clusters whose international importance had grown substantially since 2010.

The most ambitious manifestation of this new infrastructure policy was the construction of Extreme Light Infrastructure (ELI) Beamlines in Dolní Břežany. The European Commission approved financing for the Czech project in April 2011, and in August the national authorities confirmed a project budget of approximately €278 million. Completion of the technical design was followed by excavation works in 2012 and the beginning of major building construction in 2013. The first implementation phase was formally inaugurated in October 2015 after completion of the main research and support facilities. Installation of the laser systems and experimental technologies continued during 2016 and 2017, transforming the complex from a construction project into an operational scientific facility. ELI Beamlines was designed around exceptionally intense and short laser pulses capable of generating extreme electromagnetic fields and secondary sources of photons and accelerated particles. Its scientific programme connected fundamental laser physics with plasma physics, particle acceleration, high-energy-density research, materials science, atomic and molecular physics, and potential biomedical applications. The project therefore differed from a conventional specialised national laboratory because its mission was explicitly multidisciplinary and internationally user-oriented. Large parts of its technological systems had to be developed through collaboration with laboratories and companies outside Czechia, including major partnerships with

institutions in the United States and other European countries. ELI consequently became a particularly visible example of European funding, Czech institutional capacity, and global technological cooperation operating within a single physical-science project. Its construction also demonstrated that Czech research organisations had acquired the managerial capacity to implement projects on a scale substantially larger than the principal facilities created during the 1990s.

The second half of the decade was devoted increasingly to commissioning ELI Beamlines as a functioning research infrastructure rather than merely completing its buildings. Trial operation began in 2018, when parts of the first experimental hall and associated laser systems entered scientific use. The L3-HAPLS system, developed with Lawrence Livermore National Laboratory, represented a particularly important technological component because it combined high peak power with repetition rates intended to support statistically meaningful experimental campaigns. Installation and commissioning progressed from the first integrated tests towards increasingly powerful laser operation. In 2019, ELI Beamlines issued its first call for external researchers to participate in user-assisted commissioning and early experiments. Teams from several European countries, the United States, and other international research environments participated in the initial user programme. By 2019 and 2020, approximately forty experiments had been scheduled through early open calls in molecular, biomedical, materials, laser, and related research. The facility was consequently beginning to perform the function for which it had been conceived: attracting researchers to Czechia because of experimental capabilities located there. This reversal of the traditional direction of scientific mobility represented one of the most important structural achievements of Czech physics during the decade.

A complementary laser centre emerged only a short distance from ELI Beamlines. The HiLASE Centre, whose name derives from High average power pulsed LASErs, was established within the Institute of Physics of the Czech Academy of Sciences in 2011. Construction began in the following year, and the centre was formally inaugurated in September 2014. Its scientific strategy differed deliberately from the ultra-high-intensity emphasis of ELI Beamlines by concentrating on diode-pumped solid-state lasers combining high pulse energy with high repetition rate and high average power. Cooperation with the Science and Technology Facilities Council in the United Kingdom played an important role in the development of the BIVOJ laser system. At the end of 2016, a Czech-British team demonstrated 105-joule pulses at a repetition rate of ten hertz, establishing the first kilowatt-class source in this category of high-energy nanosecond diode-pumped solid-state lasers. HiLASE simultaneously developed technologies for laser shock peening, testing of optical components, laser micromachining, and other industrially relevant applications. This orientation brought advanced laser development into direct contact with materials engineering and manufacturing technologies. European projects under Horizon 2020 further supported the transformation of HiLASE towards an internationally competitive centre of excellence. By 2020, HiLASE had therefore become both a fundamental laser-development laboratory and a platform for scientific and industrial applications.

Taken together, ELI Beamlines and HiLASE transformed Dolní Břežany into a distinctive laser-research cluster. Their geographical proximity was accompanied by complementary scientific missions rather than simple duplication of equipment. ELI emphasised extreme fields, ultrashort pulses, secondary radiation and particle sources, while HiLASE concentrated particularly on high-average-power laser architectures and technological applications. Both centres required advanced optics, diagnostics, control systems, precision engineering,

vacuum technologies, and specialised scientific personnel. They therefore generated an environment in which fundamental physics, engineering, and high-technology development were unusually closely connected. The cluster also attracted international researchers to a location that had not previously been a major centre of Czech academic science. This geographical redistribution of scientific capacity illustrated the wider transformation produced by infrastructure investment during the decade. By 2020, Dolní Břežany had become one of the most visible physical-science locations in Central Europe.

Brno experienced a different but equally important form of infrastructure-driven development through the Central European Institute of Technology (CEITEC). The European Commission approved approximately CZK 5.2 billion for the project in 2011, after several years of preparation by Brno universities and research institutes. Construction began in 2012, and research facilities were progressively opened during the middle of the decade. CEITEC was intentionally interdisciplinary, connecting advanced materials and nanotechnologies with life sciences rather than establishing a purely physical-science institution. For physics, its importance lay particularly in sophisticated microscopy, nanofabrication, structural analysis, magnetic materials, semiconductor research, and nanoscale characterisation. The model of shared core facilities allowed equipment that would have been prohibitively expensive for individual research groups to serve a broader community. Open-access procedures introduced during the development of CEITEC enabled external researchers to obtain experimental time through scientific proposals. At Brno University of Technology, the materials and nanotechnology laboratories reached full operation during the second half of the decade. The centre also established interdisciplinary doctoral education in advanced materials and nanosciences, linking infrastructure development with researcher training. CEITEC thus strengthened Brno as a major centre of physical materials research while simultaneously reducing the historical concentration of expensive scientific equipment in the Prague region. Its development demonstrated how the infrastructure model could support both disciplinary excellence and interaction between physics, chemistry, engineering, and biology.

High-performance computing became another increasingly indispensable component of the national research architecture. The IT4Innovations National Supercomputing Center was established at VSB – Technical University of Ostrava in 2011 as one of the largest Czech research infrastructure projects of the period. Its first major system, Anselm, began operation in 2013, and the centre's dedicated building opened in 2014. In 2015, the Salomon supercomputer was launched with a theoretical peak performance of approximately two petaflops and initially ranked fortieth in the TOP500 list of the world's most powerful systems. High-performance computing supported physical research in areas including materials modelling, nanotechnology, computational mechanics, plasma simulation, data analysis, and complex engineering problems. IT4Innovations also strengthened Czech participation in European computing initiatives and joined the European Technology Platform for High-Performance Computing in 2016. Czechia became a participant in the European High Performance Computing Joint Undertaking in 2018, further embedding the national centre in the emerging European exascale strategy. The installation of the Barbora system and specialised artificial-intelligence computing hardware in 2019 expanded this digital research environment further. Computing infrastructure was consequently becoming as strategically significant to many branches of physics as conventional laboratory instrumentation.

Particle physics provides an especially clear example of how Czech researchers used this increasingly infrastructure-oriented environment. The Large Hadron Collider (LHC) at CERN

entered its first major physics run in 2010, bringing decades of detector construction and experimental preparation into the data-taking phase. Czech physicists from the Institute of Physics, Charles University, the Czech Technical University, and associated groups participated in major experiments, particularly ATLAS and ALICE. Their activities included detector technologies, data processing, software, physics analysis, and participation in experiment upgrades. The scale of the LHC meant that nationally identifiable scientific contributions were made within collaborations containing thousands of researchers. Czech participation nevertheless depended on sustained domestic expertise, because experiment membership required technical responsibilities and continuous institutional support rather than occasional use of CERN facilities. The national CERN-CZ research infrastructure helped organise and finance this participation. Distributed computing centres in Czechia became part of the data-processing environment required to analyse LHC results. Students could consequently conduct internationally competitive high-energy physics while remaining linked academically to Czech universities and research institutes. The integration of Czech particle physics into CERN during the 2010s therefore represented one of the most mature forms of internationalisation achieved by the national scientific system.

The discovery of the Higgs boson in 2012 provided the most internationally visible scientific event associated with this era of LHC research. ATLAS and the Compact Muon Solenoid experiment independently reported a new particle with properties consistent with the Higgs boson predicted by the Standard Model of particle physics. Czech researchers belonging to the ATLAS collaboration were among the many scientists whose work contributed to the detector, computing infrastructure, analyses, and continuing study of the new particle. Their participation illustrates an important characteristic of contemporary big science, in which discoveries cannot meaningfully be assigned to a single national research community. The scientific significance for Czechia lay instead in having developed institutions capable of participating continuously in an experiment operating at the frontier of fundamental physics. Czech groups subsequently contributed to measurements of Higgs production, top-quark processes, heavy-ion physics, and searches for physics beyond the Standard Model. Such activities placed Czech doctoral researchers and specialists within one of the principal global centres of experimental physics. The LHC experience consequently strengthened both scientific visibility and the domestic technological competencies required for future detector programmes.

Particle physics also accelerated the digitalisation of Czech experimental science. LHC experiments generated volumes of data that could not be processed exclusively at CERN, leading to the construction of an international distributed computing architecture known as the Worldwide LHC Computing Grid (WLCG). Czech computing resources became integrated into this system and supported the processing, storage, simulation, and analysis of collider data. The technical requirements encouraged cooperation among physicists, computer specialists, network engineers, and data-management experts. Skills developed for particle physics could also support other fields dealing with large scientific datasets. Grid computing reduced the practical distinction between an experimental site and a researcher's home institution because data collected in Switzerland could be processed in Prague and analysed by teams distributed across continents. This model subsequently became increasingly familiar in astronomy, astroparticle physics, and computational materials science. It also provided an important precedent for the national development of larger high-performance computing resources. Czech participation in the WLCG demonstrated that international research

infrastructure increasingly included digital systems as well as physical machines. By the late 2010s, the capacity to manage data had become inseparable from the capacity to conduct frontier experimental physics.

Nuclear physics followed the same broader movement towards integrated infrastructure while retaining a strong experimental base at Řež. The Centre of Accelerators and Nuclear Analytical Methods (CANAM) was incorporated into the Czech national infrastructure roadmap for the 2010–2019 period. It brought together accelerator and neutron capabilities that had previously developed as individual facilities within the Nuclear Physics Institute of the Czech Academy of Sciences. These included the U-120M cyclotron, the Tandetron 4130 MC accelerator, microtron facilities, and experimental systems using neutron beams from the LVR-15 research reactor. CANAM supported research in nuclear physics, materials science, engineering, chemistry, radiation studies, environmental science, medicine, and cultural-heritage analysis. The organisational consolidation of these instruments into a common infrastructure encouraged more systematic access for researchers outside the host institute. Experimental time was increasingly allocated through an open-access model in which national and international users could propose projects. An International Advisory Board established in 2011 further strengthened external scientific assessment. CANAM therefore illustrates how a long-established research site could be modernised conceptually through the infrastructure model without abandoning its historical experimental base. By the end of the decade, Řež combined national accelerator capability with participation in a much wider European nuclear-science network.

That European network included Czech participation in several major facilities under development outside the country. The Nuclear Physics Institute coordinated Czech involvement in the European Spallation Source in Lund, Sweden, where the Czech contribution included substantial in-kind technological work. A particularly important component was participation in the Beamline for European Materials Engineering Research, commonly known as BEER. Czech researchers and engineers also contributed technology associated with the neutron target system. Participation in FAIR in Darmstadt connected Czech nuclear physicists with future research on heavy ions, radioactive nuclei, antiprotons, compressed baryonic matter, and nuclear astrophysics. Additional cooperation through SPIRAL2 in France expanded access to radioactive-ion and neutron-related research. These arrangements demonstrate that infrastructure participation increasingly involved the delivery of instruments and technical subsystems rather than simply payment for future experimental access. Such in-kind contributions strengthened domestic engineering competence and made Czech teams more deeply embedded in the construction phase of European facilities. The resulting relationships connected fundamental nuclear physics with materials research, accelerator engineering, and specialised detector development. By the late 2010s, national nuclear physics therefore operated through a distributed network stretching from Řež to major European facilities under construction. This pattern closely matched the broader Czech strategy of combining specialised national capability with participation in infrastructures whose total scale could not be reproduced domestically.

Fusion physics entered the decade with COMPASS as a newly reconstructed domestic tokamak and soon moved from commissioning into scientific operation. Final commissioning of diagnostics, control systems, and power supplies continued until 2011, and regular scientific exploitation began in 2012. During that year researchers achieved a high-confinement operating regime, generally known as H-mode, on the device. Type-I edge-

localised modes were subsequently produced in 2013, enabling experiments relevant to plasma-boundary behaviour in larger fusion machines. COMPASS was particularly valuable because its plasma geometry had similarities to configurations relevant to the International Thermonuclear Experimental Reactor (ITER). Czech researchers developed specialised diagnostics for plasma edges, turbulence, runaway electrons, magnetic perturbations, and plasma-material interactions. The tokamak was also used for training and international experimental schools, strengthening its role as both a research and educational facility. By the middle of the decade, COMPASS had become an established component of European medium-sized tokamak research rather than simply a former British machine relocated to Prague.

The European organisation of fusion research changed substantially during the same period. From 2014, European fusion activities were increasingly coordinated through the EUROfusion Consortium, in which the Institute of Plasma Physics represented Czech participation together with national university and applied-research partners. Czech researchers worked within common European programmes addressing experiments, theory, diagnostics, plasma-facing components, magnetic systems, modelling, education, and preparations for ITER and future demonstration reactors. They also participated in experiments on major European devices, including the Joint European Torus, ASDEX Upgrade, TCV, and other tokamaks. The organisation of research through common work packages further integrated Czech teams into long-term European priorities. At the same time, operating COMPASS allowed Czechia to contribute an experimental platform of its own rather than relying entirely on access to foreign devices. The combined national research unit linked the Institute of Plasma Physics with Charles University, the Czech Technical University, and the Research Centre Řež. This arrangement strengthened the relationship between plasma physics, materials, nuclear technology, and university training. By the middle of the decade, Czech fusion research was therefore operating simultaneously at national and European scales. The strategic significance of this integration became even clearer when work began on a successor device capable of addressing plasma conditions closer to those relevant for future reactors. In December 2017, the COMPASS Upgrade project formally began, opening a new stage in Czech high-field tokamak development.

Astronomy and astrophysics benefited from a similarly mature model of international infrastructure participation. Czechia had joined ESO in 2007, and during the 2010s membership increasingly translated into regular scientific access to some of the world's leading ground-based observational facilities. Czech researchers could compete for observing time on the Very Large Telescope and participate in science associated with the Atacama Large Millimeter/submillimeter Array (ALMA). They were also integrated into the scientific and technological environment surrounding the development of the Extremely Large Telescope. The Astronomical Institute of the Czech Academy of Sciences remained the principal national institutional centre, while university groups contributed theoretical, observational, and computational astrophysics. Membership allowed Czech researchers to address problems whose observational requirements greatly exceeded the capabilities of domestic telescopes. At the same time, the Ondřejov Observatory and other Czech facilities continued to support long-duration monitoring, spectroscopy, solar physics, and instrument development. This combination ensured that international access complemented rather than replaced domestic astronomical expertise. Czech scientists also contributed to the development of solar observing capabilities at ALMA during the second half of the decade. Astronomy thus provided

another mature example of the relationship between national scientific competence and shared international infrastructure.

Astroparticle physics expanded strongly during the same decade and connected Czech institutions with experiments operating on entirely different geographical scales. Czech researchers participated in the Pierre Auger Observatory in Argentina, which investigates ultra-high-energy cosmic rays through a large hybrid array of surface and fluorescence detectors. Their work included data analysis, atmospheric monitoring, detector development, and studies of cosmic-ray composition and arrival directions. Czech scientists participated in collaboration results concerning anisotropy, hadronic interactions, and the energy spectrum of the most energetic known particles. Another major initiative was the Cherenkov Telescope Array, designed as the next generation of ground-based gamma-ray astronomy. Charles University had been involved from the early development phase, while the Institute of Physics joined the international consortium during the first part of the decade. Czech teams contributed to site characterisation, atmospheric monitoring, telescope optics, mirror development, and the design of small-sized telescope systems. The Institute of Physics became one of the institutional participants in the organisation preparing the observatory, while national infrastructure funding supported CTA-CZ from the middle of the decade. These activities demonstrate that Czech contributions to international facilities could involve scientific analysis, specialised instrumentation, and organisational responsibility simultaneously. Astroparticle physics consequently emerged as an important bridge between particle physics, astronomy, detector technology, and atmospheric measurement.

Condensed-matter physics underwent a quieter but scientifically important internationalisation during the 2010s. Unlike ELI or COMPASS, the field was not organised around a single highly visible national machine, because its experimental and theoretical work was distributed among many laboratories. The Institute of Physics, Charles University, CEITEC, Brno University of Technology, Masaryk University, and other centres investigated magnetic materials, semiconductors, superconductivity, surfaces, nanostructures, crystallography, and electronic transport. New nanofabrication and characterisation facilities made it possible to connect theoretical models with increasingly precise experiments at microscopic scales. European Research Council grants and multinational projects helped selected Czech groups build research teams with much greater international visibility. Spintronics became one of the most important examples of this development. Work at the Institute of Physics increasingly focused on magnetic systems in which electronic spin could be manipulated for information technologies. By the middle of the decade, Czech-based researchers had become influential contributors to the rapidly developing field of antiferromagnetic spintronics.

Antiferromagnetic spintronics illustrates particularly well how the infrastructure expansion of the decade could coexist with internationally important conceptual and experimental physics. Conventional spintronics had relied heavily on ferromagnetic materials, whose macroscopic magnetisation allowed information to be controlled but also generated unwanted magnetic fields. Czech researchers and international collaborators explored whether antiferromagnets, whose opposing magnetic moments can produce zero net magnetisation, could provide alternative principles for electronic devices. Theoretical work associated with the Prague group demonstrated mechanisms through which electrical currents could manipulate antiferromagnetic order. Experiments subsequently showed room-temperature memory behaviour and electrical switching in selected antiferromagnetic materials. A major review published in *Nature Nanotechnology* in 2016 helped define antiferromagnetic spintronics as a

coherent international research field. Collaborative research involved the Institute of Physics of the Czech Academy of Sciences, Charles University, the University of Nottingham, German institutions, and other partners. Work on materials such as CuMnAs and MnTe demonstrated that antiferromagnetic states could be detected and controlled electrically under experimentally relevant conditions. In 2017, a multilevel antiferromagnetic memory cell compatible with microelectronic concepts provided further evidence of technological potential. By 2018, review and perspective articles in *Nature Physics* were discussing multiple directions of antiferromagnetic and topological spintronics. Czech physics was therefore contributing not merely infrastructure or technical components but also ideas that were shaping a new international research agenda. The achievements of this period prepared the conceptual foundations from which research on altermagnetism would emerge in the following decade.

The increasing importance of shared nanotechnology facilities strengthened the experimental base for such research. CEITEC Nano in Brno developed clean rooms, microscopy, nanofabrication, and advanced materials-characterisation capabilities accessible to multiple scientific groups. Other facilities at the Institute of Physics supported nanostructure preparation, thin-film growth, optical measurements, structural analysis, and spintronic experiments. By the middle of the decade, national infrastructure policy was explicitly listing CEITEC Nano, the Laboratory of Nanostructures and Nanomaterials, and specialised materials facilities alongside particle, nuclear, and laser infrastructures. This classification reflected the changing scale of modern condensed-matter research, where individual instruments could be sufficiently expensive and technically demanding to require centralised operation. Open access broadened the scientific value of such equipment by allowing researchers outside the host laboratory to propose experiments. Shared facilities also encouraged cross-disciplinary interaction among physicists, chemists, materials scientists, and engineers. The infrastructure model was therefore spreading from traditional big-science domains into laboratory-scale nanoscience. By 2020, Czech materials research increasingly depended upon networks of common technological platforms rather than isolated departmental equipment.

Internationalisation during the 2010s was also strongly shaped by the European Union's Horizon 2020 framework programme, which operated from 2014 to 2020. Czech physics institutions used Horizon 2020 for collaborative research, researcher mobility, infrastructure development, and institution-building. HiLASE, for example, received support through the Widespread Teaming instrument designed to strengthen centres of excellence in countries seeking to improve research and innovation performance. Spintronics groups participated in European projects dealing with antiferromagnetic and semiconductor spin phenomena. Nuclear researchers contributed to collaborative programmes related to neutron science and the future European Spallation Source. Fusion research was supported through the EURATOM component of the European research framework and through EUROfusion. European grants therefore became intertwined with national support rather than operating as an entirely separate funding stream. Successful participation required professional project offices, international recruitment, financial administration, and sustained consortium management. These organisational competencies constituted an important but often less visible part of the modernisation of Czech physical science.

Large infrastructures also changed the relationship between Czech research organisations and scientific users. Earlier laboratory systems had generally been developed primarily for researchers employed by the host institution or their established collaborators. Facilities such

as CANAM, CEITEC, ELI Beamlines, HiLASE, and national computing centres increasingly adopted formal access procedures intended for external academic and, in some cases, industrial users. Proposals could be assessed according to scientific merit, technical feasibility, and available experimental time. This approach aligned Czech facilities with the broader European conception of research infrastructures as services for scientific communities rather than simply institutional assets. International advisory boards and peer-review mechanisms helped separate decisions about access from purely internal organisational priorities. User programmes also required technical support, scheduling systems, safety procedures, data management, and dedicated administrative staff. Consequently, the operation of a large research infrastructure became a specialised institutional activity in its own right. By 2020, Czech physics had acquired substantially more experience with this user-facility culture than it possessed at the beginning of the decade. The transition was essential for the later integration of Czech-hosted facilities into formal European research-infrastructure structures.

The expansion of infrastructure simultaneously altered the human geography of Czech science. New centres recruited researchers, engineers, technicians, software specialists, and project managers from abroad, increasing the international composition of several Czech laboratories. English became the routine working language in many teams associated with ELI Beamlines, HiLASE, CEITEC, international particle-physics collaborations, and European research projects. Doctoral students could conduct parts of their research in Czechia while participating in experiments at CERN, ESO facilities, European fusion laboratories, or overseas observatories. The availability of advanced domestic equipment also reduced the extent to which access to frontier instrumentation necessarily required permanent migration to Western Europe or North America. Regional centres in Brno and Ostrava created new career opportunities outside the traditional Prague research concentration. This did not eliminate problems of salaries, mobility, or competition for specialists, but it substantially diversified the environment in which a scientific career in Czech physics could develop. By the end of the decade, international mobility increasingly involved circulation into and out of Czech institutions rather than predominantly outward movement.

The rapid construction of research centres nevertheless created long-term challenges that became increasingly apparent as the decade progressed. European structural funding was particularly effective at financing buildings and equipment, but large infrastructures required continuous national support for operation, maintenance, upgrades, and personnel after construction ended. A petawatt-class laser, tokamak, supercomputer, accelerator, or nanofabrication centre could not remain scientifically competitive without regular technological renewal. The transition from construction funding to sustainable operation therefore became a central policy problem. Research centres also had to build stable user communities so that sophisticated equipment did not remain underutilised. Recruitment of experienced international scientists was difficult when Czech salary structures competed with institutions in Germany, Switzerland, the United Kingdom, Scandinavia, and the United States. Large projects additionally increased administrative requirements associated with procurement, reporting, safety, and European funding rules. Differences in research capacity persisted between institutions that had obtained major infrastructure investments and those that had not. The infrastructure boom consequently created new inequalities even while raising the technological level of the system as a whole. Scientific evaluation had to distinguish between the immediate publication output of mature laboratories and the longer development

times required by newly constructed facilities. The benefits of the investment cycle therefore depended increasingly on whether Czech research policy could support scientific exploitation after the initial capital phase. These sustainability questions became an important bridge between the infrastructure expansion of the 2010s and the policy challenges of the 2020s.

By the end of 2020, the position of Czech physics within European and global science was consequently very different from that at the beginning of the decade. The country remained an active member of CERN and ESO and participated in major international projects in particle, nuclear, fusion, neutron, astroparticle, and astronomical research. At the same time, ELI Beamlines, HiLASE, COMPASS, CANAM, CEITEC, and IT4Innovations had created a much stronger domestic infrastructure base. Czech researchers contributed to the Large Hadron Collider, the Pierre Auger Observatory, the preparations for the Cherenkov Telescope Array, FAIR, the European Spallation Source, and other multinational facilities. International users were increasingly travelling to Czech laboratories rather than internationalisation operating only through Czech researchers going abroad. Research centres outside Prague had strengthened the polycentric character of the national scientific landscape. New computational capabilities connected physical science with data-intensive research, numerical modelling, and emerging artificial-intelligence methods. Condensed-matter researchers associated with Czech institutions had also achieved substantial international visibility in antiferromagnetic spintronics, demonstrating that the decade was not defined by infrastructure alone. The common element connecting these developments was the ability to combine national competence with European and global scientific networks. The years 2010–2020 therefore marked the transition of Czech physics from a successfully integrated national research system into an increasingly important node within the distributed infrastructure of contemporary international science.

Contemporary Stage: 2020–2025 as a Phase of Quantum Technologies, Advanced Materials, High-Power Lasers, and Research Infrastructure Expansion

The period from 2020 to 2025 marked a further transformation of Czech physics from a successfully internationalised research system into a more technologically differentiated ecosystem increasingly organised around strategic infrastructures, advanced materials, quantum technologies, powerful computation, and specialised experimental platforms. The Czech Academy of Sciences (CAS), research universities, national infrastructures, and international organisations now operated within a substantially denser network than had existed even a decade earlier. Scientific development was increasingly shaped by the ability to combine fundamental research with expensive instrumentation, sophisticated data analysis, technological engineering, and long-term European partnerships. Several projects initiated during the 2010s reached operational maturity, while others entered construction or major modernisation phases. The period also brought unusually visible conceptual contributions from Czech-based condensed-matter physics, most notably through the emergence of altermagnetism. Quantum communication and quantum computing moved from specialised research subjects towards national infrastructure and educational priorities. Laser science consolidated around facilities capable of serving international users, while fusion research moved from operation of an established tokamak towards construction of a more advanced high-field device. New programmes in semiconductors, nanotechnology, and computational

science strengthened the connection between physics and European technological sovereignty. By 2025, Czech physical science was therefore characterised not by a single dominant speciality but by the coexistence of several strategically interconnected scientific and technological domains. The contemporary stage can consequently be understood as a period in which the infrastructure created during earlier decades began to support both frontier research and the formation of new national technological capabilities.

The opening of this period coincided with the coronavirus disease 2019 (COVID-19) pandemic, which created an immediate stress test for research organisations accustomed to laboratory access, international mobility, and shared facilities. Experiments requiring physical presence were interrupted or reorganised, conferences moved online, and international collaboration became increasingly dependent on digital communication. Large infrastructures faced the additional difficulty of maintaining technologically complex systems even when ordinary user access was restricted. At the same time, facilities capable of contributing to biomedical, structural, and materials research sought ways to support pandemic-related science. Extreme Light Infrastructure Beamlines, for example, announced fast-track access for coronavirus-related research during 2020. The crisis accelerated the adoption of remote working, digital project management, and distributed scientific collaboration throughout the Czech research system. It also demonstrated that research infrastructures depend on technical personnel and institutional continuity even during periods when ordinary experimental programmes are disrupted. Rather than reversing the internationalisation achieved during the previous decade, the pandemic encouraged institutions to develop more resilient forms of scientific cooperation.

A particularly important institutional milestone occurred on 30 April 2021, when the Extreme Light Infrastructure (ELI) received the legal status of a European Research Infrastructure Consortium (ERIC) from the European Commission. This legal form was designed specifically to enable countries and international organisations to establish and operate research infrastructures of European significance under a common governance framework. Czechia and Hungary were founding members together with Italy and Lithuania, while the Czech Republic became host of the statutory seat at ELI Beamlines in Dolní Břežany. The decision changed the position of the Czech facility from that of a nationally hosted project financed substantially through European structural investment into a component of an internationally governed European organisation. ELI ERIC was responsible for integrating participating laser facilities through common management, access procedures, scientific strategy, and user services. This arrangement created a new form of scientific internationalisation because foreign researchers would gain access to a European infrastructure whose headquarters and one of its principal facilities were located in Czechia. The establishment of the consortium also created greater institutional stability for long-term operation after the capital-intensive construction phase. It placed Czech laser research within a governance system comparable to other major European infrastructures that operate beyond the administrative boundaries of individual national laboratories. The location of the statutory seat in Dolní Břežany consequently carried significance beyond scientific prestige. It demonstrated that Czechia had developed sufficient organisational and technical capacity to host the central administration of a multinational scientific infrastructure. This represented one of the clearest structural achievements in Czech physics since independence.

During the following years, ELI Beamlines increasingly shifted from commissioning towards regular scientific user operation. Calls for experiments expanded progressively from early-

access and user-assisted commissioning programmes towards a unified ELI user system based on international peer review. Scientists from Europe, North America, Asia, and other regions submitted proposals in subjects ranging from atomic and molecular physics to materials science, particle acceleration, plasma physics, biology, and medical research. The facility's high-power lasers and secondary radiation sources allowed experiments that would be difficult or impossible to reproduce in ordinary university laboratories. By the middle of the decade, the growing number of proposals demonstrated that the infrastructure was developing an external scientific community rather than serving primarily its host institution. This distinction is essential because the scientific value of a large infrastructure depends partly on whether researchers from outside the organisation consider its capabilities sufficiently distinctive to justify competitive applications for experimental time. ELI Beamlines therefore entered the 2020s not merely as a Czech laser laboratory but increasingly as an international user facility. Its maturation was one of the strongest indicators that the infrastructure investments of the previous decade were beginning to generate a durable research environment.

The technical development of ELI Beamlines continued alongside the expansion of its user programme. The L3-HAPLS, or High-Repetition-Rate Advanced Petawatt Laser System, was designed to combine petawatt-class peak power with repetition rates considerably higher than those characteristic of many earlier high-energy laser systems. Its architecture created possibilities for repeated laser-plasma experiments in which statistical reproducibility could become much more important than in traditional single-shot high-energy physics. Other experimental areas supported X-ray generation, electron and ion acceleration, high-field physics, plasma studies, and investigations of matter under extreme conditions. The L4 ATON system represented another major technological strand, designed for very high-energy multi-petawatt operation and applications involving extreme electromagnetic fields. Development during the first half of the 2020s progressively integrated these lasers with secondary-source and experimental platforms. The scientific model consequently moved beyond the idea of constructing the most powerful possible laser in isolation. Researchers increasingly required stable repetition rates, well-characterised beams, synchronisation, diagnostics, target systems, and reliable integration with experimental stations. This emphasis on reproducibility and user readiness is characteristic of the transition from experimental prototype to scientific infrastructure. By 2025, six joint ELI user calls had attracted 563 experimental proposals involving more than 1,400 researchers from 38 countries. Of these proposals, 369 had been awarded beam time, while more than 200 experiments had already been implemented across the ELI facilities. These figures demonstrated that the European laser infrastructure had entered a substantially more mature operational phase. For Czech physics, this development meant that a facility conceived during the previous decade was now generating a sustained inward flow of international scientific activity.

The HiLASE Centre, whose name derives from High average power pulsed LASErs, developed along a complementary technological trajectory during the same period. Rather than competing directly with ELI Beamlines for maximum peak intensity, HiLASE concentrated strongly on high-average-power, high-energy diode-pumped solid-state laser systems and their scientific and industrial uses. By 2020, the centre had already established substantial expertise around the BIVOJ laser and associated technologies. During the following years, its research increasingly connected laser architecture with applications such as laser shock peening, precision processing, optical-component testing, and surface engineering. This

combination positioned HiLASE between fundamental laser development and advanced manufacturing, making it particularly relevant to the technological side of Czech physical science. The centre also benefited from European programmes intended to strengthen research excellence and international institutional capacity. Its activities demonstrated that high-power laser physics could generate technological platforms whose significance extended beyond the study of laser-matter interaction itself. Cooperation with industrial users consequently became an important complement to academic experimentation. HiLASE also provided training opportunities for researchers and engineers working with modern pulsed-laser technologies. The coexistence of HiLASE and ELI Beamlines in Dolní Břežany therefore created a research cluster in which different laser regimes could support both discovery-oriented and application-oriented science.

Fusion research underwent an equally important generational transition. The COMPASS (Compact Assembly) tokamak reached its final experimental discharge on 20 August 2021 after almost a decade of regular scientific exploitation in Prague. During its operation, the machine had supported studies of high-confinement regimes, edge-localised modes, plasma turbulence, runaway electrons, plasma-wall interaction, diagnostics, and other problems relevant to contemporary magnetic-confinement fusion. The device was removed from the experimental hall in October 2021 to make space for its much more ambitious successor. The COMPASS Upgrade (COMPASS-U) project represented not simply a replacement of an ageing machine but a substantial increase in magnetic field, plasma current, thermal loads, and experimental complexity. Its design envisaged a toroidal magnetic field of approximately five tesla and plasma current of up to two megaamperes. Such parameters would place the machine in a distinctive region between conventional medium-sized tokamaks and much larger international fusion devices. The transition from COMPASS to COMPASS-U therefore reflected the broader movement of Czech experimental physics towards specialised facilities intended to address problems of direct international relevance. The closure of the earlier tokamak was consequently best interpreted as a planned transformation of domestic fusion capability rather than as the end of a research tradition.

Construction of COMPASS-U became one of the most technically demanding Czech physics projects of the early 2020s. The Institute of Plasma Physics had to modify the existing experimental hall extensively, including reinforcement of structural elements and preparation for the mass and electromagnetic forces associated with the new device. The first major phase of civil reconstruction was completed in 2023. The machine was designed with tungsten-dominated plasma-facing components and with vessel temperatures substantially higher than those typical of many earlier experimental tokamaks. These features were intended to support investigations of plasma-material interactions, divertor physics, power exhaust, and conditions relevant to future fusion reactors. The project also incorporated powerful neutral-beam and electron-cyclotron heating systems, complex power supplies, magnetic diagnostics, and specialised material-testing equipment. Manufacturing and assembly proceeded through the first half of the decade, with detailed design reviews continuing into 2025. The International Thermonuclear Experimental Reactor (ITER) and future demonstration power-plant concepts provided an important scientific context, although COMPASS-U was not intended to reproduce the scale of those machines. Instead, its value lay in achieving unusually high magnetic fields and heat-flux conditions within a more compact experimental geometry. Czech engineers and physicists collaborated with European, American, Korean, and other international fusion institutions during the design and implementation process. The project

therefore illustrated how infrastructure development itself had become a form of international scientific cooperation.

The strategic importance of Czech fusion research was reinforced through the country's participation in the European Consortium for the Development of Fusion Energy (EUROfusion). Czech teams contributed not only through domestic tokamak development but also through experiments, modelling, diagnostics, materials research, and collaborative activities at other European devices. In 2024, Radomír Pánek, then director of the Institute of Plasma Physics, became chair of the EUROfusion General Assembly for the 2024–2025 period. This appointment indicated the degree to which Czech fusion research had become integrated into European scientific governance rather than remaining a peripheral national programme. COMPASS-U simultaneously gave Czechia a distinctive experimental asset capable of contributing specific results to shared European objectives. The field therefore combined infrastructure, international coordination, materials engineering, computational modelling, and long-term energy research. Its development during 2020–2025 demonstrated that contemporary Czech physics increasingly operated in areas where scientific questions and technological strategy could not easily be separated. Fusion research also strengthened interaction between physicists, engineers, materials scientists, and specialists in high-power electrical systems.

Advanced materials and nanoscience formed another major axis of contemporary development. CzechNanoLab emerged as a national research infrastructure combining the CEITEC Nano laboratories at the Central European Institute of Technology (CEITEC) in Brno with the Laboratory of Nanostructures and Nanomaterials at the Institute of Physics in Prague. The infrastructure offered nanofabrication, electron and light microscopy, thin-film technologies, structural analysis, and other techniques required for contemporary condensed-matter and device research. A major modernisation programme begun in 2024 received approximately CZK 361 million for new equipment. Planned acquisitions included deposition systems, advanced microscopes, analytical instrumentation, and technologies for three-dimensional fabrication at microscopic scales. This investment reflected the growing recognition that nanoscale research depends as much on common technological platforms as on individual research groups. The infrastructure also collaborated with high-technology companies working in microscopy, semiconductor devices, and space-related technologies. CzechNanoLab therefore strengthened the relationship between fundamental materials physics and technologically oriented research. It also illustrated the increasing tendency to organise expensive instrumentation as shared national infrastructure rather than duplicate similar equipment across numerous laboratories.

Within this broader materials environment, the emergence of altermagnetism became one of the most significant scientific developments associated with Czech physics during the entire 1993–2025 period. In 2022, Libor Šmejkal, Jairo Sinova, and Tomáš Jungwirth published a systematic theoretical framework describing magnetic phases that differed fundamentally from the conventional distinction between ferromagnets and antiferromagnets. The term altermagnetism was used to describe collinear magnetic systems with zero net magnetisation but with characteristic momentum-dependent spin splitting generated by crystal and spin symmetry. This combination suggested that certain materials could exhibit electronic properties normally associated with ferromagnetism while retaining the compensated magnetic order characteristic of antiferromagnets. The concept developed from earlier Czech-led research on antiferromagnetic spintronics and on methods for controlling magnetic order

electrically. Work at the Institute of Physics had already established strong international collaborations with researchers in Germany, the United Kingdom, the United States, and other countries. Altermagnetism therefore emerged from a long research trajectory rather than appearing as an isolated theoretical proposal. The 2022 papers in *Physical Review X* provided a terminology and symmetry-based classification that rapidly attracted attention across condensed-matter physics. Researchers began identifying possible altermagnetic materials and reconsidering existing experimental results from a new theoretical perspective. The scientific significance of the development lay partly in its potential technological applications, but equally in its challenge to long-established categories of magnetic order. Czech-based researchers were thus contributing to the definition of a new international research field rather than merely participating in an already established programme. This represented a qualitatively different form of scientific visibility from the country's involvement in large multinational infrastructures.

Experimental work during 2023 and 2024 substantially strengthened the status of altermagnetism as a physical research programme. Spectroscopic and transport experiments in several candidate materials provided evidence for symmetry-driven spin splitting and related effects predicted by the emerging theoretical framework. Manganese telluride, MnTe, became particularly important because its properties allowed detailed comparison between theoretical predictions and experimental magnetic structures. In December 2024, an international team reported nanoscale imaging and controlled formation of altermagnetic states in MnTe in *Nature*. The study combined X-ray magnetic circular dichroism, magnetic linear dichroism, and photoemission electron microscopy to map local altermagnetic order. Researchers observed structures ranging from approximately hundred-nanometre-scale vortices and domain walls to much larger single-domain regions. The ability to manipulate these configurations through microstructuring and thermal treatment strengthened the technological relevance of the new magnetic category. Czech researchers associated with the Institute of Physics played important roles within the collaboration. The result complemented other 2024 studies demonstrating time-reversal-symmetry-breaking effects and distinctive electronic behaviour in candidate altermagnets. By 2025, altermagnetism had generated a rapidly expanding international literature extending into spintronics, magnonics, superconductivity, topological materials, and unconventional transport phenomena. Czech physics had therefore contributed both to the conceptual language of the field and to the development of materials and experimental methods through which that language could be tested.

The rise of altermagnetism occurred within a wider Czech effort to strengthen semiconductor and microelectronic research. In October 2024, the Czech government approved a National Semiconductor Strategy intended to reinforce the country's position in European and global semiconductor value chains. The strategy was motivated partly by concerns about technological dependence, supply-chain resilience, and the strategic importance of chips to modern industry. Although semiconductor policy extends far beyond physics, its scientific foundations rely directly on condensed-matter physics, materials science, nanofabrication, quantum transport, photonics, and precision metrology. Czech universities and Academy institutes already possessed expertise in semiconductor materials, magnetic structures, thin films, crystal growth, microscopy, and nanoelectronics. Facilities such as CzechNanoLab therefore acquired additional strategic relevance within an innovation agenda concerned increasingly with technological sovereignty. The strategy also emphasised education and

specialist skills, reflecting the fact that semiconductor development depends on a highly trained scientific and engineering workforce. Research infrastructure could consequently serve not only academic projects but also pre-industrial development and cooperation with companies. The connection between physical science and industrial strategy became more explicit than it had been during the early post-Czechoslovak decades. This did not transform condensed-matter research into an exclusively applied activity, but it created a stronger institutional environment for translating fundamental materials expertise into technological capability.

Quantum technologies emerged simultaneously as a distinct area linking several established Czech research traditions. Quantum optics, theoretical quantum mechanics, solid-state physics, nanostructures, laser physics, and information theory had long been present within Czech universities and Academy institutes. During the 2020s, however, these fields increasingly began to be organised under the common concept of quantum technologies. The Czech Technical University in Prague developed dedicated study programmes integrating quantum mechanics, quantum optics, quantum information, solid-state physics, laser technology, nanomaterials, and computing. Bachelor, master's, and doctoral pathways provided a more explicit educational framework for training specialists who could move between physics and technological applications. Research groups at Charles University, Palacký University, the Institute of Scientific Instruments, the Institute of Physics, Masaryk University, and other centres contributed complementary expertise. The shift was significant because quantum technologies require interaction among theoretical physics, experimental optics, materials research, electronics, computer science, and cryptography. Rather than creating a completely new discipline, Czech institutions were reorganising existing strengths around emerging technological objectives.

Quantum communication provided the clearest example of this transition from research speciality to coordinated infrastructure. The Czech National Quantum Communication Infrastructure (CZQCI) project began in 2023 within the wider European Quantum Communication Infrastructure (EuroQCI) initiative. Its central objective was to establish a national backbone connecting Prague, Brno, and Ostrava and to integrate this network eventually with comparable infrastructure in other European countries. The project incorporated quantum key distribution (QKD), a method in which quantum states are used to establish cryptographic keys whose interception can in principle be detected through the laws of quantum mechanics. Plans included approximately 400 kilometres of optical connections and several QKD segments, together with metropolitan branches serving selected public and security-related users. The consortium joined universities, the Czech Academy, CESNET, technical institutions, and cybersecurity organisations. Experimental systems were intended not merely to demonstrate isolated quantum links but to test long-distance operation, network management, user scenarios, and interoperability. Training formed an important component because infrastructure without specialists capable of operating and validating it would have limited strategic value. The programme consequently linked fundamental principles of quantum physics with communications engineering and national cybersecurity. It also placed Czechia inside the broader European effort to develop secure quantum communication networks rather than attempting to establish an incompatible national system. By 2025, quantum communication had therefore become one of the clearest cases in which a physical principle was being translated into planned national technological infrastructure. The project also strengthened cooperation among research communities that had previously worked more

separately in optics, quantum information, telecommunications, and cybersecurity. This convergence represented a new stage in the institutionalisation of quantum science within Czechia.

High-performance computing underwent an equally important transformation. In 2021, the Karolina supercomputer was commissioned at the IT4Innovations National Supercomputing Center in Ostrava in cooperation with the European High Performance Computing Joint Undertaking (EuroHPC JU). Its peak performance of approximately 15.7 petaflops made it the most powerful Czech supercomputer at the time of installation. Karolina was designed for conventional numerical simulations, large-scale data analysis, and artificial-intelligence workloads, thereby serving a wide range of scientific disciplines including physics. Czech researchers simultaneously gained access to the much larger LUMI system in Finland through participation in the European consortium operating that machine. The relationship between domestic and shared European computing thus closely resembled the infrastructure model already familiar from particle physics, astronomy, and neutron science. In 2025, a 24-physical-qubit quantum computer associated with the LUMI-Q consortium was installed at IT4Innovations for integration with Karolina and the wider EuroHPC environment. The Ostrava centre therefore became a site where conventional supercomputing and experimental quantum computing could be developed within the same European computational ecosystem. This represented a particularly clear manifestation of the growing convergence between physics, computation, and strategic digital infrastructure.

For theoretical and experimental physics more broadly, the expansion of computing capacity changed the range of feasible scientific problems. Electronic-structure calculations, atomistic simulations, plasma modelling, detector simulations, astronomical data analysis, laser-plasma modelling, and optimisation increasingly required resources exceeding ordinary departmental computing clusters. Machine learning and artificial intelligence became additional tools for identifying patterns, accelerating simulations, controlling experiments, and processing large datasets. The contemporary physicist therefore depended increasingly on software and data infrastructures alongside traditional experimental instruments. Czech participation in European high-performance computing reduced the need to reproduce the largest computational systems nationally while maintaining substantial domestic competence. Integration with quantum computing also created opportunities to explore hybrid algorithms in which conventional and quantum processors perform different parts of a calculation. Although practical quantum advantage remained a research question rather than an established general-purpose capability, the installation of dedicated hardware in Ostrava gave Czech researchers direct access to experimental quantum-computing environments. It also created training opportunities extending beyond theoretical quantum information. The development illustrates how research infrastructure in the 2020s increasingly included digital and computational systems alongside accelerators, lasers, and telescopes. This broader conception of infrastructure became essential to nearly every advanced field of Czech physics. The distinction between computational physics and experimental physics consequently became less rigid as experiments generated larger datasets and simulations became integral to experimental interpretation. By 2025, Czech physics was therefore participating in the global movement towards hybrid scientific environments combining physical instruments, high-performance computation, and data-intensive methods. This transformation was methodological as well as technological. It changed the skills expected from younger researchers entering the discipline.

Nuclear physics also acquired important new domestic capability during this period. In May 2022, the first dedicated Czech laboratory for accelerator mass spectrometry (AMS) was formally opened at the Nuclear Physics Institute in Řež. The central instrument was the Multi-Isotope Low-Energy AMS (MILEA) system, based on a compact tandem accelerator operating at up to approximately 300 kilovolts. The facility enabled highly sensitive measurement of long-lived radionuclides including carbon-14, beryllium-10, aluminium-26, iodine-129, uranium isotopes, and other actinides. Accelerator mass spectrometry can detect extremely small isotopic abundances and requires far smaller samples than many conventional radiometric approaches. This capability expanded Czech research in radiocarbon dating, environmental science, archaeology, climate studies, nuclear safeguards, and tracing of radionuclides. The laboratory was established as a shared workplace involving the Nuclear Physics Institute, the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University, and the Institute of Archaeology. Its organisation therefore exemplified the increasingly interdisciplinary use of physical infrastructure. The opening of the facility also reduced dependence on foreign laboratories for specialised isotope measurements. Nuclear physics thus continued to modernise not only through participation in large international accelerator projects but also through carefully targeted national investment.

International nuclear-science connections remained important during the same period. Czech researchers continued to participate in the European Spallation Source (ESS) in Sweden and the Facility for Antiproton and Ion Research (FAIR) in Germany, both representing long-term European investments in neutron and nuclear science. Czech contributions included technological development and in-kind participation rather than simply future access to completed machines. Work connected with ESS included components and instrumentation relevant to neutron production and materials research. Participation in FAIR linked Czech physicists with future experiments in nuclear structure, heavy-ion collisions, radioactive nuclei, and related areas of fundamental physics. Domestic facilities at Řež continued to support training, method development, and smaller-scale experiments that complemented these international projects. The combination of national and external infrastructure therefore remained the central organisational principle of Czech nuclear physics. Increasing specialisation allowed Czech groups to contribute particular technologies or scientific competencies without attempting to reproduce the full scale of international facilities. By the mid-2020s, this model had become deeply institutionalised across Czech physical science.

Particle physics likewise entered a new experimental cycle when the European Organization for Nuclear Research (CERN) restarted the Large Hadron Collider (LHC) for its third physics run in 2022. Run 3 began on 5 July at a record proton-proton collision energy of 13.6 teraelectronvolts following more than three years of maintenance and detector upgrades. Czech researchers continued to participate particularly in A Toroidal LHC Apparatus (ATLAS) and A Large Ion Collider Experiment (ALICE), as well as in other CERN-related activities. The new run placed greater demands on detector readout, computing, data storage, and physics analysis because experiments were collecting larger and more complex datasets. Czech groups contributed through detector operation and upgrades, software, computing, phenomenological analysis, and studies of Higgs, top-quark, heavy-ion, and other processes. Their involvement demonstrates the cumulative character of scientific internationalisation, because the expertise required for Run 3 had been developed through Czech participation extending back to earlier CERN experiments. In 2025, the Breakthrough Prize in Fundamental Physics was awarded collectively to the ATLAS, ALICE, Compact Muon Solenoid, and Large

Hadron Collider beauty collaborations for achievements based on LHC data. Czech researchers associated with the relevant collaborations were therefore part of the broader scientific communities recognised by the award. The significance for Czech physics lay not in claiming national ownership of collective discoveries but in sustaining sufficiently strong groups to contribute over decades to one of the world's most demanding experimental programmes. CERN consequently remained a central example of how a medium-sized scientific system could maintain frontier research through durable specialisation and international responsibility. The continuing involvement of students and young researchers also ensured that particle physics remained closely connected with Czech higher education.

Astronomy developed within a similarly mature international framework through continued membership of the European Southern Observatory (ESO). Czech astronomers retained competitive access to the Very Large Telescope and to the Atacama Large Millimeter/submillimeter Array (ALMA), while preparations for the Extremely Large Telescope (ELT) became increasingly relevant to future research planning. Czechia hosted an ALMA Regional Centre node that supported the scientific community and contributed particularly to the development and promotion of solar observing. Czech companies also participated in technological contracts associated with ESO facilities, including instrumentation and components for existing observatories and for the ELT. This industrial involvement illustrated how membership in international research organisations could generate technological opportunities beyond direct scientific observation. The construction of the ELT passed major milestones during 2023 and 2024, although delays shifted its expected first light beyond the 2025 horizon. Czech astronomers nevertheless remained positioned to use the facility once scientific operations begin. The country's astronomical integration therefore increasingly included research access, instrument-related technology, training, and industrial participation. This was a more mature relationship than the predominantly observational access that had followed Czech accession to ESO in 2007.

Astroparticle physics achieved an important institutional milestone in January 2025 with the establishment of the Cherenkov Telescope Array Observatory (CTAO) as a European Research Infrastructure Consortium. Czechia became one of the founding members of the new organisation. The observatory is designed to operate arrays of imaging atmospheric Cherenkov telescopes in the Northern and Southern Hemispheres for the study of very-high-energy gamma rays. Its scientific questions include particle acceleration around extreme astrophysical objects, cosmic-ray origins, dark-matter searches, and transient high-energy phenomena. Czech groups had participated for years in telescope optics, atmospheric monitoring, instrumentation, and scientific preparation before the ERIC was created. Membership consequently converted long-standing project participation into a more durable state-level commitment to the observatory's construction and future operation. The organisational model also resembles other European infrastructures in which participating countries contribute cash, equipment, expertise, or scientific services within a common legal structure. CTAO will operate with an open-observatory philosophy, making high-level data and analysis resources available to a wider scientific community. Czech membership therefore strengthens the country's position at the intersection of astronomy, particle physics, detector engineering, and data science.

International infrastructure participation during this period was accompanied by a more mature conception of scientific access. Facilities increasingly operated on the principle that major equipment financed from public resources should serve broader communities through

transparent calls and scientific peer review. ELI, CzechNanoLab, accelerator laboratories, supercomputing centres, and other infrastructures developed procedures through which external researchers could obtain access to instruments or computing resources. The model encouraged research groups to specialise in maintaining sophisticated platforms while external users concentrated on scientific questions requiring those platforms. It also increased pressure on infrastructures to provide professional technical support, data policies, training, safety procedures, and reliable scheduling. These activities created new scientific occupations alongside conventional academic research, including facility scientists, beamline specialists, research-software engineers, and user-support professionals. International users also contributed to the intellectual diversity of host laboratories by bringing experimental questions developed elsewhere. Czech physical science consequently became increasingly service-oriented without ceasing to conduct its own fundamental research. Hosting a successful infrastructure required balancing institutional research agendas with the needs of external scientific communities. This operational culture represented one of the less visible but most important consequences of the infrastructure expansion that had begun during the previous decade.

The relationship between physical research and industry also became more structured during 2020–2025. High-power laser centres worked with companies interested in surface treatment, machining, optical components, and advanced manufacturing processes. Nanotechnology infrastructures collaborated with firms involved in microscopy, semiconductor production, sensors, and specialised materials. Supercomputing resources supported both academic research and computationally intensive industrial applications. Semiconductor strategy created a national policy context in which university and Academy expertise could be linked more explicitly with chip design, materials, fabrication, and high-value manufacturing. Quantum communication brought telecommunications and cybersecurity organisations into projects rooted partly in fundamental optical and quantum physics. Nuclear analytical techniques supported environmental, archaeological, biomedical, and materials-related applications. These interactions did not erase the distinction between fundamental research and industrial development. Instead, they demonstrated that sophisticated research infrastructure can create technological spillovers even when its original scientific mission is not commercial. By the middle of the decade, such connections were increasingly regarded as a normal component of the national innovation ecosystem rather than as an exceptional extension of academic activity.

Education had to adapt to these changes because the new scientific landscape required combinations of skills that traditional disciplinary programmes did not always provide. Quantum technologies demanded competence in mathematics, quantum physics, optics, computation, communication theory, and nanomaterials. Laser facilities required specialists in optical engineering, control systems, high-voltage technology, vacuum science, plasma physics, and scientific computing. Fusion research needed physicists capable of understanding plasma dynamics while collaborating closely with materials scientists and engineers. Particle physics increasingly expected familiarity with large-scale data processing and modern statistical analysis in addition to detector and theoretical knowledge. Nanotechnology depended on clean-room practice, microscopy, fabrication, and materials characterisation. Universities therefore developed more interdisciplinary study programmes and strengthened collaboration with Academy institutes and research infrastructures. Doctoral students increasingly conducted research within large teams whose daily working

language was English and whose members came from several countries. This environment prepared graduates for careers in international laboratories, high-technology firms, computing centres, and research-intensive industries. It also made human-resource development one of the principal constraints on future expansion, because new infrastructure could not function without sufficiently specialised personnel.

The increasing technological ambition of Czech physics also brought sustainability into sharper focus. Large laser systems, tokamaks, computing centres, accelerators, and clean-room facilities require substantial electricity, maintenance, cooling, specialist staff, and periodic equipment replacement. Capital investment alone therefore cannot guarantee long-term scientific competitiveness. ELI's transition towards regular user operations illustrated the need for stable operating resources after the major construction phase had ended. COMPASS-U similarly required support extending well beyond the procurement and assembly of the tokamak itself. Nanotechnology laboratories faced rapid equipment obsolescence as microscopy and fabrication technologies continued to advance. Supercomputing centres required repeated replacement cycles because computational hardware loses competitive value much faster than many conventional laboratory instruments. Research policy therefore increasingly had to distinguish between constructing new infrastructure and maintaining a sustainable scientific service around it. This distinction became particularly important after the investment-heavy period supported by European structural funds. The contemporary stage consequently demanded long-term institutional planning to ensure that facilities remained scientifically productive after their initial political visibility had faded. Infrastructure expansion thus generated obligations extending decades into the future.

These challenges were intensified by the broader scale of Czech research investment. In 2024, total expenditure on research and development (R&D) in Czechia reached approximately CZK 146.9 billion. This represented about 1.82 per cent of gross domestic product (GDP), below the average level recorded across the European Union. Business sources supplied more than CZK 93 billion, while national public resources and European Union funding together accounted for a substantial additional share. The figures demonstrate that Czech research operated with a significant national resource base, but not with the financial intensity available in countries such as Germany or Austria. Physics therefore continued to depend strongly on strategic specialisation and participation in shared European infrastructures. The ability to obtain access to CERN, ESO, EuroHPC systems, ESS, FAIR, CTAO, and other facilities reduced the need to reproduce every experimental capability inside Czechia. At the same time, the country had to maintain enough domestic expertise and infrastructure to make meaningful use of those memberships. The financial structure of Czech science thus continued to favour a networked model of sovereignty based on competence and access rather than complete technological self-sufficiency. This model had become more sophisticated by 2025 but remained dependent upon sustained national and European political support. The question of long-term operating finance consequently became as important as the initial success of infrastructure construction. Scientific competitiveness depended increasingly on the capacity to maintain both people and instruments over many funding cycles.

The contemporary stage also revealed a gradual shift from infrastructure acquisition towards strategic technology policy. The National Semiconductor Strategy approved in 2024 placed microelectronics and semiconductor capabilities within the context of European technological resilience. Quantum communication projects connected national scientific expertise with the European objective of constructing secure continental networks. The installation of the

quantum computer at IT4Innovations in 2025 linked Czech computational infrastructure directly with the European quantum-computing programme. In December 2025, the Czech government published the National Strategy for Quantum Technologies 2026+, formalising priorities in quantum computing and simulation, quantum communication, quantum sensing, quantum metrology, and quantum materials. The strategy also emphasised education, international cooperation, economic competitiveness, security, and infrastructure. Its adoption can be interpreted as the institutional culmination of developments that had accelerated throughout the first half of the decade. Areas previously represented by separate research groups were now being treated as components of an emerging national quantum ecosystem. This shift did not mean that Czechia had already achieved equal strength across all branches of quantum technology. It indicated instead that quantum science had moved from a collection of academic specialities into the sphere of national strategic planning.

By 2025, the development of Czech physics could therefore be described through several interacting forms of scientific capacity. The country hosted internationally governed laser infrastructure, constructed an advanced fusion device, maintained modern nuclear and nanotechnology facilities, and operated nationally significant supercomputing resources. It participated institutionally in CERN, ESO, CTAO, ESS, FAIR, European fusion programmes, and shared high-performance computing systems. Czech-based researchers had helped formulate altermagnetism as a new field of condensed-matter physics and contributed to its experimental validation. Quantum communication had begun to acquire national network infrastructure, while quantum computing was entering the domestic research environment through a European consortium. Materials research was increasingly linked with semiconductor strategy, nanoelectronics, spintronics, and technologically significant fabrication methods. Astronomy and particle physics continued to benefit from mature international memberships developed over previous decades. These developments demonstrate that the Czech research system no longer depended on a single pathway to international relevance. Scientific influence could arise from hosting infrastructure, contributing technology to foreign facilities, participating in multinational discoveries, developing conceptual advances, or connecting fundamental knowledge with strategic technological applications. The diversity of these pathways was itself evidence of institutional maturation.

The period from 2020 to 2025 consequently represents more than a continuation of the infrastructure expansion begun during the previous decade. It marks the point at which several of those infrastructures became operational scientific institutions with stable user communities and increasingly international governance. At the same time, the research agenda broadened towards quantum communication, quantum computing, advanced magnetic materials, semiconductor technologies, artificial intelligence, and hybrid computational systems. The development of altermagnetism demonstrated that infrastructure-oriented science could coexist with conceptual innovation of international significance. ELI ERIC showed that Czechia could host the statutory centre of a European research organisation rather than function only as a participant in facilities abroad. COMPASS-U illustrated an ambition to build a specialised national experiment addressing problems directly relevant to the international fusion programme. CzechNanoLab and the semiconductor strategy strengthened the relationship between physical research and advanced technological production. IT4Innovations connected national physics and engineering communities with European supercomputing and quantum-computing

environments. CZQCI extended quantum physics into the design of strategic communication infrastructure. The new AMS laboratory demonstrated that targeted domestic investment could still create important capabilities outside the most visible branches of big science. Czech participation in the founding of CTAO ERIC in 2025 further confirmed the country's continuing commitment to shared European scientific infrastructure. These developments collectively transformed the meaning of internationalisation from access to foreign science into reciprocal participation in a distributed European research system. By the end of 2025, contemporary Czech physics had become an ecosystem in which scientific continuity, infrastructure, conceptual discovery, technological strategy, and European integration were increasingly inseparable.

Part Two

Major Achievements of Czech Physics, 1993–2025

Particle Physics and High-Energy Research

Particle physics and high-energy research occupy a distinctive place in the history of Czech physics between 1993 and 2025 because they reveal particularly clearly how a medium-sized national scientific community can contribute to research at the global frontier. The field depends on accelerators, detectors, computing systems, and international collaborations whose scale lies far beyond the capacity of a single Czech institution. Czech success therefore cannot be measured by ownership of a national collider, but by the depth of participation in shared facilities and by the scientific and technical responsibilities assumed within them. The European Organization for Nuclear Research, better known by its historical acronym CERN, became the central institutional framework for this development after the Czech Republic entered the organisation as an independent Member State in 1993. During the following three decades, Czech groups participated in detector construction, experimental operation, software development, distributed computing, data analysis, and the interpretation of collider results. Their work ranged from precision studies of the Standard Model to searches for phenomena that might reveal physics beyond it. The Large Hadron Collider, usually abbreviated as LHC, became the most visible arena for these activities after the start of collision data taking in 2010. Czech physicists contributed especially strongly to ATLAS and ALICE, while participation also extended to forward physics, fixed-target programmes, detector research and, by the mid-2020s, a developing Czech programme within LHCb. The resulting record demonstrates that high-energy physics in Czechia evolved not as an isolated specialist field but as a technologically sophisticated component of the country’s wider international research architecture.

The roots of this achievement extend well before the LHC era and help explain why Czech groups were able to enter the new collider programme with relevant experience. Experimental particle physics in the Czech lands had developed from cosmic-ray studies, nuclear emulsions, bubble chambers, and accelerator experiments undertaken in Czechoslovak institutions from the 1950s onwards. Czech researchers subsequently participated in experiments at the Joint Institute for Nuclear Research in Dubna and at CERN, including deep-inelastic scattering and studies of hadron interactions. In the 1980s, a strong Czech team joined the H1 experiment at the Hadron-Electron Ring Accelerator in Hamburg, while another group participated in DELPHI at the Large Electron-Positron Collider at CERN. These collaborations provided experience with silicon tracking, detector electronics, precision calibration, trigger systems, and the analysis of very large experimental datasets. The Czech Republic inherited this technical and intellectual base when Czechoslovakia dissolved. Independent membership of CERN from 1 July 1993 then ensured that the transition to sovereign statehood did not interrupt participation in European particle physics. Instead, membership provided a stable framework for expanding the number of Czech scientists and technicians working at CERN and for improving domestic infrastructure. When CERN approved construction of the LHC, Czech physicists were therefore able to move from the previous

generation of experiments into the design and construction of new detectors. The continuity between H1, DELPHI, and later LHC programmes became one of the principal foundations of Czech high-energy physics after 1993.

The institutional base for Czech participation gradually became distributed across several universities and institutes rather than concentrated in a single laboratory. The Institute of Physics of the Czech Academy of Sciences developed the largest broad high-energy physics programme, combining detector research, collider data analysis, computing, and participation in several CERN projects. Charles University maintained major groups in ATLAS, theoretical particle physics, flavour physics, heavy-ion physics, and related experimental programmes. The Czech Technical University in Prague contributed through the Faculty of Nuclear Sciences and Physical Engineering and the Institute of Experimental and Applied Physics, with particularly strong links to detector technology and ALICE. The Nuclear Physics Institute of the Czech Academy of Sciences added expertise in ultra-relativistic heavy-ion collisions, silicon detectors, radiation testing, and distributed computing. Palacký University in Olomouc became involved in forward detectors and instrumentation, while other Czech institutions contributed to smaller CERN experiments and technological projects. These organisations were connected through national coordination mechanisms that eventually developed into the CERN-CZ research infrastructure. By the 2010s, Czech high-energy physics therefore functioned as a national network linked through common experimental obligations at CERN rather than as a collection of independent institutional projects.

ATLAS, whose name derives from A Toroidal LHC Apparatus, became the most extensive Czech commitment at the Large Hadron Collider. It is a general-purpose detector designed to reconstruct the products of proton-proton and heavy-ion collisions across an exceptionally broad range of energies and final states. Its scientific programme includes Higgs physics, top-quark studies, electroweak interactions, heavy-flavour physics, heavy-ion collisions, forward physics, and searches for new particles or interactions. The detector combines several complementary subsystems so that charged-particle trajectories, particle energies, muons, and missing transverse momentum can be reconstructed within a single event. This architecture is essential because evidence for new physical phenomena rarely appears directly and must instead be inferred from characteristic patterns in the particles emerging from a collision. The experiment also relies on a trigger and data-acquisition system capable of reducing an enormous initial collision rate to a manageable stream of scientifically valuable events. Computing is therefore part of the detector in an operational sense, even though much of the processing takes place outside the underground experimental cavern. Czech groups entered ATLAS early enough to participate not only in subsequent analysis but also in detector design, construction, commissioning, and long-term operation. Their responsibilities created a continuous institutional presence extending from the pre-LHC construction period through Run 1, Run 2, and Run 3. The Czech contribution consequently cannot be reduced to authorship on physics papers because detector hardware and operational service were prerequisites for every later measurement. ATLAS became both a scientific laboratory and a training environment through which generations of Czech students learned the practical organisation of modern big science.

The Czech ATLAS community developed expertise in several detector systems rather than concentrating on a single technological niche. National infrastructure reports identify Czech contributions to semiconductor components of the Inner Detector, the Tile Calorimeter, the ATLAS Forward Proton system, the Absolute Luminosity For ATLAS detector, radiation-

monitoring devices, and aspects of shielding and support engineering. Charles University has documented participation in the inner tracker, hadronic calorimetry, and forward detectors, while the Czech Technical University and Palacký University have also held responsibilities in forward instrumentation and later upgrade work. These contributions required precision mechanics, silicon-sensor testing, electronics, cooling, optical readout, radiation studies, and detailed quality assurance. Such tasks are scientifically consequential because a collider measurement can be no more reliable than the calibration, stability, and geometrical understanding of the detector that records it. Czech teams also supplied personnel for continuous shifts and detector-operation responsibilities during data-taking campaigns. The accumulated technical competence later positioned Czech laboratories to participate in major upgrades for the High-Luminosity Large Hadron Collider. Detector construction therefore served as a bridge between fundamental physics, materials research, electronics, and advanced engineering. It also gave Czech institutions a form of international visibility that depended on demonstrable technical reliability rather than national scientific size.

Semiconductor detector research became one of the strongest technological strands within this participation. Silicon tracking devices operate very close to collision regions and must measure particle positions with high precision while surviving intense radiation fields over many years. Czech groups contributed to testing and developing radiation-hard sensors and to the construction of modules for tracking systems. The Institute of Physics later became involved in the new all-silicon Inner Tracker planned for the high-luminosity phase of ATLAS. This work includes characterisation of silicon devices, irradiation studies, simulations of radiation damage, module development, and testing of electronics and mechanical integration. Czech researchers have also participated in international detector-development collaborations concerned with semiconductor technologies beyond conventional silicon, including diamond, silicon carbide, gallium nitride, and monolithic sensor concepts. These activities demonstrate how high-energy physics stimulates materials and device research whose relevance extends beyond a single experiment. Detector laboratories in Czechia provide a domestic environment in which components can be developed and validated before being installed at CERN. Such capacity is strategically important because membership in a large collaboration is strengthened when a national group can deliver hardware rather than depend entirely on facilities abroad. Participation in detector upgrades has therefore helped maintain continuity between experimental generations even during periods when the collider itself was shut down. It has also ensured that Czech groups remain scientifically embedded in ATLAS as the experiment prepares for much higher collision rates. In this sense, detector development is not an auxiliary activity but one of the core achievements of Czech particle physics.

The start of LHC collision data taking in 2010 shifted the emphasis of ATLAS from construction towards physics analysis without ending the technical responsibilities of national groups. Czech scientists participated in the rapid rediscovery of familiar Standard Model processes that was needed to demonstrate that the new detector and accelerator were understood correctly. As the integrated luminosity increased, analyses moved towards measurements of top quarks, vector bosons, heavy flavours, jets, and increasingly rare processes. The central scientific event of Run 1 was the 2012 observation by the ATLAS and Compact Muon Solenoid collaborations of a new boson with properties compatible with the Higgs particle. This discovery confirmed the existence of the long-sought excitation associated with the mechanism of electroweak symmetry breaking. Czech ATLAS members contributed as participants in the collaboration whose detector construction, operation, calibration,

computing, and analysis collectively made the result possible. The importance of this participation lies not in isolating a national fraction of the discovery, which would be artificial in an experiment of thousands of researchers, but in the fact that Czech institutions had sustained meaningful responsibilities throughout the entire experimental chain. The Higgs discovery placed the LHC at the centre of global particle physics and simultaneously demonstrated the value of long-term Czech investment in CERN. It also changed the future research programme because the newly discovered particle itself became an object of precision measurement. Czech groups subsequently participated in analyses designed to determine whether its production and decay properties conform to the Standard Model. The discovery era thus converted decades of infrastructure preparation into a continuing programme of quantitative tests of fundamental theory.

Higgs physics became an especially visible area of analysis at Charles University. The Prague ATLAS group has been continuously involved in the decay channel in which the Higgs boson produces a pair of tau leptons from Run 1 through Run 2 and into Run 3. This channel is important because it directly probes the coupling of the Higgs field to fermions rather than only to gauge bosons. Czech researchers have contributed to measurements of production cross-sections and to tests of whether the observed interaction strengths agree with Standard Model expectations. Their work also extends to searches for effects such as charge-parity violation and lepton-flavour-violating Higgs decays. Such measurements require detailed control of detector response, background processes, statistical methods, and theoretical uncertainties. The progression from discovery to precision analysis is characteristic of the maturing LHC programme. For Czech physics, it also demonstrates how a national group can acquire recognisable scientific expertise within a very large collaboration.

The scientific contribution of Czech ATLAS groups extends well beyond the Higgs sector. Researchers at Charles University and the Institute of Physics have worked on top-quark measurements, beauty-hadron physics, diffraction, photon-induced processes, forward physics, and searches for phenomena beyond the Standard Model. Beauty physics provides particularly sensitive tests because rare decays and charge-parity-violating observables can reveal indirect effects of particles too massive to be produced directly. Czech analyses have included measurements of B-meson lifetimes and studies of the charge-parity-violating phase in decays of strange B mesons. Forward proton detectors have allowed investigations of diffractive and photon-induced reactions in which particles retain much of their original momentum after the collision. Heavy-ion work within ATLAS has connected the general-purpose detector to questions more commonly associated with ALICE, including jet modification and the behaviour of strongly interacting matter. Top-quark analyses provide tests of the heaviest known elementary particle and of the interactions governing its production and decay. Searches for new particles, hidden sectors, additional dimensions, or non-standard Higgs interactions form another continuing element of the programme. The absence of a confirmed breakdown of the Standard Model has made increasingly precise measurements scientifically important rather than rendering the programme unsuccessful. Every improvement in experimental precision narrows the space in which alternative theories can remain viable. Czech groups have therefore participated in both the discovery-oriented and the precision-oriented phases of LHC physics. This breadth has made ATLAS the central platform of Czech experimental particle physics during the period under consideration.

Heavy-ion physics within ATLAS also created productive links between particle and nuclear physics communities in Czechia. Collisions of lead nuclei at ultrarelativistic energies produce

a medium whose collective behaviour is associated with quark-gluon plasma. ATLAS can study this medium through energetic probes such as jets, heavy flavours, electroweak bosons, and correlations among produced particles. Czech university researchers have contributed to heavy-ion analyses alongside colleagues working in the dedicated ALICE programme. This overlap is scientifically useful because the two experiments have different detector designs, acceptance, and analysis strengths. Independent measurements can therefore test whether observed features of the medium are robust against experimental method. Heavy-ion studies also require theoretical concepts from quantum chromodynamics, hydrodynamics, nuclear structure, and perturbative particle physics. The Czech involvement consequently helped connect institutional traditions that had previously been labelled separately as nuclear physics and high-energy physics. The LHC made that boundary increasingly artificial at the highest collision energies.

ALICE, meaning A Large Ion Collider Experiment, became the second major pillar of Czech participation at the LHC. Unlike ATLAS, it was designed specifically to investigate strongly interacting matter at extreme temperature and energy density, particularly through collisions of heavy nuclei. Its central scientific target is the quark-gluon plasma, a state in which quarks and gluons are not confined inside individual hadrons in the ordinary way. Recreating and characterising this medium provides information about quantum chromodynamics under conditions resembling those of the early Universe. ALICE measures thousands of particles emerging from central heavy-ion collisions and therefore requires excellent tracking, particle identification, vertex reconstruction, and low-momentum sensitivity. The experiment also studies proton-proton and proton-nucleus collisions, which provide essential reference systems and have themselves revealed unexpectedly collective behaviour. Heavy flavours, jets, quarkonia, light nuclei, strange particles, electromagnetic probes, and correlations all contribute to the reconstruction of plasma properties. Czech research groups entered ALICE through a combination of instrumentation and data analysis rather than through a narrowly defined single task. This combination has allowed domestic laboratories to contribute both to the functioning of the detector and to interpretation of the physical phenomena it records. ALICE therefore became a major meeting point between Czech nuclear physics, particle physics, detector engineering, and computing.

Czech participation in ALICE has involved the Nuclear Physics Institute of the Czech Academy of Sciences, the Institute of Physics, and the Czech Technical University in Prague. The Nuclear Physics Institute had already developed expertise in ultra-relativistic heavy-ion collisions through earlier CERN programmes and through participation in the STAR experiment at Brookhaven National Laboratory. This experience gave the group a natural route into ALICE, where the physics of hot and dense nuclear matter became a central research theme. The institute became involved from an early stage in the Inner Tracking System, usually abbreviated as ITS, which surrounds the collision point and reconstructs the trajectories and decay vertices of charged particles. Czech scientists contributed to operation, calibration, performance studies, and later upgrade activities associated with silicon tracking. Their analyses increasingly concentrated on jets and on the way energetic quarks and gluons lose energy while traversing quark-gluon plasma. The Czech Technical University developed a complementary ALICE programme combining instrumentation with measurements of quantum chromodynamics at high temperature and high energy. Its researchers became active in diffractive and ultraperipheral processes as well as in studies of collective behaviour. The Institute of Physics contributed through detector and computing activities and became one

of the Czech institutional members of the collaboration. These groups interacted closely through shared infrastructure and students even though their precise scientific emphases differed. The Czech ALICE programme therefore illustrates the value of institutional diversity inside a common international collaboration. It also shows how a relatively small national community can cover detector development, computing, and several distinct analysis themes when responsibilities are distributed coherently.

Detector development has been particularly important to the durability of Czech participation in ALICE. The Nuclear Physics Institute contributed to the Inner Tracking System and later used the U-120M cyclotron at Řež to test the radiation hardness of electronics and silicon components for detector upgrades. The Czech Technical University developed and maintained the Forward Diffractive Detector, a scintillator-based subsystem incorporated into the Fast Interaction Trigger of ALICE. The same university group has held responsibilities connected with the Muon Forward Tracker, which improves vertex information for muons detected at forward rapidity. These activities require knowledge of silicon sensors, scintillators, photodetectors, front-end electronics, radiation effects, and real-time detector operation. They also connect the LHC programme directly with domestic laboratories in Prague and Řež. Work on subsequent concepts, including detector systems for a possible ALICE 3 experiment, extends this technological continuity beyond the current detector generation. Czech ALICE instrumentation therefore represents a sustained research programme rather than a one-time contribution made during initial construction.

The analytical component of Czech ALICE research has addressed several of the central questions of modern quantum chromodynamics. Jet measurements investigate how energetic partons fragment into sprays of hadrons and how this process changes when the parton crosses quark-gluon plasma. The resulting phenomenon of jet quenching provides a sensitive probe of the density and transport properties of the medium. Czech groups have studied jet production and modification in proton-proton, proton-lead, and lead-lead collisions, allowing comparisons between different collision environments. Researchers at the Czech Technical University have also investigated photon-induced reactions and ultraperipheral collisions, in which electromagnetic fields surrounding relativistic nuclei act as intense sources of photons. Collective-flow analyses address correlations among produced particles and help test whether small collision systems can develop medium-like behaviour. Heavy-flavour and quarkonium measurements provide information about how charm and beauty quarks interact with the plasma. These research themes require sophisticated corrections for detector acceptance, background subtraction, unfolding, and statistical uncertainty. The Czech ALICE programme has therefore contributed to both the phenomenology of hot nuclear matter and the methodological development required to extract reliable results from extremely complex collision events.

The role of LHCb in the Czech high-energy physics story requires a more careful chronological distinction than that of ATLAS or ALICE. LHCb, originally named the Large Hadron Collider beauty experiment, is a forward spectrometer designed principally for precision studies of hadrons containing beauty and charm quarks. Its physics programme focuses on flavour-changing processes, rare decays, oscillations, charge-parity violation, and precise tests of the Standard Model. The experiment has also discovered a large number of previously unknown hadrons and has become an important laboratory for spectroscopy and quantum chromodynamics. For most of the 1993–2025 period, however, the core Czech LHC effort was concentrated in ATLAS, ALICE, and other CERN programmes rather than in an established

national LHCb group. A specifically Czech institutional LHCb programme began to take shape only in the final years of the period. The Institute of Physics entered LHCb first through technical association connected with scintillator research and detector development. In 2024, Czech work addressed advanced scintillating materials relevant to the future electromagnetic calorimeter upgrade. By 2025, the Institute of Physics was developing a broader programme in heavy-flavour analysis and detector research. LHCb should therefore be included in the history of Czech high-energy physics as an important late expansion of the national CERN portfolio, but not retroactively treated as a principal Czech experiment throughout the entire LHC era. This chronological distinction preserves the difference between the mature Czech roles in ATLAS and ALICE and the emerging LHCb engagement of the mid-2020s.

The new LHCb activity also illustrates how materials research can create an entry point into a major particle-physics collaboration. Scientists at the Institute of Physics worked with advanced cerium-doped gadolinium aluminium gallium garnet scintillators and with Czech industrial partners on materials potentially relevant to the LHCb electromagnetic calorimeter upgrade. Such scintillators must combine high light yield, fast response, radiation hardness, and manufacturability if they are to function in the extreme environment of a future high-luminosity detector. Test-beam work at CERN connected laboratory materials development in Czechia directly with the engineering requirements of the LHCb programme. The Institute subsequently began forming a physics group focused on charm and beauty decays, areas in which LHCb has exceptional experimental sensitivity. This programme offers opportunities to study charge-parity violation, rare processes, decay dynamics, and possible indirect signatures of new physics. It also broadens the Czech particle-physics portfolio beyond the general-purpose and heavy-ion emphases represented by ATLAS and ALICE. The emerging programme demonstrates how expertise developed in optical materials, detector technology, and previous collider analyses can converge within a new collaboration. By the end of 2025, LHCb thus represented an expanding frontier of Czech involvement rather than a completed historical achievement comparable in duration to ATLAS.

Czech high-energy research at CERN has never been confined to the four main LHC detectors. Czech teams have participated in TOTEM, which studies elastic and diffractive proton scattering, and they have contributed to forward detector systems that complement general-purpose LHC measurements. Charles University researchers have long participated in COMPASS, the Common Muon and Proton Apparatus for Structure and Spectroscopy, which investigated nucleon structure, spin physics, and hadron spectroscopy with high-energy muon and hadron beams. After COMPASS completed data taking, the successor experiment AMBER, or Apparatus for Meson and Baryon Experimental Research, continued aspects of the fixed-target programme. Other Czech groups have participated in NA62, which studies rare kaon decays, and in experiments concerned with antimatter, neutron reactions, axion-like particles, and precision tests of fundamental symmetries. These programmes broaden the scientific range of Czech particle physics beyond the energy frontier represented by the LHC. They also provide smaller collaborative environments in which Czech teams can assume specialised technical or organisational responsibilities. The breadth of this portfolio has made CERN a scientific ecosystem for Czech physics rather than simply the location of one accelerator.

Computing infrastructure became as important as detector hardware in enabling Czech participation in collider physics. The enormous data volumes produced by the LHC cannot be processed and stored solely at CERN, so the Worldwide LHC Computing Grid, abbreviated as WLCG, distributes these tasks among computing centres across many countries. Prague

operates a Tier-2 centre within this global system, giving Czech institutions a direct role in the processing and storage of collider data. The centre supports simulation, event reconstruction, user analysis, and data transfer for experiments in which Czech groups participate. The Nuclear Physics Institute has contributed storage capacity for ALICE, while computing servers hosted at the Institute of Physics have processed ALICE and other LHC workloads. High-throughput academic networks connect these facilities with CERN and with other grid centres. Such infrastructure allows a Czech doctoral student to analyse collision data produced near Geneva without being physically present at the detector. It also creates domestic expertise in distributed systems, workload management, data integrity, storage technologies, and scientific software. The grid model transformed the geography of collider science by making computation a genuinely international extension of the experimental apparatus. Czech participation in WLCG consequently represents a scientific contribution in its own right rather than an administrative service. Without such centres, national groups would be far less able to contribute rapidly to collaborative analyses. The Prague Tier-2 facility therefore became one of the essential foundations of Czech LHC research.

The growing complexity of LHC data also transformed the methodology of analysis. Modern particle-physics results depend on extensive Monte Carlo simulation, multivariate classification, statistical inference, detector calibration, and detailed estimates of systematic uncertainty. Czech physicists participate in these tasks through collaboration-wide software frameworks as well as through analyses led or co-led by local researchers. The shift towards larger datasets during Run 2 and Run 3 increased the importance of automated data-quality monitoring and efficient reconstruction algorithms. Machine-learning methods became progressively more common in jet identification, flavour tagging, event classification, anomaly searches, and detector optimisation. The scientific challenge is not simply to maximise classification performance, because analysis methods must remain interpretable enough for uncertainties to be quantified and results to be reproduced. Czech students trained in this environment therefore acquire a combination of physics, statistics, programming, and large-scale data-management skills. These competencies are transferable beyond particle physics even though they are developed in response to fundamental research questions. The data-analysis culture of the LHC has consequently become one of the most important channels through which high-energy physics contributes to the broader digital capacity of Czech science.

The national CERN-CZ research infrastructure provides the organisational framework that connects many of these activities. Its purpose is to coordinate Czech participation in CERN experiments and to support the domestic facilities required for detector research, construction, computing, maintenance, and data processing. Participating institutions include Charles University, the Czech Technical University in Prague, Palacký University, the University of West Bohemia, the Technical University of Liberec, the Institute of Physics, and the Nuclear Physics Institute. The infrastructure supports work in calorimetry, semiconductor tracking detectors, radiation-hard technologies, cooling, cryogenics, vacuum systems, electronics, mechanical design, and scientific computing. It also helps finance operational obligations that arise when Czech groups assume responsibilities inside international collaborations. National coordination is essential because CERN membership alone does not provide the domestic laboratories, personnel, and equipment needed to make meaningful experimental contributions. CERN-CZ therefore converts the political fact of state membership into practical scientific capacity. Its portfolio includes ATLAS, ALICE, LHCb, TOTEM, COMPASS, AMBER,

NA62, neutron and antimatter experiments, and detector research programmes. The infrastructure also represents Czech interests through committees and boards associated with CERN programmes. By integrating research, technology, and computing, CERN-CZ has become one of the clearest examples of how modern Czech physics is organised around access to a shared international facility. Its existence helps explain why Czech participation has remained continuous across several generations of experiments.

Detector research undertaken for CERN has also generated technological effects beyond the immediate experimental programme. Radiation-hard semiconductor sensors developed for tracking detectors have relevance to medical imaging, dosimetry, space instrumentation, and industrial inspection. Pixel-detector technologies associated with the Medipix family have been explored in several Czech research and application environments. Scintillator development for calorimetry and particle identification has strengthened links between the Institute of Physics and Czech high-technology manufacturers. Precision timing, fast electronics, field-programmable gate arrays, and real-time data acquisition have similarly broad technological relevance. High-energy physics imposes unusually severe requirements for radiation tolerance, spatial resolution, timing accuracy, and reliability, making its instrumentation a demanding test environment for new devices. Czech laboratories benefit when expertise acquired through CERN can be transferred into other fields of physics and engineering. Companies benefit when participation in detector production exposes them to international quality standards and specialised manufacturing challenges. Such transfer does not imply that fundamental particle physics must be justified primarily by immediate commercial returns. It does show, however, that the technological ecosystem required for collider experiments can generate capabilities with much wider scientific and economic use.

The educational impact of Czech participation in high-energy physics has been equally significant. Master's and doctoral students at Czech universities can work on real data from some of the world's largest scientific instruments while remaining enrolled in domestic programmes. Many spend extended periods at CERN, where they take detector shifts, attend collaboration meetings, present analyses, and learn to work in multinational teams. Students also participate in hardware development and testing in Prague, Řež, and Olomouc before components are installed abroad. This structure connects university teaching directly with experimental research instead of treating the two as separate institutional activities. Young physicists learn not only theoretical concepts but also software development, electronics, statistics, scientific communication, and project organisation. Some remain in academic particle physics, while others move into computing, finance, engineering, medical technology, or other data-intensive sectors. CERN participation has therefore functioned as a specialised training system for Czech science as well as a mechanism for producing research results.

The end of Run 2 in 2018 and the subsequent Long Shutdown 2 shifted attention towards major detector upgrades. ATLAS prepared for increasing collision rates through improvements to calorimetry, trigger systems, forward detectors, and the future all-silicon Inner Tracker. ALICE underwent an especially extensive transformation that included a completely new Inner Tracking System, a new Muon Forward Tracker, upgrades to the Time Projection Chamber, and continuous readout electronics. Czech teams participated in aspects of this upgrade cycle through detector operation, radiation testing, forward instrumentation, and computing. The new ALICE tracker, composed of seven layers of monolithic active pixel sensors, significantly improved vertexing and heavy-flavour measurements. Its much higher data-taking capability required correspondingly more powerful online processing and distributed computing. ATLAS

upgrade work likewise prepared Czech detector groups for the much harsher environment expected at the High-Luminosity Large Hadron Collider. This cycle demonstrates that experimental achievements at CERN depend on continuous technological renewal rather than on a detector being built once and then merely operated. Czech participation in upgrades has therefore been essential for preserving scientific relevance beyond the initial LHC discovery phase.

Run 3 began in 2022 at a proton-proton centre-of-mass energy of 13.6 teraelectronvolts and opened a new period of higher-rate precision measurements. ATLAS continued to refine Higgs, top-quark, electroweak, heavy-flavour, and new-physics studies using a rapidly expanding dataset. ALICE exploited its upgraded detector to record heavy-ion collisions at rates far beyond those achievable during earlier runs. Czech researchers remained involved in physics analysis, detector operation, computing, and preparation for future upgrades throughout this period. The new data allowed increasingly differential tests of the Standard Model and more detailed measurements of quark-gluon plasma. In 2024, Prague hosted the forty-second International Conference on High Energy Physics, bringing much of the global particle-physics community to Czechia and demonstrating the country's standing within the field. LHCb presented several precision flavour-physics results at that meeting, while Czech groups contributed through organisation and through their own experimental programmes. In April 2025, the Breakthrough Prize in Fundamental Physics recognised the ATLAS, Compact Muon Solenoid, ALICE, and LHCb collaborations for achievements based largely on Run 2 data. Czech researchers in ATLAS and ALICE were among the collaboration members whose collective work was recognised. The prize acknowledged precision Higgs measurements, studies of rare interactions and exotic nuclear matter, discoveries of new hadrons, matter-antimatter asymmetry measurements, and increasingly stringent constraints on possible new physics. It therefore captured the unusually broad scientific reach of the LHC programme to which Czech institutions had contributed over many years. For Czech physics, the recognition symbolised the maturation of a national community whose role extended from detector construction to the analysis of some of the most important collider datasets ever produced.

The achievements of Czech high-energy physics should nevertheless be interpreted within the collaborative structure of the discipline. Discoveries at CERN are products of international collaborations numbering hundreds or thousands of scientists, engineers, technicians, and students rather than national research teams acting independently. Czech contributions are therefore most accurately assessed through sustained responsibilities, technological delivery, recognised analysis expertise, computing capacity, and long-term institutional membership. This perspective avoids both understating the national contribution and exaggerating ownership of collective results. Czechia did not discover the Higgs boson as a national project, but Czech institutions helped build and operate an experiment that discovered it and subsequently participated in measuring its properties. Czech groups did not create ALICE alone, but they supplied detector systems, radiation tests, computing resources, operational work, and physics analyses central to the collaboration's programme. The same principle applies to the emerging LHCb involvement and to smaller CERN experiments. The scientific achievement lies in maintaining competence sufficient to remain a trusted contributor to projects operating at the highest international level. For a country of Czechia's population and research budget, that continuity represents a substantial institutional accomplishment. It also illustrates why access to global research infrastructure must be matched by domestic investment in people, laboratories, and computing.

Between 1993 and 2025, particle physics and high-energy research thus became one of the clearest demonstrations of Czech science's transition from post-Czechoslovak continuity to mature international integration. CERN membership provided the institutional framework, but national laboratories and universities supplied the expertise that gave membership scientific substance. ATLAS became the principal platform for Czech work at the energy frontier, combining detector construction with Higgs, top-quark, heavy-flavour, forward, heavy-ion, and new-physics analyses. ALICE established a complementary Czech strength in the physics of quark-gluon plasma and in the instrumentation required for high-multiplicity heavy-ion collisions. LHCb began to broaden the Czech portfolio in the final years of the period through scintillator development and a new heavy-flavour programme. COMPASS, AMBER, NA62, TOTEM, antimatter studies, neutron experiments, and detector research ensured that Czech participation at CERN remained scientifically diverse. The Prague Tier-2 centre and associated storage resources made distributed computing an integral part of the national contribution. Detector research linked fundamental physics with semiconductor technology, scintillators, electronics, precision mechanics, and data acquisition. The discovery and precision-study era of the LHC gave Czech scientists direct participation in the experimental tests that established the Higgs boson and explored the Standard Model at unprecedented energies. At the same time, the absence of confirmed new elementary particles beyond the Standard Model shifted increasing emphasis towards precision, rare processes, flavour physics, and higher-luminosity searches. By 2025, Czech high-energy physics had therefore become a durable national capability embedded within one of the most complex international scientific enterprises ever constructed.

Nuclear Physics, Accelerator Science, and Nuclear Technologies

Nuclear physics has been one of the fields in which Czechia most successfully preserved a strong Czechoslovak scientific inheritance while continuously adapting it to new experimental methods and European research structures. Its importance after 1993 rested on an unusually close relationship between fundamental nuclear research, accelerator science, neutron methods, materials characterisation, radiation physics, and medical applications. From the beginning of the independent Czech Republic, the principal national centre of this work was the Nuclear Physics Institute of the Czech Academy of Sciences (NPI CAS) at Řež near Prague. Around it developed a network of accelerators, neutron instruments, radiation laboratories, theoretical groups, and internationally connected experimental programmes. Over three decades, older facilities were repeatedly modernised while new accelerators and analytical systems were added to the institutional base. The resulting system allowed Czech researchers to study nuclear reactions and nuclear structure while also producing radionuclides, testing materials, measuring radiation, and applying nuclear analytical methods in fields far beyond nuclear physics itself. This architecture became increasingly open to external academic and industrial users through the Centre of Accelerators and Nuclear Analytical Methods (CANAM). Czech groups simultaneously entered major European facilities in France, Germany, and Sweden, where experiments required radioactive-ion beams, intense heavy-ion beams, antiprotons, or advanced spallation neutrons unavailable domestically. Participation in these infrastructures was accompanied by Czech technological contributions rather than being limited to the purchase of experimental access. Taken together, these developments made

nuclear physics one of the clearest examples of how Czech science combined national experimental capability with participation in a distributed European infrastructure system.

The institutional history of the Nuclear Physics Institute provides the essential background to this achievement. Its origins lie in the nuclear research centre established at Řež in 1955 as one of the principal institutions of the emerging Czechoslovak nuclear programme. Following an institutional division in 1972, the part concerned primarily with fundamental research remained within the Czechoslovak Academy of Sciences, while much of the applied nuclear programme developed separately. In 1993, the fundamental-research institute became part of the newly created Czech Academy of Sciences. The former Institute of Radiation Dosimetry was incorporated into the Nuclear Physics Institute in 1994, and the Laboratory of Neutron Activation Analysis was transferred to the institute during the same year. Since 2007, the institute has operated with the legal status of a public research institution. Its scientific portfolio has progressively broadened across experimental and theoretical nuclear physics, heavy-ion physics, neutron science, nuclear analytical methods, accelerator technologies, radiation dosimetry, and radiopharmaceutical research. This breadth is important because nuclear physics at Řež has never been organised as a single narrow experimental programme. The institute instead developed as a technologically integrated environment in which different methods could support both fundamental questions and interdisciplinary applications.

The internal structure of the institute reflects this scientific diversity. Experimental nuclear research is conducted through departments concerned with nuclear reactions, heavy ions, accelerators, neutron and ion methods, radiation dosimetry, and radiopharmaceuticals. A theoretical department studies nuclear structure, hadronic systems, subnuclear physics, and mathematical physics. The Department of Nuclear Reactions investigates nuclear astrophysics, exotic nuclei, charged-particle reactions, and fast-neutron processes. The Department of Neutron and Ion Methods combines thermal-neutron experiments with ion-beam analytical techniques and materials research. The Department of Accelerators operates the principal ion and electron accelerators and develops beam transport, target systems, and neutron-producing stations. Radiation-dosimetry research covers low-dose effects, cosmic radiation, radiobiology, radioecology, and measurement techniques. Radiopharmaceutical research connects accelerator physics with the preparation and chemical processing of medically relevant radionuclides. Heavy-ion physicists work at the interface between nuclear and subnuclear physics, including international experiments on strongly interacting matter. The result is an institutional structure in which different nuclear techniques reinforce one another instead of functioning as isolated specialities. This interdisciplinary architecture has been central to the institute's ability to sustain a wide scientific programme despite the limited scale of the Czech national research system.

The U-120M isochronous cyclotron has been the longest-serving accelerator at the centre of this research environment. Commissioned in 1977, the machine was originally designed and produced at the Joint Institute for Nuclear Research in Dubna for the acceleration of positively charged light ions. Rather than becoming obsolete after the political and technological changes of the 1990s, it underwent systematic modernisation by specialists at Řež. A major programme during the 1990s introduced negative hydrogen and deuterium ions and substantially increased the extracted beam intensity. The machine can accelerate protons, deuterons, helium-3, and alpha particles over a broad range of energies reaching several tens of megaelectronvolts. After severe flooding in 2002, many damaged subsystems were replaced or redesigned, effectively turning reconstruction into another phase of modernisation. New

beam lines, control systems, cooling systems, extraction arrangements, and target stations progressively expanded its experimental flexibility. The cyclotron consequently became a multipurpose instrument rather than a device dedicated to a single class of nuclear experiment. It supports nuclear-reaction measurements, nuclear astrophysics, radionuclide production, material irradiation, detector testing, and generation of fast-neutron fields. Its continued scientific relevance demonstrates the importance of accumulated accelerator expertise, because a complex machine can remain competitive when technical knowledge and systematic upgrading are maintained over decades.

Fast-neutron generation became one of the most distinctive applications of the U-120M. High-intensity proton and deuteron beams can be directed onto lithium, beryllium, heavy-water, and other target systems to produce neutron fields with controlled spectral properties. Quasi-monoenergetic neutron fields are generated through reactions such as lithium-7 with accelerated protons, while broad-spectrum sources can reproduce energy distributions important to reactor, accelerator, and fusion technologies. The Řež facilities allow nuclear cross-sections to be measured at energies that are difficult to investigate with reactor neutrons alone. These measurements contribute to nuclear-data libraries used in reactor calculations, radiation transport, fusion-material assessment, and accelerator shielding. Neutron generators are also used to test detectors, electronics, and structural materials under intense irradiation. Some programmes have investigated responses relevant to components intended for particle detectors at the European Organization for Nuclear Research. The facility therefore connects basic nuclear-reaction physics with engineering questions concerning radiation resistance and nuclear technology. Its scientific value lies not simply in producing neutrons but in producing characterised fields whose intensity and energy distributions can be related quantitatively to nuclear processes and technological applications.

The accelerator base expanded substantially in 2015 with the commissioning of the TR-24 cyclotron manufactured by Advanced Cyclotron Systems Inc. in Canada. The new machine provides proton beams with selectable energies between approximately 18 and 24 megaelectronvolts. Its external ion source and axial injection system allow extracted beam currents reaching hundreds of microamperes, considerably extending the high-current capabilities available at Řež. The accelerator can deliver beams to more than one irradiation position and is equipped for the development of specialised target stations. Its installation created useful complementarity with the older U-120M rather than simply replacing it. The U-120M retained unusual flexibility in particle species and energy, while TR-24 supplied high-current proton beams particularly suitable for radionuclide production and intense secondary neutron generation. The presence of two operational cyclotrons also increased the continuity with which beams could be made available to research teams. TR-24 supported the development of high-power neutron converters intended to generate very intense fields for radiation testing and nuclear-data studies. It also substantially expanded possibilities for producing radionuclides required in experimental radiopharmacy and nuclear medicine. The commissioning of TR-24 therefore represented one of the most important upgrades of the Czech domestic accelerator base during the 2010s. It illustrates the transition from preserving inherited infrastructure to constructing a deliberately complementary system of accelerators for both fundamental and applied science.

Another decisive modernisation occurred in 2005 with the installation of the Tandetron 4130 MC electrostatic tandem accelerator. Unlike the cyclotrons, the Tandetron can accelerate ions of many elements and is designed particularly for nuclear analytical methods, implantation,

and materials modification. Its terminal voltage can be varied up to approximately three megavolts, allowing ion energies from hundreds of kiloelectronvolts into the tens-of-megaelectronvolts range depending on ion species and charge state. The laboratory developed a broad suite of ion-beam analytical techniques around this accelerator. Rutherford Backscattering Spectrometry (RBS) provides information on elemental composition and depth distributions, while Elastic Recoil Detection Analysis (ERDA) is particularly useful for profiling light elements. Particle-Induced X-ray Emission (PIXE) and Particle-Induced Gamma-ray Emission (PIGE) enable sensitive elemental analysis through characteristic radiation emitted after ion bombardment. Ion microprobes allow such methods to be applied with spatial resolution approaching microscopic scales. High-energy ion implantation can also modify the physical and chemical properties of materials in controlled ways. Consequently, the Tandetron has been used in research on semiconductors, photonic materials, nanostructures, polymers, graphene-based systems, radiation-resistant materials, and other advanced functional materials. Its importance lies in making accelerator science relevant to communities that would not ordinarily describe their research as nuclear physics. The Tandetron laboratory therefore helped transform Řež into a broader centre of ion-beam science and materials characterisation.

The MT-25 microtron adds another class of radiation to the accelerator environment. Unlike the ion accelerators at Řež, the microtron accelerates electrons and has historically operated at a separate Prague workplace of the Nuclear Physics Institute. Relativistic electron beams can be used directly or converted into bremsstrahlung photon beams through interactions with appropriate targets. Photonuclear reactions can in turn generate secondary neutrons and radionuclides. These capabilities allow research in radiation physics, dosimetry, activation analysis, detector characterisation, and materials studies. Electron and photon irradiation has also been applied in interdisciplinary projects concerned with cultural heritage and analytical science. The microtron therefore complements the ion and neutron facilities rather than duplicating them. Together, the accelerators provide a range of charged-particle, electron, photon, and neutron beams that can be selected according to the physical process under investigation. This diversity became a defining strength of Czech accelerator science.

During the 2010s, these individual machines were increasingly organised through CANAM as a unified research infrastructure. CANAM was incorporated into the Czech Roadmap of Large Infrastructures for Research, Experimental Development and Innovation for the period beginning in 2010. Its purpose was to connect accelerator and neutron facilities into a synergistic platform serving both internal and external users. The infrastructure now comprises laboratories operating the U-120M and TR-24 cyclotrons, the Tandetron, the MT-25 microtron, accelerator mass spectrometry, and neutron-beam instrumentation. Fast-neutron sources driven by the cyclotrons form an additional component of this experimental system. The infrastructure provides analytical, irradiation, characterisation, modification, and isotope-production methods to users from physics, chemistry, materials science, biology, medicine, environmental science, engineering, archaeology, and heritage studies. This breadth demonstrates how contemporary nuclear infrastructure can support research communities far beyond traditional nuclear physics. CANAM also introduced a more systematic open-access model through which national and international researchers can submit scientific proposals for experimental time. Industrial access can be arranged under separate conditions where proprietary research is required. The infrastructure model therefore changed the meaning of accelerator ownership by treating the machines as shared national scientific

resources rather than equipment serving only one institute. It also provided the organisational basis needed for modernisation projects and for comparison with similar European accelerator centres. CANAM became one of the most important achievements of Czech nuclear physics because it integrated older and newer facilities within a coherent user-oriented system.

Neutron physics at Řež represents another major component of this infrastructure. The Neutron Physics Laboratory (NPL) operates experimental instruments on neutron channels of the LVR-15 research reactor, which is operated by the Research Centre Řež. Thermal-neutron beams are used for fundamental nuclear experiments, materials research, and nuclear analytical methods. Their high penetration into many materials makes neutrons particularly valuable for non-destructive investigation of bulk structure. Because neutrons interact strongly with atomic nuclei rather than with electron clouds, their scattering contrasts differ substantially from those obtained by X-rays. This allows neighbouring elements or isotopes to be distinguished in situations where X-ray diffraction may provide limited contrast. Neutron magnetic moments also make neutron scattering sensitive to magnetic structures and magnetic ordering. The Czech laboratory has developed several instruments for diffraction, small-angle scattering, residual-stress measurements, and specialised analytical techniques. These capabilities connect nuclear physics directly with solid-state physics and engineering materials research.

The neutron instruments installed at the LVR-15 reactor examine materials across several length scales. Powder diffraction reveals crystal structures and phase composition, while specialised diffractometers can investigate textures, internal stresses, and structural evolution under mechanical or thermal loading. Small-Angle Neutron Scattering (SANS) probes nanoscale heterogeneities that cannot be resolved through conventional diffraction alone. Neutron optics instruments are used both for materials investigation and for the development of beam-manipulation concepts relevant to other neutron facilities. Samples can be studied under specialised environments involving elevated temperature, cooling, or mechanical stress. Such experiments are valuable for advanced alloys, steels, engineering components, nanostructured materials, and functional systems whose properties depend critically on internal microstructure. The non-destructive nature of neutron measurements allows bulk components to be studied without sectioning them into thin specimens. Research at Řež has therefore contributed to problems extending from fundamental crystallography to industrial materials engineering. The domestic neutron programme also provided the expertise later required for Czech participation in the European Spallation Source.

Nuclear analytical methods extend the usefulness of neutron beams beyond scattering. Neutron Activation Analysis (NAA) determines elemental concentrations by irradiating samples and measuring characteristic radiation from the radionuclides produced. Prompt Gamma Activation Analysis (PGAA) detects gamma rays emitted almost immediately following neutron capture and can therefore provide information about elemental composition without requiring long decay periods. Neutron Depth Profiling (NDP) uses charged particles produced by selected neutron-induced reactions to determine concentration profiles of particular isotopes beneath material surfaces. These techniques are especially useful because they can analyse elements that are difficult to measure by conventional chemical or spectroscopic methods. At Řež they have been applied to materials science, environmental samples, geology, archaeology, cultural heritage, and forensic questions. Ion-beam analytical techniques at the Tandetron provide complementary elemental and depth information using charged particles rather than neutrons. Selecting between PIXE, PIGE, RBS, ERDA, NAA, PGAA,

and NDP allows researchers to adapt the measurement to the elemental sensitivity, depth range, and sample characteristics required. This methodological diversity represents a practical achievement of Czech nuclear science that is less visible than large accelerator experiments but is scientifically important across many disciplines. Analytical nuclear physics has consequently become one of the strongest interfaces between fundamental physical methods and interdisciplinary research in Czechia. It also supports external users who may have no other domestic access to comparable analytical techniques. The success of these methods illustrates how investment in nuclear infrastructure can generate benefits in fields that are not conventionally classified as nuclear science.

Fundamental nuclear-reaction research remains an equally important part of the institute's mission. The Department of Nuclear Reactions uses charged-particle and neutron beams to investigate the probabilities and mechanisms of reactions among atomic nuclei. One major theme is nuclear astrophysics, where reaction rates determine how chemical elements are produced inside stars and during explosive astrophysical events. Direct measurements at stellar energies can be extremely difficult because reaction probabilities become very small at the relevant energies. Czech researchers therefore use indirect experimental methods to constrain reaction rates that cannot be measured efficiently in a laboratory through direct bombardment alone. Experiments at the U-120M cyclotron have addressed reactions associated with hydrogen burning and with reaction networks such as the Carbon–Nitrogen–Oxygen (CNO) cycle. International work with facilities in Italy, France, Hungary, the United States, and other countries extends these studies to beams and energies unavailable at Řež. Research also investigates charged-particle and neutron reactions relevant to nuclear technology and nuclear-data evaluation. Measurements of excitation functions establish how reaction probabilities change with projectile energy. Such information is important both for fundamental nuclear modelling and for practical calculations involving radionuclide production or radiation fields. The Czech programme therefore places the same accelerator experiments within a continuum extending from stellar nucleosynthesis to applied nuclear data.

Exotic nuclei constitute a second major direction of the nuclear-reaction programme. Stable nuclei occupy only a small region of the possible combinations of protons and neutrons permitted by nuclear forces. Nuclei far from stability can possess unusual shell structures, extended spatial distributions, short lifetimes, and decay modes that challenge models developed near the valley of stability. Czech researchers investigate such systems through international collaborations where radioactive-ion beams can be produced with sufficient intensity. Particularly important cooperation developed with the Grand Accélérateur National d'Ions Lourds (GANIL) in France and its Système de Production d'Ions Radioactifs Accélérés en Ligne 2 (SPIRAL2) infrastructure. Experiments involving proton-rich fluorine isotopes, for example, have explored resonant states beyond the proton drip line and deviations from simple mirror symmetry. These studies test how nuclear forces behave when the balance between protons and neutrons becomes extreme. Domestic experiments at Řež complement these measurements by developing methods, detectors, neutron sources, and reaction studies that can be transferred to international facilities. Participation in radioactive-beam science has therefore allowed Czech nuclear physics to address questions inaccessible through stable-ion accelerators alone. The combination of local accelerator capability and foreign radioactive beams is characteristic of the distributed infrastructure model developed after 1993.

The theoretical study of nuclear structure provides the conceptual counterpart to these experiments. Researchers at the Nuclear Physics Institute develop microscopic and many-body models intended to describe nuclei from their constituent nucleons and interactions. Ab initio approaches seek to calculate properties of light and medium nuclei with controlled approximations starting from nuclear forces rather than from purely phenomenological descriptions. Other work addresses hypernuclei, in which one or more nucleons are replaced by hyperons containing strange quarks. These systems provide information about interactions involving strange baryons that cannot be obtained from ordinary nuclei alone. Theoretical research also examines double-beta decay, a process whose detailed nuclear matrix elements are important to experiments searching for neutrinoless double-beta decay and therefore for possible Majorana properties of neutrinos. Effective field theory provides a framework for organising nuclear interactions and their uncertainties across different momentum scales. Few-body methods and calculations of meson–baryon systems extend the programme towards the boundary between nuclear and hadron physics. Nuclear-reaction theory also contributes to understanding processes relevant to stellar environments, fusion, and radioactive waste. Such theoretical work is essential because accelerator measurements yield observables whose interpretation depends on models of nuclear structure and reaction mechanisms. Czech nuclear physics has therefore retained a balance between experiment and theory even though the most visible national assets are experimental facilities. The intellectual achievement of the field lies as much in connecting measurements with nuclear interactions as in operating complex accelerators.

Weak-interaction studies form another specialised component of the Czech programme. Beta decay provides information about nuclear structure and the electroweak interaction, while precision measurements can test theoretical corrections required for fundamental constants. Czech researchers have participated in experiments concerned with beta spectra and in international efforts related to neutrino properties. The institute also contributes to the Karlsruhe Tritium Neutrino experiment (KATRIN), whose purpose is to determine the absolute neutrino-mass scale through precision measurement of the endpoint of the tritium beta spectrum. These activities connect low-energy nuclear physics with questions more commonly associated with particle physics and cosmology. They also require highly precise detector calibration, control of systematic effects, and detailed theoretical calculations. The overlap illustrates why modern nuclear physics cannot be separated rigidly from the wider study of fundamental particles. Czech work in this area adds a precision-measurement dimension to the accelerator and heavy-ion programmes centred at Řež. It also demonstrates the variety of experimental scales encompassed by the national nuclear-physics community.

Radionuclide research provides one of the most direct links between accelerator physics and medicine. The Department of Radiopharmaceuticals was established at the Nuclear Physics Institute in 1997, initially with the objective of introducing positron-emission-tomography radionuclides and selected single-photon-emission radiopharmaceuticals into Czech medical practice. Positron Emission Tomography (PET) requires short-lived positron-emitting isotopes that can be incorporated into biologically active compounds and transported rapidly from production sites to hospitals. Single Photon Emission Computed Tomography (SPECT) uses gamma-emitting radionuclides and has complementary diagnostic applications. The development programme therefore required accelerator targets, radiochemical processing, quality control, and cooperation with medical institutions. Cyclotron beams at Řež allowed researchers to investigate production routes for both established and unconventional

radionuclides. Nuclear-reaction measurements were essential because efficient production depends on knowing the excitation functions and competing reaction channels with sufficient accuracy. The department also developed solid, liquid, and gas target systems in collaboration with accelerator specialists. Its creation demonstrated how accelerator infrastructure originally associated with basic nuclear physics could be adapted to emerging biomedical requirements. Medical isotope research became one of the most important applied branches of the institute.

Routine commercial production of radiopharmaceuticals was transferred in 2009 to the institute's subsidiary RadioMedic, allowing the scientific department to concentrate increasingly on research and development. Research programmes have investigated positron-emitting copper, gallium, yttrium, iodine, and other radionuclides suitable for imaging or combined diagnostic and therapeutic approaches. Cyclotron production of technetium-99m has been studied as a possible alternative or supplement to conventional generator-based supply chains. Scientists have developed methods for labelling monoclonal antibodies and their fragments with non-conventional radionuclides for tumour imaging. Microfluidic systems have been explored as a way of automating radiolabelling procedures while reducing reagent use and radiation exposure. The TR-24 cyclotron strengthened this programme by providing high-current proton beams and by supporting new high-power target stations. U-120M remained valuable where different particle species or energy ranges were required. Measurements of reaction excitation functions help determine the energies that maximise the desired isotope while minimising unwanted radioactive contaminants. Radionuclide research therefore depends directly on fundamental knowledge of nuclear reactions even when the final application is clinical. The Czech programme exemplifies the wider trend towards theranostics, in which related radionuclides or molecular carriers can support both diagnosis and targeted therapy. It also demonstrates how national accelerator infrastructure can contribute to medical innovation without abandoning its fundamental-research mission. The development of radiopharmaceutical science at Řež is consequently one of the clearest examples of knowledge transfer within Czech nuclear physics.

A major new capability was added in 2022 with the opening of the first Czech laboratory dedicated to Accelerator Mass Spectrometry (AMS). The laboratory operates a Multi-Isotope Low-Energy AMS (MILEA) system based on a compact tandem accelerator with a maximum acceleration voltage of approximately 300 kilovolts. Accelerator mass spectrometry differs from ordinary mass spectrometry by using acceleration and molecular-destruction stages to achieve extremely high suppression of interfering species. This makes it possible to measure isotope ratios involving radionuclides present at extraordinarily low concentrations. The Czech system can measure carbon-14, beryllium-10, aluminium-26, calcium-41, iodine-129, uranium isotopes, plutonium, and other long-lived radionuclides. Carbon-14 measurements provide a modern basis for radiocarbon dating of archaeological, palaeoenvironmental, geological, and biological samples. Cosmogenic isotopes such as beryllium-10 and aluminium-26 can be used to study landscape evolution and exposure histories. Anthropogenic radionuclides such as iodine-129 and uranium-236 provide tracers for environmental processes and nuclear activities. The laboratory is operated jointly with the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University and the Institute of Archaeology of the Czech Academy of Sciences. Its establishment therefore extended nuclear analytical science into a domain connecting physics directly with archaeology, geology, environmental history, and climate research.

Radiation dosimetry forms another long-standing applied branch of the institute. The Department of Radiation Dosimetry joined the Nuclear Physics Institute in 1994 but inherited a research tradition extending to the early 1950s. Its work combines dosimetry, microdosimetry, radiobiology, radiation protection, and environmental measurements. Microdosimetry investigates the stochastic deposition of energy in microscopic volumes relevant to biological damage rather than considering only macroscopic absorbed dose. Radiobiological studies examine molecular and cellular effects of ionising radiation, including damage to deoxyribonucleic acid. Environmental programmes measure radionuclides from natural and anthropogenic sources and use radiocarbon to investigate both dating problems and modern environmental processes. Cosmic-radiation dosimetry addresses radiation fields encountered at ground level, in aircraft, and in near-Earth space. Such measurements are particularly important for aviation personnel and for understanding radiation exposure associated with solar activity. The department has therefore linked nuclear-physics instrumentation with radiation protection and biomedical science. Applied nuclear physics at Řež consequently includes not only the production and analysis of radionuclides but also detailed investigation of how ionising radiation interacts with matter and living systems.

Czech nuclear physics also expanded through participation in the Facility for Antiproton and Ion Research (FAIR) being constructed at Darmstadt in Germany. The Czech Republic entered a formal FAIR partnership path in March 2019 through an agreement involving the Nuclear Physics Institute and FAIR GmbH. FAIR is organised around several scientific pillars addressing compressed nuclear matter, antiproton physics, nuclear structure and astrophysics, and atomic, plasma, biological, and materials applications. Czech researchers participate in all four broad areas through the FAIR-CZ research infrastructure. Their involvement includes Compressed Baryonic Matter (CBM), the High Acceptance Di-Electron Spectrometer (HADES), the antiProton ANnihilation at DArmstadt experiment (PANDA), Nuclear Structure, Astrophysics and Reactions (NuSTAR), and programmes within Atomic, Plasma Physics and Applications (APPA). The scientific objectives range from the properties of dense nuclear matter to exotic nuclei, hadron spectroscopy, radiation biology, and matter exposed to intense heavy-ion beams. FAIR will provide beam intensities and radioactive species that cannot be generated at Czech accelerators. The value of participation therefore lies in extending the energy, intensity, and isotope range available to Czech scientists while preserving domestic groups capable of exploiting those beams. The partnership represents one of the principal routes through which Czech nuclear physics is preparing for the next generation of European accelerator science. It also places national research within experiments expected to operate over several decades.

The Czech contribution to FAIR is technological as well as scientific. For HADES, Czech teams have worked on electromagnetic calorimetry and associated detector components needed to identify photons and electron–positron pairs. In CBM, Czech researchers contribute to forward spectator detection used to characterise the geometry and dynamics of heavy-ion collisions. The PANDA programme uses antiprotons to investigate hadrons containing strange and charm quarks, and Czech participation includes development and production of lead-tungstate scintillation crystals for the electromagnetic calorimeter. Cooperation with the Czech company CRYTUR has linked this detector programme with domestic high-technology crystal production. NuSTAR receives Czech detector modules intended for studies of radioactive nuclei and unusual decay modes. Within APPA, Czech groups contribute to the Biology and Material Science programme and to vacuum or beamline components required for irradiation

research. These contributions require mechanical design, materials expertise, scintillator development, electronics, simulation, and stringent quality assurance. In-kind delivery consequently gives Czech teams practical responsibility for hardware that becomes an integral part of the future facility. Such participation generally provides deeper scientific integration than a model based solely on paying membership fees and later requesting beam time. FAIR-CZ therefore demonstrates how national technological capability can be exchanged for long-term access and scientific responsibility within European big science.

The Nuclear Structure, Astrophysics and Reactions programme at FAIR is particularly relevant to established Czech expertise. NuSTAR will exploit radioactive ions separated by the Superconducting Fragment Separator to investigate nuclei far from stability. Czech groups plan experiments concerned with unusual forms of radioactivity and with reaction mechanisms relevant to nuclear astrophysics. These measurements extend directly from the work already undertaken with exotic nuclei at GANIL and SPIRAL2. Theoretical Czech teams can use experimental results to constrain models of nuclear structure and the properties of neutron-rich matter. Such models are relevant not only to laboratory nuclei but also to neutron stars and astrophysical nucleosynthesis. FAIR therefore provides a natural high-intensity extension of research themes already present at Řež. The scientific continuity between domestic accelerators and international radioactive-beam facilities is one of the strongest features of the Czech programme. It allows researchers to develop methods locally before applying them under more extreme experimental conditions abroad.

The European Spallation Source (ESS) in Lund provides a second major axis of Czech infrastructure participation. ESS is designed as a high-intensity pulsed neutron facility based on a powerful proton linear accelerator and a spallation target rather than a nuclear reactor. Czechia has participated in the project from an early stage and became a member of the European Research Infrastructure Consortium created to govern the facility. The national contribution is planned at up to roughly two per cent of construction costs and has been structured largely as in-kind technological delivery. Approximately half of the Czech contribution has been associated with the Beamline for European Materials Engineering Research (BEER). The instrument is being developed jointly with German partners as a highly flexible neutron diffractometer designed for engineering materials under realistic processing and loading conditions. It will support in-situ and in-operando studies of phase transformations, residual stress, crystallographic texture, precipitation, deformation, and joining processes. Czech neutron physicists brought to this project long experience accumulated through diffraction experiments at the LVR-15 reactor. The work therefore represents a direct transfer of national expertise into the construction of a pan-European facility. ESS also expands the future experimental scale available to Czech neutron science far beyond the flux and time structure achievable with existing domestic reactor channels. Participation consequently links the established Řež neutron programme with the next generation of European neutron instrumentation.

The remaining Czech contribution to ESS has included technological systems associated with the neutron target station. The spallation target uses a rotating tungsten wheel struck by the high-power proton beam to generate neutrons. Removing heat from this system requires sophisticated helium and water cooling technology operating under demanding engineering conditions. Czech in-kind work has therefore extended beyond instrument design into systems essential to the operation of the neutron source itself. This contribution has required cooperation between physicists, engineers, research institutes, and industrial partners. It also

demonstrates that nuclear research infrastructures create technological challenges in thermomechanics, materials engineering, control systems, and radiation-resistant design. Czech participation in ESS is consequently broader than future scientific use of neutron beams. It involves helping construct the source and instrument environment that will make the later experiments possible. The model closely parallels Czech participation in FAIR, where technological delivery creates both technical competence and scientific access. Through ESS, domestic neutron science has therefore become an active contributor to Europe's future neutron landscape.

Cooperation with SPIRAL2 at GANIL provides another important international dimension. SPIRAL2 is an extension of the French heavy-ion laboratory designed to produce intense stable and radioactive ion beams together with high-flux neutron capabilities. The Nuclear Physics Institute has worked with the project through a European associated laboratory framework since the late 2000s. Czech participation has included production targets, detectors, irradiation systems, and research related to nuclear astrophysics and radioisotopes. The Czech SPIRAL2-CZ infrastructure became part of the national roadmap of large research infrastructures, providing a formal mechanism for domestic participation. Research programmes connect radioactive-ion beams with studies of exotic nuclei and reactions occurring in stellar environments. Fast-neutron work is also relevant to activation of materials intended for future power and fusion systems. Czech expertise in target design and neutron generation developed at U-120M can therefore contribute directly to experiments undertaken in France. SPIRAL2 exemplifies a broader pattern in which domestic accelerator science functions as a technical and methodological preparation ground for experiments at much larger international facilities. Together with FAIR and ESS, it extends the geographical reach of Czech nuclear physics across a network of specialised European infrastructures. The programme also reinforces the field's ability to move researchers and technology bidirectionally between Řež and foreign laboratories.

By 2025, the international architecture of Czech nuclear physics consequently extended considerably beyond the boundaries of a single institute. NPI served as host institution for national infrastructures coordinating Czech participation in ESS, FAIR, and SPIRAL2 while also partnering in programmes connected with CERN and Brookhaven National Laboratory. Domestic experiments remained essential because accelerator and neutron facilities at Řež supported student training, detector development, reaction studies, materials analysis, and preparatory measurements. International infrastructures then provided beam energies, particle species, luminosities, and neutron intensities that could not be reproduced nationally. This division of labour allowed Czech groups to specialise without withdrawing from major areas of contemporary nuclear physics. In-kind technological contributions ensured that international participation was based on capability rather than passive access alone. The same researchers could therefore move between local experiments and multinational collaborations during a scientific career. This model represents one of the most mature forms of integration achieved by Czech physics after 1993. It also reduces the risk that participation in European big science might erode the domestic experimental culture on which meaningful participation ultimately depends.

The major achievements of Czech nuclear physics between 1993 and 2025 are therefore best understood as the construction of a connected scientific system rather than as a list of isolated discoveries. The Nuclear Physics Institute preserved and modernised a complex experimental base inherited from Czechoslovakia while expanding it through the Tandetron, TR-24, MILEA,

and renewed neutron and target systems. CANAM transformed these instruments into an integrated infrastructure open to external research communities. Fundamental programmes addressed nuclear reactions, astrophysical processes, exotic nuclei, nuclear structure, hadronic systems, beta decay, and the behaviour of nuclear matter. Applied methods extended accelerator and neutron techniques into materials research, environmental science, cultural heritage, medicine, radiation protection, and industry. Radionuclide and radiopharmaceutical research established a direct connection between nuclear-reaction physics and modern diagnostic or therapeutic technologies. Participation in FAIR, ESS, and SPIRAL2 gave Czech researchers access to a much broader international experimental landscape while simultaneously creating opportunities to supply specialised Czech instrumentation. The field consequently developed a productive balance between national facilities and European infrastructures rather than treating one as a substitute for the other. This balance allowed a comparatively small scientific system to remain active across an unusually wide spectrum of nuclear science. By 2025, accelerator and nuclear research at Řež had become both a centre of Czech fundamental physics and a technological platform serving many neighbouring scientific disciplines. Its evolution provides one of the clearest examples of how continuity, infrastructure modernisation, interdisciplinary application, and international integration combined to shape Czech physical science after independence.

Condensed Matter Physics and Advanced Materials

Condensed matter physics has been one of the broadest and most continuously productive branches of Czech physics throughout the period from 1993 to 2025. Its importance arises from the fact that it connects fundamental questions about the collective behaviour of matter with materials whose electrical, magnetic, optical, mechanical, and thermal properties can be exploited technologically. Czech research after 1993 developed from strong traditions in solid-state physics, crystallography, low-temperature physics, semiconductor science, magnetism, superconductivity, and physical metallurgy. These traditions were not preserved as isolated classical disciplines, but progressively converged with nanoscience, computational materials physics, quantum materials, and advanced characterisation. The Institute of Physics of the Czech Academy of Sciences (FZU) became the principal national centre of this development, while Charles University, Masaryk University, Brno University of Technology, and other institutions maintained important complementary schools. Improvements in diffraction, spectroscopy, microscopy, thin-film growth, nanofabrication, cryogenic measurements, and computation fundamentally changed the scale at which materials could be studied. Researchers moved from macroscopic measurements of bulk solids towards increasingly detailed investigation of electronic states, defects, interfaces, nanoscale structures, and collective quantum phenomena. At the same time, many research programmes became closely connected with European neutron, synchrotron, and high-magnetic-field facilities. Czech condensed matter physics therefore illustrates particularly well how scientific continuity can be combined with methodological and conceptual transformation. By 2025, the field extended from conventional solids and engineering alloys to unconventional superconductors, two-dimensional systems, topological states, ferroic structures, spintronic materials, and other forms of quantum matter.

The institutional foundations of this research were already strong when the independent Czech Republic was established. Solid-state physics had occupied an important position in the Institute of Physics and in university departments during the Czechoslovak period, with research covering crystal structure, semiconductors, low-temperature phenomena, magnetic materials, phase transitions, and physical metallurgy. After 1993, these areas had to adapt to competitive grant financing, international evaluation, and much greater access to foreign laboratories. The conceptual label of condensed matter physics gradually became more appropriate because the field was extending beyond ideal crystalline solids towards disordered systems, surfaces, nanostructures, polymers, low-dimensional materials, and strongly correlated electron systems. Materials research similarly became less separable from fundamental physics as scientists increasingly sought to understand how microscopic structure generated macroscopic functionality. International cooperation expanded particularly quickly because modern characterisation often required synchrotron radiation, neutron scattering, extreme magnetic fields, or experimental techniques unavailable within a single Czech laboratory. Theoretical work also became more closely connected with computation as first-principles methods and many-body models became practical research tools. This transformation meant that the distinction between traditional solid-state physics and modern materials science became increasingly porous. By the 2000s, Czech condensed matter research was already developing as an interconnected field rather than a collection of inherited subdisciplines.

The Institute of Physics provided the largest concentration of this activity through its solid-state and condensed-matter divisions and their specialised laboratories. Research ranged from electronic-structure theory and magnetism to semiconductor materials, dielectrics, superconductors, functional alloys, surface physics, nanostructures, crystallography, and optical properties of solids. The coexistence of these subjects within one institution encouraged interaction between researchers concerned with preparation, theory, structural analysis, and measurement. A material could be grown or deposited in one laboratory, structurally characterised in another, measured magnetically or electronically in a third, and interpreted through calculations performed by theoretical groups. This integrated model became increasingly important as research questions depended upon correlations between atomic structure and several physical properties at once. The Department of Condensed Matter Theory developed expertise in electronic structure, strong correlations, magnetism, and quantum many-body phenomena. Experimental departments investigated magnetic oxides, superconductors, semiconductors, ferroics, thin films, carbon-based materials, and functional metallic systems. The Department of Functional Materials concentrated on how structural transformations and controlled microstructures could generate useful responses to thermal, mechanical, electrical, or magnetic stimuli. Semiconductor laboratories developed wide-band-gap materials, nanodiamond systems, heterostructures, and optoelectronic materials. Structural-analysis teams contributed advanced X-ray and electron crystallography, including internationally used crystallographic software. This broad institutional architecture allowed FZU to follow materials from theoretical prediction and synthesis to microscopic characterisation and functional testing.

Charles University provided a second major centre in which fundamental condensed matter physics and materials research remained closely linked to education. Its Department of Condensed Matter Physics investigates structural and electronic properties of intermetallic compounds, magnetic multilayers, thin films, nanoscale systems, and materials containing

strongly correlated electrons. Measurements are performed across broad ranges of temperature, magnetic field, and pressure, allowing phase transitions and competing electronic states to be explored under controlled external conditions. The department has retained particularly strong traditions in magnetism, low-temperature physics, uranium and rare-earth compounds, superconductivity, diffraction, and computational materials science. Its educational programmes reflect the breadth of the research field through specialisations in atomic and electronic structure, materials physics, low-temperature physics, macromolecular systems, and surface modification. Students are trained not only in quantum and statistical theory but also in diffraction, microscopy, spectroscopy, transport measurements, and computational approaches. This continuity between teaching and active experimental research has helped sustain specialist expertise across generations. Charles University has therefore remained an essential part of the Czech condensed-matter ecosystem rather than functioning merely as a supplier of graduates to Academy laboratories.

Brno developed a complementary research environment around Masaryk University, Brno University of Technology, and the Central European Institute of Technology (CEITEC). The Department of Condensed Matter Physics at Masaryk University studies bulk and layered metals, semiconductors, insulators, high-temperature superconductors, polymers, and low-dimensional structures. Optical spectroscopy from the far-infrared to ultraviolet range is used to investigate vibrational and electronic excitations and their evolution with temperature. X-ray diffraction and reflectometry provide complementary information about structural organisation and interfaces in multilayer systems. Theoretical groups address strongly correlated electrons, transition-metal oxides, unconventional superconductivity, frustrated magnetism, and spin-state phenomena using analytical and numerical methods. CEITEC considerably expanded this environment by providing clean rooms, nanofabrication platforms, microscopy, spectroscopy, and advanced materials laboratories accessible to several institutions. Brno consequently developed strong capabilities in nanomagnetism, spintronics, semiconductor structures, molecular materials, and micro- and nano-engineering. Shared facilities reduced the need for each research group to reproduce expensive instrumentation independently. They also increased cooperation between physicists, chemists, materials scientists, and electrical engineers. By the 2020s, Prague and Brno formed complementary poles of Czech condensed matter and advanced materials research.

Electronic-structure theory became one of the intellectual foundations linking these experimental areas. The central problem is to determine how electrons occupy and move through a material and how their quantum states generate electrical, magnetic, optical, and structural properties. Czech researchers increasingly employed first-principles calculations based on density functional theory (DFT), in which electronic structure can be estimated from the spatial distribution of electron density without fitting every material to a purely empirical model. Such calculations became important for metals, semiconductors, surfaces, interfaces, magnetic materials, oxides, and compounds containing rare-earth or actinide elements. For systems in which electron–electron interactions are too strong for conventional band theory to provide an adequate description, Czech theoreticians also developed and applied many-body techniques. Dynamical Mean-Field Theory (DMFT), quantum Monte Carlo methods, exact diagonalisation, model Hamiltonians, and related approaches allowed strongly correlated states to be investigated. Theoretical spectroscopy connected calculated electronic structures with X-ray and photoemission measurements. Computation thus evolved from a supplementary method into an integral component of materials research. The

interaction of theory with experiment became particularly productive in magnetism, superconductivity, and quantum materials.

Strongly correlated electron systems became increasingly prominent because they generate physical behaviour that cannot be understood by treating electrons as almost independent particles. Transition-metal oxides, rare-earth compounds, and actinide materials can exhibit competing magnetic, metallic, insulating, and superconducting states whose appearance depends sensitively on temperature, pressure, doping, or magnetic field. Czech theoretical groups investigated Hubbard-type models, spin models, exchange interactions, Kondo physics, and correlation effects in realistic materials. Experimental groups complemented this work through magnetisation, electrical transport, specific heat, optical spectroscopy, and scattering measurements. Masaryk University developed particular expertise in the optical response of high-temperature cuprate superconductors and in strongly correlated transition-metal oxides. FZU researchers studied lanthanide and actinide compounds using electronic-structure methods that incorporate local correlations and relativistic effects. Charles University maintained long-standing programmes on intermetallic compounds containing uranium and rare-earth elements. These systems provided natural laboratories for studying how localised magnetic moments interact with itinerant electrons. Their behaviour also created conceptual bridges between conventional solid-state physics and the modern language of quantum materials. Strong correlations consequently became one of the areas in which Czech condensed matter physics moved most clearly from classical material description towards contemporary many-body physics. Theoretical and experimental cooperation was essential because similar macroscopic behaviour can emerge from very different microscopic mechanisms. Progress therefore depended upon comparing several measurement techniques with increasingly sophisticated computational models.

Crystallography and structure analysis formed another area in which Czech research made an internationally identifiable methodological contribution. Knowledge of atomic arrangement is indispensable because electronic, magnetic, mechanical, and optical properties cannot be interpreted reliably without understanding the underlying structure. Czech laboratories maintained expertise in single-crystal and powder X-ray diffraction, neutron diffraction, electron diffraction, and the analysis of modulated or aperiodic structures. A particularly important achievement was the development of the JANA crystallographic computing system at the Institute of Physics. JANA evolved over several decades from software specialised in modulated crystals into a general system capable of treating conventional, modulated, composite, twinned, and magnetic structures. JANA2006 supported refinements using single-crystal or powder X-ray data, neutron diffraction, and electron-diffraction information. The software became widely used internationally because many structurally complex materials cannot be treated adequately through the assumptions of ordinary three-dimensional periodic crystallography alone. Václav Petříček, Michal Dušek, Lukáš Palatinus, and collaborators developed tools that allowed higher-dimensional descriptions and sophisticated symmetry treatments to become practical for experimental crystallographers. Regular international workshops in Prague disseminated these methods and trained users from outside Czechia. The later JANA2020 system extended the approach further and incorporated advances in magnetic and electron crystallography. Structural-analysis software therefore became one of the less publicly visible but internationally significant achievements of Czech materials physics.

Diffraction research itself changed profoundly during the period because national laboratory measurements became increasingly integrated with large international facilities. Conventional X-ray diffractometers remained indispensable for routine structural characterisation, phase identification, texture analysis, and investigation of thin films. Neutron diffraction provided complementary sensitivity to magnetic ordering and to atomic species that may be difficult to distinguish with X-rays. Synchrotron radiation offered very high brilliance, tuneable photon energy, and specialised spectroscopic methods for examining electronic and magnetic structure. Czech groups consequently conducted experiments at institutions such as the European Synchrotron Radiation Facility (ESRF), Deutsches Elektronen-Synchrotron (DESY), the Institut Laue-Langevin (ILL), the ISIS Neutron and Muon Source, and German neutron facilities. These experiments allowed magnetic structures, pressure-induced phases, complex oxides, superconductors, and low-dimensional materials to be investigated with techniques unavailable domestically. Access to international facilities thus became a normal extension of Czech laboratory research rather than a separate scientific activity. The ability to prepare high-quality samples and perform preliminary characterisation at home was essential for competing successfully for scarce beam time abroad. Czech structural research therefore developed through a productive combination of domestic instrumentation and European large-scale facilities.

Microscopy and nanofabrication expanded the spatial scale of materials research from bulk averages towards individual grains, domains, interfaces, and nanoscale structures. Scanning Electron Microscopy (SEM) became a routine method for examining surface morphology and microstructure, while Transmission Electron Microscopy (TEM) provided atomic- and nanoscale structural information. Scanning Probe Microscopy (SPM), including Atomic Force Microscopy (AFM), allowed surfaces, local electronic behaviour, magnetic textures, and mechanical properties to be studied with high spatial resolution. Focused ion beams made it possible to prepare microscopic specimens or modify structures directly. Electron-beam and optical lithography allowed devices and model systems to be fabricated with dimensions approaching the nanoscale. CEITEC Nano in Brno and the Laboratory of Nanostructures and Nanomaterials in Prague eventually became the two principal nodes of the CzechNanoLab national infrastructure. These facilities combined clean-room fabrication with advanced electron microscopy, deposition, spectroscopy, and surface analysis. Open-access operation meant that the infrastructure served researchers beyond the host institutions and supported cooperation with high-technology companies. A major CzechNanoLab modernisation programme launched in 2024 provided further investment in new microscopes, deposition systems, analytical equipment, and microscopic three-dimensional fabrication. By 2025, nanoscale preparation and characterisation had therefore become a permanent component of Czech condensed matter research.

Semiconductor physics represents one of the clearest areas in which classical solid-state research evolved into advanced materials and device-oriented science. Czech laboratories studied the electronic band structures, defects, interfaces, carrier transport, and optical responses that determine semiconductor functionality. Silicon remained technologically important, but research increasingly expanded towards compound and wide-band-gap semiconductors with properties unavailable in conventional silicon electronics. Low-dimensional semiconductor structures, multilayers, nanocrystals, quantum dots, and heterojunctions became important experimental systems. The electrical properties of a semiconductor depend critically on impurities and defects, so methods capable of detecting

electronic states deep inside the forbidden energy gap remained valuable. Surface and interface control became equally important as devices were miniaturised and a growing fraction of the material became influenced by boundaries. Optical spectroscopy provided information about band gaps, excitons, defects, and carrier recombination. Electrical transport measurements revealed mobility, carrier density, and localisation phenomena. Czech semiconductor research therefore shifted progressively from describing bulk materials towards engineering electronic behaviour through composition, dimensionality, and interface design.

Gallium nitride and related III–V semiconductor compounds became important examples of this transition. Gallium nitride possesses a wide electronic band gap and can support high electric fields, high-temperature operation, and efficient light emission. Research at the Institute of Physics developed expertise in epitaxial growth and characterisation of gallium-nitride-based structures and quantum wells. Metalorganic Vapour Phase Epitaxy (MOVPE) made it possible to control the deposition of semiconductor layers with composition and thickness tailored at the nanometre scale. Such structures are relevant to light-emitting devices, high-frequency electronics, power electronics, and quantum optical applications. Czech work also examined defects and interfaces because these strongly influence carrier transport and optical efficiency. Interaction with international semiconductor programmes placed domestic research within a rapidly developing European effort to strengthen wide-band-gap electronics. By the 2020s, gallium nitride research was connected with European projects concerned with more efficient integrated electronic technologies. The field required close cooperation among materials growers, microscopists, spectroscopists, device physicists, and electrical engineers. Semiconductor science therefore illustrates the increasingly interdisciplinary character of Czech condensed matter research. Its development also shows how fundamental understanding of crystal growth and defects can acquire direct technological significance. The expertise established during the period became relevant to both conventional electronics and emerging quantum-photonic structures.

Diamond and zinc oxide represent two additional wide-band-gap material families in which Czech laboratories developed substantial expertise. Synthetic diamond combines exceptional hardness, thermal conductivity, chemical resistance, optical transparency, and electronic properties that can be deliberately modified through doping and defects. FZU researchers developed Chemical Vapour Deposition (CVD) methods for producing diamond films, nanocrystalline coatings, membranes, and nanostructured surfaces. Diamond research extended into electrodes, sensors, biological interfaces, heat management, photonics, and optically active colour centres relevant to quantum sensing. Nanodiamond particles added further possibilities because their surfaces can be chemically functionalised while retaining useful optical and mechanical properties. Zinc oxide was studied as a semiconductor and nanostructured material for optoelectronic, sensing, and photovoltaic concepts. Its ability to form a variety of nanoscale morphologies made it particularly useful for studying how structure controls transport and optical response. Work on diamond and zinc oxide therefore connected conventional semiconductor physics with surface chemistry, nanotechnology, photonics, and biophysical applications. These programmes demonstrate the increasing diversity of materials considered within Czech solid-state research.

Ultrafast and terahertz spectroscopy provided another important methodological route into semiconductor and functional-material physics. Terahertz radiation lies between the microwave and infrared regions of the electromagnetic spectrum and is sensitive to low-energy

electronic, lattice, and collective excitations. Time-resolved terahertz measurements can follow how optically generated charge carriers move, become localised, or recombine on picosecond and sub-picosecond timescales. The Laboratory of Terahertz Spectroscopy at FZU developed internationally connected research on semiconductor nanostructures, metamaterials, ferroelectrics, superconductors, graphene-related systems, and other functional materials. Studies of zinc oxide and titanium dioxide nanocrystals examined charge injection and carrier transport relevant to photovoltaic processes. Measurements on disordered semiconductors showed how nanoscale confinement can produce electrical behaviour that is not visible through ordinary direct-current measurements alone. Terahertz spectroscopy also became useful in superconductivity because the energy scales of superconducting gaps and vortex dynamics often lie in this spectral range. The technique therefore linked semiconductor physics, photonics, superconductivity, and nanoscience within a common experimental framework. Czech researchers combined measurements with simulations and effective-medium models to interpret the spectra quantitatively. These developments illustrate how methodological innovation can create connections among material classes that otherwise appear unrelated. By 2025, ultrafast spectroscopy had become an established component of Czech advanced-materials research.

Magnetism has remained one of the strongest themes running through Czech condensed matter physics from 1993 to 2025. Research has covered ferromagnets, antiferromagnets, ferrimagnets, frustrated systems, magnetic oxides, intermetallic compounds, nanomagnets, and magnetically ordered semiconductor structures. Experimental methods include magnetometry, magnetotransport, neutron diffraction, magnetic X-ray spectroscopy, electron microscopy, and local magnetic imaging. Czech scientists have investigated how exchange interactions, spin–orbit coupling, crystallographic symmetry, electronic correlations, and dimensional confinement determine magnetic order. Materials containing rare-earth and transition-metal elements have been particularly useful because their magnetic behaviour can change sharply with composition, temperature, pressure, and applied field. Magnetic multilayers and thin films introduced an interface dimension in which electronic states can differ strongly from those of the corresponding bulk material. Nanostructuring further altered magnetic domains and switching processes by imposing geometric confinement. The combination of theoretical electronic-structure work with precise transport and scattering experiments created a strong basis for later Czech achievements in spintronics. Magnetism thus evolved from a classical materials discipline into a central component of modern quantum and information-oriented materials research.

Spintronics illustrates this transformation particularly clearly because it treats the electron's spin, as well as its electric charge, as a controllable information-bearing degree of freedom. Czech groups developed strong programmes in magnetic semiconductors, spin-dependent transport, spin–orbit effects, nanomagnetism, and antiferromagnetic materials. The Institute of Physics became internationally visible through work connecting electronic-structure theory with the experimental control of magnetic order. Brno groups at CEITEC developed complementary expertise in the fabrication and imaging of nanomagnets and in the dynamics of magnetic heterostructures. Research increasingly focused on ways of manipulating magnetic states with electrical currents, electric fields, strain, thermal gradients, or ultrafast optical pulses. Antiferromagnets attracted particular attention because their compensated magnetic moments can reduce stray fields and support dynamics faster than those of many conventional ferromagnets. This work culminated during the 2010s in influential Czech

contributions to antiferromagnetic spintronics. Studies of materials such as CuMnAs demonstrated that electrical currents could switch antiferromagnetic order in device-like structures. The same conceptual and experimental environment later contributed to the development of altermagnetism during the 2020s. That later achievement belongs to a distinct chapter, but its roots lie directly in the condensed-matter research architecture described here. Spintronics therefore provides an important bridge between the study of magnetic materials and the emergence of new quantum-functional concepts. It also demonstrates how Czech materials physics could shape international research agendas rather than merely adopt them.

Superconductivity remained another major branch of Czech solid-state and low-temperature research. A superconductor loses electrical resistance below a critical temperature and expels magnetic flux in the Meissner state, making it one of the most striking manifestations of macroscopic quantum coherence. Czech groups investigated both conventional superconducting systems and the more complex high-temperature superconductors discovered in copper oxides. FZU research examined electromagnetic response, magnetic flux penetration, vortex dynamics, pinning, and current transport in superconducting materials. Charles University maintained programmes combining low-temperature measurements with studies of magnetism and correlated-electron compounds. Masaryk University investigated the optical properties of high-temperature cuprates and theoretical models for unconventional superconductivity. Experimental work increasingly relied on cryogenic systems, high magnetic fields, spectroscopy, and precise transport measurements. Superconductivity thus remained a productive meeting point between fundamental quantum physics, materials preparation, and the technological problem of carrying current without dissipation.

The study of superconductivity became increasingly intertwined with the broader field of strongly correlated and quantum materials. Uranium compounds provide an important Czech example because their 5f electrons can display both localised and itinerant behaviour and can support unusual combinations of magnetism and superconductivity. Charles University developed a sustained research tradition in uranium intermetallics extending from the late Czechoslovak period into the entire post-1993 era. Single-crystal growth, electrical transport, magnetisation, specific heat, neutron scattering, pressure experiments, and measurements in high magnetic fields were used to map complex phase diagrams. International neutron and high-field facilities became essential because several relevant phases appear only under conditions unavailable in ordinary laboratory magnets. In the 2020s, research increasingly addressed uranium ditelluride, UTe_2, a candidate unconventional superconductor whose superconducting state has been discussed in connection with spin-triplet pairing and topology. The Czech programme emphasised high-quality crystals because disorder can obscure intrinsic superconducting behaviour. Such work demonstrates how materials preparation itself becomes a fundamental scientific problem when quantum states are exceptionally sensitive to defects. The interplay among superconductivity, magnetism, electronic correlations, symmetry, and topology placed these compounds firmly within the emerging category of quantum materials. Czech low-temperature physics therefore evolved naturally into research on some of the most conceptually difficult states of contemporary condensed matter. This progression preserved older expertise in magnetic intermetallics while applying it to new questions concerning unconventional quantum order.

Superconductivity also entered mesoscopic and nanoscale physics through hybrid structures combining quantum dots, semiconducting nanowires, molecules, or other small systems with

superconducting electrodes. In these structures the superconducting state can penetrate neighbouring materials through the proximity effect and generate bound states with strongly quantum-mechanical transport properties. Czech theoreticians at FZU and Charles University studied superconducting quantum dots, Josephson junctions, Andreev bound states, and interacting impurity models. These systems provide controlled environments in which Coulomb interaction, superconductivity, spin, and quantum coherence can compete within a small number of electronic states. Multi-terminal Josephson junctions additionally allow phase-dependent phenomena and possible topological behaviour to be investigated. Experimental research used terahertz and magneto-optical methods to examine thin superconducting films and their response to magnetic fields. Collaboration with European networks linked Czech groups to a wider programme concerned with superconducting nanodevices and quantum materials. Such research is relevant both to fundamental many-body physics and to the physical principles underlying superconducting quantum circuits. It therefore illustrates another route through which traditional low-temperature physics entered the technological landscape of quantum science.

Functional materials formed a different but equally important bridge between fundamental solid-state physics and practical application. FZU created its Department of Functional Materials in 2009 by combining groups concerned with functional composites, nanodiamond technologies, and controlled material microstructures. A major research theme has been Shape Memory Alloys (SMAs), whose internal crystal structure can change through a martensitic transformation and generate large reversible deformations. Nickel–titanium alloys are particularly important because they can exhibit both shape-memory behaviour and superelasticity. Czech researchers investigated the microscopic mechanisms governing martensitic transformation, twinning, plasticity, cyclic degradation, and the movement of phase boundaries. Thermomechanical tests were combined with X-ray diffraction, neutron diffraction, Scanning Electron Microscopy, Transmission Electron Microscopy, electrical resistometry, thermal imaging, and digital image correlation. In-situ techniques made it possible to observe structural changes while samples were mechanically or thermally loaded rather than only before and after deformation. This approach linked microscopic structural mechanisms directly with macroscopic functional performance. Applications include medical devices, actuators, aerospace components, adaptive structures, and mechanically active textiles. Research also addressed magnetic shape-memory materials in which magnetic fields can generate structural rearrangements. Magnetocaloric compounds provided a related functional theme because magnetic transitions can be exploited for heat exchange. Shape-memory research therefore demonstrates how detailed solid-state physics can guide the engineering use of phase transformations. It also illustrates the unusually close relationship between physical metallurgy and functional-material science within the Czech research tradition.

Ferroic materials constituted another major class of functional solids. Ferroelectrics possess switchable electric polarisation, while multiferroics can combine electric, magnetic, or structural order parameters within the same material. Czech researchers studied ferroelectric phase transitions, relaxor behaviour, domain walls, lattice dynamics, and the symmetry principles governing ordered states. FZU groups made extensive use of dielectric spectroscopy, optical methods, diffraction, theoretical modelling, and symmetry analysis. Relaxor ferroelectrics became especially important because nanoscale polar structures generate behaviour fundamentally different from that of simple textbook ferroelectrics. During

the late 2010s and early 2020s, attention expanded towards topological structures such as ferroelectric vortices and skyrmion-like configurations. European projects involving Czech teams investigated whether topological solitons could exist and be controlled in antiferroic materials. These studies illustrate how classical research on phase transitions evolved into the physics of emergent nanoscale textures. Ferroics therefore became part of the broader Czech transition from conventional functional materials towards quantum and topological materials.

Advanced materials research also included thermoelectric, scintillating, luminescent, photovoltaic, and energy-related solids. Thermoelectric materials convert temperature differences into electrical voltage and therefore require a delicate optimisation of electrical conductivity, thermopower, and thermal transport. Czech work on oxides investigated how electronic structure, crystal chemistry, and magnetic state influence these coupled transport properties. Scintillator research examined crystals in which ionising radiation is converted into detectable light for particle physics, medical imaging, security, and industrial measurement. FZU researchers studied rare-earth-doped oxides and garnets, defect centres, energy-transfer processes, and radiation damage affecting scintillation efficiency. Semiconductor research increasingly included metal-halide perovskites and other absorber materials relevant to photovoltaics and light emission. Defect passivation became a major question because non-radiative recombination can substantially reduce device efficiency even when the underlying material absorbs light strongly. Nanodiamond and carbon-based materials were explored for electrochemical and energy-storage applications as well as for sensing. Materials physics therefore became increasingly relevant to energy conversion and sustainable technologies during the 2010s and 2020s. These programmes did not replace basic solid-state research but expanded the range of physical properties that researchers sought to control. Their common principle was the establishment of quantitative links between composition, atomic structure, defects, and macroscopic function. By 2025, advanced materials had consequently become one of the principal interfaces between Czech fundamental physics and technological innovation.

Two-dimensional and surface materials provided another rapidly developing research direction. Graphene demonstrated that reducing a crystalline material to a single atomic layer can generate electronic properties radically different from those of its three-dimensional parent system. Czech laboratories studied graphene growth, functionalisation, interfaces, and charge transport using microscopy, photoelectron spectroscopy, and theoretical calculations. Transition-Metal Dichalcogenides (TMDs) such as molybdenum or tungsten chalcogenides added semiconducting and magnetic possibilities to the two-dimensional materials landscape. FZU groups investigated magnetically modified TMDs, ultrathin iron chalcogenides, and surfaces of topological or layered compounds. Molecular Beam Epitaxy (MBE) and ultra-high-vacuum surface preparation allowed atomically controlled layers to be produced for spectroscopy and microscopy. Angle-Resolved Photoemission Spectroscopy (ARPES) provided direct information about electronic band structure and surface states. Scanning Tunnelling Microscopy (STM) added local information about atomic arrangements and electronic density of states. These methods allowed Czech researchers to examine how topology, superconductivity, magnetism, and dimensional confinement interact at surfaces and interfaces. Two-dimensional materials consequently became a natural meeting point for semiconductor physics, surface science, magnetism, and quantum materials.

The concept of quantum materials increasingly provided a common language for several of these previously separate programmes. A quantum material is not simply any solid governed

by quantum mechanics, but a material in which collective quantum phenomena determine unusual and potentially controllable macroscopic properties. Strongly correlated electron systems, unconventional superconductors, topological materials, low-dimensional magnets, ferroics, and spintronic compounds can all fall within this broad category. Czech research entered this field from several directions rather than through the creation of a single dedicated institute. FZU contributed theory, spectroscopy, magnetism, surface science, spintronics, superconductivity, and advanced materials synthesis. Charles University contributed low-temperature physics, uranium compounds, quantum transport, magnetic materials, and increasingly explicit research on unconventional or topological superconductivity. Brno institutions added nanofabrication, nanomagnetism, semiconductor structures, molecular magnetism, and advanced spectroscopy. National projects in the 2020s explicitly adopted the term quantum materials and linked it with sustainable technologies. Such programmes reflected a conceptual shift from investigating individual material properties towards understanding interacting electronic, magnetic, structural, and topological degrees of freedom. The same material might now be studied simultaneously as a magnet, a semiconductor, a topological system, and a platform for quantum devices. This integrative perspective explains why condensed matter physics became central to the emerging Czech quantum-technology ecosystem. It also provides the scientific context from which research on altermagnetism, quantum communication materials, and superconducting nanodevices developed. Quantum materials therefore represent not a break with Czech solid-state traditions but their contemporary reorganisation around emergent collective phenomena.

Progress across the field depended on increasingly sophisticated experimental conditions. Cryogenic systems allowed measurements from room temperature down to temperatures where superconductivity, quantum coherence, or magnetic ordering could emerge. High-field magnets revealed phase transitions and electronic states that remain inaccessible in weak fields. Pressure cells changed interatomic distances without altering chemical composition and could therefore tune magnetism, superconductivity, or structural order continuously. Magnetometry provided measurements of magnetic susceptibility and ordered moments, while calorimetry detected thermodynamic signatures of phase transitions. Electrical transport measurements characterised metallic, semiconducting, superconducting, and magnetoresistive behaviour. Optical, infrared, Raman, and terahertz spectroscopies probed excitations over complementary energy scales. X-ray and neutron scattering established structural and magnetic order, while electron and scanning-probe microscopies provided local information. The strength of Czech materials research increasingly lay in combining several of these methods on the same physical system rather than relying on a single experimental signature.

International research infrastructures considerably extended the experimental range available to Czech groups. Neutron scattering at the Institut Laue-Langevin, the ISIS Neutron and Muon Source, Forschungs-Neutronenquelle Heinz Maier-Leibnitz, and other facilities allowed magnetic and nuclear structures to be examined with high precision. Synchrotron experiments at the European Synchrotron Radiation Facility and Deutsches Elektronen-Synchrotron enabled high-resolution diffraction, magnetic spectroscopy, photoemission, and studies under extreme environments. European high-magnetic-field facilities provided access to field strengths that could not be maintained routinely in Czech laboratories. International muon facilities added local probes of magnetism and superconductivity, while specialised surface-science laboratories supplied complementary spectroscopy and microscopy. Czech

researchers increasingly designed domestic experiments with these future large-facility measurements in mind. High-quality crystals or thin films were prepared and characterised locally before scarce international beam time was requested. The resulting data were then interpreted through theoretical models and complementary laboratory measurements in Czechia. This workflow made international infrastructures effectively part of the national condensed-matter research environment even though the machines themselves were situated abroad. Training at these facilities also exposed students to experimental standards, instrumentation, and scientific communities operating at an international level. Large-scale access therefore strengthened domestic research rather than substituting for it. The development of condensed matter physics after 1993 is consequently inseparable from the progressive integration of Czech laboratories into the European infrastructure network.

The major achievement of Czech condensed matter physics between 1993 and 2025 was thus not a single discovery or material but the development of a highly diversified research system capable of connecting structure, electronic states, collective phenomena, and technological function. Traditional strengths in crystallography, solid-state theory, magnetism, semiconductors, superconductivity, and low-temperature physics were preserved while being transformed by computation, nanofabrication, advanced spectroscopy, and international infrastructure access. FZU provided the largest multidisciplinary concentration, while Charles University sustained strong programmes in correlated matter, magnetism, superconductivity, and materials structure. Brno developed a complementary ecosystem around Masaryk University, Brno University of Technology, and CEITEC, particularly in nanoscience and advanced materials. Czech crystallographers contributed internationally used methodological tools such as the JANA system, while shared infrastructures such as CzechNanoLab strengthened domestic experimental capability. Semiconductor research expanded from conventional electronic materials towards wide-band-gap systems, diamond, nanostructures, and quantum-photonic materials. Functional-material programmes demonstrated how martensitic transformations, ferroic order, and controlled microstructures could be converted into useful responses. Superconductivity and correlated-electron research moved progressively towards unconventional, topological, and mesoscopic quantum systems. Magnetic-material research created the intellectual foundations for the particularly prominent Czech contributions to antiferromagnetic spintronics and, later, altermagnetism. By 2025, condensed matter and advanced materials research had therefore become one of the principal areas in which Czech physics combined deep scientific continuity with internationally visible conceptual and technological innovation.

Magnetism, Spintronics, and Altermagnetism

Magnetism is one of the areas in which Czech condensed-matter physics developed a particularly distinctive international profile between 1993 and 2025. The field combined older traditions in magnetic alloys, intermetallic compounds, rare-earth and actinide systems, semiconductor magnetism, and low-temperature physics with new programmes in spin-dependent electronics. The Institute of Physics of the Czech Academy of Sciences (FZU) became the most internationally visible Czech centre for spintronics, while Charles University and research groups in Brno maintained important complementary programmes in magnetic materials and theory. During the 1990s and early 2000s, Czech scientists investigated how

electronic structure, crystal symmetry, defects, and carrier concentration determine magnetic order in solids. This work provided a foundation for research in which magnetism could be manipulated electrically rather than only through external magnetic fields. Spintronics broadened the technological meaning of magnetism by treating electron spin as an active variable for storing, transmitting, and processing information. Czech groups contributed to this transition through theory, materials research, magnetotransport, optical methods, device experiments, and international collaboration. From the middle of the 2010s, Prague-based research became especially influential in the emerging field of antiferromagnetic spintronics. During the early 2020s, the same intellectual programme contributed to the symmetry-based identification of altermagnetism as a distinct magnetic phase. This sequence from magnetic materials to spintronics, antiferromagnetic devices, and altermagnetism represents one of the most coherent scientific trajectories in modern Czech physics.

The Czech tradition in magnetism was broader than the later spintronics programme and included several established schools of magnetic materials research. Charles University developed long-running expertise in rare-earth and uranium intermetallics, magnetic phase transitions, magnetocrystalline anisotropy, metamagnetism, superconductivity, and the response of materials to high magnetic fields and pressure. Its researchers combined crystal growth with magnetisation, transport, heat-capacity, diffraction, and spectroscopic measurements to connect microscopic electronic states with macroscopic magnetic behaviour. The study of uranium compounds was especially notable because the partially localised character of 5f electrons produces unusually rich competition between magnetism, metallicity, and superconductivity. Czech researchers also investigated frustrated magnets, Heusler alloys, layered magnets, magnetic oxides, and low-dimensional systems. These traditions trained successive generations of physicists in the experimental and theoretical methods needed to analyse ordered magnetic matter. They also established a culture of using international neutron, synchrotron, and high-field facilities when domestic instruments could not reach the necessary experimental conditions. Spintronics therefore emerged in Czechia within a much wider materials-science environment rather than as a disconnected technological speciality. The later success of antiferromagnetic and altermagnetic research drew strength from this accumulated understanding of magnetic symmetry, electronic structure, crystal quality, and phase behaviour.

An important intermediate stage was the Czech contribution to the physics of ferromagnetic semiconductors during the late 1990s and 2000s. Researchers associated with FZU, Charles University, the University of Nottingham, and several American and European institutions investigated diluted magnetic semiconductors (DMSs), especially gallium manganese arsenide. In this material, manganese simultaneously provides local magnetic moments and influences the carrier population, producing a close connection between semiconductor transport and collective magnetism. Czech theorists helped develop microscopic descriptions of carrier-mediated ferromagnetism and analysed how disorder, compensation, strain, and magnetic anisotropy affect the observed properties. Experimental collaborations examined magnetotransport, magneto-optical effects, annealing, defects, and the dependence of the Curie temperature on material quality. The research was important because it united semiconductor physics with concepts previously associated mainly with metallic ferromagnets. It also encouraged the development of techniques for growing and characterising thin magnetic layers suitable for device fabrication. The resulting expertise in epitaxy, nanostructures, transport, and spin-dependent phenomena became directly relevant

to later spintronics. Tomáš Jungwirth and Czech collaborators became prominent contributors to the international literature on ferromagnetic semiconductors and spin-dependent transport. Theoretical work from this period also strengthened long-term links between Prague, Nottingham, Texas, and later Mainz. These networks became important when the Czech programme shifted from ferromagnetic semiconductors towards spin-orbit phenomena and antiferromagnetic materials.

Spintronics itself rests on the principle that electronic devices can exploit spin-dependent properties in addition to electric charge. In conventional magnetic memory, ferromagnetic layers provide easily readable magnetisation states but also generate stray magnetic fields and operate on characteristic dynamical timescales that can limit device density and speed. Research during the 2000s increasingly focused on phenomena through which electric currents could generate, transport, or manipulate spin angular momentum. Czech researchers participated prominently in the theoretical and experimental study of the spin Hall effect, in which charge currents in materials with spin-orbit interaction generate transverse spin currents. The corresponding inverse effect allows spin currents to be converted back into measurable charge signals. These mechanisms became central tools for modern spintronics because they enable electrical creation and detection of spin without requiring a conventional ferromagnetic injector in every device. Czech contributions linked microscopic theory with magnetotransport and semiconductor experiments. The field also encouraged researchers to think about current-induced torques as a general route to manipulating magnetic order.

The conceptual shift towards spin-orbit phenomena was crucial for the later Czech breakthrough in antiferromagnetic spintronics. Spin-orbit coupling (SOC) links the motion of electrons through a crystal to their spin and makes electrical currents capable of generating non-equilibrium spin polarisation. In crystals lacking particular inversion symmetries, this spin polarisation can exert torques on magnetic moments. FZU researchers and international collaborators investigated these mechanisms first in semiconductor and ferromagnetic systems and then asked whether analogous effects could control antiferromagnets. The problem was challenging because antiferromagnets contain magnetic sublattices whose moments point in opposite directions and usually produce little or no net magnetisation. A uniform magnetic field therefore couples inefficiently to the antiferromagnetic order parameter compared with its effect on a ferromagnet. Electrical control required a mechanism capable of exerting opposite effective fields on the two magnetic sublattices. Symmetry rather than merely field strength became the central design principle. This transition from manipulating net magnetisation to manipulating sublattice order opened a fundamentally new branch of Czech spintronics. It also prepared the conceptual language that would later become essential for classifying altermagnets.

Antiferromagnets offered several potential advantages that made this difficult problem worth pursuing. Their compensated magnetic structure produces negligible macroscopic stray fields, allowing neighbouring elements to be placed close together without strong dipolar interference. The orientation of their order can also be relatively insensitive to external magnetic-field perturbations, which is attractive for robust information storage. Antiferromagnetic exchange interactions are typically much stronger than the anisotropy energies controlling ferromagnetic dynamics. Their intrinsic dynamical frequencies can therefore extend into the terahertz regime rather than being limited primarily to gigahertz scales. Antiferromagnets are also abundant among magnetic compounds, offering a wider materials landscape than traditional ferromagnetic spintronics alone. Yet these same

properties historically made them difficult to detect and manipulate because the opposite magnetic sublattices tend to cancel in ordinary magnetic measurements. The principal challenge was thus to discover electrical, optical, or transport observables that couple to the internal order even when the net moment vanishes. Czech theory and experiment became internationally important precisely because they addressed this control-and-readout problem in a technologically realistic setting. The programme required close cooperation among electronic-structure theorists, materials growers, transport physicists, optical spectroscopists, and nanofabrication specialists. It also depended on long-standing collaboration between FZU and the University of Nottingham, together with partners in Germany, Switzerland, Spain, the United States, and elsewhere, producing a research environment that combined the flexibility of an academic network with the continuity of a stable Prague-based group. By the middle of the 2010s, this network was positioned to demonstrate effects that had previously been regarded as extremely difficult to realise in antiferromagnets.

A decisive theoretical step came in 2014 with the prediction of relativistic Néel-order fields generated by electrical current in certain antiferromagnetic crystals. Jakub Železný, Tomáš Jungwirth, and collaborators showed that crystal symmetry could produce current-induced fields whose sign alternates between opposite magnetic sublattices. Such a staggered field couples directly to the Néel vector, which describes the orientation of antiferromagnetic order. The mechanism is fundamentally different from applying an ordinary uniform magnetic field, because the latter acts similarly on both sublattices and is therefore inefficient for reorienting a compensated antiferromagnet. The theory identified material symmetries in which local inversion asymmetry on individual magnetic sites can generate the required alternating spin polarisation. It predicted that electrical currents could trigger rapid reorientation of the antiferromagnetic axis through relativistic spin-orbit torques. Importantly, the same work proposed an antiferromagnetic memory concept in which information could be written electrically and detected through magnetoresistance. This transformed antiferromagnetic spintronics from an attractive general idea into a concrete symmetry-based device programme. The prediction also demonstrated the strength of combining first-principles electronic structure with transport theory.

Copper manganese arsenide, CuMnAs, became the principal experimental material through which this prediction was tested. It is a collinear antiferromagnet whose crystal structure provides the local inversion asymmetry required for opposite current-induced spin polarisations on the two manganese sublattices. Thin films could be grown epitaxially on semiconductor substrates, allowing microfabricated electrical devices to be produced using techniques familiar from semiconductor physics. The material's compensated magnetic order avoided the large stray fields characteristic of ferromagnetic memory elements. In 2016, an international team involving FZU and the University of Nottingham reported electrical switching of antiferromagnetic order in CuMnAs in *Science*. Current pulses applied along different crystallographic directions produced reproducible changes in resistance associated with reorientation of the antiferromagnetic state. The experiment provided a direct realisation of the current-induced Néel spin-orbit torque predicted in the earlier Czech-led theoretical work. The result established antiferromagnets as electrically writable active elements rather than passive materials used only to pin ferromagnetic layers.

The 2016 demonstration was important not only because switching occurred, but because the write and read operations could be implemented through standard electrical methods. Writing

was produced by current pulses, while the state was detected through anisotropic magnetoresistance associated with the orientation of the antiferromagnetic order. This removed the need for impractically large magnetic fields and made the concept compatible with lithographically patterned devices. The experiment also highlighted the central role of symmetry, because rotating the current direction changed the orientation of the effective staggered field. Subsequent work at FZU examined how domain structure, pulse amplitude, pulse duration, temperature, and device geometry affect the switching response. The research revealed that electrical pulses reconfigure ensembles of antiferromagnetic domains rather than simply rotating a perfectly uniform magnetic state. This complexity created both challenges and opportunities because domain redistribution can generate analogue or multilevel behaviour rather than only binary switching. The same mechanism also proved capable of operating over an exceptionally wide range of timescales. The CuMnAs programme therefore evolved quickly from proof of principle towards a broader exploration of memory functionality and antiferromagnetic dynamics. It became one of the best-known examples of Czech participation in an emerging field of condensed-matter physics.

In 2017, Czech-led experiments demonstrated a multi-level CuMnAs memory cell with features relevant to microelectronic implementation. Devices produced deterministic resistance changes in response to trains of electrical pulses rather than merely switching between two fixed states. The response allowed the cell to count or integrate input pulses, suggesting possible functions combining memory with elementary signal processing. Researchers demonstrated operation in a standard printed circuit board controlled through a conventional computer interface. Pulse lengths could be reduced towards the sub-nanosecond regime while retaining electrical write functionality. The study showed that antiferromagnetic order could be incorporated into ordinary device architectures without requiring external superconducting magnets or specialised cryogenic environments. Operation at ambient conditions was particularly important for demonstrating technological plausibility. The multilevel response also connected antiferromagnetic spintronics with emerging interest in neuromorphic and analogue information-processing concepts. The device architecture therefore demonstrated that the same magnetic element could perform more complex functions than simple binary storage. Although the devices were still research prototypes, the work moved the field beyond a single switching experiment. It demonstrated that a compensated antiferromagnet could support reproducible electrical write, store, and read functions within one microfabricated element.

The speed advantage associated with antiferromagnetic dynamics was explored experimentally in 2018. A Czech-led international team used ultrashort electrical transients to write antiferromagnetic memory states in CuMnAs at room temperature. The study demonstrated reversible writing extending to terahertz frequencies, far above the characteristic write frequencies of conventional ferromagnetic memories. A common current-induced spin-torque mechanism described the switching across an extraordinary range of pulse durations. This result connected the microscopic exchange scale of antiferromagnets with a practical electrical control experiment. It also brought together FZU, Charles University, German ultrafast laboratories, Nottingham, and Swiss collaborators. Terahertz pulses provided a way to perturb the magnetic state on timescales comparable with intrinsic antiferromagnetic dynamics. The experiment therefore transformed the frequently stated theoretical promise of ultrafast antiferromagnets into a directly measured device capability.

Czech antiferromagnetic spintronics had by this stage produced a linked sequence of theoretical prediction, electrical switching, multilevel memory, and ultrafast operation.

The international impact of this work became particularly visible in 2018, when *Nature Physics* devoted a coordinated focus to antiferromagnetic spintronics. Czech-affiliated researchers participated prominently across several articles addressing electrical transport, spin torque, topology, optical control, magnetic textures, and the wider prospects of the field. Tomáš Jungwirth and collaborators discussed the multiple directions in which antiferromagnetic spintronics was expanding beyond the original memory concept. Jakub Železný and co-authors reviewed spin transport and spin torque in antiferromagnetic devices. Libor Šmejkal and collaborators connected antiferromagnetic spintronics with topological structures in real and momentum space. Petr Němec and international partners reviewed ultrafast optical control and the emerging field of antiferromagnetic opto-spintronics. The appearance of this collection indicated that antiferromagnetic spintronics had become an identifiable research field rather than a small number of isolated demonstrations. Czech researchers occupied an unusually central position in that consolidation. The scientific agenda also broadened from device switching towards anomalous transport, topology, relativistic effects, ultrafast dynamics, and non-collinear magnetic structures. This broadening became crucial for the later move towards magnetic phases that combine compensated order with electronic effects previously associated mainly with ferromagnets. The 2018 focus therefore marks an important intellectual bridge between the CuMnAs memory programme and the emergence of altermagnetism. It also showed that the Prague research network had acquired the ability to influence how an international subfield defined its central problems.

Czech magnetism nevertheless remained broader than the FZU spintronics programme. Charles University continued research on uranium and rare-earth intermetallics, frustrated magnets, Heusler alloys, van der Waals magnets, high-field phase transitions, and unconventional superconductivity. Its Magnetism Group combined crystal growth with thermodynamic, transport, magnetic, diffraction, and spectroscopic measurements over exceptionally wide ranges of temperature, field, and pressure. The Department of Condensed Matter Physics also maintained theoretical research on spin-dependent transport, magnetisation dynamics, non-equilibrium magnetic states, graphene, and low-dimensional magnetic systems. Brno research groups contributed to nanomagnetism, magnetic thin films, spin dynamics, and advanced microscopy within the broader materials environment associated with Masaryk University, Brno University of Technology, and the Central European Institute of Technology (CEITEC). These activities provided alternative experimental systems and methodological approaches to those used in Prague spintronics. They also strengthened national expertise in the preparation and characterisation of magnetic materials. The Czech contribution to modern magnetism should therefore not be reduced to a single laboratory or scientific personality. Its international visibility in spintronics emerged from a wider domestic culture of magnetic-materials research.

Despite the progress of antiferromagnetic spintronics, a fundamental conceptual difficulty remained. In conventional collinear antiferromagnets, opposite spin sublattices are often related by translation or inversion symmetries that preserve spin degeneracy in the electronic band structure when relativistic effects are neglected. This helps explain why ordinary antiferromagnets can appear electronically similar to non-magnetic materials despite possessing microscopic magnetic order. Many desirable spintronic responses, however, require substantial spin splitting or broken time-reversal symmetry in momentum space.

Researchers began identifying compensated magnets in which Hall effects, magnetoresistance, or spin-polarised bands appeared despite the absence of a macroscopic ferromagnetic moment. Describing all such systems simply as unusual antiferromagnets increasingly obscured the underlying symmetry distinctions. Theoretical work associated with Czech researchers therefore shifted towards a more general classification of magnetic phases based on combined spin and crystal symmetries. This shift turned a device-oriented research question into a fundamental problem in the taxonomy of magnetism, whose resolution would become the concept of altermagnetism.

The route to altermagnetism emerged from several theoretical observations made during the late 2010s and early 2020s. Researchers showed that compensated collinear magnets could support large spin-dependent electronic effects when opposite spin sublattices were connected by crystal rotations rather than by the translations or inversions characteristic of conventional antiferromagnets. This possibility changed the interpretation of band spin splitting because a material could possess zero net magnetisation while retaining strongly spin-polarised electronic states. The momentum dependence of the splitting could alternate in sign in a manner controlled by crystal symmetry. Such a state could consequently share the absence of stray fields and high dynamical scales of antiferromagnets with some of the electrical readout advantages of ferromagnets. Theoretical predictions included unconventional Hall responses, magnetoresistance, spin currents, and current-induced torques. Libor Šmejkal, Jairo Sinova, Tomáš Jungwirth, and collaborators developed these ideas through increasingly systematic symmetry analysis. In February 2022, they published predictions of giant and tunnelling magnetoresistance in unconventional compensated magnets with alternating spin-momentum coupling. Later that year, their work established a symmetry-based classification in which the relevant systems formed a distinct magnetic phase. The alternating nature of the spin polarisation led them to introduce the term altermagnetism. The proposal therefore arose from a combination of spintronics, symmetry classification, and electronic-structure theory rather than from the discovery of one previously unknown material. It reframed a collection of apparently anomalous antiferromagnetic behaviours as manifestations of a common magnetic principle.

The 2022 *Physical Review X* work defined altermagnetism at the non-relativistic level through spin-group symmetries. In conventional ferromagnets, spin-up and spin-down electronic bands are split and one spin population is favoured, producing a net magnetisation. In conventional collinear antiferromagnets, symmetry can enforce spin degeneracy even though individual atomic sites carry opposite magnetic moments. Altermagnets occupy a third situation in which the magnetic moments compensate in real space but the electronic bands are spin split in momentum space. Opposite spin states are related by crystallographic rotations, producing an alternating pattern of spin polarisation across the Brillouin zone. Depending on crystal symmetry, this pattern can possess d-wave, g-wave, or higher even-parity character. The splitting can arise from non-relativistic exchange and therefore need not be limited to the comparatively small energy scale of spin-orbit interaction. At the same time, the total magnetic moment can remain vanishingly small. This combination resolves the apparent contradiction between compensated magnetic order and strong spin-polarised electronic behaviour.

The distinction has substantial consequences for experimental observables. A conventional antiferromagnet can be difficult to read electrically because its opposite sublattices often cancel in bulk transport responses. An altermagnet can retain compensated real-space order

while displaying strongly anisotropic spin-split electronic bands. Time-reversal-symmetry-breaking phenomena that are familiar from ferromagnets can consequently become allowed even without a large macroscopic magnetisation. These may include the anomalous Hall effect (AHE), magneto-optical responses, spin-polarised currents, and unusual magnetoresistance. Altermagnets can also support spin-current generation mechanisms in which the spin polarisation changes systematically with electron momentum. Such effects are potentially valuable because they offer electrical routes for reading or manipulating magnetic order. The absence of strong stray fields simultaneously preserves one of the most attractive features previously associated with antiferromagnetic devices. The physical combination is therefore not merely intermediate between ferromagnetism and antiferromagnetism but qualitatively different. This explains why the introduction of a separate name and symmetry category rapidly gained international attention.

Spintronic consequences were explored theoretically even before the terminology became broadly established. Giant magnetoresistance (GMR) and tunnelling magnetoresistance (TMR) are foundational effects of commercial spintronics because the electrical resistance of a structure depends on the relative spin-dependent electronic properties of its magnetic components. Conventional implementations rely on ferromagnetic electrodes whose exchange-split bands act as spin filters. Czech-affiliated theory showed that analogous large effects could arise in compensated magnets through alternating non-relativistic spin-momentum coupling. Calculations predicted magnetoresistance approaching technologically significant scales in carefully oriented multilayers composed of such materials. The same electronic structure could support spin-transfer torques and other means of electrical manipulation. Importantly, these mechanisms did not require a net ferromagnetic moment to produce spin-dependent transport. Altermagnetic devices could therefore, in principle, combine strong electrical readout with weak sensitivity to external magnetic fields and reduced dipolar crosstalk. Theoretical work also identified candidate materials spanning metals, semiconductors, insulators, and systems related to superconducting compounds. This breadth suggested that the new phase might be common rather than represented by only a few exceptional crystals. Material discovery consequently became an international search guided by symmetry databases, first-principles calculations, and re-examination of compounds previously classified as ordinary antiferromagnets. The Czech programme thus moved from demonstrating one antiferromagnetic memory material to helping define a much larger materials landscape.

Hexagonal manganese telluride, α-MnTe, became one of the most important experimental prototypes of altermagnetism. The compound was already known as an antiferromagnetic semiconductor with a Néel temperature close to room temperature. Its manganese moments form compensated sublattices whose relationship by crystal rotation produces the symmetry required for altermagnetic band splitting. MnTe was particularly attractive because high-quality thin films and bulk crystals could be produced and because its transport, magnetic, and photoemission properties were experimentally accessible. FZU researchers worked with collaborators at Charles University, the University of West Bohemia, the Paul Scherrer Institute, Johannes Kepler University Linz, Nottingham, Mainz, and other institutions to examine the material. Electronic-structure calculations predicted strongly momentum-dependent spin splitting despite the absence of ordinary ferromagnetic magnetisation. The material also displayed anomalous Hall behaviour under conditions consistent with broken

time-reversal symmetry. These properties made MnTe a bridge between the theoretical symmetry classification and direct experimental tests of the proposed phase.

A major experimental confirmation appeared in *Nature* in February 2024 through measurements of altermagnetic lifting of Kramers spin degeneracy in MnTe. The collaboration used spin- and angle-resolved photoemission spectroscopy (ARPES) together with first-principles electronic-structure calculations. ARPES maps the energy and momentum of electrons emitted from a material and can therefore reveal directly how electronic bands are split. The measurements identified spin splitting with the symmetry behaviour expected for the altermagnetic phase. Crucially, the splitting occurred in a centrosymmetric crystal with essentially compensated magnetic order, excluding the conventional explanations based simply on ferromagnetic magnetisation or inversion-asymmetric relativistic splitting. Several researchers from FZU participated in the study, together with Czech collaborators from the University of West Bohemia and Charles University. Independent photoemission work published in *Physical Review B* during the same period observed strongly anisotropic splitting in MnTe reaching values on the order of several tenths of an electronvolt. The large scale of the effect supported the theoretical expectation that altermagnetic splitting can have a predominantly non-relativistic exchange origin. These spectroscopic results transformed altermagnetism from a symmetry-based theoretical proposal into an experimentally established electronic phenomenon. They also provided a concrete way of distinguishing altermagnets from conventional compensated antiferromagnets. The international visibility of the *Nature* result placed Czech-affiliated research at the centre of one of the most active new topics in magnetism.

Other experiments in 2024 expanded the observable phenomenology beyond photoemission. A collaboration including Czech researchers investigated X-ray magnetic circular dichroism (XMCD) in α-MnTe and showed that compensated altermagnetic order can generate a characteristic dichroic response. XMCD normally detects differences in the absorption of left- and right-circularly polarised X-rays and is widely used to probe element-specific magnetic moments. Theoretical modelling and experiment demonstrated that the spectral response in MnTe contains information tied to the orientation of the compensated magnetic structure. This provided another route for detecting altermagnetic order that does not rely on a large net magnetisation. Transport experiments also analysed anisotropic magnetoresistance and the anomalous Hall effect in MnTe. Their angular dependence reflected the interplay between crystal symmetry and magnetic order. These results were important because a new phase becomes scientifically useful only when several independent experimental methods can identify and characterise it. By combining photoemission, X-ray spectroscopy, electrical transport, microscopy, and theory, the international programme around MnTe developed a much stronger evidential foundation than any single measurement could provide.

The spatial structure of altermagnetic order became directly accessible in another *Nature* study published in December 2024. Researchers used X-ray magnetic circular and linear dichroism combined with photoemission electron microscopy (PEEM) to image magnetic domains in thin-film MnTe. The measurements revealed domain walls, vortices, and other magnetic textures on nanometre and micrometre length scales. Patterned sample edges and thermal treatments could influence the domain configuration, demonstrating that the altermagnetic state was not merely observable but could be manipulated structurally. The study also connected microscopic imaging with electrical measurements of the anomalous Hall response. Czech-affiliated researchers Libor Šmejkal, Tomáš Jungwirth, and Dominik

Kriegner participated in the international collaboration. The ability to visualise domains is important for both fundamental physics and prospective devices because electrical signals often depend on the distribution and motion of magnetic textures. Imaging also showed that compensated magnetism can possess rich spatial structure despite generating little external magnetic field. The experiment therefore added real-space evidence to the momentum-space spectroscopy that had established altermagnetic band splitting earlier in the year. Together, the 2024 results transformed MnTe into a benchmark system for studying the relationship between crystal symmetry, electronic structure, transport, and magnetic textures.

The technological implications of altermagnetism remain prospective, but the physical opportunities are substantial. Altermagnets can in principle generate large spin-polarised currents without the strong macroscopic magnetic fields produced by ferromagnets. Their compensated order may allow dense device integration and reduced sensitivity to external magnetic perturbations. Exchange-driven band splitting can also be much larger than many purely relativistic spin splittings, potentially supporting robust operation at elevated temperatures. Alternating momentum-dependent spin polarisation introduces new mechanisms for generating and detecting spin currents. The predicted GMR and TMR effects suggest possible electrical readout schemes based directly on altermagnetic electrodes. Spin-transfer and spin-orbit torques may provide complementary methods for manipulating the order parameter. Magnetic textures and magnons offer additional channels for information transport or ultrafast dynamics. Because candidate altermagnets include metals, semiconductors, insulators, and compounds with superconducting tendencies, the field intersects several major branches of quantum materials research. The combination of altermagnetism with topology, superconductivity, and two-dimensional systems is therefore of particular theoretical interest. None of these possibilities guarantees immediate commercial technology, and practical devices will require suitable materials, reproducible switching, scalable fabrication, and low-energy operation. The importance of the Czech contribution lies at this stage primarily in establishing the physical principles and experimentally testable signatures on which such future technologies could be built.

The rapid international expansion of altermagnetism during 2022–2025 is itself evidence of the significance of the Czech-led theoretical framework. Within a few years, research groups in Europe, Asia, and North America began applying the classification to oxides, chalcogenides, pnictides, ruthenates, two-dimensional materials, and candidate superconductors. Major journals published dedicated perspectives, experimental confirmations, reviews, and theoretical studies addressing the new phase. European funding also supported projects explicitly devoted to altermagnetism and spintronics without conventional magnetisation. The field drew together communities that had previously worked rather separately on antiferromagnets, topological matter, Hall effects, magnetic spectroscopy, and spin transport. Czech institutions benefited from this expansion because the original Prague-based programme was already connected to Nottingham, Mainz, the Paul Scherrer Institute, and multiple European materials laboratories. Altermagnetism therefore became an example of Czech research helping to set an international scientific agenda rather than merely contributing to one created elsewhere. The development also strengthened the global visibility of Czech condensed-matter physics during the first half of the 2020s.

The broader national effect was to reinforce links among magnetism, quantum materials, semiconductor physics, nanofabrication, and advanced spectroscopy. FZU continued to concentrate spintronics and nanoelectronics expertise, while Charles University provided

complementary work in magnetic quantum matter, transport, spectroscopy, and theory. Czech participation in synchrotron and X-ray facilities became increasingly important because techniques such as ARPES, XMCD, and PEEM are difficult to reproduce in ordinary university laboratories. Domestic thin-film growth, transport measurements, structural characterisation, and theoretical calculations remained essential for preparing and interpreting experiments conducted at international facilities. The University of West Bohemia contributed electronic-structure and materials expertise to prominent altermagnetic studies. Masaryk University researchers also participated in theoretical and spectroscopic work on altermagnetic systems. The field therefore began to spread beyond the original Prague spintronics core even while FZU remained its most visible Czech centre. This widening institutional base increased the likelihood that altermagnetism would become a sustained research programme rather than a short-lived response to a single discovery. It also strengthened the integration of Czech magnetism into the wider European quantum-materials ecosystem. The result was a national research landscape in which fundamental symmetry, materials synthesis, device concepts, and large-facility spectroscopy could be pursued as parts of one connected programme.

Between 1993 and 2025, Czech research in magnetism therefore followed an unusually coherent progression from established magnetic materials towards internationally influential concepts in spintronics and quantum matter. The traditional study of rare-earth compounds, uranium intermetallics, magnetic semiconductors, and low-dimensional magnets created the materials and theoretical background from which new questions could emerge. Work on ferromagnetic semiconductors trained Czech groups in the control of spin-dependent transport and established durable international collaborations. Research on the spin Hall effect and spin-orbit torques then provided mechanisms for manipulating magnetic order electrically. The 2014 prediction of staggered current-induced Néel fields created a concrete path towards antiferromagnetic devices. Electrical switching of CuMnAs in 2016, multilevel memory in 2017, and terahertz writing in 2018 established Czech-led antiferromagnetic spintronics as an important international research programme. The theoretical generalisation of compensated spin-split magnets culminated in the 2022 identification and naming of altermagnetism as a distinct symmetry class. Experiments in 2024 then demonstrated characteristic spin splitting, dichroism, transport responses, and domain structures in MnTe, giving the new concept a broad empirical foundation. These developments did not replace conventional magnetism but enlarged the conceptual map through which magnetic materials are classified and exploited. Their scientific significance lies in linking symmetry, electronic structure, dynamics, and potential information functionality within a common framework. By 2025, magnetism and spintronics had consequently become one of the areas in which Czech physics exerted an influence on the terminology, research questions, and experimental priorities of an international field.

Optics, Photonics, and Laser Physics

Optics, photonics, and laser physics became one of the most dynamically expanding areas of Czech physical science between 1993 and 2025. After the establishment of the independent Czech Republic, the field developed from strong Czechoslovak traditions in laser engineering, spectroscopy, optical instrumentation, nonlinear optics, and the physics of light–matter interaction. Czech laser science initially relied on relatively compact research groups and

inherited laboratory systems, but it progressively acquired facilities of European and eventually global significance. The field simultaneously broadened from the generation and characterisation of coherent light towards photonics, ultrafast phenomena, laser-driven plasmas, secondary radiation sources, precision metrology, optical fibres, and advanced materials processing. The Institute of Physics of the Czech Academy of Sciences, the Institute of Plasma Physics, the Institute of Photonics and Electronics, Palacký University in Olomouc, the Institute of Scientific Instruments in Brno, and several technical universities became important institutional centres. The Prague Asterix Laser System (PALS) provided the first major post-1993 example of Czechia operating a high-power laser as an international user facility. During the 2010s, HiLASE and Extreme Light Infrastructure Beamlines greatly increased the available pulse energy, repetition rate, peak power, and range of experimental techniques. High-intensity and ultrafast laser research thereby became connected with plasma physics, materials science, particle acceleration, spectroscopy, nanotechnology, medical research, and industrial manufacturing. By 2025, Czech optics and laser physics formed a diversified research ecosystem extending from quantum and fibre photonics to multi-petawatt light–matter interaction.

The post-1993 development of Czech high-power laser science was built directly upon work undertaken during the final decades of Czechoslovakia. Researchers at the Institute of Physics had begun operating the PERUN iodine laser in 1985 after substantially reconstructing a system originally obtained from the Lebedev Physical Institute in Moscow. A more powerful version, PERUN II, entered operation in 1992 in a new laser laboratory in Prague. During the first half of the 1990s, the PERUN programme supported experiments on multiply charged ions, laser-produced X-ray sources, and plasma phenomena relevant to high-energy-density research. Czech scientists also maintained collaborations with laboratories in Poland, Russia, France, Switzerland, Germany, and the European Organization for Nuclear Research. The system nevertheless had insufficient pulse energy for some of the most demanding experiments, including several approaches to plasma-based X-ray lasers. This technological limitation became increasingly important as European high-power laser research moved towards larger pulse energies and more sophisticated target experiments. The Czech group therefore needed either a major domestic upgrade or access to a substantially more powerful facility. An unusual opportunity emerged when the Max Planck Institute for Quantum Optics in Garching decided to terminate operation of its ASTERIX IV iodine laser. The resulting transfer to Prague became the decisive event that transformed Czech laser-plasma research at the end of the 1990s.

The agreement transferring ASTERIX IV to the Czech Academy of Sciences was signed in June 1997 after Czech researchers successfully competed to obtain the system. The project required cooperation between the Institute of Physics and the Institute of Plasma Physics because neither institute alone possessed all the scientific and technical resources needed for dismantling, transport, reconstruction, and future operation. In November 1998, the two institutes formally established the PALS Research Centre as a joint laboratory. A new laser hall was constructed in Prague specifically to accommodate the transferred system and its experimental target areas. Installation and commissioning were essentially completed by the end of 1999 after the laser had been dismantled in Germany and rebuilt in Czechia. Operational testing continued during the first half of 2000. The completed facility was ceremonially launched on 8 June 2000 and began serving users later that year. The PALS project therefore

converted international transfer of equipment into a durable national research capability rather than treating ASTERIX IV as a temporary technological acquisition.

The central PALS laser is a high-power photodissociation iodine system operating at a fundamental wavelength of 1.315 micrometres. It can deliver pulses of up to approximately one kilojoule with durations in the range of roughly 200 to 350 picoseconds. At full energy and a pulse duration of about 350 picoseconds, the system reaches a peak power close to three terawatts. Frequency conversion allows operation at the second and third harmonics, extending experiments from the near-infrared towards visible wavelengths. An auxiliary beam can be timed relative to the main pulse, enabling pump–probe arrangements, target preconditioning, or independent generation of diagnostic plasmas. The laser's optical chain combines an oscillator with several progressively larger amplifiers in a master-oscillator power-amplifier architecture. Spatial filters suppress small-scale beam irregularities and protect optical components from damaging intensity concentrations. PALS can focus its radiation onto targets at power densities of approximately 10^14 to 10^16 watts per square centimetre. These conditions are sufficient to produce hot dense plasmas, strong shock waves, intense X-ray emission, and highly charged energetic ions. The facility consequently occupies an important intermediate regime between conventional laboratory lasers and the later petawatt systems developed at Extreme Light Infrastructure Beamlines. Its long-term value has rested not merely on nominal pulse energy but on stable operation, flexible diagnostics, target technologies, and the ability to support international experimental campaigns.

Laser–matter interaction became the unifying scientific theme of PALS because a sufficiently intense pulse can transform a solid or gaseous target into plasma within an extremely short time. Energy deposited by the laser drives rapid ionisation, steep temperature gradients, pressure waves, particle acceleration, and strong electromagnetic fields. Czech researchers used these processes to investigate matter under conditions far removed from ordinary thermodynamic equilibrium. Experiments examined how energy is absorbed and transported through dense plasmas and how hydrodynamic instabilities develop under intense irradiation. Shock waves generated in solids provided information relevant to equations of state and the response of materials at very high pressure. Laser plasmas also supplied intense short-lived sources of electromagnetic radiation and energetic charged particles. The experimental programme therefore linked plasma physics with atomic physics, spectroscopy, radiation physics, and materials science. Numerical hydrodynamics and radiation-transport calculations became increasingly important for interpreting the short-lived states created during each laser shot. PALS helped establish in Czechia a research culture in which laser engineering, plasma diagnostics, target preparation, simulation, and application experiments operated as parts of one scientific programme.

Soft X-ray generation became one of the most important research directions developed around PALS. Hot laser-produced plasma contains highly ionised atoms whose electronic transitions can emit strongly in the extreme-ultraviolet and soft X-ray regions. Under suitable conditions, population inversion can be created and the plasma can function as the active medium of a short-wavelength laser. Czech scientists had already investigated collisional X-ray laser schemes with PERUN and during cooperation with ASTERIX IV in Germany. PALS made it possible to continue this work at much higher pulse energies within a domestic facility. Experiments developed plasma-based point sources of non-coherent soft X-rays and studied coherent amplification in selected highly charged ions. Short-wavelength beams could then be

used for plasma diagnostics, imaging, microstructuring, or irradiation of biological and material samples. The same experiments required high-resolution spectroscopy capable of resolving emission from transient highly ionised species. This strengthened Czech expertise in X-ray optics, spectrometers, multilayer mirrors, and related diagnostics. Laser-generated X-ray science therefore became both a fundamental research topic and a technological field supporting other experiments.

Energetic ion production formed a second major application of laser-created plasmas. When an intense laser pulse strikes a solid target, rapid electron heating and strong electric fields can accelerate ions away from the plasma surface. PALS experiments investigated highly charged ions with energies relevant to accelerator injection, materials modification, and plasma diagnostics. Czech researchers had already collaborated with CERN on laser ion sources during the PERUN period, providing useful continuity after the transfer of ASTERIX IV. The higher energy of PALS widened the accessible range of ion charge states and plasma conditions. Ion emission measurements required specialised time-of-flight detectors, ion collectors, spectroscopy, and modelling of plasma expansion. These studies also contributed to understanding the conversion of optical energy into directed particle energy. The research anticipated later programmes at petawatt facilities where laser-driven acceleration became a central route to generating electrons, protons, and heavier ions.

High-energy-density physics and laboratory astrophysics became increasingly important as researchers learned to use high-power lasers to reproduce selected physical processes normally associated with stars, planetary interiors, or astrophysical shocks. The aim of laboratory astrophysics is not to reproduce an entire astronomical object but to create a scaled experiment governed by comparable dimensionless physical parameters. PALS shock experiments allowed researchers to investigate compressible flows, radiative shocks, plasma jets, and the response of matter under extreme pressure. Multiple beams or auxiliary pulses could generate backlighting radiation for imaging rapidly evolving structures. Spectroscopy provided measurements of plasma temperature, ionisation, and opacity. Such experiments demanded precise target fabrication because the geometry and composition of microscopic targets strongly influence the resulting hydrodynamics. International teams used the Prague facility to compare experimental observations with numerical simulations and astrophysical models. Research on warm dense matter provided a related connection with planetary physics and inertial-fusion science. In this regime, matter lies between ordinary condensed matter and fully ionised ideal plasma, making both its electronic and ionic behaviour difficult to calculate. PALS therefore allowed Czech laser science to participate in research questions whose scientific reach extended far beyond conventional optics. The facility also created methodological continuity with the high-energy-density platforms later developed at Extreme Light Infrastructure Beamlines.

The international user model was central to the scientific significance of PALS from the beginning of regular operation. Between 2000 and 2003, European experiments received support through the Fifth Framework Programme for transnational access to major research infrastructures. The facility subsequently became a founding participant in Laserlab-Europe, which coordinated access and cooperation among leading European laser laboratories from 2004 onwards. External researchers could therefore propose experiments in Prague rather than collaborating only through bilateral agreements with Czech groups. This structure brought specialised targets, diagnostics, theoretical approaches, and application questions from other European laboratories into the Czech facility. Czech students and researchers gained

continuous exposure to international experimental teams without having to conduct all work abroad. Open access also encouraged the laboratory to maintain high technical reliability, transparent scheduling, safety procedures, and user support. PALS consequently became an early Czech example of research infrastructure defined by the community it served rather than by the host institutes alone. The later operating models of HiLASE and Extreme Light Infrastructure Beamlines developed within a national environment already familiar with transnational laser access.

The scientific limitations of picosecond kilojoule lasers simultaneously encouraged Czech researchers to move towards shorter pulses and higher intensities. Peak intensity can be raised dramatically when comparable pulse energy is compressed from hundreds of picoseconds into the femtosecond regime. Such pulses interact with matter faster than many thermal and mechanical relaxation processes can respond. Electrons can therefore be driven far from equilibrium before substantial lattice heating occurs. Ultrafast optics made it possible to study carrier dynamics, phase transitions, molecular motion, and structural rearrangements on their intrinsic timescales. Titanium-doped sapphire lasers and chirped-pulse amplification became standard technologies for generating intense femtosecond pulses internationally. Czech groups adopted these approaches in university laboratories and increasingly in dedicated national facilities. Short-pulse systems also became important diagnostic companions to longer-pulse high-energy lasers. By the end of the 2000s, ultrafast technology had become one of the principal directions through which Czech laser physics could advance beyond the parameter space of PALS. This change also widened the range of temporal phenomena that could be investigated directly in Czech laboratories.

The Extreme Light Infrastructure project transformed this ambition into a new scale of national laser capability during the 2010s. The Czech branch, known as Extreme Light Infrastructure Beamlines, was designed as a high-energy and high-repetition-rate facility generating ultra-short pulses and laser-driven secondary radiation or particle beams. Its laser architecture combined several complementary systems rather than relying on a single beamline. L1 ALLEGRA was developed around optical parametric chirped-pulse amplification and thin-disk pumping to generate sub-20-femtosecond pulses at kilohertz repetition rates. L2 DUHA was designed for approximately 100-terawatt operation using optical parametric amplification and high-repetition-rate pumping. L3 HAPLS, whose name means High-Repetition-Rate Advanced Petawatt Laser System, used titanium-doped sapphire amplification and powerful diode-pumped laser technology. L4 ATON was conceived as a kilojoule-class system capable of being compressed into the multi-petawatt regime. Together, these sources covered parameter combinations ranging from high-repetition-rate ultrafast pulses to exceptionally energetic shots. The architecture reflected a broader change in laser science because experiments increasingly required not only high peak power but also stability, repetition rate, synchronisation, and precise temporal control. Extreme Light Infrastructure Beamlines therefore represented a platform for high-field and ultrafast science rather than simply an attempt to maximise one numerical performance record. Its creation marked the point at which Czech laser physics became responsible for developing and operating some of the most advanced light sources in Europe.

Ultrafast optics at the facility depended on more than the ability to compress a single laser pulse. Experiments studying electronic or structural dynamics often require two or more pulses whose relative arrival times are controlled with femtosecond precision. Czech teams therefore developed synchronisation systems linking laser chains, secondary radiation

sources, and diagnostic beams. Optical Parametric Chirped Pulse Amplification (OPCPA) became especially important because it can amplify broad optical spectra while preserving the bandwidth needed for very short pulses. The L1 system was designed to deliver pulses shorter than twenty femtoseconds with high repetition rate, making it suitable for ultrafast spectroscopy and secondary-source generation. Timing technology was developed to coordinate L1, L2, L3, and L4 where experiments required combinations of energetic pump pulses and short diagnostic probes. Pump–probe methods exploit controlled delays so that one pulse initiates a process while another records how the system evolves. Repeating this sequence at different delays can reconstruct dynamics too rapid for ordinary electronic detectors to follow directly. Such methods are relevant to melting, carrier relaxation, phase transitions, molecular reactions, and magnetic dynamics. Ultrafast laser infrastructure consequently allows time itself to become an experimental coordinate alongside energy, momentum, and position. Czech expertise in synchronisation therefore became an essential enabling technology for modern laser science. The resulting timing architecture became as important to demanding experiments as the nominal energy of the individual laser pulses.

The L3 HAPLS system illustrates the technological challenge of combining petawatt peak power with useful repetition rate. It was designed and constructed through cooperation between Lawrence Livermore National Laboratory in the United States and the Czech facility. After delivery to Dolní Břežany in 2017, an integrated American-Czech team installed and commissioned the laser. An early operating point achieved pulses of roughly sixteen joules compressed to approximately twenty-seven femtoseconds at a repetition rate of 3.3 hertz. This corresponded to a peak power of about half a petawatt while allowing shots to be repeated frequently enough for systematic experimental campaigns. The system relies on powerful laser-diode pump units and titanium-doped sapphire amplification. Higher repetition rate is important because many modern experiments require large datasets, parameter scans, or statistical analysis rather than a few isolated shots. HAPLS also serves as a driver for secondary electron, ion, photon, and X-ray sources. Its commissioning therefore represented an important step from conventional high-intensity experimentation towards reproducible petawatt-class user science. The collaboration with Lawrence Livermore also demonstrated that Czech laser infrastructure had become integrated into global technological development rather than relying exclusively on European partnerships.

L4 ATON was developed to explore a complementary regime in which much higher pulse energy is available at lower repetition rate. The system uses optical parametric pre-amplification followed by amplification in neodymium-doped glass and can operate in nanosecond, picosecond, and femtosecond modes. Its design targeted kilojoule-scale energies and eventual operation in the ten-petawatt class. Such pulses can produce electric fields intense enough to drive matter into strongly nonlinear and relativistic interaction regimes. The high energy is especially valuable for high-energy-density plasma experiments, laboratory astrophysics, strong shock generation, and laser-driven particle acceleration. In September 2025, an ELI Beamlines campaign compressed 786 joules into a pulse of approximately 154 femtoseconds. This corresponded to a peak power of about 5.1 petawatts and represented a major milestone in the commissioning of the system. The result demonstrated that the Czech facility could operate securely at multi-petawatt power while retaining very high pulse energy. L4 ATON therefore extended Czech laser science into a parameter regime qualitatively beyond that of PALS. It also provided a direct technological link between kilojoule laser engineering and ultrafast high-field physics. It thereby created experimental opportunities in which pulse

energy, duration, and temporal shape could be selected according to the physics of a particular target.

The scientific purpose of such lasers is ultimately determined by the experiments they drive rather than by peak power alone. At extreme intensity, electrons in a target can move relativistically within the electromagnetic field of the pulse. Their motion creates strong charge separation, currents, magnetic fields, and secondary radiation. Laser wakefield acceleration can use plasma waves to accelerate electrons over distances much shorter than those required in conventional radio-frequency accelerators. Other target geometries can accelerate protons or heavier ions through intense electrostatic fields generated during the interaction. High-order harmonic generation and plasma-based processes can convert optical radiation into shorter-wavelength extreme-ultraviolet or X-ray pulses. Compton scattering can generate high-energy photons when laser light interacts with relativistic electron beams. These secondary sources may have applications in ultrafast imaging, dense-matter diagnostics, nuclear physics, materials science, and potentially medicine. The laser therefore acts as an energy driver whose output is transformed into new probes of matter.

The plasma-physics platform at Extreme Light Infrastructure Beamlines brought several of these directions together within a single experimental environment. The platform was designed for high-energy-density physics, warm dense matter, plasma optics, laboratory astrophysics, and ultra-high-intensity interaction. It can accept several synchronised laser beams with different pulse durations and energy levels. Large vacuum chambers provide space for complex target assemblies, particle diagnostics, X-ray spectrometers, optical probes, and magnetic-field systems. The facility also includes pulse-manipulation and plasma-mirror technologies for improving temporal contrast before a high-intensity pulse reaches its target. High contrast is essential because even a weak prepulse can ionise or expand a target before the main femtosecond interaction occurs. Numerical simulation accompanies experiments because relativistic plasma dynamics cannot usually be reconstructed from a single diagnostic observable. Particle-in-cell calculations, hydrodynamic codes, and radiation-transport models therefore operate alongside experimental measurements. This integrated design reflects the increasing complexity of laser–matter interaction research at multi-petawatt intensities. Czech plasma physicists can now address questions that previously required access to foreign facilities at the extreme end of high-power laser technology. International users simultaneously bring complementary expertise, making the Czech platform part of a broader global network of high-field laboratories. The result is a continuation of the user-facility philosophy pioneered by PALS, but at much higher intensity and with far more diverse experimental capabilities.

HiLASE, whose name expands to High average power pulsed LASErs, developed a deliberately different approach to advanced laser science. Established at the Institute of Physics in 2011 and opened in Dolní Břežany in 2014, the centre concentrated on high pulse energy combined with high average power and repetition rate. This emphasis addressed one of the central engineering challenges of modern laser technology because increasing pulse energy often produces thermal distortions that degrade optical quality at high repetition rates. HiLASE therefore developed diode-pumped solid-state systems with advanced cooling, beam control, and optical architectures. The centre's programme linked fundamental laser development directly with materials processing and industrial applications. Its physical proximity to Extreme Light Infrastructure Beamlines created a complementary cluster rather than a duplication of scientific purpose. Extreme Light Infrastructure Beamlines concentrated strongly on ultra-

intense and high-field science, whereas HiLASE emphasised efficient high-average-power sources and repeatable application-oriented operation. The two centres nevertheless shared expertise in optical materials, pulse control, diagnostics, and laser engineering. Together, they made Dolní Břežany one of the most concentrated locations for advanced laser research in Central Europe.

The BIVOJ system became the most visible demonstration of the HiLASE high-energy strategy. It is a cryogenically cooled diode-pumped solid-state slab laser developed in cooperation with the Science and Technology Facilities Council Central Laser Facility in the United Kingdom. In 2016, the Czech-British team demonstrated pulses of approximately 105 joules with a duration of ten nanoseconds at a repetition rate of ten hertz. This corresponded to an average output power above one kilowatt and established a world-leading result for that class of high-energy pulsed laser. The achievement was scientifically important because traditional high-energy lasers often operate at repetition rates too low for efficient industrial processing or statistically rich experiments. In January 2021, the system surpassed its earlier performance and reached a maximum pulse energy of 146.5 joules at the same ten-hertz repetition rate. The improvement required careful management of optical damage, thermal effects, beam quality, and amplifier performance. BIVOJ can also be used at harmonic wavelengths generated from the fundamental near-infrared output. The system consequently became both an experimental platform and a technology demonstrator for future high-energy lasers operating at useful repetition rates. Its development illustrates the Czech shift from adapting transferred laser systems towards participating directly in the creation of new high-power architectures. The technological knowledge obtained from BIVOJ also supported international work on diode-pumped laser concepts intended for other major facilities.

Ultrashort high-average-power processing was developed at HiLASE through the PERLA family of thin-disk laser systems. PERLA uses ytterbium-doped yttrium aluminium garnet technology to produce picosecond and sub-picosecond pulses with high beam quality and substantial average power. The platform was designed specifically to combine precision processing with throughput high enough to be relevant outside a purely experimental laboratory. Frequency conversion extends operation from the fundamental near-infrared wavelength into visible and ultraviolet regions. Multi-beam optical arrangements can divide a single pulse into many spatially controlled beams that process a surface simultaneously. In 2021, HiLASE researchers reported a PERLA platform delivering up to roughly half a kilowatt of average power for multi-beam micro- and nanomachining studies. Direct laser interference patterning allowed periodic structures to be produced on steel, Invar, tungsten, and other materials. Such microstructures can modify wettability, friction, optical appearance, corrosion behaviour, or biological response without coating the entire surface with a different material. The use of picosecond pulses limits the size of the heat-affected zone compared with many longer-pulse machining methods. PERLA therefore represents the intersection of ultrafast optics, nonlinear frequency conversion, precision beam shaping, and advanced manufacturing.

Laser Shock Peening (LSP) became one of the principal application areas developed at HiLASE. In this method, a powerful laser pulse produces a rapidly expanding plasma at a material surface and generates a shock wave that propagates into the component. The process introduces compressive residual stresses that can counteract tensile stresses responsible for fatigue cracking and stress-corrosion failure. Unlike ordinary thermal surface treatment, the principal mechanism is mechanical shock rather than bulk heating. HiLASE built a dedicated experimental station using robotic positioning so that complex three-dimensional components

could be treated reproducibly. Research investigated steels, aluminium alloys, and other materials used in energy, transport, and aerospace applications. Studies also considered alloys relevant to nuclear engineering where resistance to stress-corrosion cracking is particularly important. The BIVOJ laser's combination of high pulse energy and repeated operation made it well suited to developing more efficient LSP procedures.

Laser micromachining provided a second route from fundamental laser physics into advanced materials technology. Focused ultrashort pulses can remove or restructure material with micrometre-scale precision while minimising collateral thermal damage. Czech researchers developed cutting, drilling, texturing, and direct laser interference methods for metals, composites, ceramics, and functional surfaces. Surface microstructures can be designed to alter friction, wettability, adhesion, optical response, icing behaviour, or resistance to bacterial attachment. High repetition rates make such processing much more attractive for manufacturing than conventional ultrafast systems that deliver only modest average power. Multi-beam approaches further increase throughput by processing many points simultaneously. Precise control of pulse duration, wavelength, fluence, polarisation, and spatial profile is essential because different materials respond through different combinations of melting, ablation, ionisation, and nonlinear absorption. These application experiments therefore feed information back into laser design rather than merely consuming a finished optical tool. In this way, materials processing became a test of beam stability and pulse quality as well as an industrial application. The Czech programme demonstrates how advanced photonics can connect laboratory-scale optical physics with scalable manufacturing concepts.

Laser-induced damage research formed a third application field with direct relevance to the laser systems themselves. Every high-power laser ultimately depends on mirrors, windows, coatings, crystals, and other optical components that must survive intense electromagnetic fields. A microscopic defect, contamination particle, or local absorption centre can initiate irreversible damage even when the average energy density appears acceptable. The Laser-Induced Damage Threshold (LIDT) quantifies the conditions under which such failure begins. HiLASE developed dedicated testing capabilities for optical components under pulse regimes relevant to high-energy and high-average-power lasers. Measurements help manufacturers improve polishing, coating, cleaning, material selection, and quality-control procedures. The research also provides data needed to design safer operating margins for facilities such as HiLASE and Extreme Light Infrastructure Beamlines. Optical damage therefore represents an important meeting point between fundamental light–matter interaction and practical laser engineering. Improvements in component durability can raise the usable energy and average power of future systems without changing the basic gain medium. The field also connects Czech laser laboratories with domestic optical companies capable of producing crystals, coatings, and precision components. This interaction between research infrastructure and specialised industry has become one of the technological consequences of the Czech laser programme. By 2025, LIDT expertise had become part of a broader ecosystem concerned with reliable operation of increasingly powerful optical systems.

Photonics in Czechia extends far beyond the large laser centres in Dolní Břežany and Prague. The Institute of Photonics and Electronics of the Czech Academy of Sciences maintains research programmes in fibre lasers, nonlinear optics, specialty optical fibres, nano-optics, optical biosensing, optoelectronics, and coherent sources in the mid-infrared spectral region. Fibre lasers are especially attractive because the waveguide geometry confines light over long

distances and provides efficient heat removal from a relatively small active medium. Rare-earth ions incorporated into glass fibres can provide optical gain at wavelengths suited to manufacturing, spectroscopy, sensing, and medical applications. Czech researchers developed techniques for preparing fibre preforms, introducing dopants through nanoparticle suspensions, drawing specialty fibres, and constructing high-power amplifiers. Nonlinear optical processes within fibres can also shift wavelength or generate new spectral components. The institute's work therefore combines materials chemistry, glass technology, waveguide physics, laser engineering, and nonlinear optics. Such research complements the bulk solid-state lasers developed at HiLASE because fibre geometry offers different advantages in efficiency, compactness, and beam delivery. The coexistence of both approaches broadens the technological basis of Czech laser science.

Specialty fibres also provide a route to spectral regions where conventional silica technology becomes less effective. Czech research has addressed thulium- and holmium-doped fibres for operation near two micrometres and has explored fluoride components for still longer mid-infrared wavelengths. Mid-infrared light is important because many molecules possess strong vibrational absorption features in this region, enabling sensitive spectroscopy and sensing. Appropriate fibre lasers may also be useful for medical procedures because water and biological tissues exhibit wavelength-dependent absorption. Nonlinear frequency conversion offers another route to wavelengths that are difficult to obtain directly from standard gain materials. The Institute of Photonics and Electronics developed fibre components such as tapers, splitters, amplifiers, and specialised splices needed for all-fibre systems. Research on optical biosensors uses photonic structures to detect very small changes in refractive index caused by molecular binding near a surface. Nano-optical methods extend detection towards individual particles or biomolecular interactions. These programmes show that photonics after 1993 developed not only towards ever higher power but also towards sensitivity, integration, spectral flexibility, and precise manipulation of light. The field consequently connects Czech fundamental optics with telecommunications, medicine, environmental monitoring, and biotechnology.

Olomouc developed another nationally important optical centre around the Department of Optics of Palacký University and the Joint Laboratory of Optics shared with the Institute of Physics. The Department of Optics has maintained a research tradition extending across quantum optics, optical information processing, digital holography, spectroscopy, special optical beams, optical metrology, and laser physics. Czech researchers in Olomouc became particularly visible in the theoretical and experimental study of non-classical light and quantum information. Lasers provide the coherent pump fields required for many of these experiments, while nonlinear optical crystals generate correlated or entangled photons through parametric processes. Photon-counting detectors and interferometers then allow the statistical and quantum properties of light to be reconstructed. The Joint Laboratory added expertise in wave optics, optical measurement, optoelectronic instrumentation, and the construction of specialised optical systems. These activities represent a different scale of laser science from PALS or Extreme Light Infrastructure Beamlines, but they address equally fundamental questions about coherence, interference, measurement, and information. They also support technological applications in imaging, communications, and precise optical characterisation. The strength of the Olomouc programme demonstrates that Czech photonics developed through several specialised regional centres rather than through high-power laser facilities alone.

Precision optical instrumentation has also remained important at the Institute of Scientific Instruments of the Czech Academy of Sciences in Brno. Its research combines laser interferometry, length metrology, fibre-optic instrumentation, optical sensing, precision mechanics, and the development of specialised measurement systems. Interferometry uses the phase relationship between coherent light beams to detect displacements or optical-path changes with extremely high sensitivity. Such techniques are fundamental to dimensional metrology, the calibration of precision instruments, and experiments requiring traceability to national standards. Brno researchers have developed new interferometric arrangements, signal-processing methods, and instruments for demanding measurement conditions. Fibre-optic research includes the design, splicing, shaping, and characterisation of conventional and specialty fibres. Optical fibre sensors can respond to temperature, strain, radiation, or other environmental variables while allowing signals to be transmitted over long distances. These systems are valuable in industrial settings where electrical sensors may be vulnerable to electromagnetic interference or difficult to deploy. The work therefore links fundamental wave optics with measurement science and engineering. It also connects Czech optical research with national metrology and precision manufacturing. Through such programmes, photonics contributes to scientific infrastructure even when the laser is used as a measurement standard rather than as a source of extreme intensity. This metrological tradition complements the more spectacular high-power branch of Czech laser physics.

The increasing interaction between research institutions and industrial users became one of the defining features of Czech photonics during the 2010s and 2020s. HiLASE developed commercial and collaborative programmes in laser shock peening, microprocessing, optical-damage testing, beam delivery, and customised laser systems. The Institute of Photonics and Electronics worked with companies on fibre components, lasers, sensors, and optical technologies. Precision-optics companies supplied crystals, coatings, mechanical assemblies, and specialised components for research facilities in Czechia and abroad. Large projects created demanding procurement standards that encouraged domestic suppliers to improve production tolerances and quality assurance. At the same time, research laboratories gained practical feedback on reliability, manufacturability, and maintenance requirements outside academic environments. Laser processing offered particularly direct routes for transferring scientific knowledge into aerospace, automotive, energy, semiconductor, and medical technologies. Photonic sensing and fibre technologies created additional links with telecommunications, biotechnology, and environmental monitoring. The result was not a simple conversion of academic research into products but a two-way innovation process in which industrial problems also shaped new research questions.

Between 1993 and 2025, Czech optics, photonics, and laser physics therefore developed through a sequence of increasingly ambitious but scientifically connected stages. PERUN preserved the expertise of the late Czechoslovak laser school during the first years of the independent republic. The transfer and reconstruction of ASTERIX IV created PALS, which established Czechia as an operator of an international high-power laser user facility and strengthened research on plasma, X-rays, ions, shock waves, and high-energy-density matter. Participation in Laserlab-Europe embedded this facility within a wider continental community and normalised transnational access. The development of ultrafast optics then shifted attention towards femtosecond dynamics, high peak intensity, precise synchronisation, and new forms of secondary radiation. HiLASE demonstrated that Czech laser science could contribute original high-average-power architectures and translate them into materials

processing, component testing, and industrial technologies. Extreme Light Infrastructure Beamlines extended the national capability into the petawatt and multi-petawatt regimes and provided platforms for relativistic laser–matter interaction, particle acceleration, and ultrafast science. The Institute of Photonics and Electronics broadened the field through fibre lasers, nonlinear optics, specialty fibres, and optical sensing. Olomouc and Brno maintained strong programmes in quantum and wave optics, imaging, metrology, interferometry, and photonic instrumentation. Across these centres, the common scientific principle was increasingly precise control of light in energy, time, wavelength, phase, polarisation, and space. The achievement of Czech laser science lies therefore not only in record powers or large facilities, but in the creation of a connected optical research ecosystem capable of linking fundamental physics with plasma science, materials research, precision measurement, information technologies, and advanced manufacturing.

Extreme Light Infrastructure and High-Power Laser Technologies

Extreme Light Infrastructure Beamlines and HiLASE represent the most visible transformation of Czech laser science from a nationally organised research field into a host of internationally significant high-power laser infrastructure. Both centres are located in Dolní Břežany, immediately south of Prague, and both were developed by the Institute of Physics of the Czech Academy of Sciences. Their scientific missions are complementary rather than duplicative. Extreme Light Infrastructure Beamlines concentrates on ultra-intense and ultrashort laser pulses, secondary photon and particle sources, and user experiments under extreme physical conditions. HiLASE, whose name derives from High average power pulsed LASERs, focuses particularly on high-energy diode-pumped solid-state lasers with high repetition rates and on applications requiring reliable average power. Together they created a concentration of laser engineering, plasma physics, materials research, optics, computation, precision mechanics, and advanced manufacturing that had no Czech equivalent before the 2010s. The cluster also altered the international direction of scientific mobility because foreign researchers increasingly travelled to Czechia to use facilities located there. This development was especially significant for a country whose physicists had historically depended on access to large experimental installations abroad. By 2025, Dolní Břežany had therefore become both a Czech research centre and a node of the European scientific infrastructure system.

The origins of Extreme Light Infrastructure, usually abbreviated as ELI, lie in the European effort to construct research facilities capable of exploring light–matter interaction at unprecedented intensity and on extremely short timescales. The project entered the European Strategy Forum on Research Infrastructures roadmap and was subsequently organised as a distributed infrastructure rather than as a single laboratory. After an international preparatory process, the Czech Republic, Hungary, and Romania received mandates to implement complementary pillars of the project. The Czech pillar was assigned the Beamlines mission, centred on high-energy, high-repetition-rate lasers and the generation of secondary photon and particle beams. The Institute of Physics of the Czech Academy of Sciences became the Czech implementing institution. In April 2011, the European Commission approved financing for the ELI Beamlines project. In August of the same year, the project budget of approximately €278 million was formally signed by the Czech Minister of Education, Youth and Sports. The scale of the investment was exceptional within the history of Czech physical science and depended heavily

on European structural funding. The project therefore combined a European infrastructure strategy with a national decision to develop a scientific capability far beyond the scale of an ordinary institutional laboratory. Its approval marked the transition of Czech laser physics from participation in international facilities towards responsibility for constructing one of them.

Construction of the Dolní Břežany complex converted this strategic decision into a demanding engineering project. Excavation began in 2012, major building construction followed in 2013, and the first construction phase was completed in June 2015. The centre was ceremonially opened on 19 October 2015, while installation and commissioning of lasers and experimental systems continued during the following years. The building had to combine vibration control, radiation shielding, large experimental halls, clean technical environments, high-capacity cooling, vacuum systems, electrical infrastructure, and precise optical alignment. Such requirements meant that the scientific architecture of the centre was inseparable from civil engineering and specialised technical design. The first phase of trial operation began in 2018, when selected experimental capabilities became available for commissioning and external scientific use. From that point, the central institutional challenge shifted progressively from constructing infrastructure to delivering reproducible experiments. This transition from project implementation to stable user operation became the decisive test of whether the investment could function as a genuine international research facility.

The laser architecture of ELI Beamlines was designed around several systems occupying different regions of pulse energy, duration, repetition rate, and peak power. This diversity was deliberate because no single laser configuration can optimise kilohertz repetition, petawatt peak power, kilojoule energy, and user stability simultaneously. The L1 ALLEGRA system was developed for high-repetition-rate ultrashort pulses and relies on optical parametric chirped-pulse amplification. The L2 DUHA system was designed to provide approximately one hundred terawatts at substantially higher repetition rates than traditional large high-energy lasers. The L3 HAPLS system, whose name means High-Repetition-Rate Advanced Petawatt Laser System, uses titanium-doped sapphire amplification to combine petawatt-class pulses with repeated operation. The L4 ATON system was conceived as a kilojoule-class laser capable of compression into the multi-petawatt regime. Three of the principal laser chains rely heavily on diode-pumped solid-state technologies to control thermal loading and improve repetition rate. The facility therefore does not treat peak power as its only performance criterion. Pulse contrast, beam quality, synchronisation, stability, repetition rate, and integration with experimental stations are equally important for reproducible user science. This architecture makes it possible to match the laser driver to the physical question rather than forcing every experiment into a single operating regime. It also explains why ELI Beamlines is better understood as a platform of coordinated laser and experimental systems than as one record-setting laser.

L1 ALLEGRA represents the high-repetition-rate and ultrafast end of this architecture. It was developed substantially in-house by the ELI Beamlines team and uses ytterbium-doped yttrium aluminium garnet thin-disk technology as part of its pumping concept. Optical parametric chirped-pulse amplification provides the broad spectral bandwidth needed for very short pulses while avoiding several limitations of conventional gain media. The system was designed to operate around the kilohertz scale and to deliver multi-terawatt ultrashort pulses with high temporal contrast. These characteristics are especially valuable for experiments that require repeated measurements rather than isolated extreme-energy shots. High repetition enables statistical studies, parameter scans, coincidence measurements, and time-resolved

spectroscopy with substantially improved data accumulation. ALLEGRA also drives short-wavelength secondary sources used in atomic, molecular, materials, and biomolecular research. Its scientific importance therefore lies in combining ultrafast temporal resolution with the repetition rate required for modern user experiments. In the wider Czech laser portfolio, ALLEGRA complements the much higher pulse energies delivered by the petawatt and kilojoule systems.

L2 DUHA, whose name derives from Dual-beam Ultra-fast High-energy Optical Parametric Chirped-Pulse Amplifier, was designed to occupy an intermediate regime between kilohertz ultrafast operation and the highest-energy petawatt systems. Its target parameters are approximately two joules per pulse, a peak power of about one hundred terawatts, and a repetition rate reaching fifty hertz. Like ALLEGRA, its short-pulse amplification is based on optical parametric chirped-pulse amplification. The pumping concept employs ytterbium-doped yttrium aluminium garnet with gas cooling designed to limit thermal distortion at substantial average power. This combination is attractive for laser–plasma experiments in which many repeatable shots are needed to optimise acceleration or secondary-source performance. DUHA is linked to the TERESA target area, whose name expands to TEstbed for high REpetition-rate Sources of Accelerated particles. That environment is intended for the development and testing of particle sources under conditions where shot rate becomes an experimental variable in its own right. High repetition also permits feedback systems and automated optimisation to be used more effectively than in low-frequency laser experiments. The system therefore contributes to a broader technological transition from spectacular single-shot demonstrations towards stable laser-driven sources. This transition is important if laser acceleration is eventually to support applications requiring reproducible beams rather than occasional proof-of-principle events. DUHA also provides a useful technological bridge between ultrafast optics and the engineering of high-average-power laser systems. Its role within ELI Beamlines illustrates the facility's emphasis on combining intensity with operational practicality.

The L3 HAPLS system is one of the most internationally distinctive elements of the Czech facility. It was developed through cooperation with Lawrence Livermore National Laboratory in the United States and was transferred to Dolní Břežany for installation and commissioning. The system combines a powerful diode-pumped pump laser with titanium-doped sapphire amplification of an ultrashort pulse. Its design objective is petawatt-class peak power at repetition rates approaching ten hertz, a combination that had been exceptionally difficult for earlier high-energy laser technology. An early commissioned operating point produced pulses of roughly sixteen joules compressed to about twenty-seven femtoseconds at several shots per second. Such performance allows relativistic laser–plasma interaction to be repeated often enough for systematic experimental programmes rather than rare isolated shots. HAPLS can drive laser-wakefield electron acceleration, high-energy photon generation, hard X-ray sources, and other secondary beams. The collaboration also transferred important expertise in diode pumping, thermal control, pulse compression, diagnostics, and high-field laser safety into the Czech research environment. Because the system was designed for user operation, reliability and repeatability are as scientifically important as its nominal peak power. HAPLS consequently represents both an advanced laser instrument and an example of Czech participation in transatlantic high-power laser technology development.

L4 ATON extends ELI Beamlines into a different extreme by combining very high pulse energy with femtosecond compression. The system uses optical parametric pre-amplification

followed by amplification in neodymium-doped glass to reach the kilojoule energy class. Its design allows operation in nanosecond, picosecond, and compressed femtosecond modes according to the requirements of a particular experiment. The long-term objective is peak power in the ten-petawatt class, placing ATON among the most powerful laser systems conceived for user science. In a September 2025 test campaign, the system delivered 786 joules compressed to approximately 154 femtoseconds. This corresponded to a peak power of about 5.1 petawatts and demonstrated reliable operation at a major intermediate commissioning milestone. The achieved pulse energy was reported as the highest then demonstrated worldwide at the multi-petawatt power level. ATON therefore gave the Czech facility access to experimental regimes that are qualitatively beyond those of its earlier national laser infrastructure.

Petawatt-class power has scientific meaning because it allows electromagnetic fields to drive electrons into relativistic motion within a single laser cycle. Under such conditions, the optical field can ionise matter almost instantaneously and generate extreme charge separation, currents, magnetic fields, and plasma waves. These processes differ fundamentally from ordinary optical heating and require relativistic plasma physics for their description. Laser wakefield acceleration can use collective plasma waves to accelerate electrons over distances far shorter than those required by conventional radio-frequency accelerators. Solid targets can generate energetic proton and heavier-ion beams through several mechanisms whose efficiency depends sensitively on pulse contrast, target thickness, and intensity. Intense electron beams can in turn generate X-rays or gamma rays through betatron motion, Compton scattering, bremsstrahlung, or other interactions. Extreme fields also create opportunities to investigate non-linear electrodynamics and radiation-reaction effects as experimental intensity increases. The scientific importance of a petawatt facility therefore lies not simply in concentrating enormous power into a short pulse but in creating new sources and new physical regimes. ELI Beamlines was designed so that these regimes could be coupled to dedicated diagnostics and user stations rather than explored only as laser-performance tests. This integration is essential if high-field physics is to produce reproducible quantitative science. It also allows one laser shot to become the starting point for several layers of physical transformation from photons to plasma, accelerated particles, and secondary radiation.

The experimental organisation of ELI Beamlines reflects this transformation from a laser source into a multi-purpose research infrastructure. The facility contains several experimental halls supplied by different combinations of the L1 to L4 laser systems. E1 is devoted principally to materials, molecular, atomic, and biomolecular applications using primary laser pulses and short-wavelength secondary radiation. E2 is designed for hard X-ray science using laser-accelerated electrons and related photon-generation mechanisms. E3 houses the Plasma Physics Platform for high-energy-density physics, warm dense matter, laboratory astrophysics, and extreme laser–plasma interaction. E4 is dedicated to ion acceleration and applications of laser-driven ion beams. E5 is associated with electron acceleration and advanced X-ray generation. Additional test areas support the development of high-repetition-rate laser–plasma sources and the commissioning of new technologies. This division of experimental space allows different scientific communities to use the same laser infrastructure without requiring identical target systems or diagnostics.

The E1 experimental hall demonstrates particularly clearly how a high-power laser infrastructure can serve materials and life sciences as well as fundamental plasma physics. It contains laser-driven short-wavelength sources and end stations for atomic, molecular,

optical, materials, and biomolecular experiments. High Harmonic Generation produces coherent extreme-ultraviolet photons with energies extending through a broad short-wavelength range. A plasma X-ray source provides complementary hard X-ray radiation for structural and spectroscopic measurements. Synchronisation between the primary laser pulses and secondary photon sources allows pump–probe experiments in which one pulse initiates a process and another records its subsequent evolution. Such experiments can follow electronic, molecular, magnetic, and structural dynamics on femtosecond or picosecond timescales. Time-resolved diffraction and spectroscopy can therefore reveal transient states that disappear long before conventional measurements can record them. Coherent diffractive imaging offers routes to reconstructing microscopic structures without relying exclusively on ordinary optical lenses. The scientific programme connects laser physics directly with condensed matter, chemistry, molecular science, and biomedical research. E1 therefore illustrates why ELI Beamlines is a multidisciplinary infrastructure rather than solely a laboratory for the physics of extreme intensity.

Hard X-ray generation forms another major part of the Beamlines concept. In the E2 experimental hall, a petawatt-class laser can be focused into gas targets to accelerate electrons through plasma wakefields. The accelerated electrons then generate femtosecond X-rays through betatron motion inside the plasma or through scattering processes involving an additional laser pulse. Depending on the configuration, the resulting radiation can extend from kiloelectronvolt X-rays towards gamma-ray energies. Because the emitting source can be microscopic and the pulse extremely short, the radiation is attractive for time-resolved imaging and spectroscopy. The facility has also developed the Gammatron beamline as a platform for high-energy photon production and related experiments. Secondary photon sources can probe dense matter, rapid structural change, or objects whose internal structure is difficult to study with visible light. They can also be synchronised with the driving optical laser in ways that are difficult to achieve with conventional large accelerator sources. This capability brings together plasma acceleration, relativistic electron dynamics, radiation physics, and X-ray instrumentation. Reliable operation requires control of electron-beam energy, pointing, divergence, photon spectrum, and shot-to-shot stability. Much of the scientific challenge therefore lies in converting a highly non-linear plasma interaction into a source sufficiently characterised for external users. The progress of E2 reflects the broader effort to turn laser-driven radiation from an experimental phenomenon into a research tool.

The Plasma Physics Platform in E3 is the part of ELI Beamlines most directly connected with high-energy-density physics. It was designed for experiments involving hot dense plasma, warm dense matter, shock waves, plasma optics, laboratory astrophysics, and matter exposed to very intense electromagnetic fields. The hall can accommodate large target chambers, complex diagnostics, pulsed magnetic systems, and several laser beams with different pulse durations. This flexibility makes it possible to separate the roles of driver, heater, backlighter, and diagnostic pulse within one experiment. High-energy nanosecond pulses can compress or shock a target, while ultrashort pulses can generate secondary probes or create relativistic interactions. Plasma mirrors and other contrast-enhancement techniques help prevent weak precursor light from destroying a target before the main pulse arrives. Experiments are closely coupled to hydrodynamic, radiation-transport, and particle-in-cell simulations because the states created are transient and spatially complex. E3 therefore provides a direct bridge between the earlier Czech laser-plasma tradition at PALS and the much more extreme parameter space of ELI Beamlines.

Ion acceleration in the E4 hall adds another class of user-accessible secondary source. The principal platform is the ELI Multidisciplinary Applications of laser-Ion Acceleration, usually abbreviated as ELIMAIA. An ultra-intense laser interacting with a thin solid target can create strong electric fields capable of accelerating protons and heavier ions over micrometre-scale distances. The resulting beam differs from a conventional accelerator beam in energy spread, divergence, pulse duration, and temporal structure. ELIMAIA therefore includes beam transport, selection, dosimetry, and diagnostic systems intended to convert the raw laser-driven source into a controlled experimental beam. The platform supports studies of acceleration mechanisms as well as irradiation experiments on materials and biological samples. Potential long-term applications include compact injectors, radiobiology, high-dose-rate irradiation, detector testing, and concepts related to particle therapy. These applications remain dependent on improvements in reproducibility, spectral control, repetition rate, and beam transport. The existence of a dedicated user area allows those engineering questions to be investigated systematically rather than treated as secondary issues.

Electron acceleration and associated X-ray generation constitute a parallel pathway in the E5 programme. Laser wakefield acceleration uses the electric fields of a plasma wave to accelerate electrons over centimetre or even millimetre-scale distances. These gradients can exceed those used in conventional accelerators by orders of magnitude, although beam quality and reproducibility remain central challenges. ELI Beamlines developed dedicated systems for coupling petawatt-class pulses to gas targets in which the required plasma waves can form. Accelerated electrons can be used directly in experiments or sent through magnetic structures and scattering geometries to generate bright X-ray pulses. Such radiation can be synchronised naturally with the driving laser because both originate from the same optical system. This makes laser-driven accelerators attractive for ultrafast pump–probe experiments in which timing precision is critical. Research also addresses electron injection, beam energy spread, emittance, stability, and shot-to-shot control. These are not merely technical details because the usefulness of a secondary beam depends on whether its parameters can be measured and repeated. The E5 programme therefore links fundamental relativistic plasma physics with the longer-term goal of compact accelerator-based light sources. Its development expands the role of Czech high-power laser science into a domain historically dominated by large radio-frequency accelerators.

The importance of secondary sources is one of the defining differences between ELI Beamlines and a conventional high-power laser laboratory. The primary optical pulse is often only the first stage in a chain that produces extreme-ultraviolet photons, X-rays, gamma rays, electrons, protons, heavier ions, or neutrons. Each secondary source has a different combination of pulse duration, brightness, spectrum, coherence, divergence, and penetration depth. Researchers can therefore choose a probe matched to the physical process they want to observe. Short-wavelength photons are valuable for structural and electronic measurements because they resolve much smaller spatial scales than visible light. Relativistic electrons provide compact sources of penetrating radiation and can test accelerator concepts. Ions deposit energy differently from electrons or photons and are useful for materials irradiation and radiobiological studies. Laser-driven neutrons can probe nuclei and dense objects while opening possibilities for nuclear science and radiation testing. Combining several sources within a synchronised optical infrastructure creates experimental possibilities that would be difficult to reproduce by assembling independent machines. Secondary-source development therefore converts the extreme laser field into a versatile scientific toolbox.

The international user programme is the mechanism through which these capabilities become a European research infrastructure rather than a closed Czech laboratory. ELI Beamlines issued its first external commissioning call in 2019 for experiments in the E1 hall. Research teams from the United States and numerous European countries responded, demonstrating international demand before full infrastructure operation had been achieved. After the establishment of Extreme Light Infrastructure European Research Infrastructure Consortium, user access was progressively organised through joint calls covering the participating ELI facilities. Proposals are assessed for technical feasibility and scientific merit through international review procedures. For eligible scientific access, researchers can receive beam time without paying the full operating cost of the infrastructure. This model allows groups without their own petawatt lasers to pursue experiments at the frontier of high-field physics. It also places strong requirements on the facility because external users need predictable scheduling, calibrated diagnostics, safety support, data services, and specialist staff. By spring 2025, the joint ELI programme had completed six user calls. More than 1,400 researchers from 38 countries had participated in 563 proposals, of which 369 were allocated beam time. More than 200 experiments had already been implemented across the ELI facilities. These figures show that international use had become a routine operational function rather than a future aspiration.

A decisive institutional change occurred on 30 April 2021 when the European Commission established the Extreme Light Infrastructure European Research Infrastructure Consortium, abbreviated as ELI ERIC. The European Research Infrastructure Consortium legal form allows states and international organisations to govern a research infrastructure jointly under a dedicated European framework. Czechia, Hungary, Italy, and Lithuania became the founding members, while Germany and Bulgaria initially participated as observers. The members agreed that the Czech Republic would serve as the host Member State. The statutory seat was placed at ELI Beamlines in Dolní Břežany. This was the first European Research Infrastructure Consortium whose statutory headquarters were hosted in Czechia. The decision transformed ELI from a set of nationally implemented projects into an international organisation responsible for common access, governance, management, and strategy. It also created a more sustainable institutional basis for operation after the construction phase financed largely through structural investment. For Czech physics, the change was as important organisationally as the achievement of a new laser-power record.

By 2025, the membership structure of ELI ERIC had broadened beyond the original four founding states. Bulgaria became a full member from the beginning of that year, while Germany retained observer status. Romania, where the ELI Nuclear Physics facility operates at Măgurele, had joined as a founding observer from 2024. The Czech and Hungarian facilities were progressively integrated under common ELI governance and a joint user programme. This institutional model means that ELI Beamlines is physically located in Czechia but is not scientifically defined as a Czech-only facility. Its strategy is shaped through participating states, international advisory structures, users, and the broader European laser community. At the same time, the host country retains substantial responsibility for the local scientific, technical, and organisational environment that makes operation possible. Hosting therefore combines national investment with international governance rather than substituting one for the other.

HiLASE developed from a different technological premise and consequently occupies a complementary position in Dolní Břežany. The centre was established in 2011 within the

Institute of Physics of the Czech Academy of Sciences, and construction began in 2012. Its new facility was inaugurated in September 2014 and reached full research operation during the following years. The original Czech investment was approximately €32 million and was subsequently reinforced by European projects aimed at creating a sustainable centre of excellence. HiLASE partnered closely with the Central Laser Facility of the Science and Technology Facilities Council in the United Kingdom. The central research objective was to develop diode-pumped solid-state lasers combining high pulse energy, high repetition rate, high average power, efficiency, and operational reliability. This parameter combination is especially important for applications because industrial users generally require many repeatable pulses rather than a small number of exceptional shots. HiLASE therefore placed technological scalability and application readiness at the centre of its scientific strategy. Its mission connected laser development with materials processing, optical-component testing, manufacturing, and industrial collaboration. The centre became an important counterpoint to ELI Beamlines, whose primary mission remained fundamental research with ultra-intense fields and secondary sources.

The BIVOJ laser became the best-known demonstration of the HiLASE high-energy approach. It is a cryogenically cooled diode-pumped solid-state laser based on ytterbium-doped yttrium aluminium garnet ceramic and a multi-slab amplifier architecture. The system was developed with the Central Laser Facility in the United Kingdom and transferred to Dolní Břežany after construction and testing. In 2016, a joint Czech-British team amplified ten-nanosecond pulses to 105 joules at a repetition rate of ten hertz. This represented the first kilowatt-average-power source in that class of high-energy nanosecond diode-pumped solid-state lasers. The result demonstrated that pulse energy above one hundred joules could be combined with repeated operation rather than achieved only in low-frequency shots. In 2021, BIVOJ exceeded its earlier record by operating above 145 joules and reaching a maximum measured pulse energy of 146.5 joules at ten hertz. Such performance creates demanding requirements for cryogenic cooling, optical quality, amplifier efficiency, beam stability, and protection against damage. These engineering challenges are scientifically important because they determine whether high-energy laser technology can move towards continuous experimental and industrial use. BIVOJ therefore became both a research instrument and a demonstrator of a new high-average-power laser architecture. Its development strengthened Czech competence in a field relevant to future scientific facilities and advanced manufacturing.

HiLASE also developed the PERLA family of thin-disk lasers for picosecond and sub-picosecond applications. These systems prioritise high average power, excellent beam quality, short pulses, and operation suitable for precision materials processing. Frequency conversion allows selected systems to operate at several wavelengths rather than only at their fundamental near-infrared output. Beam-splitting technologies can divide the laser into many individually useful beams so that large areas are processed simultaneously. In 2021, HiLASE and an industrial partner demonstrated simultaneous surface structuring with 40,401 beams. The centre also reported a record processing rate for producing laser-induced periodic surface structures on stainless steel. Such achievements address a central industrial limitation of ultrafast laser machining, namely that excellent precision is of little practical value if throughput remains too low. PERLA therefore represents an application-driven counterpart to the high-energy BIVOJ system. Together, the two platforms allow HiLASE to study how laser parameters can be optimised for very different technological tasks.

Laser Shock Peening is one of the clearest examples of this translation from high-power laser physics to engineering. The method uses an intense nanosecond pulse to create a rapidly expanding surface plasma and a shock wave that introduces deep compressive residual stresses into a component. Those stresses can improve resistance to fatigue and stress-corrosion cracking, extending the lifetime of metallic parts exposed to cyclic or aggressive environments. HiLASE operates a dedicated Laser Shock Peening station using BIVOJ together with robotic positioning for complex geometries. Research has addressed steels and alloys relevant to aerospace, energy, transport, and nuclear engineering. A second major application is Laser Induced Damage Threshold testing, which determines the optical fluence at which mirrors, coatings, crystals, or other components begin to fail. Such measurements are indispensable for designing reliable high-power laser systems because microscopic defects can trigger catastrophic damage well below ideal material limits. HiLASE also develops laser micromachining for cutting, drilling, texturing, and creating functional micro- and nanostructures. These applications allow surface wettability, friction, optical response, adhesion, corrosion behaviour, or biological interaction to be modified without changing the entire bulk material. The centre has therefore created an unusually direct link between advanced laser architecture and controlled modification of engineering materials. Application research also provides feedback to laser developers because industrial processing exposes weaknesses in stability, lifetime, beam delivery, and automation. The technological programme consequently operates as a two-way interaction between fundamental laser engineering and manufacturing requirements.

The coexistence of ELI Beamlines and HiLASE created the core of a wider research and innovation cluster around Dolní Břežany. The area is promoted through the STAR, or Science and Technology Advanced Region, cluster, which connects research centres, high-technology companies, innovation organisations, and local development initiatives. HiLASE is an active member of this cluster, while ELI Beamlines provides an international research anchor of exceptional scale. The neighbouring Biotechnology and Biomedicine Centre of the Academy of Sciences and Charles University, known as BIOCEV, adds life-science capability to the regional research landscape. Brain4Industry, established as a consortium in 2021 and later provided with a dedicated innovation centre in Dolní Břežany, strengthened the bridge between research and manufacturing. Its programmes include additive manufacturing, digitalisation, artificial intelligence, materials, and advanced production technologies. Laser processing can therefore interact locally with three-dimensional printing, computational design, surface engineering, and industrial prototyping. The concentration of institutions also creates a labour market for optical engineers, physicists, software specialists, technicians, and advanced manufacturing experts. Dolní Břežany consequently developed from a suburban municipality into a scientifically specialised location with international visibility. This cluster effect is an important part of the ELI and HiLASE achievement because large infrastructure generates broader value when surrounding institutions can absorb and extend its technological capabilities.

International partnership has been essential to both centres and reveals two different models of scientific cooperation. ELI Beamlines has worked with laboratories such as Lawrence Livermore National Laboratory and with numerous European institutes on lasers, diagnostics, experimental systems, and user research. HiLASE developed BIVOJ with the British Central Laser Facility and used European Teaming support to strengthen long-term institutional excellence. Both centres cooperate with companies supplying optical components, crystals,

vacuum technologies, precision mechanics, control systems, and specialised diagnostics. These relationships expose Czech suppliers to unusually demanding tolerances and reliability requirements. They also allow research centres to access industrial manufacturing expertise that would be inefficient to reproduce internally. Technology transfer takes several forms, including collaborative research, testing services, contract development, training, licensing, and spin-off activity. HiLASE created the Hi-Beams spin-off in 2021 with an industrial partner to commercialise selected surface-treatment technologies. ELI ERIC similarly includes innovation and technology development within its institutional mission. The laser cluster therefore demonstrates how a research infrastructure can function simultaneously as a scientific facility, a technological development environment, and a meeting point between international research and regional industry. Such effects are particularly important for Czechia because they convert public investment in physics into specialised engineering competence that can persist outside individual research projects.

By 2025, the Czech high-power laser programme had therefore reached a level that would have been difficult to anticipate when the country entered the post-Czechoslovak period in 1993. ELI Beamlines had progressed from a European infrastructure proposal through construction and commissioning into an international user facility operating within ELI ERIC. Its lasers covered regimes from high-repetition ultrafast operation to petawatt and multi-petawatt peak power, while its experimental halls converted those pulses into X-rays, gamma rays, electrons, ions, neutrons, and extreme plasma states. The 5.1-petawatt ATON result in 2025 demonstrated the continuing expansion of the upper intensity and energy limits of the Czech facility. HiLASE had meanwhile established world-leading high-average-power systems and translated them into laser shock peening, microprocessing, optical testing, and other technological applications. The two centres together transformed Dolní Břežany into a research cluster that links fundamental physics, laser engineering, materials science, computation, advanced manufacturing, and international user access. The establishment of ELI ERIC in 2021 gave this development an institutional significance extending beyond individual scientific records because Czechia became the host state of a European research organisation. The mature user programme showed that the value of the infrastructure was increasingly measured by the science performed by international teams rather than only by construction milestones. This combination of host-country responsibility, technological capability, and open international use made high-power laser infrastructure one of the clearest achievements of Czech physics between 1993 and 2025.

Plasma Physics and Controlled Thermonuclear Fusion

The development of plasma physics and controlled thermonuclear fusion became one of the most technically ambitious branches of Czech physics between 1993 and 2025. Its institutional centre was the Institute of Plasma Physics of the Czech Academy of Sciences (IPP CAS), which combined theory, experiment, diagnostics, materials engineering, and large-scale device development. Czech fusion research did not begin after independence, because the country inherited long experience with magnetic confinement, electric discharges, plasma diagnostics, and the CASTOR tokamak. The post-1993 period nevertheless changed the scale and international context of this work. Research moved progressively from a small educational and diagnostic tokamak towards the internationally relevant COMPASS device and then

towards construction of the high-field COMPASS Upgrade machine. Czech teams became integrated first into the European Atomic Energy Community fusion programme and later into the European Consortium for the Development of Fusion Energy (EUROfusion). Their scientific priorities increasingly aligned with the problems that must be solved for the International Thermonuclear Experimental Reactor (ITER) and for a future demonstration fusion power plant, commonly referred to as DEMO. These problems included plasma confinement, edge turbulence, heat exhaust, disruptions, runaway electrons, plasma-facing materials, and the engineering of components exposed to extreme thermal loads. At the same time, IPP CAS retained programmes in thermal plasma, plasma chemistry, coatings, and materials processing that supplied expertise directly relevant to fusion technology. By 2025, Czech plasma physics had therefore developed into a research system in which fundamental plasma theory, tokamak experimentation, materials science, and European infrastructure planning were tightly interconnected.

IPP CAS entered the independent Czech period with a scientific identity substantially broader than fusion alone. The institute studied high-temperature magnetised plasma, pulsed discharges, thermal plasma jets, plasma chemistry, laser-generated plasma, optical diagnostics, and plasma interaction with materials. This breadth was important because many technologies required by magnetic-confinement fusion depend on knowledge developed outside the tokamak itself. Materials exposed to plasma must be characterised before and after irradiation, diagnostics require advanced optics and electronics, and numerical models depend on experimental measurements from several plasma regimes. During the early 1990s, the institute underwent substantial organisational restructuring and reduced its workforce while placing greater emphasis on internationally evaluated scientific output. Czech researchers nevertheless maintained theoretical work connected with reactor-scale fusion concepts and with the interaction of waves, energetic particles, and tokamak plasma. They also collaborated with foreign laboratories on diagnostics and installed a Czech-built X-ray spectrometer on the Tokamak à Configuration Variable (TCV) in Switzerland in 1994. These activities preserved expertise during a financially difficult transition and prevented Czech plasma science from becoming isolated from European research. By the end of the decade, the institute was positioned to enter a much more formal system of European fusion cooperation.

Theory and experiment developed at IPP CAS as mutually dependent parts of the same fusion programme. Magnetic-confinement plasma is a highly collective system in which transport, turbulence, electric fields, currents, waves, energetic particles, and magnetic geometry interact across very different spatial and temporal scales. Experimental measurements can therefore rarely be interpreted through a single diagnostic signal. Czech researchers used numerical models to study particle transport, anomalous diffusion, magnetic perturbations, edge turbulence, wave–particle interactions, and later the behaviour of runaway electrons and plasma exhaust. Theoretical groups also contributed to scenario development for existing and future tokamaks. Modelling helped determine which measurements would be most informative before an experiment and then provided a framework for interpreting the observed plasma behaviour. Experimental results in turn exposed weaknesses in simplified models and supplied data for validating more advanced codes. This iterative relationship became increasingly important as Czech fusion research moved from CASTOR to COMPASS and towards the much more demanding COMPASS Upgrade. It also allowed Czech groups to contribute to international devices even when they were not responsible for operating the

machine itself. The integration of theory, diagnostics, and experiment became one of the defining methodological strengths of the national programme.

The CASTOR tokamak provided the principal domestic experimental platform during the first post-Czechoslovak decade. Its name expanded as Czech Academy of Sciences TORus, although the machine had originally been built in Moscow in the early 1960s as the small tokamak TM-1. It was transferred to Prague in the 1970s and entered operation at the institute in 1977. A major refurbishment in 1985 introduced a new vacuum vessel and an active feedback system for plasma position, after which the name CASTOR became established. The machine had a circular plasma cross-section, a major radius of about 0.4 metres, and a toroidal magnetic field below roughly 1.5 tesla. Its plasma current was limited to about 25 kiloamperes and typical discharge durations remained below fifty milliseconds. Although modest in scale, CASTOR provided a flexible environment for experiments that could be modified comparatively quickly. It therefore remained scientifically useful throughout the 1990s and early 2000s even as much larger European tokamaks addressed reactor-scale questions.

CASTOR became particularly valuable for the detailed investigation of edge plasma and turbulence. The machine carried arrays of Langmuir probes, magnetic coils, microwave diagnostics, radiometers, spectrometers, bolometers, and particle analysers. Probe systems allowed Czech physicists to measure plasma potential, density, electron temperature, ion temperature, fluctuations, and flows directly in the outer plasma region. Experiments examined turbulent transport and the way fluctuating electric fields can redistribute particles across magnetic surfaces. Researchers also investigated plasma rotation and the influence of externally imposed electric fields on edge turbulence. Microwave methods provided complementary measurements of density and fluctuations without inserting probes into the hot plasma. Lower-hybrid electromagnetic waves were used for additional heating and for studies of wave–plasma interaction. The resulting programme trained researchers in diagnostics that would later become important on COMPASS. CASTOR therefore acted as both a scientific device and an experimental school in which instruments, data-acquisition methods, and physical interpretations could be developed at relatively low cost. Its importance to Czech fusion science was consequently greater than would be suggested by its modest size. These experiments also established an instrumentation culture that later proved essential when measurements had to be transferred to more complex diverted plasmas.

The decisive institutional change of the 1990s came with formal Czech integration into the European fusion programme. On 22 December 1999, an association agreement was signed between the European Atomic Energy Community (Euratom) and IPP CAS. The agreement established the Euratom–IPP.CR Association and made the Prague institute the coordinator of Czech participation in European controlled-fusion research. Czech scientists gained structured access to common programmes, mobility schemes, technology activities, and major European devices. Additional agreements enabled participation in the Joint European Torus (JET) programme and access to European high-performance computing for fusion applications. The association also required Czech work programmes and results to be coordinated and evaluated within a wider European strategy. Fusion research therefore became less dependent on bilateral contacts and more deeply embedded in an organised continental programme. This integration was particularly important because no national tokamak in Czechia could reproduce the parameter range of JET or other large European machines. It allowed domestic experimental competence to develop in parallel with

participation in devices at higher plasma current, temperature, and heating power. The 1999 agreement consequently prepared the institutional conditions for the later transfer of COMPASS and for Czech membership in EUROfusion.

The limitations of CASTOR eventually made a more advanced domestic tokamak necessary if Czech researchers were to contribute directly to questions relevant to ITER. In 2004, the United Kingdom Atomic Energy Authority and the European fusion programme formally offered the COMPASS-D tokamak to the Institute of Plasma Physics in Prague. The device had previously operated at the Culham Science Centre in the United Kingdom and possessed a diverted plasma configuration much closer to that envisaged for modern reactor-scale tokamaks. Czech authorities decided in 2005 to accept the machine with governmental support. Dismantling at Culham, transport, construction of a new building, development of power supplies, and installation in Prague occupied the following several years. CASTOR was withdrawn from fusion research at the end of 2006 to free institutional resources for the new facility. It was subsequently transferred to the Czech Technical University in Prague, where it continued educational operation under the name GOLEM. The transfer preserved the value of the older machine for student training while allowing IPP CAS to move towards a substantially more capable research device. First plasma in the reconstructed COMPASS was achieved on 9 December 2008, followed by a prolonged period of commissioning. Regular scientific exploitation began after completion of major diagnostics, controls, and power systems during 2009–2011. The project itself became a training ground in large-scale tokamak engineering because Czech teams had to integrate inherited hardware with newly designed national systems.

COMPASS represented a major increase in the experimental capability of Czech magnetic-confinement research. The machine had a major radius of approximately 0.56 to 0.60 metres and could operate with shaped diverted plasmas rather than only the circular limited configurations characteristic of CASTOR. Its geometry was approximately one tenth of ITER dimensions on a linear scale and allowed plasma shapes relevant to reactor-oriented studies. COMPASS was one of the smaller tokamaks capable of operating in high-confinement mode, usually called H-mode. This regime is characterised by the formation of an edge transport barrier that substantially improves energy confinement. H-mode is important because it forms the baseline operational scenario for ITER. The ability to reproduce its essential edge physics in a compact and flexible machine gave COMPASS a role disproportionate to its physical dimensions. New power supplies, neutral-beam heating, real-time control, and extensive diagnostics were developed around the transferred vacuum vessel and magnet system. Czech researchers could therefore perform experiments directly related to the behaviour of the plasma edge, pedestal, and divertor. COMPASS moved the national programme from small-tokamak diagnostics into a parameter regime connected explicitly with European reactor research.

Diagnostics were one of the areas in which the Czech team made COMPASS particularly capable. The machine incorporated hundreds of magnetic coils for equilibrium reconstruction and the measurement of fast magnetic fluctuations. Microwave interferometry and reflectometry provided information about plasma density and edge structures. High-resolution Thomson scattering measured electron density and temperature profiles in both the core and edge plasma. Spectroscopic systems recorded visible, ultraviolet, and X-ray radiation from impurities and plasma processes. Fast cameras and infrared thermography allowed researchers to follow visible plasma events and heat deposition on divertor surfaces. Neutral-

particle analysers, neutron detectors, and beam-emission techniques provided information about energetic particles and plasma flows. Langmuir and ball-pen probe arrays gave unusually detailed measurements of the edge and scrape-off region. This concentration of diagnostics made COMPASS especially valuable for experiments in which several physical mechanisms had to be separated from one another.

One of the principal milestones was the achievement of high-confinement mode in November 2012. Neutral-beam heating first produced the transition into H-mode, and an ohmically heated H-mode was also observed during controlled current ramp-down. The transition was accompanied by the expected decrease in visible hydrogen emission together with increases in stored plasma energy and density. In 2013, the machine achieved Type-I Edge Localised Modes, usually abbreviated as ELMs. These transient instabilities periodically expel particles and energy from the edge transport barrier and represent an important concern for future reactor surfaces. COMPASS could therefore investigate both the improved confinement provided by the H-mode pedestal and the instabilities produced by the same steep edge gradients. Detailed measurements of this narrow region became one of the strongest components of the Czech programme. The results were directly relevant to understanding how reactor plasmas can retain high energy confinement while limiting damaging transient heat loads. H-mode experiments thus established COMPASS as a credible European facility for edge and divertor physics. The appearance of these regimes also enabled direct comparison with observations from larger European tokamaks.

Research on the plasma edge and the Scrape-Off Layer (SOL) became the scientific signature of COMPASS. The SOL is the region outside the last closed magnetic surface in which field lines intersect material components rather than remaining confined indefinitely inside the plasma. Energy and particles leaving the confined plasma must pass through this region before reaching the divertor or other plasma-facing structures. Czech teams measured density, temperature, electric fields, turbulent fluctuations, parallel flows, and radial transport in this boundary layer. They investigated how the H-mode pedestal and edge turbulence influence the width and intensity of heat and particle fluxes reaching the divertor. Experiments compared low- and high-confinement regimes and examined how plasma shape changes the distribution of exhaust power. Magnetic perturbations were applied to study whether edge behaviour and instabilities could be controlled externally. Impurity seeding was investigated as a method of radiating part of the plasma energy before it reaches solid surfaces. These studies addressed one of the central engineering problems of fusion, namely how to maintain a hot well-confined core while preventing the exhaust region from destroying the surrounding components.

Plasma–material interaction consequently became inseparable from the physics of power exhaust. The divertor must receive a substantial fraction of the heat and particles leaving the confined plasma, making its surfaces some of the most severely loaded components in a tokamak. COMPASS experiments combined edge probes with infrared thermography and spectroscopy to determine where energy was deposited and how material surfaces responded. Researchers studied impurity release, recycling of hydrogen isotopes, erosion, deposition, and the redistribution of heat along magnetic field lines. The programme also examined detached divertor conditions, in which radiation and atomic processes reduce the thermal load before the plasma reaches the target. Achieving reliable detachment without destroying core confinement is regarded as a key requirement for reactor-scale fusion. Czech work therefore connected local measurements in a medium-sized tokamak with a global technological problem facing ITER and DEMO. The ability to combine detailed edge diagnostics

with controllable plasma geometry made COMPASS particularly useful for testing and validating models of these processes. The results also informed the design priorities of COMPASS Upgrade, where power exhaust became an even more central objective. Plasma–material interaction thus evolved from an applied side topic into one of the organising themes of Czech fusion physics.

Another important research theme concerned runaway electrons. During a rapid disruption of a tokamak plasma, strong electric fields can accelerate a small population of electrons to relativistic energies. These runaway electrons may carry substantial current and can damage plasma-facing structures if they strike the wall in a concentrated beam. The problem is especially serious for large devices because the available energy increases greatly with plasma current. COMPASS provided experiments in which runaway beams could be generated, diagnosed, controlled, and deliberately perturbed. Researchers examined the conditions under which runaways form and how magnetic perturbations or other interventions influence their confinement. Hard X-ray detectors and other diagnostics helped quantify energetic electron losses. Disruption studies also investigated asymmetric mechanical forces and rapid changes in plasma current. These experiments contributed to the wider European effort to develop reliable disruption prediction and mitigation strategies for ITER. They also created diagnostic and modelling expertise that has been incorporated into the scientific planning of COMPASS-U. The topic later acquired even greater importance because future high-current devices can convert a significant fraction of plasma current into relativistic runaway beams during disruptions.

Theoretical and computational work expanded alongside these experiments. Czech plasma physicists modelled equilibrium, transport, turbulence, edge stability, impurity radiation, disruptions, and interactions between energetic particles and magnetic fields. Numerical codes were used both to interpret COMPASS measurements and to predict scenarios for future machines. Some modelling was performed within broader EUROfusion tasks so that Czech results could be compared directly with experiments on other European tokamaks. Cross-machine comparison is essential because no single device reproduces all the dimensionless parameters expected in a fusion reactor. Scaling studies therefore attempt to determine which physical trends remain valid when plasma size, magnetic field, current, density, and heating power change. COMPASS contributed particularly useful edge measurements because its relatively compact dimensions made high-resolution diagnostic access easier than on much larger devices. Theoretical groups could then test models of pedestal formation, SOL transport, and divertor heat loads against these data. The same models became part of the design work for COMPASS Upgrade. Theory thus provided continuity between the scientific exploitation of an existing machine and the engineering of its successor.

European fusion organisation changed again in 2014 with the creation of EUROfusion. The consortium coordinated national research units around a common roadmap intended to support ITER and ultimately the development of fusion electricity through DEMO. IPP CAS became the leading Czech participant and coordinated a national research unit that also involved universities and other research organisations. Czech teams contributed to work packages on plasma experiments, theory and modelling, diagnostics, materials, technology, education, and future device design. The arrangement gave researchers access to experimental campaigns on several European tokamaks and to common computational resources. It also imposed a stronger strategic connection between national work and the priorities identified in the European fusion roadmap. Power exhaust, disruption mitigation,

advanced confinement, plasma-facing materials, and tritium-related technologies consequently acquired greater prominence. COMPASS served as Czechia's principal experimental contribution to this distributed European programme until 2021. The transition from bilateral association to consortium membership therefore deepened rather than reduced Czech integration into European fusion science.

Czech researchers participated in experiments on the Joint European Torus and on medium-sized European devices such as the Axially Symmetric Divertor Experiment Upgrade (ASDEX Upgrade), the Tokamak à Configuration Variable (TCV), and the Tungsten Environment in Steady-state Tokamak (WEST). These machines offer different combinations of size, magnetic field, plasma shape, wall materials, and heating systems. Comparing results across them allows researchers to distinguish general plasma physics from effects specific to one device. Czech scientists contributed diagnostics, experimental proposals, modelling, data analysis, and operational expertise. Mobility within EUROfusion also allowed students and early-career researchers to work directly at leading European laboratories. This experience was important because COMPASS could not reproduce the full parameter range of larger machines. Conversely, high-resolution methods developed in Prague could be transferred to devices where certain measurements were more difficult. International campaigns therefore created a reciprocal exchange of techniques rather than a one-way dependence on foreign facilities. The Czech programme became scientifically stronger because its domestic machine and external access served complementary purposes. This circulation of people and methods made European facilities function as extensions of the Czech national research environment.

The relationship to ITER gave this work a clear long-term reference point. ITER is designed to demonstrate sustained production of fusion power from a magnetically confined deuterium–tritium plasma on a scale far beyond existing experimental tokamaks. Its baseline plasma scenarios rely on diverted H-mode operation, making edge confinement and power exhaust directly relevant to the COMPASS programme. The similar plasma shape of COMPASS allowed experiments whose results could contribute to scaling studies for the larger machine. Czech research on pedestal structure, Edge Localised Modes, heat-flux widths, magnetic perturbations, runaway electrons, and divertor conditions therefore addressed questions with explicit ITER relevance. Diagnostics developed by IPP CAS also contributed to broader European work on measurement systems intended for ITER and later DEMO. The connection should not be interpreted as meaning that COMPASS reproduced ITER conditions, because its size, current, heating power, and plasma energy were much smaller. Its value lay in isolating particular physical processes under controlled conditions and testing models that could then be applied across machines. Medium-sized tokamaks are especially useful for this purpose because they are flexible enough to modify configurations and diagnostics comparatively rapidly. Czech fusion research consequently occupied a specialised position within the wider international division of experimental tasks. ITER relevance therefore depended on validated similarity and scaling rather than on any claim that a medium-sized tokamak could duplicate reactor conditions.

After twelve years of Prague operation, COMPASS reached the end of its experimental programme on 20 August 2021. The device had accumulated approximately twenty-one thousand plasma discharges and had supported both scientific campaigns and the training of a generation of fusion researchers. Its closure was planned rather than the consequence of scientific failure. The experimental hall was needed for construction of a successor capable of addressing higher magnetic fields and much more severe exhaust conditions. COMPASS was

removed from the hall during the following months as civil and engineering preparation for the new machine progressed. The scientific expertise accumulated during its operation was retained through continued EUROfusion participation and through design work on the successor project. Many diagnostics concepts, control methods, modelling tools, and experimental questions therefore carried directly into the new programme. The end of COMPASS consequently represented a technological transition rather than a break in Czech tokamak research.

The concept of COMPASS Upgrade, commonly shortened to COMPASS-U, emerged from recognition that European fusion research lacked a flexible medium-sized tokamak operating simultaneously at high magnetic field and reactor-relevant heat loads. Radomír Pánek and colleagues presented the proposed design internationally in 2016, and the project formally began on 1 December 2017. The central objective was to preserve the experimental flexibility that had made COMPASS valuable while moving into a much more demanding parameter range. COMPASS-U was planned with a major radius of roughly 0.9 metres and a minor radius near 0.27 metres. Its toroidal magnetic field is designed to reach 5 tesla, while plasma current can reach 2 megaamperes. These values are several times larger than those of the previous Prague tokamak and substantially increase the electromagnetic and thermal forces that the machine must withstand. The design also includes strong auxiliary heating through Neutral Beam Injection (NBI) and Electron Cyclotron Resonance Heating (ECRH). High density, high magnetic field, and compact dimensions together create especially intense power loads in the edge and divertor region. COMPASS-U is therefore designed as a specialised experiment for precisely the power-exhaust problems that emerged as a major theme of COMPASS research.

The machine is intended to explore several advanced plasma configurations rather than reproduce one conventional divertor geometry. Planned shapes include lower single-null, double-null, negative-triangularity, and snowflake configurations. Negative triangularity has attracted interest because it may provide favourable confinement or stability characteristics while altering edge transport. Snowflake divertors use a higher-order magnetic null to spread exhaust power over a larger region and modify the divertor plasma. COMPASS-U also includes a closed divertor intended to reach high neutral density and strong plasma–neutral interaction. These features are valuable for studying detachment and other approaches to reducing target heat flux. Advanced confinement regimes such as Quiescent H-mode and improved-confinement modes can be compared with more conventional H-mode scenarios. The machine is designed so that divertor concepts can be modified rather than being permanently fixed to one geometry. This flexibility allows experimental comparison of competing power-exhaust strategies under the same basic machine conditions. It is one of the reasons COMPASS-U is expected to occupy a distinctive niche in the European tokamak portfolio.

High-temperature wall operation is another defining feature of the new device. The vacuum vessel and first-wall system are designed for nominal operation around 300 degrees Celsius and potentially up to 500 degrees Celsius. These temperatures are much closer to the conditions expected in future reactor environments than the comparatively cool walls of many experimental tokamaks. Operating hot changes hydrogen-isotope retention, impurity behaviour, recycling, and the thermal response of plasma-facing components. The design therefore allows researchers to study how edge plasma changes when the wall behaves less like a cold particle reservoir and more like a reactor-relevant surface. A fully metallic plasma-facing environment is planned, with tungsten used either as bulk material or as a coating over Inconel components. Tungsten is attractive because of its high melting point, low sputtering

yield under many relevant conditions, and experience accumulated on other European tokamaks. It is nevertheless not an ideal material in every respect, because tungsten impurities entering the hot plasma can radiate strongly and degrade confinement. COMPASS-U will therefore study not only whether tungsten survives intense loads but also how the plasma and material influence one another during operation. This reciprocal interaction is central to the design of any future fusion power plant. This combination of elevated wall temperature and tungsten coverage was chosen specifically to bring surface conditions closer to those expected in future fusion devices.

By 2025, the plasma-facing component design had progressed to detailed engineering review. The machine was planned to achieve complete tungsten coverage of surfaces directly exposed to the plasma through a combination of bulk tungsten and tungsten-coated Inconel 718. Bulk tungsten tiles are used in the divertor and other regions expected to receive the largest thermal loads. Coated Inconel allows mechanically robust structures to operate at elevated temperature while limiting direct exposure of nickel-based alloy constituents to the plasma. The divertor is designed for transient local heat fluxes approaching about one hundred megawatts per square metre, although routine operation requires substantially lower loads through detachment and other exhaust-control techniques. This requirement makes heat-flow management a primary physics problem rather than simply a question of choosing stronger materials. In April 2025, international experts reviewed the final design of first-wall limiters and the preliminary design of the tungsten divertor. The review concluded without identifying fundamental obstacles to the proposed designs. These milestones showed that Czech plasma–material research had moved from measurements on an existing tokamak to engineering components specifically for reactor-relevant power density. COMPASS-U thus became both a physics experiment and a materials technology demonstrator.

Liquid-metal concepts add a more experimental approach to the same exhaust problem. A conventional solid divertor must withstand repeated bombardment without melting, cracking, excessive erosion, or unacceptable impurity release. Liquid metals offer the possibility of a surface that can flow, redistribute heat, and in principle renew itself after exposure. COMPASS-U is designed to provide a European test environment for such technologies under strong heat flux and high-density divertor conditions. Candidate concepts can be compared with solid tungsten targets within a flexible magnetic configuration. The research asks not only whether a liquid surface survives but also whether evaporated material contaminates the confined plasma or changes its stability. Magnetic forces, wetting, capillary behaviour, temperature control, and tritium compatibility all create additional engineering problems. Czech materials and plasma specialists therefore have to work together rather than treating the divertor as an isolated mechanical component. The possibility of testing both conventional and innovative exhaust technologies is one of the features intended to make COMPASS-U relevant to DEMO design.

Materials engineering at IPP CAS provides an important domestic basis for this work. The institute developed water-stabilised and hybrid water–argon plasma torches for producing coatings and for processing materials at very high temperatures. Plasma spraying has been used to manufacture thick coatings, functionally graded materials, and surfaces designed for demanding thermal environments. Researchers have investigated tungsten and other materials intended for plasma-facing applications and have characterised their microstructure, porosity, thermal behaviour, and response to hydrogen isotopes. The Laboratory of Plasma Technologies opened in Prague-Letňany in 2012 and added modern

facilities for plasma spraying, sintering, and materials analysis. Spark Plasma Sintering (SPS) provided another route for consolidating powders into dense materials with controlled microstructures. Radio-frequency inductively coupled plasma spraying and cold-spray technologies later widened the available processing methods. This expertise is not limited to fusion, but fusion supplies some of its most extreme materials requirements. The institutional proximity of plasma physicists and materials engineers therefore gives Czech fusion research an unusually direct route from materials preparation to exposure under relevant plasma conditions. The same laboratories could therefore prepare candidate materials, characterise them microscopically, and relate their properties to exposure under plasma-relevant conditions.

Technology development for COMPASS-U extends far beyond the vacuum vessel and first wall. Magnetic-field coils must generate several tesla while resisting very large electromagnetic forces during each plasma pulse. The support structure consequently became a massive stainless-steel assembly designed to counteract forces in the meganewton range. The toroidal-field coils are cooled to cryogenic temperatures to reduce electrical resistance before high-field operation. Power supplies must deliver very large currents on controlled timescales while remaining synchronised with plasma initiation and shaping systems. Neutral-beam injectors are planned to provide several megawatts of auxiliary heating and to drive or diagnose plasma processes. Electron-cyclotron systems will provide additional microwave heating and control at frequencies appropriate to the strong magnetic field. Vacuum, fuelling, cryogenics, control, data acquisition, protection, and diagnostics all have to operate as one coordinated machine. By the end of 2025, manufacturing, civil reconstruction, power-system installation, plasma-facing-component design, and assembly work were proceeding through overlapping project phases. The engineering scale demonstrates why contemporary fusion research is simultaneously physics, materials science, electrical engineering, cryogenic technology, computing, and systems integration. The development programme consequently required long-term coordination between physicists and engineering teams rather than sequential construction of independent subsystems.

The rebuilding of the Prague experimental halls illustrates this systems challenge in physical form. To accommodate COMPASS-U, the existing experimental space required extensive demolition and structural reinforcement. Concrete walls were thickened, new supporting structures were introduced, and the basement was rebuilt to carry the loads of the new tokamak and its auxiliary equipment. The first phase of civil construction was completed in June 2023. The reconstructed hall was also designed to accommodate a dedicated materials test system associated with advanced fusion materials and power-exhaust concepts. This co-location reflects the scientific objective of integrating tokamak experiments with component development. Infrastructure work continued while major machine components were being manufactured in several European countries. International design reviews included experts from leading tokamaks and from the ITER organisation. Such external scrutiny helps reduce project risk and ensures compatibility with standards used elsewhere in fusion research. The construction of COMPASS-U therefore represents a national research project implemented through a genuinely international engineering network.

Education and researcher training have remained central throughout this transition. CASTOR provided generations of Czech students with direct access to a working tokamak at a scale suitable for hands-on experiments. After its transfer to the Czech Technical University, the device continued as GOLEM and became closely associated with teaching in plasma and

fusion technology. COMPASS then allowed students and doctoral researchers to participate in experiments directly relevant to the European fusion programme. IPP CAS organised summer training courses in which students from Czechia and other countries could design experiments, operate diagnostics, and analyse tokamak data. Mobility through Euratom and EUROfusion enabled young researchers to work at JET, ASDEX Upgrade, TCV, WEST, and other international facilities. This combination of domestic practical access and international mobility helped produce specialists capable of moving between experiment, theory, diagnostics, and engineering. COMPASS-U is intended to continue this educational role at a substantially higher technological level. Human-capital development is especially important because fusion projects operate over decades and require expertise to be transferred across generations.

The broader Czech fusion programme also extends beyond IPP CAS. The Research Centre Řež contributes materials, nuclear technology, reactor engineering, and other expertise relevant to fusion energy. The Nuclear Physics Institute, Czech Technical University in Prague, Charles University, and the University of West Bohemia participate in research or education connected with the national EUROfusion unit. This distribution matters because a future fusion power plant would combine plasma confinement with neutron-resistant structures, tritium systems, heat transfer, remote maintenance, electricity generation, and complex safety engineering. No single plasma laboratory can develop all of these technologies independently. Czech participation therefore increasingly links tokamak physics with materials and nuclear engineering communities outside the institute. The European programme reinforces this integration by organising research around common challenges rather than purely institutional boundaries. Fusion science thus acts as an interdisciplinary framework connecting several branches of Czech physics and engineering. The national contribution is strongest when specialised domestic capabilities are coordinated with the much larger European programme. This wider institutional network also helps ensure that Czech fusion research remains connected to the technologies required beyond the plasma chamber itself.

By 2025, Czech plasma physics and controlled thermonuclear fusion had consequently passed through three distinct experimental generations. CASTOR provided a flexible small tokamak on which edge diagnostics, turbulence studies, plasma control, and researcher training could develop. COMPASS introduced diverted ITER-like geometry, neutral-beam heating, H-mode physics, detailed pedestal and scrape-off-layer studies, disruption research, and strong integration with the European fusion programme. COMPASS-U was conceived to push these capabilities towards much higher magnetic field, plasma current, wall temperature, and divertor heat flux. The scientific continuity among the three machines is important because each generation preserved expertise while altering the physical scale and technological challenge. European integration progressed in parallel from the Euratom association of 1999 to full participation in EUROfusion and close connection with ITER priorities. Czech researchers also developed materials, diagnostics, modelling, and fusion technologies that extended beyond operation of the domestic tokamak itself. Plasma–material interaction and power exhaust emerged as particularly important specialisations because they lie among the unresolved barriers between successful plasma confinement and a practical fusion reactor. The COMPASS-U programme was designed precisely around these gaps rather than around an attempt to reproduce a large reactor in miniature. This strategic specialisation gives Czechia a defined role within the distributed European fusion research system. The achievement of the field therefore lies not in having reached commercial fusion, which

remained an international long-term objective, but in building a sustained national capability able to address several of the difficult physical and technological problems on the route towards it.

Astronomy, Astrophysics, and Cosmology

Astronomy, astrophysics, and cosmology developed into one of the most internationally connected areas of Czech physics between 1993 and 2025. The field combined long-established observational traditions with increasingly sophisticated theoretical, computational, and multi-wavelength approaches. Its principal national institution was the Astronomical Institute of the Czech Academy of Sciences, whose scientific programme ranged from the solar atmosphere to stars, exoplanets, galaxies, compact objects, and the dynamics of Solar System bodies. Ondřejov Observatory remained the most important Czech site for optical, solar, radio, meteor, and spectroscopic observations. At the same time, Czech researchers increasingly depended on major observatories and space missions that could provide sensitivities, angular resolution, or wavelength coverage unavailable domestically. Membership of the European Southern Observatory became the decisive institutional step in this internationalisation. University groups in Prague, Brno, and Opava strengthened theoretical astrophysics, gravitation, cosmology, high-energy astrophysics, and the training of younger researchers. The emergence of exoplanet research, X-ray astrophysics, advanced studies of black holes, and modern galaxy evolution broadened the national research agenda beyond its older observational specialities. Czech astronomy consequently evolved through a productive combination of domestic observatories, theoretical schools, international infrastructures, and access to global data archives. By 2025, the country possessed a diversified astronomical community capable of contributing both specialised observations and internationally recognised theoretical work.

The institutional continuity of Czech astronomy was particularly visible in the history of the Astronomical Institute of the Czech Academy of Sciences. Its origins extend through the State Observatory and the Czechoslovak Academy of Sciences, while Ondřejov itself had developed from the private observatory founded by Josef Jan Frič at the end of the nineteenth century. The modern Astronomical Institute of the Czechoslovak Academy of Sciences was created in 1954 through the reunification of previously separated astronomical workplaces. At the end of 1992, the Institute became part of the newly organised Czech Academy of Sciences. In 1993, its official headquarters were transferred from Prague to Ondřejov, while its Prague workplace moved to Spořilov. This administrative change strengthened the institutional role of the observatory without eliminating the importance of research groups based in the capital. The Institute subsequently developed four broad scientific departments concerned with solar physics, stellar astrophysics, interplanetary matter, and galaxies together with relativistic astrophysics and astrodynamics. Its post-1993 development therefore represents continuity of scientific traditions accompanied by a substantial widening of methods, objects, and international collaborations. The institutional history also illustrates why Czech astronomy after independence should be understood as transformation of a mature research system rather than creation of a new discipline.

Ondřejov Observatory remained the principal domestic observational base of Czech astronomy throughout the period. Its largest optical instrument is the Perek two-metre telescope, commissioned in 1967 and used primarily for stellar spectroscopy. Electronic detectors replaced the older photographic approach around the beginning of the post-Czechoslovak period, with charge-coupled device technology becoming standard after 2000. The telescope is equipped with single-order and echelle spectrographs and can provide high-resolution spectra needed for measurements of stellar atmospheres, radial velocities, circumstellar matter, and binary systems. A major modernisation completed in 2019 substantially altered the optical configuration and introduced fibre transfer from the primary focus to the spectrograph rooms. This increased efficiency and expanded the range of fainter targets that could be observed effectively from Ondřejov. The telescope is used not only by Astronomical Institute researchers but also by scientists and students from Charles University, Masaryk University, Slovak institutions, and other international partners. Smaller robotic telescopes such as D50 and BART complement the two-metre telescope by providing rapid or long-term photometric monitoring. Ondřejov also hosts solar optical instruments, radio telescopes, meteor cameras, and technical laboratories, making the site scientifically more diverse than a single-telescope observatory. The coexistence of these facilities enables long-duration monitoring programmes that are difficult to justify on heavily oversubscribed international telescopes. Domestic observations therefore provide continuity and flexibility, while international infrastructure supplies the sensitivity and resolution needed for more demanding projects.

Solar physics has remained one of the strongest and most historically continuous research areas at the Astronomical Institute. Czech researchers study solar flares, prominences, filaments, active regions, sunspots, the chromosphere, corona, solar wind, and the processes responsible for the storage and release of magnetic energy. These phenomena are investigated through optical, radio, extreme-ultraviolet, and X-ray observations combined with theoretical modelling and numerical simulations. The Ondřejov Solar Patrol maintains systematic monitoring of solar activity and provides regular records and forecasts. A multichannel flare spectrograph supplies detailed information about rapidly evolving optical emission during energetic events. Radio telescopes at Ondřejov monitor the solar atmosphere at decimetric wavelengths and provide diagnostics of energetic electrons and plasma processes. The scientific objective is not merely to catalogue solar activity but to determine how magnetic fields reorganise and accelerate particles during eruptions. Solar research therefore connects observational astronomy directly with plasma physics and space weather.

The Czech solar programme became increasingly multi-wavelength and internationally distributed after 1993. Data from Ondřejov are routinely combined with measurements from spacecraft and major ground-based observatories in order to reconstruct the physical evolution of eruptions across several atmospheric layers. Researchers participate in investigations using the Solar Orbiter mission of the European Space Agency and in work connected with the European Solar Telescope under development in the Canary Islands. Czech scientists also use observations from the Atacama Large Millimeter/submillimeter Array, commonly abbreviated as ALMA, to study the chromosphere at wavelengths that complement optical and ultraviolet diagnostics. The first ALMA images of the Sun released in 2017 revealed the thermal structure of the chromosphere and included a detailed view of a large sunspot. Czech astronomers were among the researchers involved in developing and supporting the solar observing mode of the array. From 2016, the Czech ALMA Regional Centre

node at Ondřejov provided specialised scientific and technical support for solar observations as well as for extragalactic projects. This role is unusual within the European ALMA support network because solar observing requires calibration and data-reduction procedures that differ from many conventional astronomical programmes. The Institute also contributed to interpretation of data from the Metis coronagraph on Solar Orbiter, including studies of eruptive prominences and coronal plasma. These activities demonstrate how a traditional national strength in solar observation evolved into participation in space-based and millimetre-wave research infrastructures. Czech solar physics therefore became increasingly integrated into global observing campaigns while preserving its own continuous monitoring capability at Ondřejov.

Theoretical solar physics developed in parallel with this observational expansion. Numerical magnetohydrodynamic models are used to investigate magnetic reconnection, flux ropes, flare loops, coronal heating, turbulence, and the transport of energetic particles. Radiative-transfer calculations help determine how plasma temperature, density, velocity, and non-equilibrium particle distributions affect observed spectral lines. Czech researchers developed specialised software for synthesising coronal emission produced by non-Maxwellian electron distributions. They also contributed to three-dimensional modelling of polarised spectral-line formation in structured solar atmospheres. Heliospheric research examines solar-wind particles, waves, turbulence, and nonlinear structures using spacecraft measurements together with kinetic simulations. Interactions between the solar wind and planetary magnetospheres extend this work from solar physics into space plasma science. These theoretical programmes are important because the Sun provides a nearby laboratory in which plasma processes can be observed at resolutions impossible for other stars. Results obtained in solar physics can therefore inform the interpretation of stellar flares, winds, and magnetically active atmospheres. The Czech programme consequently connects the detailed physics of the nearest star with broader problems of astrophysical plasma.

Stellar astrophysics represents a second major observational tradition centred on Ondřejov. Research in the Stellar Department focuses especially on hot massive stars, evolved stars, binaries, variable objects, circumstellar environments, exoplanet host stars, and high-energy transients. Massive stars are scientifically important because their winds, radiation, and final explosions strongly influence the chemical and dynamical evolution of galaxies. Czech researchers model non-local thermodynamic equilibrium stellar atmospheres in order to interpret spectra whose formation cannot be described by simple equilibrium assumptions. They investigate line-driven stellar winds and the structures that produce temporal variations in spectroscopic observations. Binary systems receive particular attention because mass transfer, tidal interactions, and focused winds can alter stellar evolution radically compared with isolated stars. The Perek telescope provides long-term high-resolution spectra that allow such variability to be followed over months or years. International ultraviolet, X-ray, and optical datasets then extend the same objects into wavelength regimes inaccessible at Ondřejov. The combination of modelling and repeated spectroscopy has produced a distinctive Czech specialisation in the physics of hot stars and their circumstellar matter. These programmes also provide the stellar-physics foundation needed for understanding supernova progenitors and compact-object binaries. By the 2020s, machine-learning and archive-based methods were increasingly used to classify variable stars and extract physical information from large observational datasets. Stellar astrophysics in Czechia therefore moved from individual-object spectroscopy towards an increasingly data-rich and multi-wavelength form of research.

High-energy stellar astrophysics broadened this programme towards cataclysmic variables, X-ray binaries, supernovae, and gamma-ray bursts. Gamma-ray bursts, commonly abbreviated as GRBs, are extremely luminous transient events whose prompt high-energy emission may last from fractions of a second to many minutes. Their optical afterglows fade rapidly, making robotic telescopes valuable because observations must begin soon after an alert. The BART and D50 telescopes at Ondřejov were used for rapid optical follow-up and for longer monitoring of other variable high-energy sources. Czech astronomers participated in the International Gamma-Ray Astrophysics Laboratory, whose mission name is INTEGRAL, and in other space-based high-energy programmes. Data from large international telescopes allowed spectra and redshifts of distant bursts to be combined with the rapid response available from smaller domestic instruments. Czech researchers also contributed to observations linking some long-duration gamma-ray bursts with supernovae. One internationally visible case involved observations of the first supernova associated with an ultra-long gamma-ray burst using instruments at the European Southern Observatory. High-energy transient research consequently connected Czech stellar astronomy with relativistic shocks, stellar collapse, compact remnants, and cosmological distances. It also demonstrated the continuing value of modest robotic telescopes when they are integrated into global alert and follow-up networks.

The emergence of exoplanet research was one of the most important changes in Czech stellar astronomy during the 2000s and 2010s. The Extrasolar Planet Research group at the Astronomical Institute combines transit photometry with precision spectroscopy and radial-velocity measurements. Planetary candidates identified by the Kepler, K2, and Transiting Exoplanet Survey Satellite missions can be followed from the ground to determine whether the observed signal is genuinely planetary. The Perek two-metre telescope contributes spectroscopy of host stars and selected candidates. Larger telescopes at European Southern Observatory sites provide the precision required for characterising smaller or more distant systems and for examining exoplanet atmospheres. Czech researchers investigate orbital parameters, stellar activity, planetary masses, atmospheric properties, and the architecture of multiplanet systems. The programme also develops astroinformatic methods because modern exoplanet surveys produce data volumes too large for purely manual analysis. Exoplanet science therefore became a new bridge between traditional stellar spectroscopy and the rapidly expanding study of planetary systems beyond the Solar System. This transition substantially widened the scientific role of the Stellar Department.

The Czech-led PLATOSpec project provided a particularly important technological expression of this new exoplanet programme. It revived the 1.52-metre telescope at the European Southern Observatory's La Silla site in Chile after almost two decades without regular scientific operation. Czech institutions led the telescope modernisation, working with Chilean and German partners on the telescope, calibration system, spectrograph, and data pipeline. The refurbished telescope returned to operation in 2022 and was designed for remote control. A new high-resolution PLATOSpec spectrograph achieved first light in 2024. Its radial-velocity precision is intended to reach approximately three metres per second under suitable observing conditions. The instrument was designed to screen and characterise stars with candidate planets and to provide ground-based support for the Planetary Transits and Oscillations of stars mission, usually called PLATO. It also offers support for future atmospheric studies associated with the Atmospheric Remote-sensing Infrared Exoplanet Large-survey mission. The project is significant because Czech astronomers moved from competing for limited time on existing international telescopes towards leading an instrument and telescope programme

located at a premier southern observatory. PLATOSpec consequently illustrates the increasing technological maturity of Czech observational astronomy.

Planetary research within the Czech astronomical system extends beyond exoplanets to the small bodies and dynamics of the Solar System. The Department of Interplanetary Matter at the Astronomical Institute studies asteroids, meteoroids, meteorites, and their interactions with the terrestrial atmosphere. The European Fireball Network provides systematic optical monitoring of bright meteors and enables their atmospheric trajectories, heliocentric orbits, fragmentation, and possible meteorite falls to be reconstructed. Czech researchers have played leading roles in automated fireball observation and in interpreting the physical processes that occur when meteoroids enter an atmosphere at high velocity. Asteroid studies investigate rotation, shapes, binary systems, bulk properties, and the relationships among asteroids, meteoroids, and meteorites. A 0.65-metre telescope at Ondřejov provides photometric data that are combined with observations from international networks. Czech astronomers have also participated in high-angular-resolution studies of large main-belt asteroids using the Very Large Telescope. In 2021, a French-Czech-led collaboration used the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument to obtain detailed images of forty-two large asteroids. Such work helps reconstruct collisional histories, internal structures, and the early evolution of the Solar System. Astrodynamics research at the Institute additionally examines natural and artificial bodies, gravitational and non-gravitational forces, trans-Neptunian objects, Earth rotation, and planetary gravity fields. The planetary-science programme therefore spans scales from metre-sized atmospheric impactors to extrasolar planetary systems.

Czech membership in the European Southern Observatory, commonly abbreviated as ESO, fundamentally changed the observational possibilities available to this research community. The accession agreement was signed in Prague on 22 December 2006 after negotiations between the Czech government and ESO. Czechia formally became the organisation's thirteenth Member State on 30 April 2007. It was the first member of ESO from Central and Eastern Europe. Membership gave Czech astronomers the right to compete for observing time at the organisation's facilities under the same scientific peer-review system as researchers from other Member States. It also created opportunities for Czech scientists and engineers to participate in advisory bodies, fellowships, instrumentation, and technical programmes. The importance of membership cannot be reduced to telescope access because ESO operates as a long-term institutional framework for European astronomical strategy. Czech groups could now plan research programmes around instruments whose sensitivities and angular resolution were far beyond those available domestically. University students and early-career astronomers also gained clearer pathways into internationally competitive observational work. Czech companies became eligible for technological contracts associated with ESO instruments and facilities. Membership therefore integrated science, training, engineering, and industrial participation within the same European organisation. It was one of the most consequential infrastructure decisions in the history of Czech astronomy after independence.

The Very Large Telescope, commonly abbreviated as VLT, at Paranal Observatory became one of the most important facilities available through this membership. Its four 8.2-metre Unit Telescopes and specialised instruments allow high-resolution imaging, spectroscopy, polarimetry, adaptive-optics observations, and optical interferometry. Czech astronomers used VLT instruments for stellar physics, gamma-ray bursts, exoplanets, asteroids, active galactic nuclei, and relativistic sources. Membership also provided access to ESO-operated or

partnered facilities at La Silla and to the Atacama Pathfinder Experiment. Through ESO's partnership in ALMA, Czech astronomers gained access to one of the world's most powerful millimetre and submillimetre interferometers. The Extremely Large Telescope, usually abbreviated as ELT, added a longer-term dimension to Czech involvement because its 39-metre primary mirror is intended to extend European astronomy towards much greater sensitivity and angular resolution. Czech companies have contributed technological components to ESO instrumentation and to the ELT programme. The resulting relationship therefore combines scientific access with industrial and engineering participation. ESO membership effectively expanded the observational territory of Czech astronomy from domestic telescopes to some of the world's leading sites in the Chilean Atacama Desert.

ALMA became especially important because Czechia developed a specialised role in supporting its European user community. The Czech ALMA Regional Centre node has operated at the Astronomical Institute since 2016 as a national large research infrastructure. It supports researchers in Central and Eastern Europe with proposal preparation, observation planning, data-quality assessment, storage, calibration, and data reduction. Its scientific specialisations include solar observations and extragalactic radio astronomy. Solar support is particularly distinctive because Ondřejov researchers possessed long-standing expertise in solar radio physics before ALMA began regular solar observing. The node also involves cooperation with Czech universities and chemical spectroscopy specialists, reflecting the broad scientific requirements of millimetre astronomy. By hosting this service, Czechia contributes expertise back into the international infrastructure rather than functioning only as an observing-time consumer. The centre has therefore become a practical example of how ESO membership can generate specialised responsibilities inside a distributed European support system.

Galaxy formation and evolution constitute another major component of Czech astrophysics. The Galaxies Department of the Astronomical Institute studies isolated galaxies, galaxy groups and clusters, star formation, star clusters, interstellar gas, and interactions between galaxies and their environments. Observational data in infrared, ultraviolet, optical, radio, and X-ray bands are compared with analytical models and numerical simulations. One important problem is ram-pressure stripping, in which gas is removed from a galaxy as it moves through the hot medium of a galaxy cluster. Such stripping can suppress future star formation and therefore alter the evolutionary trajectory of a galaxy. Czech researchers also investigate the dynamics of the Milky Way and the Magellanic Clouds, active galactic nuclei, and the distribution of interstellar matter. Computer simulations are essential because galaxy evolution is governed simultaneously by gravity, hydrodynamics, magnetic fields, radiation, and stellar feedback. The field therefore connects observations of individual objects with the broader problem of how large-scale cosmic environments influence baryonic matter. Research on galaxies also provides a natural bridge to black-hole astrophysics because many galaxies contain active supermassive black holes in their nuclei. The Czech programme consequently spans both the internal physics of galaxies and their place in the larger cosmic web.

Relativistic astrophysics became one of the internationally recognised theoretical specialities of Czech astronomy. The Prague Relativistic Astrophysics group at the Astronomical Institute studies black holes, neutron stars, accretion discs, relativistic jets, and radiation produced in strong gravitational fields. General relativity provides the theoretical framework because Newtonian gravity is inadequate in the immediate neighbourhood of compact objects. Czech researchers model X-ray spectra, timing variability, polarisation, and the orbital motion of

matter around black holes. A particularly important diagnostic is the relativistically broadened iron emission line produced when X-rays irradiate the inner regions of an accretion disc. Gravitational redshift, Doppler shifts, and relativistic light bending distort this line in ways that encode information about the geometry and motion of the emitting matter. The group developed transfer functions and computational tools for modelling such relativistic spectral signatures. Researchers also investigate the electrodynamics of magnetised black holes and the interaction of stars with the environment around the Galactic Centre. Sagittarius A*, the supermassive black hole at the centre of the Milky Way, provides an important natural laboratory because stellar orbits, flares, accretion, and relativistic effects can be studied at comparatively small astronomical distances. These problems increasingly connect theoretical calculations with X-ray, infrared, radio, and polarimetric observations. Czech relativistic astrophysics therefore exemplifies the convergence of mathematical relativity with data-driven astronomy.

The Czech theoretical tradition in gravitation extends beyond the Astronomical Institute. The Institute of Theoretical Physics at Charles University has systematically developed general relativity, relativistic astrophysics, and cosmology since the second half of the twentieth century. Jiří Bičák and his students established a research school concerned with exact solutions of Einstein's equations, gravitational radiation, black holes, cosmological models, and mathematical aspects of relativistic gravity. After 1993, this tradition continued through research on black-hole space-times, gravitational waves, perturbation theory, relativistic discs, lensing, and inhomogeneous cosmology. In 2014, the Albert Einstein Centre for Gravitation and Astrophysics was established to connect leading Czech groups in these fields. The centre brought together researchers from Charles University, the Astronomical Institute, the Mathematical Institute of the Czech Academy of Sciences, and Silesian University in Opava. Its programme included black-hole physics, gravitational radiation, exact solutions, higher-dimensional gravity, lensing, conservation laws, and cosmology. This collaboration strengthened the link between mathematically rigorous relativity and observationally motivated astrophysics. It also created a national framework through which doctoral students and international postdoctoral researchers could move among several institutions. The Czech contribution to relativistic astronomy is therefore best understood as a networked school rather than the work of a single department.

Silesian University in Opava became another important centre of relativistic astrophysics and cosmology. Its Institute of Physics was reorganised as an independent university unit in 2020, building on research groups that had already developed within the Faculty of Philosophy and Science. The Research Centre for Theoretical Physics and Astrophysics studies gravitational theories, black holes, compact objects, accretion structures, particle motion, and applications of general relativity. Research also addresses quantum-field and particle-physics problems with astrophysical or cosmological consequences. The Opava school is particularly associated with theoretical modelling of strong-gravity environments and the behaviour of matter and radiation near compact objects. The university also maintains specialised teaching in astrophysics, general relativity, and cosmology. Its development strengthened the regional distribution of Czech theoretical astronomy beyond Prague. Cooperation through the Albert Einstein Centre further integrated Opava researchers with colleagues at Charles University and the Czech Academy of Sciences. This network has allowed Czech relativistic astrophysics to sustain several independent but interacting theoretical schools.

Masaryk University in Brno added a strongly observational high-energy dimension to the Czech astrophysical landscape during the 2010s and 2020s. Its High-Energy Astrophysics group studies the hot gaseous atmospheres of galaxies and galaxy clusters, accreting supermassive black holes, and gamma-ray bursts. X-ray imaging and spectroscopy provide the principal observational tools for analysing gas at temperatures of millions of degrees. Radio interferometry and multi-wavelength observations reveal jets, cavities, shocks, and other structures created when black holes release energy into their surroundings. This feedback can prevent hot gas from cooling efficiently and thereby regulate the formation of new stars in massive galaxies. The group also investigates the distribution and chemical enrichment of baryonic matter in galaxy outskirts, groups, clusters, and the cosmic web. Such studies connect the small spatial scales of black-hole accretion with the much larger scales of galaxy and cluster evolution. Brno researchers participate in preparations for future X-ray observatories and use existing space missions together with radio facilities. The group also developed interest in small satellites for the detection and localisation of gamma-ray bursts. High-energy astrophysics at Masaryk University therefore links compact objects, galaxy evolution, observational cosmology, and space instrumentation. Its emergence significantly broadened the institutional geography of Czech astrophysics.

Cosmology in Czechia developed primarily through theoretical physics and observational studies of large-scale structure rather than through a dedicated national cosmological observatory. Charles University researchers investigate relativistic cosmology, exact and inhomogeneous cosmological solutions, gravitational lensing, and the mathematical structure of space-time. Masaryk University approaches cosmological questions through galaxy clusters, the cosmic web, baryonic matter, and the evolution of large-scale structure. Silesian University provides teaching and research in relativistic cosmological models and their relation to gravitational theory. Astronomical Institute groups contribute through galaxy evolution, active galactic nuclei, black-hole demographics, and studies of high-redshift sources. Czech researchers therefore engage with cosmology through several observational and theoretical entry points rather than a single dominant school. The standard cosmological framework requires dark matter and dark energy, but much of the observable Universe consists of baryonic gas whose distribution and thermal history also require explanation. X-ray studies of clusters and circumgalactic media provide one route to tracing this otherwise difficult-to-detect matter. Gravitational lensing and the dynamics of galaxies offer complementary probes of mass distributions. High-redshift galaxies and gamma-ray bursts extend observations into earlier stages of cosmic history. Relativistic theory provides the mathematical structure within which these observations are interpreted. Czech cosmology consequently forms a bridge linking general relativity, high-energy astrophysics, galaxy evolution, and large international surveys.

The increasing importance of multi-wavelength data changed the practical organisation of Czech astrophysics after 2000. A single astronomical object can now be observed in radio, millimetre, infrared, optical, ultraviolet, X-ray, and gamma-ray bands, with each wavelength revealing different physical components. Solar flares provide a clear example because optical spectra, radio bursts, extreme-ultraviolet images, and X-ray emission trace different temperatures and particle populations. Active galactic nuclei similarly combine radio jets, infrared dust emission, optical lines, ultraviolet radiation, and X-rays from the inner accretion flow. Gamma-ray bursts require rapid high-energy detection followed by optical, infrared, and sometimes radio observations of their fading afterglows. Czech groups increasingly organised

their work around coordinated datasets rather than around a single telescope or wavelength. This methodological change intensified cooperation among observatories and made public archives scientifically important. It also required more advanced calibration, statistics, and computational processing. The result was an astrophysical culture in which access to data became nearly as important as ownership of instruments.

Astroinformatics became a natural response to the rapidly increasing volume and complexity of these observations. The Stellar Department explicitly incorporated methods for working with large astronomical archives, while ALMA support required substantial expertise in radio-interferometric calibration and image reconstruction. Survey missions such as Gaia, Kepler, K2, and the Transiting Exoplanet Survey Satellite produced catalogues containing far more sources than could be inspected individually. Machine learning began to assist classification of variable stars, transient sources, galaxies, and other objects. Numerical simulations of galaxies, accretion flows, solar plasma, and relativistic systems similarly generated large computational datasets. Czech researchers therefore increasingly required programming, statistics, database management, and high-performance computation alongside traditional observational skills. Remote access to telescopes and distributed international archives further weakened the old connection between an astronomer's physical location and the site of observation. The PLATOSpec telescope in Chile, for example, was designed for remote operation through an international collaboration led from Czechia. This digital transformation allowed a relatively small national community to exploit data from globally distributed instruments much more effectively. It also created stronger links between astronomy, computer science, and national high-performance computing infrastructure.

International infrastructure access changed researcher training as profoundly as it changed scientific capability. Czech membership in ESO enabled students and early-career scientists to compete for fellowships, studentships, observing time, and technical placements within the organisation. A 2019 agreement between the Czech Ministry of Education, Youth and Sports and ESO strengthened opportunities for on-the-job training. Students trained at Ondřejov could therefore progress from operating a national telescope to working with instruments on much larger facilities in Chile. Conversely, domestic instruments remained essential because they offered repeated hands-on experience that cannot easily be obtained during a few nights of highly competitive international observing time. The Perek telescope has continued to serve university education as well as research. The ALMA Regional Centre node trains users in proposal preparation, calibration, and data reduction rather than merely processing data on their behalf. Theoretical schools in Prague and Opava provide parallel training in relativity, black-hole physics, and cosmology. Brno adds expertise in X-ray astronomy, radio interferometry, and satellite-oriented high-energy astrophysics. This combination of domestic practice and international infrastructure has helped Czech astronomy reproduce highly specialised expertise across generations. It also reduces the risk that membership fees for large facilities become detached from the development of a capable national user community. The educational dimension is therefore an integral component of Czech astronomical infrastructure.

Several internationally visible results illustrate what this infrastructure integration made possible. Czech astronomers participated in the first solar observing campaigns with ALMA and helped establish millimetre astronomy as a new diagnostic of the solar chromosphere. Czech and French researchers were involved in the exceptionally detailed Very Large Telescope imaging campaign that characterised forty-two of the largest asteroids in the main

belt. Czech scientists also contributed to observations associating a supernova with an ultra-long gamma-ray burst. Work at the Astronomical Institute on black-hole accretion has developed models used to interpret X-ray spectra and polarisation from matter moving in strong gravitational fields. Exoplanet researchers created the Czech-led PLATOSpec programme at La Silla to provide precision spectroscopic follow-up of transit candidates. These examples cover the Sun, Solar System, stars, compact objects, and planetary systems, illustrating the breadth of the national community. They also show that Czech achievement in astronomy frequently emerges through international teams rather than isolated national observing programmes. The relevant measure of success is therefore the ability to contribute distinctive expertise, instruments, models, or observations within collaborations using world-class facilities.

By 2025, Czech astronomy had become institutionally polycentric even though the Astronomical Institute remained its principal national research organisation. Ondřejov concentrated solar physics, stellar spectroscopy, exoplanets, meteors, asteroids, and radio astronomy, while the Institute's Prague groups contributed galaxy research, relativistic astrophysics, astrodynamics, and space geodesy. Charles University linked observational astronomy with a strong theoretical tradition in gravitation and cosmology. Masaryk University developed high-energy astrophysics centred on hot gas, supermassive black holes, gamma-ray bursts, and multi-wavelength observations. Silesian University in Opava strengthened relativistic astrophysics, black-hole theory, computational physics, and cosmological education. Other Czech institutions contributed through instrumentation, data processing, space research, and participation in international observing projects. The national community therefore resembled a network of specialised nodes rather than a single central observatory. ESO membership and access to ALMA, the Very Large Telescope, La Silla instruments, and the future Extremely Large Telescope provided the shared international layer connecting many of these nodes. This organisational structure allowed relatively small groups to concentrate on distinctive scientific problems while drawing on infrastructure far beyond national scale. It also made collaboration among Czech institutions increasingly valuable because observing proposals, instrumentation projects, and theoretical programmes often crossed formal institutional boundaries.

The major achievement of Czech astronomy, astrophysics, and cosmology between 1993 and 2025 was therefore the successful combination of domestic continuity with access to the observational and theoretical frontier. The Astronomical Institute preserved Ondřejov as a functioning national observatory while modernising its instruments and expanding its scientific programme. Solar physics developed from local optical and radio monitoring into globally coordinated multi-wavelength and space-based research. Stellar astrophysics retained strong spectroscopy while incorporating high-energy transients, large archives, and exoplanet characterisation. Relativistic astrophysics established an internationally connected Czech school concerned with black holes, accretion, radiation, and strong gravity. Galaxy research and high-energy astrophysics connected compact objects with star formation, gaseous atmospheres, clusters, and the cosmic web. University programmes in Prague, Brno, and Opava strengthened cosmology, general relativity, numerical astrophysics, and the education of new researchers. Membership of the European Southern Observatory gave Czech astronomers regular access to world-class facilities and encouraged technological, industrial, and institutional participation in European astronomy. By 2025, Czech astronomy consequently operated as a mature component of global astrophysics while retaining national

observational facilities and theoretical traditions capable of producing distinctive scientific contributions.

Astroparticle Physics and Cosmic-Ray Research

Astroparticle physics became one of the most internationally integrated areas of Czech physical science between 1993 and 2025 because its central questions could be addressed only through very large detectors and long-term multinational collaborations. The field occupies the boundary between particle physics, astrophysics, cosmology, and atmospheric science, using particles and high-energy photons from space as probes of phenomena inaccessible in terrestrial laboratories. Czech researchers developed particular strength in the study of ultra-high-energy cosmic rays and in the detector technologies required to observe the extensive particle cascades that these primaries create in the atmosphere. The Institute of Physics of the Czech Academy of Sciences became the principal national centre of this programme, working closely with Charles University and Palacký University Olomouc. The Pierre Auger Observatory in Argentina provided the major experimental platform for ultra-high-energy cosmic-ray research, while the Cherenkov Telescope Array became the principal Czech route into next-generation ground-based gamma-ray astronomy. These projects required expertise in optical systems, atmospheric monitoring, electronics, simulations, data analysis, and statistical reconstruction as well as in astrophysical interpretation. Czech participation consequently involved both the production of scientific results and the construction, maintenance, calibration, and upgrading of instruments. The field also illustrates a broader transformation of Czech physics from participation in individual foreign experiments towards sustained responsibility inside global research infrastructures. By 2025, Czech astroparticle physics had become a mature programme linking cosmic-ray composition, source searches, gamma-ray astronomy, detector development, and international infrastructure governance.

Cosmic rays are charged particles arriving at Earth from extraterrestrial sources and span an enormous range of energies and possible origins. At lower energies their trajectories are strongly altered by Galactic magnetic fields, making it difficult to identify individual sources directly from arrival direction. The most energetic particles known in nature reach energies above 10^18 electronvolts and are conventionally classified as ultra-high-energy cosmic rays. Their flux is extremely small, so direct detection in space becomes impractical at the highest energies and the atmosphere itself must be used as part of the detector. When a primary nucleus strikes an atmospheric particle, it initiates an extensive air shower containing billions of secondary particles distributed over a large area. The electromagnetic component consists mainly of electrons, positrons, and photons, while muons and hadrons provide additional information about the primary particle and the underlying interaction physics. Measurements of the energy spectrum reveal features commonly known as the ankle, the instep, and the high-energy suppression, each of which may contain information about source populations and propagation. The mass composition of the incoming flux is equally important because protons and heavier nuclei are deflected differently and generate measurably different atmospheric showers. Arrival-direction anisotropy can reveal whether the highest-energy particles originate predominantly within the Milky Way or from extragalactic environments. Czech researchers entered this scientific problem through an experimental strategy in which accurate detector

calibration and atmospheric characterisation were as important as the final astrophysical interpretation.

The Pierre Auger Observatory near Malargüe in Argentina became the decisive infrastructure for this Czech programme. Its surface detector extends across roughly 3,000 square kilometres and uses a large array of water-Cherenkov stations to sample secondary particles reaching the ground. A complementary fluorescence detector observes the faint ultraviolet light emitted when shower particles excite nitrogen molecules in the atmosphere. The combination of the two methods makes Auger a hybrid observatory because selected events are reconstructed simultaneously from their particle footprint at ground level and from their longitudinal development through the atmosphere. Surface stations operate with a very high duty cycle and provide the large event statistics required for rare ultra-high-energy particles. Fluorescence telescopes operate mainly during clear, dark nights but provide a near-calorimetric estimate of shower energy and a direct measurement of the atmospheric depth at which the cascade reaches maximum development. That depth, conventionally denoted Xmax, is one of the principal observables used to infer cosmic-ray mass composition. The complementary strengths of the two detector systems made Auger exceptionally powerful for studying the energy, mass, arrival direction, and interaction properties of the most energetic particles.

Czechia participated in the Pierre Auger Observatory from the formative period of the project and gradually assumed responsibilities that extended well beyond data analysis. The Institute of Physics became the host institution of the national AUGER-CZ research infrastructure, representing Czech participation in the Pierre Auger Observatory, with Charles University and Palacký University Olomouc as major partners. Czech optical expertise was particularly important in the construction of the fluorescence detector. Glass mirror technology developed in Czech laboratories and industry was used in fifteen of the twenty-seven fluorescence telescopes operating within the Observatory. The Joint Laboratory of Optics of the Institute of Physics and Palacký University contributed to mirror preparation, optical testing, coatings, and long-term assessment of mirror performance. Czech groups also accepted substantial responsibility for operation and maintenance of the fluorescence detector system over many years. This work required regular presence at the remote Argentine site, coordination with other national teams, calibration campaigns, and the management of detector performance over long operating periods. The technological contribution therefore became a durable institutional commitment rather than a one-time delivery of components. National support was formalised further when AUGER-CZ was included in the Czech Roadmap of Large Research Infrastructures from 2010. The infrastructure helped finance participation in detector operations, upgrades, atmospheric monitoring, computing, and scientific analysis. This combination of hardware responsibility and physics analysis became characteristic of Czech involvement in international astroparticle research.

Atmospheric monitoring became one of the areas in which Czech groups developed especially recognisable expertise. Fluorescence measurements depend on the transmission of ultraviolet light through tens of kilometres of atmosphere, so aerosols, clouds, humidity, and molecular density directly influence reconstructed shower energy and longitudinal development. Czech researchers developed and operated robotic telescopes known as FRAM, meaning F/Photometric Robotic Atmospheric Monitor. These instruments use stars as calibrated light sources to determine atmospheric transparency without illuminating the sky with an artificial beam. The method is particularly suitable for observatories where additional

light could interfere with normal data taking. Czech teams also developed all-sky cameras capable of monitoring cloud cover across a very wide field and relating local atmospheric conditions to detector performance. Similar expertise was applied to lidar systems, background cameras, and methods for evaluating fluorescence light transmission. The resulting programme placed optical astronomy techniques inside an experiment whose primary aim is particle astrophysics. It also created a technological bridge from the Pierre Auger Observatory to the later Cherenkov Telescope Array programme.

The scientific analysis of Auger data placed Czech physicists directly inside the central questions of ultra-high-energy cosmic-ray research. One major objective was to determine whether the highest-energy particles are predominantly protons or contain substantial fractions of heavier nuclei. Heavy nuclei generally produce showers that reach maximum development higher in the atmosphere and display smaller event-to-event fluctuations than proton showers of the same energy. Auger therefore measures distributions of Xmax and compares them with simulations based on models of hadronic interactions. Surface-detector observables provide additional information because muons and the timing structure of particle signals depend upon primary mass. In 2016, the collaboration reported evidence that the composition around the ankle could not be described adequately by a single nuclear species or by only protons and helium. Czech collaboration members were co-authors of this result and participated in the broader programme of composition-sensitive analysis. Later measurements increasingly suggested a trend towards heavier and less mixed compositions at the highest energies, although interpretation remains dependent on uncertainties in hadronic-interaction models. The problem is therefore simultaneously astrophysical and particle-physical because uncertainties in the microscopic interaction of nuclei with air influence conclusions about cosmic sources. Czech analysis groups contributed to both sides of this inference problem.

The energy spectrum provides a second fundamental observable because changes in its slope can reveal transitions between source populations or energy-loss processes during propagation. Auger measurements confirmed the ankle at energies of several exaelectronvolts and characterised the suppression of the flux at the highest energies with unprecedented statistics. The suppression can arise from limits on the maximum energies achieved by astrophysical accelerators, from energy losses during propagation through cosmic radiation backgrounds, or from a combination of both effects. Composition measurements are needed to distinguish among these possibilities because protons and heavy nuclei lose energy through different interaction channels. Czech researchers participated in analyses linking spectral features with the changing mass composition. They also contributed to simulations used to infer source properties from the combined spectrum and composition data. The resulting picture increasingly favoured astrophysical models in which several nuclear species are accelerated and modified during propagation. This is an important example of Czech science contributing to a global result through collaborative analysis rather than through a nationally isolated measurement.

Arrival directions provide the most direct route towards identifying the astronomical origin of cosmic rays, but magnetic deflection makes this task difficult. Charged particles do not travel in perfectly straight lines through Galactic and extragalactic magnetic fields, and the amount of deflection increases with electric charge and decreases with particle energy. Large event samples are therefore needed to search statistically for anisotropy rather than relying only on individual directional coincidences. In 2017, the Pierre Auger Collaboration reported a large-

scale dipole anisotropy in the arrival directions of cosmic rays above 8 × 10^18 electronvolts. The signal exceeded the conventional threshold for statistical discovery and had an amplitude of roughly 6.5 per cent. Its direction was inconsistent with a simple origin in the Galactic centre and provided strong evidence that particles above this energy are predominantly extragalactic. Czech researchers were members of the collaboration responsible for the measurement and participated in the continuing interpretation of arrival-direction data. Subsequent analyses examined intermediate angular scales and compared the observed sky with distributions of nearby starburst galaxies, active galactic nuclei, and other possible source populations. No unique class of sources had been established by 2025, partly because magnetic deflection and uncertain mass composition blur directional information. The value of the Auger programme therefore lies as much in constraining possible source scenarios as in searching for a single definitive counterpart. Combining improved composition estimates with anisotropy measurements is expected to increase the sensitivity of future source searches.

Ultra-high-energy air showers also allow particle interactions to be tested at centre-of-mass energies well beyond those reached directly by terrestrial accelerators. The interpretation requires extrapolating hadronic-interaction models from collider measurements to much higher energies and to collisions involving nuclei rather than only protons. Auger data revealed persistent differences between observed showers and simulations, especially in the number of muons reaching ground level. A major 2016 analysis found that leading interaction models tuned to Large Hadron Collider data underestimated the hadronic component required to reproduce measured showers. Czech physicists participated in this collaboration-wide programme and later developed analyses focused specifically on muon content, shower maxima, and hadronic-model consistency. The discrepancy does not by itself prove new particle physics because uncertainties in multiparticle production accumulate strongly during the many generations of an atmospheric cascade. It nevertheless makes cosmic-ray observations an important complement to accelerator experiments. By the 2020s, Czech researchers were using composition-sensitive observables and machine-learning techniques to test interaction models over a very broad energy range. Astroparticle physics thus allowed the Czech community to connect astrophysical measurements with questions normally associated with high-energy particle physics.

The application of machine learning became particularly important as the collaboration sought composition information from the enormous surface-detector dataset. Fluorescence measurements provide excellent sensitivity to Xmax but are limited by their relatively small observational duty cycle. Surface detectors operate almost continuously and therefore record many more events, including the rarest particles at the highest energies. Deep neural networks can learn correlations between the time-dependent signals in the water-Cherenkov stations and the longitudinal development of simulated air showers. After calibration against hybrid events, these methods can infer Xmax for individual events detected only by the surface array. In 2025, the Pierre Auger Collaboration published measurements extending such event-by-event Xmax inference to energies approaching 10^20 electronvolts. The analysis increased the available statistics by roughly an order of magnitude compared with fluorescence-only measurements in the relevant range. It supported the conclusion that the average composition becomes heavier and its fluctuations smaller towards the highest energies. Czech collaboration members contributed to this wider programme of composition and interaction studies, including researchers at the Institute of Physics. The result demonstrates how

detector data collected by infrastructure designed decades earlier can acquire new scientific value through modern computational methods.

The AugerPrime upgrade was designed to reduce the composition ambiguities that remained after the first major phase of the Observatory. Its most visible component is the installation of a plastic scintillator detector above each principal water-Cherenkov surface station. Scintillators and water-Cherenkov detectors respond differently to the electromagnetic and muonic components of an air shower, allowing those contributions to be separated more effectively. The upgrade also introduced new station electronics, additional small photomultipliers, underground muon detectors in a denser sub-array, and radio antennas for measuring coherent emission from showers. Improvements to the fluorescence detector increased the potential observing time and extended its contribution to cross-calibration. Czech teams participated in upgrade work, including testing new electronics and maintaining the optical and atmospheric systems on which precise reconstruction depends. The objective was not simply to extend the Observatory's lifetime but to transform each high-energy event into a richer measurement of particle type and shower physics. AugerPrime consequently prepared Czech cosmic-ray research for a second observational phase focused more directly on composition-tagged anisotropy and source identification.

Detector development around Auger also encouraged Czech researchers to explore lower-cost concepts for future enormous cosmic-ray observatories. The Fluorescence detector Array of Single-pixel Telescopes, abbreviated as FAST, was developed internationally as a simplified fluorescence concept using a much smaller number of camera pixels than conventional Auger telescopes. Czech opticians contributed to optical design, mirror technology, simulations, calibration concepts, and prototype work. The scientific motivation is straightforward because the flux of the most energetic cosmic rays is so small that substantially larger collecting areas are required for major statistical gains. Conventional fluorescence stations are technically sophisticated and expensive, making direct replication over vastly larger territories difficult. A simplified telescope could potentially trade some image detail for much larger instrumented area. Czech groups used the expertise accumulated through Auger mirror systems and atmospheric calibration when addressing this problem. Prototype activities linked Olomouc optical laboratories with international cosmic-ray groups in Japan, the United States, and Argentina. Such research shows that detector innovation had become an independent scientific output of Czech astroparticle physics. It also created technologies potentially relevant to observatories beyond Pierre Auger itself.

The Cherenkov Telescope Array (CTA) opened a complementary branch of Czech astroparticle physics centred on very-high-energy gamma rays rather than charged cosmic rays. Gamma rays are electrically neutral and therefore preserve information about the direction of their astrophysical sources during propagation. At energies from tens of gigaelectronvolts into the teraelectronvolt regime, however, their flux becomes too small for satellite detectors of practical size to collect large samples. Ground-based observatories instead detect the extensive air showers produced when gamma rays interact in the atmosphere. Relativistic charged particles in those showers emit brief flashes of Cherenkov light when they travel through air faster than the local phase velocity of light. Imaging Atmospheric Cherenkov Telescopes, commonly abbreviated as IACTs, record the shape and orientation of those flashes with fast optical cameras. Stereoscopic observations by several telescopes improve reconstruction of the shower direction, energy, and impact point. Image morphology and timing can also discriminate gamma-ray showers statistically from the much more numerous

showers generated by charged cosmic rays. The technique therefore transforms the atmosphere into both a calorimeter and an optical radiator whose performance depends critically on telescope optics, camera response, Monte Carlo simulation, and knowledge of atmospheric transparency.

The Cherenkov Telescope Array Observatory, abbreviated as CTAO, was conceived as the next major leap beyond existing instruments such as the High Energy Stereoscopic System, the Major Atmospheric Gamma Imaging Cherenkov telescopes, and the Very Energetic Radiation Imaging Telescope Array System. Its design uses arrays in both hemispheres so that most of the sky can be observed at very high energies. CTAO-North is being developed at the Roque de los Muchachos Observatory on La Palma in Spain, while CTAO-South is being developed near the European Southern Observatory site at Paranal in Chile. The full concept covers an approximate energy range from 20 gigaelectronvolts to 300 teraelectronvolts. Different telescope sizes are required because the optimum collecting geometry changes strongly with photon energy. Large-Sized Telescopes are designed principally for the lower-energy end, where Cherenkov flashes are faint and very large mirror areas are needed. Medium-Sized Telescopes cover much of the central energy range where many known gamma-ray sources emit strongly. Small-Sized Telescopes are intended to cover a broad area in the southern array and detect the rarest showers at the highest energies. The array approach therefore combines optical aperture with ground coverage rather than attempting to build a single enormous telescope. CTAO is also intended to operate as an open observatory in which high-level data and analysis products are made available to a much wider astronomical community. This model represents an important institutional transition from collaboration-owned gamma-ray experiments towards a proposal-driven astronomical infrastructure.

Czech participation in CTA grew directly from expertise accumulated at the Pierre Auger Observatory. The Institute of Physics became the host institution for the national CTA-CZ research infrastructure, representing Czech participation in the Cherenkov Telescope Array, while Charles University, Palacký University Olomouc, and the Astronomical Institute of the Czech Academy of Sciences contributed specialised expertise. Czech researchers joined scientific working groups, simulation programmes, site-selection studies, optical development, and atmospheric monitoring. The Joint Laboratory of Optics in Olomouc adapted its experience with large segmented mirrors to the requirements of Cherenkov telescopes. Researchers manufactured or tested mirror prototypes, investigated reflective and protective coatings, and developed methods for evaluating optical quality and environmental durability. The same groups also developed camera and alignment concepts connected with large telescope optical systems. Czech Education and Scientific Network (CESNET) computing and network infrastructure supported the data-intensive side of Czech participation. This combination meant that CTA-CZ was never only an astrophysical observing programme. It was simultaneously a detector-development, optical-engineering, atmospheric-science, computing, and data-analysis programme.

Site characterisation became one of the earliest Czech contributions to CTA because a Cherenkov observatory requires exceptionally well-understood night-sky and atmospheric conditions. Czech all-sky cameras were installed at candidate sites in Namibia, Argentina, Chile, Mexico, the United States, and the Canary Islands. Their images were analysed to estimate cloud coverage and the optical quality of potential observing locations. FRAM telescopes provided a complementary method in which calibrated stellar photometry measures aerosol extinction along selected lines of sight. The technique is non-invasive

because it does not produce laser light that would interrupt astronomical observations. Czech researchers later demonstrated a wide-field photometric method capable of determining vertical aerosol optical depth with high precision during clear nights. Atmospheric monitoring is not an auxiliary meteorological task in gamma-ray astronomy because changes in transparency alter the measured brightness of Cherenkov flashes and can bias reconstructed energies. Real-time knowledge of clouds and aerosols is therefore required both for data-quality decisions and for quantitative corrections. The methods developed within Czech groups were designed to operate robotically, reducing the need for continuous human supervision at remote observatory sites. These systems transferred directly the Czech experience gained through fluorescence detection at Pierre Auger into the new context of gamma-ray Cherenkov astronomy. Atmospheric instrumentation consequently became one of the strongest technological continuities linking the two major Czech astroparticle projects. It also established a specialised Czech role within collaborations whose principal telescopes were constructed through contributions from many countries.

Mirror technology provided another direct line of continuity between Auger and CTAO. Cherenkov telescopes require large optical collecting areas, but conventional monolithic astronomical mirrors would be unnecessarily expensive and heavy for arrays containing many instruments. Their reflectors are therefore assembled from numerous segments whose optical figure, alignment, reflectivity, durability, and cost must be optimised simultaneously. Czech laboratories developed methods for manufacturing and testing candidate mirror structures and coatings under environmental conditions relevant to long-term field operation. The work included measurements of reflectance, focal quality, surface deformation, ageing, and protective-layer performance. Experience with the Czech mirror segments used in the Pierre Auger fluorescence telescopes provided a valuable practical baseline. The technological challenge differs from conventional optical astronomy because Cherenkov pulses last only a few nanoseconds and the telescope must image a relatively broad field rather than achieve diffraction-limited resolution. Cost-effective serial production is consequently as important as exceptional optical quality. This engineering perspective allowed Czech groups to make contributions whose influence extended across an entire telescope array.

The Czech optical contribution became particularly visible in the Large-Sized Telescope (LST) programme at CTAO-North. Each Large-Sized Telescope uses a parabolic reflector approximately twenty-three metres in diameter assembled from nearly two hundred individual mirror segments. Czech specialists from the Joint Laboratory of Optics participated in responsibility for the optical system, including mirror testing, preparation, and installation procedures. The first Large-Sized Telescope had already provided an operational prototype on La Palma before the remaining three instruments were assembled. During 2025, mirror installation was completed on LST-2, LST-3, and LST-4. The work required each segment to be positioned with millimetre-scale mechanical accuracy before the active mirror-control system could refine the optical alignment. Czech participation therefore extended from laboratory characterisation in Olomouc to installation at the final observing site in the Canary Islands. The completed four-telescope configuration is intended to provide rapid sensitivity to low-energy gamma rays and transient phenomena. It will be especially important for variable sources such as gamma-ray bursts, active galactic nuclei, and Galactic compact objects. The 2025 milestone demonstrated that Czech optical expertise had moved from prototype research into the construction of a major European astronomical facility.

Small telescope development supplied a parallel experimental pathway within Czechia itself. The Single-Mirror Small-Size Telescope, abbreviated as SST-1M, was developed by an international collaboration as one possible approach to the high-energy part of CTA. Its four-metre Davies–Cotton reflector feeds a camera based on silicon photomultipliers rather than traditional vacuum photomultiplier tubes. Although CTAO ultimately selected a different concept for its production Small-Sized Telescopes, two SST-1M prototypes retained substantial scientific and technological value. In 2022, both telescopes were installed at Ondřejov Observatory and commissioned as a stereoscopic system. Czech researchers at the Institute of Physics and the Joint Laboratory of Optics became closely involved in operation, calibration, simulation, and data analysis. The relatively low altitude of Ondřejov made the site unusually demanding for very-high-energy gamma-ray detection and therefore useful for validating detailed atmospheric and detector models. Observations of the Crab Nebula between 2023 and 2024 produced a clear astrophysical benchmark for the system. A peer-reviewed 2025 analysis demonstrated gamma-ray observations in both single-telescope and stereoscopic modes. The experiment therefore converted equipment originally developed for CTA into a functioning Czech gamma-ray testbed. It also allowed students and engineers to work directly with imaging atmospheric Cherenkov telescopes without travelling to a distant international site. SST-1M consequently strengthened the domestic experimental basis of Czech gamma-ray astronomy even though it did not become the final CTAO production telescope.

Gamma-ray astronomy addresses astrophysical questions that overlap strongly with the cosmic-ray problem. Supernova remnants, pulsar wind nebulae, binary systems, stellar clusters, active galactic nuclei, and gamma-ray bursts can accelerate particles to energies vastly greater than those found in ordinary thermal plasmas. Gamma rays produced when those particles interact with matter or radiation can reveal the location and mechanism of acceleration. Hadronic acceleration is of particular interest because interactions of energetic protons and nuclei can create neutral pions that decay into gamma rays. Leptonic processes such as inverse Compton scattering can produce similar high-energy photons from relativistic electrons. Distinguishing these mechanisms often requires detailed spectra, morphology, time variability, and observations at other wavelengths. CTAO was designed to provide substantial improvements in sensitivity and angular and energy resolution across several decades of photon energy. Czech physicists participate in this scientific programme through simulations, analysis methods, source modelling, and detector development. The connection with cosmic-ray physics is therefore fundamental rather than merely institutional. Gamma-ray observations can identify candidate particle accelerators, while Auger measures the charged particles that may have escaped from such environments and propagated to Earth.

The search for PeVatrons is one of the most important examples of this connection. A PeVatron is an astrophysical accelerator capable of producing particles with energies approaching 10^15 electronvolts or higher. Such sources are required to explain the Galactic cosmic-ray spectrum up to the region commonly known as the knee. Gamma rays extending into the multi-teraelectronvolt range without a strong spectral cut-off can provide evidence for particles accelerated to much higher energies. CTAO-South is particularly important for this problem because it will observe the central regions of the Milky Way with a dense array of telescopes. Its Small-Sized Telescopes are designed to provide the collecting area needed for rare photons at the highest energies. Czech detector and analysis work therefore contributes indirectly to the search for the sources of Galactic cosmic rays. The same observations can test whether

supernova remnants alone can explain the required acceleration or whether other source classes such as pulsar wind nebulae, stellar clusters, microquasars, and the Galactic Centre are necessary. High-energy gamma-ray astronomy consequently offers a directional complement to the composition and anisotropy information obtained from charged cosmic rays.

Extragalactic gamma-ray sources extend the programme towards active galactic nuclei, relativistic jets, and transient events over cosmological distances. Very-high-energy photons from active galactic nuclei can vary rapidly, implying that the emitting regions are compact and dynamically extreme. Their spectra also carry information about absorption by diffuse extragalactic background light during propagation. Gamma-ray bursts present an even greater observational challenge because some events evolve on timescales of seconds or minutes. Large-Sized Telescopes were designed with rapid repositioning in mind so that CTAO can respond to external alerts from satellites and other observatories. Czech participation in the LST optical system therefore has a direct scientific connection to time-domain astrophysics. Fast follow-up can also link gamma-ray observations with gravitational-wave or neutrino alerts. This multi-messenger approach seeks common sources through independent carriers that respond differently to magnetic fields and intervening matter. The Pierre Auger Observatory already participated in searches for ultra-high-energy neutrinos associated with transient phenomena, including the 2017 binary-neutron-star merger observed through gravitational waves. CTAO will add highly directional gamma-ray sensitivity to this international network. Czech astroparticle physics consequently became increasingly connected with a broader transformation of astronomy from isolated wavelength bands towards coordinated transient observation.

The search for neutral particles is also important within the Auger programme itself. Ultra-high-energy photons would generate atmospheric showers with characteristics that differ from those initiated by ordinary hadronic nuclei. Neutrinos can penetrate deeply through matter and may produce distinctive deeply developing or Earth-skimming air showers. The absence or detection of such events constrains models of cosmic-ray sources, propagation, and exotic physics. Auger has therefore conducted systematic searches for photons and neutrinos in addition to its primary charged-particle programme. These channels are especially valuable because neutral particles preserve source-direction information much better than charged nuclei. Czech collaboration members participate within the common detector, reconstruction, and analysis framework supporting these searches. The resulting programme places the Observatory within multi-messenger astrophysics even though its principal scientific identity remains ultra-high-energy cosmic-ray research.

Data analysis and simulation provide the common methodological core of both Pierre Auger and CTAO. Extensive air showers cannot be reconstructed directly from first principles for each observed event because the cascade contains enormous numbers of particles and depends probabilistically on hadronic and electromagnetic interactions. Monte Carlo frameworks therefore simulate primary interactions, particle propagation, Cherenkov and fluorescence light production, atmospheric transmission, and detector response. For Auger, simulations connect measured ground signals and longitudinal profiles with energy, mass, and hadronic-interaction parameters. For CTAO, they are essential for converting camera images into reconstructed gamma-ray direction and energy while suppressing the dominant cosmic-ray background. Czech researchers contributed to large simulation campaigns used in optimisation of the CTA array layout and evaluation of detector performance. They also

developed machine-learning approaches for composition inference, gamma–hadron separation, and increasingly complex reconstruction tasks. Computing infrastructure and high-speed networking therefore became as indispensable as mirrors, cameras, and particle detectors. The participation of CESNET and Czech computing centres allowed national groups to remain integrated in these distributed workflows. Modern astroparticle physics thus relies on a virtual experimental infrastructure layered on top of the physical observatories. This combination of instrumentation and computation has become an important training environment for Czech students entering data-intensive physics.

The atmosphere itself became a scientific and instrumental object because both major Czech astroparticle programmes use it as part of their detectors. At Pierre Auger, fluorescence light must propagate through the atmosphere from an extensive air shower to telescopes kilometres away. At CTAO, Cherenkov light emitted high above the ground must survive molecular scattering, aerosols, and clouds before reaching the optical cameras. Uncorrected atmospheric variation can therefore mimic changes in primary energy or distort the reconstructed spectrum of an astronomical source. Czech researchers developed passive photometric techniques, all-sky cloud monitoring, optical calibration methods, and associated analysis software to quantify these effects. This work required collaboration with atmospheric scientists as well as with particle physicists and astronomers. It also created transferable expertise because the same calibration principles can support multiple observatories using atmospheric light. The Czech contribution is notable precisely because it addresses a systematic uncertainty that is scientifically essential but less publicly visible than a telescope or particle detector. By 2025, atmospheric characterisation had become one of the most recognisable technical specialisations of the Czech astroparticle community. This expertise strengthened Czech participation in international detector working groups and helped connect Auger experience with CTAO requirements.

The formal establishment of the Cherenkov Telescope Array Observatory as a European Research Infrastructure Consortium on 7 January 2025 marked an important institutional milestone for Czech participation. Czechia became one of the founding members together with Austria, France, Germany, Italy, Poland, Slovenia, Spain, and the European Southern Observatory. The new legal structure gave CTAO a stable organisation responsible for construction and future operation rather than leaving the project dependent on a preparatory collaboration alone. Czech institutions therefore entered not merely as scientific partners but as participants in the governance framework of a European research infrastructure. This status also secured a long-term setting for national contributions to hardware, software, atmospheric systems, and science exploitation. The observatory retained a global character because partners from outside Europe continued to contribute to telescope development and scientific planning. By 2025, the broader CTAO Consortium included around 1,500 researchers and engineers from more than 150 institutes in roughly twenty-five countries. Czech membership in such an organisation illustrates how specialised national expertise can be embedded in a facility whose physical sites are located abroad. The legal milestone also paralleled Czech involvement in other European research infrastructures and reinforced astroparticle physics as a strategic component of national large-infrastructure policy. It additionally gave Czech researchers a formal route into the long-term scientific and technical planning of the Observatory. The transition from CTA design studies to CTAO ERIC therefore closed an important institutional phase of Czech gamma-ray astronomy and opened the period of construction and operations.

The national research community supporting these projects became increasingly interconnected during the 2010s and early 2020s. The Institute of Physics concentrated much of the cosmic-ray analysis, detector development, CTA coordination, and international infrastructure responsibility. The Joint Laboratory of Optics linked the Institute with Palacký University and supplied a strong experimental base for mirrors, coatings, calibration, and optical instrumentation. Charles University contributed particle and nuclear physics expertise together with researchers involved in CTAO scientific programmes. The Astronomical Institute added astrophysical interpretation and participation in gamma-ray astronomy, strengthening the connection with conventional observational astronomy. Students could therefore move between cosmic-ray physics, particle physics, optics, and astrophysics without leaving the Czech research environment. Collaboration meetings and joint projects reduced the institutional separation between detector specialists and scientists focused primarily on source physics. This network also helped transfer expertise from Auger to CTAO and from large international experiments back into domestic laboratories. Czech astroparticle physics consequently developed as a distributed national programme rather than as the activity of one isolated research group.

International collaboration has been fundamental because neither the Pierre Auger Observatory nor CTAO could be built, operated, or scientifically exploited by a single country. The Pierre Auger Collaboration includes hundreds of researchers from institutions across Europe, the Americas, and other participating regions. Detector construction, maintenance, calibration, simulation, and analysis are divided among national teams with responsibilities that must remain compatible over decades. Czech groups gained scientific influence by accepting technically demanding tasks whose successful completion benefits the entire collaboration. CTAO follows a related model but adds the institutional logic of an open astronomical observatory and a European Research Infrastructure Consortium. Hardware is supplied through international in-kind collaborations, while central organisation coordinates systems engineering, construction, data management, and operations. The Czech role in mirrors and atmospheric monitoring is therefore embedded in a much larger division of labour involving telescope structures, cameras, software, and site infrastructure. Such cooperation requires common technical standards and transparent validation because a failure in one subsystem can degrade scientific performance across the observatory. Astroparticle physics has thus provided Czech researchers with sustained experience in the governance and engineering culture of very large international scientific projects. This institutional competence is itself an important achievement of the field.

Between 1993 and 2025, Czech astroparticle physics therefore evolved from participation in an emerging cosmic-ray project into a broad research programme spanning ultra-high-energy particles and very-high-energy gamma rays. The Pierre Auger Observatory gave Czech teams a central platform for investigating cosmic-ray spectrum, mass composition, arrival directions, hadronic interactions, photons, neutrinos, and multi-messenger phenomena. Czech optical systems, fluorescence-detector responsibilities, atmospheric monitors, and upgrade work made that participation technological as well as analytical. The 2017 observation of large-scale anisotropy provided strong evidence for an extragalactic origin of cosmic rays above 8 × 10^18 electronvolts, while composition studies progressively revealed a complex mixture of nuclei. Measurements of excessive muon content relative to current hadronic models demonstrated that the same data can test particle interactions at energies beyond accelerator reach. AugerPrime and modern machine-learning methods opened a new phase in which

composition information can be extracted from much larger event samples. CTA and later CTAO extended Czech expertise into directional gamma-ray astronomy through mirrors, atmospheric monitoring, simulations, telescope operation, and scientific analysis. The SST-1M system at Ondřejov created a domestic experimental bridge to imaging atmospheric Cherenkov astronomy, while Czech responsibility for Large-Sized Telescope optics connected national laboratories directly with construction on La Palma. Czechia's role as a founding member of CTAO ERIC in 2025 gave these scientific and technical contributions a durable institutional framework, making astroparticle physics one of the clearest examples of Czech science combining specialised detector technology with internationally significant research on the most energetic phenomena in the Universe.

Nanophysics, Nanotechnology, and Nanoscale Characterisation

Nanophysics and nanotechnology became increasingly important components of Czech condensed-matter and materials research between 1993 and 2025. Their development reflected a broader international shift from studying bulk properties towards controlling matter at dimensions where surfaces, interfaces, quantum confinement, and individual defects can determine the behaviour of an entire device. Czech physicists entered this transition with established strengths in semiconductor physics, thin films, crystallography, magnetism, surface science, electron microscopy, and materials engineering. During the 1990s, these traditions increasingly converged with lithography, scanning-probe methods, nanoscale deposition, and computational modelling. The Institute of Physics of the Czech Academy of Sciences (FZU) became a principal centre of this development in Prague, while Brno University of Technology (BUT), Masaryk University, and the Central European Institute of Technology (CEITEC) created a second major concentration of nanoscience. The progressive availability of clean rooms and high-resolution microscopes changed the scale at which Czech researchers could design and test physical structures. Nanostructures could now be fabricated intentionally, modified at surfaces and interfaces, and correlated with local electronic, magnetic, optical, or mechanical properties. The field consequently developed at the intersection of fundamental physics, materials science, electrical engineering, chemistry, and instrumentation. By 2025, Czech nanophysics had become an infrastructure-intensive research domain in which the ability to fabricate and characterise matter at the nanometre and atomic scales was itself a major national scientific capability.

The physical significance of the nanoscale arises because reducing a material to dimensions of a few nanometres can change the mechanisms that govern its behaviour. A surface contains atoms with a different coordination environment from atoms inside the bulk, so its electronic and chemical properties can differ substantially from those of the underlying crystal. Interfaces between two materials can create electronic states, strain, charge transfer, magnetic coupling, or structural reconstructions that do not exist in either component separately. Quantum confinement can discretise electronic energy levels when the characteristic dimensions of a semiconductor approach the wavelength of its charge carriers. The motion of electrons can also become sensitive to individual defects, grain boundaries, surface roughness, or atomic-scale variations in composition. Thermal and mechanical behaviour changes because the ratio between surface area and volume rises sharply as structures become smaller. These effects mean that nanotechnology is not simply conventional

engineering performed with smaller tools. It requires a physical understanding of how collective bulk properties emerge from local structure and how those properties change when dimensionality is reduced. Czech research increasingly focused on this relationship between geometry, atomic arrangement, and functionality. The resulting nanophysics programme therefore developed as a natural extension of established Czech work in solids while simultaneously creating new links with device engineering and advanced characterisation.

One of the most important institutional steps was the creation of the Laboratory of Nanostructures and Nanomaterials (LNSM) at FZU in 2008. The infrastructure brought together laboratories that had previously developed complementary expertise in semiconductor nanostructures, thin films, electron microscopy, nanocrystalline materials, lithography, and scanning-probe methods. In 2010, LNSM was included in the Czech Roadmap of Large Infrastructures, giving its open-access role a formal national framework. From 2012, its operation under an open-access model received dedicated support from the Ministry of Education, Youth and Sports. The laboratory was designed not only as an internal facility for FZU researchers but as a platform available to universities, research organisations, and industrial users. Its structure allowed materials to move through several stages from growth and patterning to local microscopy, spectroscopy, transport measurements, and theoretical interpretation. This organisation was particularly valuable because nanoscale experiments often depend on several methods that cannot be separated cleanly into independent projects. LNSM therefore represented an early Czech move towards treating nanofabrication and nanocharacterisation as shared research infrastructure rather than as equipment owned by individual groups.

Semiconductor nanostructures formed one of the original scientific cores of LNSM and connected nanophysics directly with the earlier Czech tradition in semiconductor materials. Molecular Beam Epitaxy (MBE) allowed crystalline layers to be grown in Ultra-High Vacuum under carefully controlled fluxes of constituent atoms. The method made it possible to prepare gallium arsenide and aluminium gallium arsenide heterostructures as well as magnetic semiconductor layers relevant to spintronics. Metalorganic Vapour Phase Epitaxy (MOVPE) provided a complementary route to compound-semiconductor structures and devices. By controlling layer thickness, composition, strain, and doping, researchers could engineer electronic states that did not occur in the corresponding bulk materials. Interfaces only a few atomic layers thick became active elements whose quality could determine carrier mobility, optical emission, or magnetic response. Semiconductor growth therefore required continuous feedback from structural analysis, surface science, and electronic measurements. Czech groups used these capabilities in research on heterostructures, quantum-confined systems, spin-dependent transport, and optoelectronic materials. The same infrastructure also supported preparation of test structures whose lateral dimensions were defined subsequently by lithographic processes. This combination of epitaxial growth and device patterning moved Czech semiconductor physics progressively towards nanoelectronics rather than limiting it to the study of bulk crystals. It also supplied materials and microstructures used in the development of antiferromagnetic spintronics described elsewhere in this book.

Carbon-based nanomaterials and diamond added a second family of structures with very different physical properties. Chemical Vapour Deposition (CVD) and related plasma processes at FZU were used to prepare nanocrystalline diamond, silicon-containing structures, carbon materials, and composite systems. Diamond combines exceptional hardness and thermal conductivity with a wide electronic band gap and surfaces that can be

chemically functionalised. At the nanoscale, these properties make it relevant to sensors, electrodes, heat management, photonics, and bioelectronic interfaces. Graphene and other carbon nanostructures introduced low-dimensional electronic systems whose transport is strongly influenced by surface adsorption and local defects. Czech laboratories therefore developed deposition and characterisation methods capable of controlling surface chemistry as well as bulk composition. Scanning-probe and electron microscopy supplied information about morphology, grain structure, and local properties. Electrical and optical measurements then connected these structural observations with device behaviour. Carbon nanomaterials consequently became another area in which physics, surface chemistry, and engineering could be studied within the same infrastructure.

Lithography provided the essential transition from material preparation to deliberately designed nanoscale devices. Optical lithography remained valuable for micrometre structures and for many processing steps that did not require the finest dimensions. Electron Beam Lithography (EBL) allowed patterns to be written at much smaller scales by exposing an electron-sensitive resist with a tightly focused beam. Reactive-ion etching, ion milling, and lift-off processes could then transfer those patterns into semiconductors, metals, dielectrics, or magnetic layers. Focused Ion Beam (FIB) methods offered a complementary route for local milling, deposition, and preparation of microscopic specimens. FZU and CEITEC laboratories developed workflows in which lithographic definition could be combined with contact metallisation and electrical connection to macroscopic measurement equipment. Such processing was required for spintronic devices, nanoscale sensors, test transistors, plasmonic structures, and low-dimensional transport experiments. The ability to fabricate contacts is scientifically crucial because a nanostructure cannot function as an electronic device if its local state cannot be addressed reproducibly from the external circuit. Clean-room operation also becomes essential because a dust particle may be much larger than the feature being manufactured and can destroy an entire device. Czech nanotechnology therefore required not only sophisticated instruments but also process discipline, contamination control, calibration, and repeatable fabrication recipes. By the 2010s, nanolithography had become a routine enabling technology for several branches of Czech experimental physics. It linked the abstract design of a device directly with measurable electrical, optical, or magnetic functionality.

Surfaces and interfaces became a distinct scientific subject because nanoscale systems often contain more boundary atoms than bulk material in the active region. Surface-sensitive experiments therefore sought to determine atomic arrangement, electronic states, chemical composition, and adsorption with minimal disturbance of the specimen. Ultra-High Vacuum environments reduced contamination sufficiently for well-defined surfaces to remain stable during preparation and measurement. X-ray Photoelectron Spectroscopy (XPS), low-energy electron methods, thermal desorption, and ion-scattering techniques provided complementary information about composition and bonding. Diffraction methods revealed the periodic arrangement of atoms and the reconstruction of surfaces after deposition or adsorption. Such measurements were frequently performed in situ so that a newly grown film could be analysed without exposure to ordinary atmosphere. This capability is especially important for ultrathin layers whose properties can change after only a small amount of oxidation or contamination. Czech surface science therefore became tightly connected with thin-film growth and nanodevice fabrication rather than operating as an isolated analytical discipline. Interfaces could be engineered deliberately and then examined before subsequent layers were added.

Scanning-probe microscopy gave Czech researchers a second route to surfaces by replacing the averaging inherent in many spectroscopic techniques with real-space measurements of local structure. Scanning Tunnelling Microscopy (STM) uses the quantum tunnelling current between a conducting tip and a surface to map electronic and topographic features with atomic-scale sensitivity. Atomic Force Microscopy (AFM) measures forces between a sharp probe and the sample and can therefore investigate conducting as well as insulating structures. LNSM developed low-temperature Ultra-High Vacuum STM and AFM systems for studying individual molecules and artificial nanostructures on surfaces. The measurements could be combined with theoretical simulations to separate true molecular structure from distortions produced by the flexible probe apex. Czech researchers contributed influential models explaining how functionalised tips generate the exceptionally detailed contrast observed in high-resolution molecular imaging. In 2016, an international team including FZU scientists demonstrated reconstruction of the electrostatic force field of individual molecules with submolecular resolution. These results showed that scanning-probe microscopy could provide information not only about where atoms are located but also about the local distribution of forces and charge. The Czech programme consequently moved from nanoscale imaging towards quantitative characterisation of molecular electronic structure. This work became one of the internationally visible methodological contributions of Czech nanophysics. It also demonstrated the value of combining experiment with atomistic calculation within the same research programme.

Scanning-probe methods also made it possible to manipulate and test individual nano-objects rather than merely image them. A functionalised tip can change the charge state of a molecule, move an adsorbate, probe mechanical response, or influence a chemical reaction on a surface. Such experiments provide direct access to phenomena that would be hidden in measurements averaged over billions of molecules. FZU groups investigated low-dimensional molecular structures, on-surface chemistry, single-electron charge states, and transport through molecules. Their theoretical tools included first-principles calculations and home-built simulation methods designed specifically for high-resolution probe images. These calculations helped identify which part of an observed contrast arose from electronic structure and which part resulted from the mechanical response of the probe itself. The resulting methodology supported collaborations with laboratories in the Netherlands, Germany, Japan, China, and other countries. Atomic-scale surface science thus became a Czech contribution to the broader effort to understand and control matter one molecule at a time. This research also provided conceptual links to molecular electronics and quantum technologies.

Electron microscopy became the other major pillar of nanoscale characterisation because high-energy electrons possess wavelengths far shorter than visible light. Scanning Electron Microscopy (SEM) provides high-resolution images of surfaces and can be combined with detectors for composition, crystallographic orientation, and local electrical contrast. Transmission Electron Microscopy (TEM) sends electrons through an electron-transparent specimen and can reveal internal structures, interfaces, defects, and nanoparticles. Scanning Transmission Electron Microscopy (STEM) focuses the electron beam into a fine probe and records signals point by point, making advanced elemental and structural mapping possible. Energy-Dispersive X-ray Spectroscopy (EDS) identifies chemical elements from characteristic X-rays emitted by the specimen. Electron Energy Loss Spectroscopy (EELS) extracts information from the energy lost by transmitted electrons and can probe composition, bonding, and electronic excitations. Focused ion beams can prepare site-specific TEM

lamellae only tens of nanometres thick from larger devices or materials. Czech laboratories combined these methods so that a failure, interface, precipitate, or defect first located at micrometre scale could subsequently be analysed at nanometre or atomic scale. Electron microscopy therefore became indispensable for establishing causal links between nanoscale structure and macroscopic material performance. It also supplied a common methodological language connecting physics, metallurgy, semiconductor engineering, and nanotechnology.

The Laboratory of Electron Microscopy within LNSM illustrates this integrated approach at FZU. Its instruments support structural and chemical analysis of metals, alloys, semiconductors, superconductors, oxides, minerals, thin films, and nanostructured materials. Researchers can determine phase composition, grain orientation, defect structures, magnetic domains, and local chemical variation. In situ microscopy extends these measurements by allowing a specimen to be heated, mechanically loaded, or otherwise modified while its microstructure is observed. Nanoindentation inside a microscope can correlate local deformation with structural features such as grains or interfaces. Such experiments are particularly valuable for nanocrystalline materials in which mechanical properties depend strongly on grain boundaries. Advanced sample preparation ensures that a region identified in a bulk object can be thinned without losing its structural context. The microscopy laboratory consequently operates not merely as an imaging service but as a platform for quantitative materials physics. Its role within LNSM also ensures that the same specimens can be connected with deposition, lithography, scanning-probe microscopy, and theoretical calculations.

Brno acquired a comparable but larger clean-room environment through the creation of CEITEC. The European Commission approved the main CEITEC project in 2011, and construction of its research facilities began during the following year. At BUT, the programme concentrated particularly on advanced materials, nanotechnologies, and microtechnologies. The CEITEC Nano laboratories entered full operation in 2016 and became the largest clean-room nanocentre in Czechia. They were designed as a single-site facility where nanostructures could be fabricated, characterised, structurally analysed, packaged, and tested without relying on unrelated laboratories scattered across several institutions. The infrastructure included dedicated nanofabrication and nanocharacterisation spaces, a structural-analysis laboratory, and X-ray computed tomography. Clean-room conditions were selected according to the sensitivity of individual processes, with the most demanding fabrication steps requiring very low particle concentrations. This environment allowed researchers to work with semiconductor wafers, ultrathin films, nanoparticles, nanowires, magnetic structures, and two-dimensional materials. CEITEC Nano also adopted an open-access model from the outset and served users from universities, research institutes, and companies. The facility therefore combined the logic of an academic laboratory with that of a national technological platform. Its creation substantially increased the capacity of Brno to participate in European nanoscience and advanced semiconductor research.

The nanofabrication programme at CEITEC covers both bottom-up and top-down approaches. Bottom-up fabrication exploits physical or chemical processes through which atoms, molecules, or nanoscale building blocks assemble into a desired structure. Physical Vapour Deposition (PVD), MBE, magnetron sputtering, CVD, plasma-enhanced deposition, and electrochemical methods allow researchers to control film growth and nucleation under different conditions. Such methods are used for ultrathin layers, semiconductor nanowires, nanotubes, quantum dots, metallic structures, and two-dimensional materials. Top-down fabrication begins with a larger material and defines smaller structures through lithography,

etching, or focused beams. Electron-beam lithography and scanning-probe techniques can generate features on the scale of tens of nanometres or below under suitable conditions. Combining both strategies is often essential because a device may require a self-organised material whose position is subsequently defined by lithography. CEITEC researchers therefore study not only how to make a structure but also how growth mechanisms, substrate properties, diffusion, and interfaces determine its final geometry. This process-oriented approach is central to nanotechnology because fabrication errors that are negligible in macroscopic engineering can dominate device behaviour at nanometre scales.

Nanocharacterisation at CEITEC was designed to follow the fabrication process step by step rather than being applied only to finished devices. Scanning-probe microscopes provide local maps of surface height, electrical potential, conductivity, magnetic behaviour, and mechanical properties. Electron microscopes reveal morphology, composition, defects, and crystallographic structure over complementary spatial scales. Surface-sensitive spectroscopies determine chemical states and contamination that can be invisible in ordinary imaging. X-ray methods add structural information from larger volumes and can be combined with computed tomography for three-dimensional inspection of components. Optical and magneto-optical techniques provide another layer of information for structures intended for photonics or spintronics. This combination allows a fabrication process to be interrupted, measured, corrected, and resumed before errors become embedded irreversibly in a complex device. The approach also supports failure analysis because the origin of a defective component can be traced from its macroscopic electrical behaviour back to a nanoscale structural feature. Such iterative feedback is one of the principal advantages of locating fabrication and characterisation within the same infrastructure. CEITEC Nano therefore functions as an experimental workflow rather than simply as a collection of expensive instruments.

Transmission electron microscopy became one of the most technologically demanding elements of this Brno infrastructure. The TITAN Themis 60-300 microscope installed for research use in 2016 provided high-resolution imaging and analytical capabilities for advanced materials. Its variable accelerating voltage allowed investigators to balance spatial resolution against beam damage in specimens with different sensitivities. Atomic-scale imaging could reveal interfaces, lattice defects, precipitates, and local structural distortions that directly influence electronic or mechanical properties. Spectroscopic and diffraction methods added information about chemical composition and crystal structure. Such capabilities are important to semiconductor research because nanoscale defects can control leakage, breakdown, carrier mobility, and long-term reliability. They are equally relevant to magnetic, energy, catalytic, and structural materials. In 2025, CEITEC Nano also installed a lower-voltage transmission electron microscope better suited to many low-contrast and light-element materials that do not require the full complexity of the TITAN system. This combination allowed instrument choice to be matched more closely to the physical problem and reduced pressure on the highest-end microscope, making electron microscopy both a frontier research tool and a routine part of a broader national characterisation service.

The growth of electron microscopy in Brno also connected academic nanophysics with a distinctive regional industrial ecosystem. Brno is an important centre for the development and manufacture of electron microscopes, creating opportunities for direct interaction between instrument producers and researchers who use advanced microscopy. CEITEC and BUT groups have collaborated with industrial specialists on non-destructive inspection, failure

analysis, and the development of new measurement techniques. Semiconductor devices provide an especially demanding test case because a defect may be buried inside a complex three-dimensional architecture and cannot simply be exposed without altering it. Scanning electron methods can first locate suspicious regions while preserving the component, after which a focused ion beam can prepare a cross-section for transmission microscopy. The resulting structural information can then be interpreted with specialists in defect physics and device engineering. This workflow illustrates how nanoscale characterisation can shorten the distance between fundamental materials science and industrial problem solving. It also provides manufacturers with access to experimental methods that would be difficult to justify within every individual company. The interaction is reciprocal because industrial requirements for speed, reproducibility, automation, and metrology generate new research questions for academic microscopy. Czech nanotechnology consequently benefited from an unusually close relationship between scientific infrastructure and a high-value instrumentation industry.

Nanoelectronics became one of the principal application domains in which these fabrication and microscopy capabilities converged. Conventional semiconductor technology continuously reduces device dimensions, making interfaces, surface roughness, strain, and atomic-scale defects increasingly consequential. Czech research also explores approaches that could complement conventional Complementary Metal–Oxide–Semiconductor (CMOS) technology rather than merely reproduce industrial manufacturing processes. Candidate systems include low-dimensional semiconductors, spintronic structures, single-electron devices, molecular junctions, graphene-based elements, and quantum-confined conductors. Test devices such as quantum point contacts or single-electron transistors allow fundamental transport phenomena to be examined under controlled geometries. Metallic and graphene nanoelectrodes can provide electrical access to molecules or magnetic nanostructures that would otherwise be inaccessible to macroscopic circuitry. Nanolithography makes the device geometry reproducible, while microscopy reveals whether the fabricated structure matches the intended design. Electrical measurements then determine how electrons actually move through the nanoscale system. The scientific value lies in connecting microscopic structure with transport rather than in competing directly with commercial semiconductor production. This research gives Czech physicists access to physical regimes in which charge, spin, dimensional confinement, and interfaces interact strongly. It also provides relevant expertise for the expanding Czech and European semiconductor ecosystem.

Two-dimensional materials widened this nanoelectronic landscape by offering crystals only one or a few atomic layers thick. Graphene became the most familiar example because its electronic structure produces high carrier mobility and unusual transport behaviour. Transition-metal dichalcogenides provide semiconducting, metallic, and sometimes magnetic alternatives that can be assembled into layered heterostructures. MXenes and other emerging two-dimensional systems further expand the available combinations of conductivity, surface chemistry, magnetism, and optical response. Czech groups in Brno and Prague investigate how these materials grow, interact with substrates, and respond to adsorbates or irradiation. Because nearly every atom in a two-dimensional material is close to a surface, environmental conditions and interfaces become central physical variables. Scanning-probe microscopy, photoelectron spectroscopy, electron microscopy, and transport measurements therefore have to be combined to obtain a reliable picture. Layered materials also provide model systems for studying moiré structures, interface coupling, and the crossover between bulk and

low-dimensional physics. Their investigation brings nanophysics into direct contact with quantum materials and future electronic or photonic device concepts.

Nanophotonics and plasmonics provide a parallel route in which nanoscale geometry controls the behaviour of light rather than primarily the flow of electrical current. Metallic nanostructures can support collective electron oscillations known as plasmons, which concentrate electromagnetic fields into volumes much smaller than the free-space wavelength of light. This field enhancement can increase spectroscopic sensitivity and alter interactions between light and molecules near a surface. Czech researchers have fabricated ordered metallic nanoparticles and nanoantennas for plasmonic experiments and sensing concepts. Dielectric and semiconductor nanostructures provide complementary ways of controlling optical resonances with lower dissipative losses. Surface-Enhanced Raman Spectroscopy uses plasmonic enhancement to amplify the weak vibrational signatures of molecules near suitable nanostructured surfaces. Such methods connect nanofabrication with chemical sensing, biosensing, and optical spectroscopy. Precise morphology is crucial because resonance frequencies and field enhancement depend strongly on particle size, shape, spacing, and substrate. Electron microscopy and scanning-probe methods therefore become integral parts of the photonic experiment rather than post-production inspection tools. Nanophotonics consequently illustrates how Czech infrastructure enables the same nanoscale structure to be designed theoretically, fabricated lithographically, measured microscopically, and tested optically.

Nanomagnetism and spintronics provide another domain in which nanoscale dimensions create functionality absent from bulk magnetic materials. Reducing a magnetic structure changes domain formation, anisotropy, switching fields, and the propagation of spin excitations. CEITEC groups investigate magnetic thin films, patterned nanomagnets, domain-wall dynamics, magnetoresistance, and spin waves. FZU contributes complementary expertise in epitaxial magnetic semiconductors, antiferromagnets, nanofabrication, and electronic-structure theory. Its optospintronic laboratories add ultrafast magneto-optical methods for following magnetic dynamics on extremely short timescales. Lithography allows magnetic bars, wires, junctions, and multilayers to be patterned reproducibly, while microscopy visualises the resulting magnetic or structural state. Electrical transport then measures effects such as giant or tunnelling magnetoresistance and current-induced switching. Optical pump–probe methods provide access to fast magnetic dynamics that cannot be followed with conventional electrical instrumentation. This convergence of fabrication and characterisation was essential to the Czech development of antiferromagnetic spintronics during the 2010s. It also helped create the experimental environment from which later research on altermagnetism could emerge. Nanomagnetism thus shows how the infrastructure described in this chapter directly supported one of the most internationally visible achievements of Czech condensed-matter physics.

Nanoscale materials engineering extended beyond electronic and magnetic devices to bulk materials whose internal structure is refined to the nanometre scale. Severe plastic deformation can produce ultrafine-grained or nanocrystalline metals in which the density of grain boundaries is much higher than in conventional alloys. These boundaries strongly influence strength, ductility, diffusion, corrosion, and thermal stability. The original LNSM structure therefore included a centre concerned with bulk metal nanomaterials as well as semiconductor nanostructures. Electron microscopy was essential for determining grain size, dislocation structures, phase distribution, and structural changes during heating or

mechanical loading. Nanoindentation and mechanical testing linked these local observations with material performance. Similar approaches were applied to ceramic and composite materials in the wider Czech research environment. This branch of nanotechnology demonstrates that nanoscale engineering does not require the final object itself to be microscopic.

The formation of CzechNanoLab in 2020 represented a major organisational step because it connected the Prague and Brno infrastructure traditions within one distributed national platform. LNSM at FZU and CEITEC Nano at BUT became complementary nodes rather than separate facilities competing to reproduce the same instruments. The arrangement widened the range of technologies available to users by combining Prague strengths in epitaxial semiconductors, carbon materials, spintronics, scanning probes, electron microscopy, and theoretical support with Brno strengths in clean-room nanofabrication, advanced microscopy, surface analysis, structural characterisation, and tomography. Open-access procedures allowed researchers to use equipment irrespective of their home institution when the proposed work met scientific or innovation criteria. The infrastructure also supported self-service operation for trained users, an approach that develops practical expertise rather than reducing researchers to passive recipients of measurements. External users from academia and industry could therefore integrate CzechNanoLab capabilities directly into their own research programmes. This distributed model is well suited to nanotechnology because no single laboratory can economically maintain every deposition, lithography, microscopy, and spectroscopy technique at the highest level. CzechNanoLab consequently provided a national answer to the increasing capital intensity of nanoscale research. It also positioned Czechia for participation in broader European efforts to coordinate nanofabrication infrastructures. By 2025, the platform had become an important part of the country's research architecture in physics, advanced materials, nanoelectronics, and related technologies. Its creation illustrates how institutional integration can be as important as acquisition of an individual instrument.

Open access changed the sociology of Czech nanoscience as well as the distribution of equipment. A research group no longer needed to own an electron-beam writer, high-end microscope, or epitaxy system in order to formulate a project requiring those capabilities. Instead, access could be obtained through a shared facility whose specialists maintained calibration, safety, cleanliness, and technical continuity. This arrangement lowers duplication and increases utilisation of expensive instruments. It also encourages collaboration because external users bring scientific questions that may differ from those originally envisaged by the host laboratory. Facility staff acquire broad methodological experience by working with many materials and device types. Students benefit because they can be trained on instruments that would otherwise exist only in a small number of elite laboratories. Companies gain access to advanced metrology or fabrication without purchasing systems that may be needed only intermittently. The resulting exchange of knowledge can therefore influence both academic science and high-technology industry. CzechNanoLab and its constituent centres exemplify the transition from laboratory ownership towards infrastructure-based nanoscience.

The integration of nanophysics with engineering became especially visible in semiconductor and chip-related research during the early 2020s. CEITEC Nano can support a sequence extending from a silicon wafer through deposition and lithography to a contacted test chip and its subsequent microscopic analysis. BUT combines this infrastructure with expertise in physical engineering, microelectronics, materials science, and circuit design. Researchers

therefore investigate not only conventional semiconductor processes but also future approaches based on new materials, low-dimensional systems, spin phenomena, and non-standard device architectures. In 2025, BUT explicitly strengthened educational and research links around semiconductor technologies in response to growing Czech and European demand for specialists. CEITEC clean rooms became part of practical training in which students could experience real fabrication steps rather than only study them theoretically. This educational role is scientifically significant because nanotechnology depends heavily on tacit process knowledge that cannot be learned from equations or simulation alone. Industrial collaboration additionally exposes researchers to yield, reliability, contamination, and failure-analysis problems that are often less visible in small academic prototypes. The resulting ecosystem links fundamental device physics with process engineering and workforce development. It also places nanoscience within the broader Czech strategy of strengthening semiconductor competence. By 2025, the boundary between research infrastructure and technological training had therefore become increasingly permeable.

The CzechNanoLab+ modernisation project launched in 2024 demonstrated that nanoscale infrastructure requires continual renewal rather than one-time construction. The project received CZK 361 million for equipment modernisation and innovation after obtaining the highest evaluation in its funding call. Fifteen major investment units were planned across the Brno and Prague nodes. Approximately two thirds of the funding was directed to CEITEC Nano, with the remaining third assigned to LNSM. The planned acquisitions included new deposition equipment, advanced microscopes, analytical instruments, and technology for microscopic three-dimensional fabrication. These investments were intended both to replace ageing systems and to introduce methods not previously available within the infrastructure. The programme reflects the exceptionally rapid obsolescence cycle of nanotechnology equipment, where improvements in detectors, electron optics, automation, vacuum engineering, and data processing can quickly alter experimental capability. Maintaining international competitiveness therefore depends on systematic upgrades as much as on the initial establishment of a laboratory. The modernisation also responded to increasing demand from semiconductor, microscopy, and other high-technology users. By the end of 2025, CzechNanoLab was consequently in another phase of technical renewal while remaining operational for external research.

The evolution of microscopy itself became an important research subject rather than merely a service supporting other disciplines. Czech scientists developed new approaches to scanning-probe interpretation, surface-sensitive measurements, electron-beam analysis, and nanometrology. Instrument development is scientifically significant because an improvement in spatial, temporal, chemical, or energy resolution can reveal phenomena that were previously inaccessible. Brno groups worked on microscopy methods capable of detecting semiconductor defects and analysing complex nanoelectronic structures with minimal damage. Prague researchers developed theoretical tools that explain high-resolution STM and AFM contrast at the scale of individual chemical bonds. CEITEC groups combined electron microscopy with in situ growth studies so that the formation of nanowires or thin films could be observed rather than inferred only from final specimens. Surface laboratories linked microscopy with spectroscopy to identify both morphology and chemical state. Such developments reduce the distinction between instrument builder and scientific user because the measurement method itself becomes part of the research question. They also strengthen Czech industrial competence in scientific instrumentation, especially in the Brno region. This

methodological work has enduring value because later experiments can reuse the measurement principles even when the original material system changes. Nanoscale characterisation therefore became an area in which Czech physics contributes not only measurements but also methodologies.

The interdisciplinary reach of Czech nanotechnology expanded because nanoscale methods are applicable wherever structure controls function. Physicists use them to study quantum confinement, electronic transport, magnetism, and optical resonances. Materials scientists apply the same techniques to defects, phase boundaries, coatings, composites, and mechanical degradation. Electrical engineers use lithography and microscopy to develop and diagnose semiconductor or spintronic devices. Chemists exploit surface analysis and controlled deposition to investigate catalysis and molecular self-assembly. Biomedical researchers can use nanostructured surfaces, nanoparticles, or imaging methods when biological systems must be analysed at comparable length scales. The infrastructure therefore brings together communities that may ask very different questions but require similar fabrication and characterisation tools. CEITEC was deliberately organised around this interdisciplinary logic, while CzechNanoLab extended it into a national platform. The result is a research environment in which expertise can move from one application domain to another more easily than within narrowly departmental laboratories. This transfer of methods is one of the principal reasons nanotechnology became an integrating rather than merely specialised branch of Czech science.

Between 1993 and 2025, Czech nanophysics, nanotechnology, and nanoscale characterisation therefore developed from dispersed expertise into a coordinated infrastructure capable of supporting research from the atomic scale to functional devices. FZU preserved strong traditions in semiconductors, thin films, surface science, microscopy, magnetism, and materials physics while creating LNSM as a shared platform in 2008. Prague groups advanced epitaxy, lithography, carbon nanomaterials, spintronic structures, scanning probes, electron microscopy, and theory within a common technological environment. Czech contributions to high-resolution STM and AFM helped clarify how functionalised probes image molecular structure and enabled mapping of electrostatic fields at submolecular resolution. Brno added a major clean-room and microscopy capability through CEITEC Nano, which reached full operation in 2016 and connected nanofabrication with structural analysis, surface science, tomography, and advanced electron microscopy. The formation of CzechNanoLab in 2020 integrated the Prague and Brno nodes into a distributed national research infrastructure. Nanoelectronics, two-dimensional materials, plasmonics, nanomagnetism, semiconductor technology, and nanostructured bulk materials all benefited from this shared experimental base. Open access encouraged universities, research institutes, and high-technology companies to use facilities that would have been uneconomic to duplicate independently. The CzechNanoLab+ modernisation begun in 2024 showed that maintaining this capability requires continuous investment in new fabrication and characterisation methods. The field thus moved beyond isolated nanoscale experiments towards a durable technological base for multiple branches of science. By 2025, nanoscience had consequently become one of the clearest areas in which Czech physics, materials science, instrumentation, and engineering functioned as an integrated research ecosystem.

Quantum Physics and Emerging Quantum Technologies

Quantum physics occupies a distinctive position in the development of Czech science between 1993 and 2025 because it links some of the most fundamental questions of modern physics with a rapidly expanding family of technologies. Czech researchers entered the post-Czechoslovak period with established expertise in quantum optics, atomic physics, solid-state physics, laser science, mathematical physics, and precision measurement. During the following three decades, these traditions increasingly converged with quantum information science, secure communication, quantum materials, sensing, and quantum computing. The change did not occur through the creation of a single national quantum laboratory, but through interaction among several universities and institutes of the Czech Academy of Sciences. Palacký University in Olomouc became particularly visible in quantum optics and photonic quantum information, while the Czech Technical University in Prague developed strong theoretical and educational activity in quantum technologies. The Institute of Scientific Instruments of the Czech Academy of Sciences in Brno contributed through ion trapping, optical clocks, quantum metrology, and later quantum communication infrastructure. Charles University, Masaryk University, the Institute of Physics of the Czech Academy of Sciences, and other centres added expertise in quantum materials, superconductivity, spin physics, sensing, and many-body theory. During the 2020s, these previously distributed capabilities began to be treated more explicitly as elements of a national quantum ecosystem. By 2025, Czech quantum science therefore combined long-established fundamental research with the first large infrastructure projects intended to translate quantum principles into communication, computation, sensing, and technological applications.

The underlying scientific transition is often described internationally as a movement from the first to the second quantum revolution. The first quantum revolution produced the physical foundations of semiconductor electronics, lasers, magnetic resonance, atomic clocks, and many other twentieth-century technologies. The second seeks to control individual quantum states and deliberately exploit superposition, entanglement, coherence, tunnelling, and measurement back-action as technological resources. This distinction is useful for understanding Czech development because the country's strongest quantum capabilities initially arose inside older disciplines rather than under the label of quantum technology. Quantum optics grew from laser and optical physics, quantum materials from condensed matter, and quantum metrology from precision spectroscopy and instrumentation. Quantum information theory provided a new conceptual language that could connect these otherwise different experimental platforms. During the 2000s and 2010s, Czech groups increasingly worked on tasks such as generating single photons, controlling entanglement, designing quantum measurements, manipulating coherent states, and modelling quantum information processing. At the same time, advances in nanofabrication and low-temperature physics made solid-state quantum systems increasingly accessible. European programmes then encouraged national communities to organise these activities around common objectives in communication, computing, sensing, simulation, and materials. The Czech trajectory is therefore best understood not as the sudden appearance of a new discipline, but as the coordinated technological maturation of several existing branches of physics.

Quantum optics provided one of the earliest areas in which Czech researchers achieved sustained international visibility after 1993. The Department of Optics at Palacký University in Olomouc developed theoretical and experimental programmes concerned with the quantum

properties of light and their application to information processing. Its research addressed quantum interference, entanglement, teleportation, quantum measurements, quantum state estimation, continuous variables, and the generation of non-classical light. Photons are particularly attractive carriers of quantum information because they can propagate over long distances and can be manipulated with well-developed optical components. Their weak interaction with the environment helps preserve coherence, although the same weak interaction makes deterministic photon–photon gates difficult to realise. Czech research therefore examined both the advantages and the limitations of linear optical quantum information processing. The Olomouc school combined mathematical optimisation of quantum protocols with experiments using single-photon detectors, nonlinear crystals, interferometers, and feed-forward electronics. This close interaction between theory and experiment became one of the defining features of Czech quantum optics.

Several internationally recognised results illustrate the breadth of the Olomouc programme during the first two decades of the independent Czech Republic. In 2002, Jaromír Fiurášek, Miloslav Dušek, and Radim Filip proposed a universal measurement apparatus controlled by quantum software, introducing a programmable quantum multimeter for qubits. Subsequent work examined continuous-variable quantum cloning, purification, remote quantum interactions, and methods for manipulating imperfect quantum states. Experimental studies increasingly tested whether theoretically proposed operations could survive optical loss, imperfect detectors, and other realistic sources of noise. The laboratory investigated single-photon and multi-photon interference, quantum state reconstruction, programmable quantum devices, and entangled photonic states. Researchers also developed procedures for suppressing losses and noise in optical communication while preserving genuinely quantum properties. In 2018, an Olomouc team demonstrated a nondestructive detector of exchange symmetry for photonic qubits, providing another example of quantum information concepts implemented with optical hardware. In 2020, researchers experimentally realised a linear-optical two-qubit gate designed to protect encoded quantum information against collective dephasing. Work during the early 2020s also examined quantum non-Gaussian states, photon coincidences, coherence, and advanced resources for continuous-variable processing. These projects strengthened the international position of Palacký University in a field where progress depends equally on abstract information theory and precise control of individual optical quanta. They also supplied concepts and experimental competence directly relevant to later Czech participation in quantum networks and secure communications.

Quantum non-Gaussianity became one of the distinctive research themes pursued by the Olomouc community. Gaussian states and Gaussian operations are comparatively accessible in optical laboratories because they can be generated with coherent light, squeezing, linear optics, and homodyne detection. Many advanced quantum-information tasks, however, require resources that cannot be reproduced by Gaussian operations alone. Czech researchers therefore developed criteria capable of identifying genuinely non-Gaussian states even when experimental imperfections blur their ideal signatures. Theoretical studies were accompanied by experiments on single-photon and multiphoton sources, conditioned measurements, and squeezed states. In 2021, Lukáš Lachman and Radim Filip introduced criteria for quantum non-Gaussian photon coincidences that distinguish higher-quality quantum resources from light generated by ordinary Gaussian parametric processes. Such certification is technologically relevant because a quantum device needs reliable methods for determining whether its output actually contains the non-classical resources assumed by a

protocol. The research thus connected foundational questions about the hierarchy of quantum states with practical diagnostics for emerging photonic technology. It also demonstrated that Czech quantum optics contributed methods for characterising quantum resources rather than only implementing established protocols.

Experimental quantum information processing in Olomouc developed around the controlled preparation, transformation, and detection of individual or correlated photons. Spontaneous parametric down-conversion in nonlinear crystals provides pairs of photons whose polarisation, arrival time, or other degrees of freedom can be entangled. Interferometers then combine optical paths so that probability amplitudes rather than classical intensities determine the outcome of a measurement. Single-photon detectors record individual quantum events, while coincidence electronics identifies correlations among photons arriving in different channels. Using these tools, Czech researchers investigated quantum gates, state teleportation, cloning, measurement, quantum memories, and protocols for distributing correlations. The laboratory also developed specialised photon sources and worked with superconducting single-photon detectors, which improve detection efficiency and timing performance compared with many conventional devices. Electronic feed-forward allowed a measurement result in one part of an experiment to control an operation performed subsequently on another optical mode. Such conditional operations are important because they allow probabilistic linear-optical processes to be combined into more powerful information-processing schemes. The resulting experiments required stabilisation of optical phase, polarisation, timing, and interferometric path lengths over timescales much longer than an individual quantum event. This technological discipline helped make photonic quantum information one of the most experimentally mature areas of Czech quantum science.

Quantum communication emerged naturally from this optical and information-theoretical background. Its most established technological form is Quantum Key Distribution (QKD), in which quantum states are used to establish cryptographic keys between distant users. The security principle differs from that of ordinary public-key cryptography because an attempt to measure unknown quantum states necessarily changes the statistics observed by legitimate participants. QKD therefore provides a method for detecting certain forms of interception rather than relying only on the assumed computational difficulty of a mathematical problem. Czech researchers studied discrete-variable and continuous-variable approaches, entanglement-based systems, practical noise, photon-source quality, and the performance of quantum channels. Palacký University groups investigated how losses and imperfections influence secure key rates and how non-classical optical resources can improve communication. Masaryk University and the Czech Technical University contributed theoretical knowledge in quantum information and cryptographic protocols. CESNET added the network-engineering expertise needed to move from laboratory demonstrations towards operational fibre infrastructure. By the end of the 2010s, Czech quantum communication had therefore acquired both the physical and networking foundations required for a larger national project.

An important early demonstration of this transition occurred in 2021 through a long-distance quantum-key experiment using the Czech academic network. CESNET and the IT4Innovations National Supercomputing Center cooperated with the Polish academic network to establish a quantum channel between Ostrava and Cieszyn. The approximately seventy-five-kilometre fibre route crossed the Czech-Polish border and demonstrated inter-city as well as international distribution of quantum keys. The experiment was significant because it used real

telecommunications infrastructure rather than a short laboratory fibre spool. Environmental fluctuations, fibre losses, network operations, and existing data traffic impose constraints that are much less visible in a controlled optical laboratory. Successful key exchange therefore demonstrated that Czech network operators had begun to acquire practical knowledge of integrating quantum channels with conventional communication systems. The work also anticipated the later objective of connecting national quantum communication infrastructures across European borders. It provided experience with equipment interoperability and operational procedures before the Czech National Quantum Communication Infrastructure was launched. The demonstration should not be interpreted as a complete national quantum network, but it showed that key physical and engineering principles were already transferable into deployed fibre. The 2021 experiment consequently formed a practical bridge between earlier academic quantum-optics research and the infrastructure-oriented phase of the 2020s. It also strengthened cooperation among physicists, cybersecurity specialists, optical-network engineers, and supercomputing institutions.

The Czech National Quantum Communication Infrastructure (CZQCI) formalised this transition when implementation began in 2023. The project is part of the wider European Quantum Communication Infrastructure (EuroQCI) effort to create quantum-secured communication capabilities across the European Union. Its Czech consortium includes CyberSecurity Hub, CESNET, the Institute of Scientific Instruments, the Czech Technical University in Prague, Masaryk University, Palacký University, VSB – Technical University of Ostrava, and Brno University of Technology. The planned national backbone connects Prague, Brno, and Ostrava and is complemented by metropolitan branches intended for public authorities and experimental use cases. A dedicated test and training environment is designed to expose users to several QKD technologies rather than to one proprietary architecture. The project therefore combines infrastructure deployment with interoperability testing, training, and development of operational expertise. European Digital Europe funding and Czech national resources support the programme. The objective is not merely to demonstrate that quantum keys can be exchanged, but to learn how such systems can be operated over long periods inside realistic telecommunications environments. CZQCI consequently represents the first Czech attempt to treat quantum communication as a network infrastructure rather than as a sequence of independent physics experiments.

The physical principles of CZQCI also reveal why quantum communication requires cooperation among disciplines that previously operated rather separately. A QKD device may use weak optical pulses or individual photons, but the secure service ultimately has to coexist with conventional fibres, amplifiers, routers, encryption units, and network-management software. Loss in optical fibre limits the distance over which direct quantum links can operate without trusted nodes or future quantum repeaters. Detector efficiency and dark counts influence key rates, while polarisation and phase fluctuations can degrade the quantum signal. Classical authentication is still required because quantum mechanics alone does not prove the identity of the communicating parties. The generated quantum keys must subsequently be delivered safely to conventional encryption systems that protect ordinary high-bandwidth data. Network operators therefore have to coordinate quantum and classical channels while preserving the assumptions on which the security proof depends. Czech participation brings together optical quantum physicists, information theorists, cybersecurity specialists, metrologists, and telecommunications engineers for precisely this reason. Training forms a formal part of CZQCI because deployment without specialists capable of diagnosing physical

and network-layer failures would have limited long-term value. The programme thus illustrates how quantum technology differs institutionally from an isolated scientific instrument. By 2025, Czech quantum communication had become a systems-engineering challenge grounded in fundamental quantum physics.

Precision measurement supplied another major route from fundamental quantum physics towards practical technology. The Institute of Scientific Instruments of the Czech Academy of Sciences in Brno developed a Quantum Metrology group concerned with laser cooling of ions, ion traps, optical clocks, Coulomb crystals, and time and frequency measurement. An ion confined by electromagnetic fields can be isolated sufficiently well that its internal quantum transition becomes an exceptionally stable frequency reference. Laser cooling reduces the ion's kinetic motion and therefore suppresses Doppler-related uncertainties that would otherwise broaden the transition. Optical clocks exploit transitions at frequencies far higher than those used in traditional microwave atomic clocks, potentially improving fractional frequency precision. Ion trapping also creates a well-controlled experimental platform for studying coherent quantum dynamics and interactions among several trapped particles. The Brno programme therefore combines quantum optics with vacuum engineering, precision electronics, laser stabilisation, and metrology. It illustrates how Czech instrumentation traditions can be extended into technologies whose operating principle depends directly on controlled quantum states. Quantum metrology also creates natural links to sensing because an extremely precise frequency reference can detect very small physical perturbations.

The technological requirements of ion-based quantum metrology are unusually demanding and therefore generate expertise with value beyond clock construction itself. Electric traps have to create stable confinement while introducing minimal stray fields and electrical noise. Vacuum chambers must suppress collisions with background gas over long experimental periods. Lasers require narrow linewidths, stable frequencies, and precise control of polarisation and intensity. Fluorescence from a single trapped ion may contain only a small number of photons and must therefore be detected with high efficiency. Microwave and radio-frequency electronics have to manipulate motional and internal quantum states without introducing excessive decoherence. Several trapped ions can form Coulomb crystals whose collective motion provides additional quantum degrees of freedom. Similar techniques are used internationally in quantum computing, simulation, precision spectroscopy, and fundamental tests of physics. The Czech programme therefore develops a technological vocabulary shared by several branches of the second quantum revolution. Projects on transportable optical clocks and high-accuracy ion-based clocks during the 2020s placed this expertise within European metrology networks. Such systems are relevant to time distribution, geodesy, tests of fundamental constants, and the synchronisation of advanced scientific infrastructure. Quantum metrology consequently represents one of the areas where the boundary between fundamental measurement science and strategic technology is particularly narrow.

Quantum sensing broadened the same principle by using coherent quantum systems as exceptionally sensitive probes of magnetic, electric, inertial, thermal, or other physical quantities. Czech activities include trapped ions, atomic and optical methods, superconducting concepts, and solid-state defects. Nitrogen-vacancy centres in diamond became a particularly promising platform because their electron spin can be prepared and read optically at room temperature. The spin resonance depends on the local magnetic environment, allowing the defect to function as a microscopic magnetometer. Nanostructuring

can bring the active centre close to a sample and can improve collection of the emitted fluorescence. By the middle of the 2020s, Charles University was expanding activity in this direction in cooperation with diamond specialists at the Institute of Physics. Proposed and developing applications included nanoscale magnetometry and microscopic Nuclear Magnetic Resonance (NMR) on very small sample volumes. Such sensors connect quantum coherence with nanofabrication, photonics, microwave electronics, and microfluidics. The emerging programme demonstrates how Czech expertise in diamond materials and optical spectroscopy could be redirected towards quantum measurement technologies.

Diamond sensing also illustrates the importance of materials engineering to quantum technology. A nitrogen-vacancy centre is an atomic-scale defect consisting of a nitrogen atom adjacent to a missing carbon atom in the diamond lattice. Its usefulness depends not only on the quantum mechanics of the defect but also on crystal purity, defect concentration, surface termination, and the ability to fabricate nanoscale optical structures without destroying spin coherence. Chemical Vapour Deposition can produce high-quality diamond material with controlled composition and defect environments. Plasma etching can then form nanopillars, gratings, or other structures that guide fluorescence towards the optical detector. Microwave antennas manipulate the spin state, while green laser light is commonly used for optical preparation and red fluorescence for readout. Optically Detected Magnetic Resonance (ODMR) converts changes in spin resonance into an experimentally accessible optical signal. This combination allows a sensor to operate at ambient temperature rather than requiring a cryogenic superconducting magnet. For Czech research, the platform is especially attractive because it connects existing strengths in nanodiamond growth at the Institute of Physics with spectroscopy and quantum sensing at Charles University. It therefore provides an example of how an established materials capability can become the foundation of a new quantum technology rather than requiring an entirely new experimental ecosystem. The same logic applies more broadly to quantum materials, where technological performance depends critically on atomic structure, defects, and interfaces.

Quantum materials consequently became another major component of the Czech quantum landscape. The term refers broadly to solids in which collective quantum effects produce unusual electronic, magnetic, optical, or topological properties that can potentially be controlled technologically. Czech research already had strong foundations in superconductivity, magnetism, spintronics, correlated electron systems, low-dimensional materials, and semiconductor nanostructures. During the 2020s, these activities were increasingly framed explicitly in terms of quantum technologies. The Quantum Materials for Applications in Sustainable Technologies project, abbreviated as QM4ST, began in 2023 and linked Masaryk University with Charles University, the University of West Bohemia, and Brno University of Technology through CEITEC. Its programme combines theoretical modelling, synthesis, spectroscopy, thin-film research, and device-oriented studies. Target topics include spintronics, superconductivity, multiferroics, photonics, energy conversion, catalysis, and other functional phenomena with quantum-mechanical origins. The project therefore expands the idea of quantum technology beyond computing and secure communication. It also emphasises that materials whose emergent properties arise from quantum interactions can contribute to sustainable energy and electronics even when they are not used as qubits.

Superconductivity provides one of the clearest examples of the overlap between quantum materials and quantum information processing. A superconductor supports a coherent macroscopic quantum state in which electrical resistance vanishes below a critical

temperature. Josephson junctions formed between superconductors can behave as nonlinear quantum circuit elements and are widely used internationally to construct superconducting qubits. Czech theoretical groups at Charles University and the Institute of Physics study superconducting heterostructures, quantum dots coupled to superconductors, Josephson effects, and many-body quantum dynamics. These systems allow researchers to examine how Coulomb interaction, spin, superconducting pairing, and quantum coherence compete in nanoscale devices. Some configurations can act as controllable artificial atoms or can provide elements for future qubit architectures. The same research also investigates quantum phase transitions and microwave response, which are relevant to understanding how a device moves between distinct quantum regimes. Numerical Renormalisation Group, Quantum Monte Carlo, and related methods provide theoretical tools for treating the strong correlations present in such structures. Although Czechia did not operate a domestic superconducting quantum processor during most of the 1993–2025 period, its condensed-matter community contributed to the underlying device physics. This work forms an important conceptual bridge between quantum materials and the hardware architectures used in contemporary quantum computing. It also reinforces the need for close cooperation between theoretical many-body physics and nanoscale fabrication.

Czech quantum-information theory developed in parallel with these experimental platforms and provided methods applicable regardless of the physical implementation of a qubit. Researchers studied quantum channels, entanglement, quantum walks, quantum algorithms, state estimation, cloning limits, error correction, measurement theory, and the thermodynamics of information. The Czech Technical University in Prague developed a particularly strong tradition around mathematical descriptions of quantum information and communication. Palacký University contributed both discrete-variable and continuous-variable theories rooted in quantum optics. Charles University groups addressed many-body dynamics, quantum chaos, quantum information, metrology, and the interplay between energy and information. Masaryk University added expertise in quantum algorithms and cybersecurity through the wider national quantum communication programme. These theoretical activities are important because quantum hardware remains noisy and platform-dependent, while the principles of information processing must be formulated at a more abstract level. Error mitigation, tomography, benchmarking, and resource certification all depend on understanding what a device should ideally accomplish before its imperfections are measured. By 2025, the Czech theoretical community therefore covered much of the conceptual chain from fundamental quantum mechanics to the algorithms and diagnostics required by practical technologies.

Quantum thermodynamics became one example of how this theory expanded into new territory during the 2020s. The field asks how concepts such as work, heat, entropy, irreversibility, and information should be formulated when the system itself is quantum mechanical. Entanglement and coherence can behave as resources, while measurement and feedback can alter the energetic balance of a microscopic process. At Charles University, research groups investigated many-body thermalisation, entropy, quantum batteries, work extraction, metrology, and information processing. Such problems are relevant both to fundamental statistical physics and to the efficiency limits of future quantum devices. A quantum processor cannot be treated as an abstract sequence of perfect gates because every real operation is embedded in a noisy physical environment. Understanding this interaction requires theoretical tools that connect open-system dynamics with information theory. The

emergence of dedicated research activity in quantum information and thermodynamics in 2025 therefore reflects the widening scope of the Czech quantum programme beyond traditional optics and condensed matter. It also shows how new groups could be built on the mathematical and many-body expertise already present in Czech physics. This subject also creates conceptual links to the design of more efficient quantum control protocols. Its growth broadened the Czech quantum-information agenda beyond communication and computation alone.

Education became an increasingly explicit strategic component as quantum technologies moved from specialist research into an identifiable technological sector. The Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague created a multidisciplinary Quantum Technologies study pathway extending through bachelor, master's, and doctoral levels. The curriculum combines quantum mechanics with optics, quantum information, lasers, solid-state physics, nanomaterials, computation, and laboratory work. Students encounter quantum communication and information processing as well as the physical technologies needed to implement these concepts. Laboratory training is important because quantum experiments require practical competence in optics, vacuum systems, electronics, detectors, and data acquisition. The programme also reflects the fact that no single traditional degree fully covers the range of skills needed by a quantum engineer or experimental quantum physicist. By the academic year 2024–2025, dedicated courses included quantum laboratories, quantum optics, quantum information and communication, quantum field theory, laser systems, and photonic structures. Doctoral study extended this integration towards independent research in quantum information, communication, materials, nanostructures, and advanced modelling. The creation of a vertically connected educational pathway represented an important institutional step because it allowed students to identify quantum technology as a coherent professional field rather than assembling relevant subjects informally from different departments. It also helped align university education with the emerging national demand for specialists in quantum communication, computing, sensing, and materials.

Palacký University retained a complementary educational model built around the longer-established disciplines of optics and mathematical physics. Its courses in quantum information theory address quantum states, measurements, entanglement, algorithms, error correction, teleportation, cryptography, and quantum networks. Advanced experimental photonics introduces students to single-photon generation and detection, time-correlated counting, interferometry, entangled states, and laser stabilisation. Quantum communication courses cover both discrete and continuous variables and discuss photon-pair sources, homodyne detection, quantum key distribution, and optical quantum gates. Students can participate directly in research through the Laboratory of Quantum Optics and Quantum Informatics. This environment allows theoretical protocols to be tested immediately against experimental limitations such as photon loss and phase drift. It also creates continuity between student projects and internationally funded research programmes. The educational model therefore embeds quantum technology within a strong optics tradition rather than separating it into a new administrative discipline. Together with the dedicated programme at the Czech Technical University, it illustrates two different but complementary routes for training the Czech quantum workforce.

National coordination began before most of the large infrastructure projects of the 2020s. In 2016, Czech researchers established the National Initiative for Quantum Technologies (NIKT)

in connection with preparations for the European Quantum Flagship. The initiative brought together specialists from Palacký University, the Czech Technical University, Masaryk University, the Institute of Scientific Instruments, and other organisations. Its purpose was to promote emerging technologies based directly on quantum phenomena and to strengthen Czech participation in European programmes. The creation of NIKT was significant because quantum activities had previously been distributed among optics, information theory, metrology, materials science, and other fields without a common national label. The initiative did not replace universities or research institutes, but it provided a framework for communicating expertise to public authorities and potential industrial partners. It also helped articulate the argument that Czechia possessed research strengths from which a larger quantum technology programme could grow. The European Quantum Flagship, launched in 2018, then provided a major continental framework for long-term investment in quantum communication, computing, simulation, sensing, and fundamental science. Czech groups participated in European and QuantERA projects addressing secure networks, non-Gaussian physics, multi-user key distribution, quantum imaging, quantum dots, and optical quantum technologies. By the early 2020s, national coordination and European project participation were therefore reinforcing one another. This institutional layer prepared the ground for the more infrastructure-oriented initiatives that followed.

The first half of the 2020s brought a noticeable increase in project scale and strategic ambition. Palacký University participated in Horizon Europe programmes on scalable continuous-variable cluster-state technologies and secure quantum networks. Czech researchers also joined projects concerned with quantum dots for entanglement-based key distribution, multimode quantum light, super-resolution imaging, and photonic quantum metrology. The Institute of Scientific Instruments combined its metrology expertise with CZQCI and projects on quantum-encrypted communication and transportable optical clocks. Masaryk University linked quantum communication with cybersecurity and quantum materials with sustainable technologies. Charles University consolidated research groups covering quantum sensing, quantum information, quantum materials, ultrafast quantum electronics, and many-body theory. VSB – Technical University of Ostrava developed a new role in quantum computing through IT4Innovations. These programmes demonstrate that Czech quantum development was no longer concentrated almost exclusively in optical laboratories. It increasingly involved national communications networks, supercomputing infrastructure, advanced materials facilities, and strategic education. The concept of a Czech quantum ecosystem therefore acquired a more concrete institutional meaning during 2023–2025.

Quantum computing became the most visible new infrastructure component when Czechia was selected to host a European quantum computer within the LUMI-Q consortium. The system, later named VLQ, was installed at the IT4Innovations National Supercomputing Center in Ostrava during 2025. It uses twenty-four superconducting transmon qubits arranged around a central resonator in a star-shaped topology. This architecture is designed to reduce the number of swap operations required to move quantum information between otherwise distant qubits. Reducing such operations is important because every additional gate consumes part of the limited coherence time and introduces further error. The quantum processor is integrated with the Karolina supercomputer, creating a platform for hybrid quantum–classical workflows. The LUMI-Q consortium brings together partners from several European countries and is supported jointly through the European High Performance Computing Joint Undertaking and participating states. The system was formally inaugurated in Ostrava on 23 September

2025. Its installation represented the first time that a general-purpose programmable quantum computer of this kind was physically hosted in Czechia.

VLQ should be understood as an experimental computing platform rather than as a machine that supersedes classical supercomputers. Twenty-four physical qubits remain far from the fault-tolerant quantum computers envisaged for solving the most demanding algorithms with large logical registers. Current superconducting devices are affected by gate errors, finite coherence, readout imperfections, calibration drift, and environmental noise. Their scientific value lies in allowing researchers to develop algorithms, benchmark hardware, study error mitigation, and learn how quantum processors can cooperate with classical high-performance computing. Integration with Karolina is therefore central to the Czech strategy because many realistic workflows are expected to remain hybrid for the foreseeable future. A classical supercomputer can perform optimisation, data preparation, simulation, and post-processing while a quantum processor is used for selected operations that may eventually offer an advantage. Candidate research areas include optimisation, materials simulation, quantum chemistry, machine learning, and studies of quantum algorithms themselves. The hosting of VLQ also gives Czech students and companies direct institutional contact with quantum hardware rather than access only through foreign cloud services. Because the system is part of the EuroHPC environment, it simultaneously serves a European user community and embeds Ostrava within continental quantum-computing infrastructure. The Czech achievement therefore lies as much in acquiring operational competence and integrating the device with supercomputing as in the raw qubit count. VLQ made quantum computing a tangible component of Czech research infrastructure by the end of 2025.

Quantum materials and computing are also beginning to converge through the problem of simulating strongly interacting quantum systems. Classical computers can represent many quantum problems efficiently when correlations remain limited, but the required memory can grow exponentially with system size in the most difficult cases. This complexity is one of the motivations for quantum simulation and for future quantum computers capable of representing quantum states more directly. Czech condensed-matter groups already possess expertise in superconductivity, correlated electrons, magnetism, topological phases, and nanoscale devices that could provide scientifically meaningful test problems. Conversely, improved quantum simulation may eventually help predict properties of materials that are difficult to calculate accurately with classical approximations. QM4ST therefore belongs to the same national quantum landscape as VLQ even though its immediate research outputs are physical materials rather than quantum algorithms. Research on superconducting heterostructures and quantum dots also creates direct links to possible qubit devices. The emergence of altermagnetism adds another example of a Czech-led materials concept whose electronic structure may support future spin-based technologies. These connections show that the national quantum ecosystem is most productive when materials, devices, algorithms, and measurement methods are treated as interacting layers rather than separate disciplines.

A similar convergence is visible between quantum sensing and quantum communication. Both depend on the ability to prepare, manipulate, transmit, and measure fragile quantum states under realistic environmental conditions. A single-photon detector developed for quantum communication may also be useful in quantum metrology or spectroscopy. Frequency-stabilised lasers required for optical clocks can provide references for coherent communication and precision experiments. Low-noise electronics and cryogenic systems support superconducting sensors as well as quantum processors. Nanofabrication

techniques developed for spintronic or photonic devices can be adapted to diamond sensors and integrated quantum optics. Mathematical tools for tomography and estimation can diagnose errors in sensors, channels, and computing devices alike. This technological overlap explains why the Czech quantum strategy increasingly emphasised shared infrastructure, education, and interdisciplinary training rather than a set of isolated sectoral programmes. It also creates opportunities for relatively small national groups to contribute components or expertise to several quantum platforms. By 2025, the boundaries among quantum optics, metrology, materials, communications, and computing were therefore becoming progressively less rigid.

The year 2025 provided a symbolic culmination of this transition because it was designated internationally as the International Year of Quantum Science and Technology. Czech universities and research organisations used the occasion to expand outreach, specialist seminars, student activities, and discussion of national priorities. Charles University organised events connecting university groups with Palacký University, the Institute of Physics, the Czech Technical University, industrial partners, and international visitors. The same year saw the inauguration of VLQ, continuing deployment of CZQCI, expansion of quantum-materials projects, and growth of dedicated quantum education. Czech researchers also intensified dialogue with foreign institutions about cooperation in quantum technologies and artificial intelligence. These developments did not mean that the national ecosystem had reached the scale of the largest programmes in Germany, France, the United Kingdom, the United States, or China. They did show, however, that quantum technologies had moved beyond a loose collection of specialist research topics in Czechia. The field was beginning to acquire coordinated infrastructure, visible educational pathways, international partnerships, and national strategic attention. This institutional consolidation may ultimately prove as important as any individual experimental result from the first half of the decade.

The clearest formal expression of that strategic shift came at the end of 2025 with publication of the Czech National Strategy for Quantum Technologies 2026+. The document identified quantum computing and simulation, quantum communication, quantum sensing and metrology, and quantum materials as principal technological domains. It also defined broader pillars concerned with research and development, education and talent, economic competitiveness, international cooperation, security, and infrastructure. The strategy explicitly connected national activity with European initiatives and recognised the dual-use significance of several quantum technologies. It emphasised that a functioning ecosystem requires links among universities, institutes of the Czech Academy of Sciences, companies, state institutions, and international partners. The document also reflected concern about the cybersecurity implications of future quantum computers and the need for both quantum communication and post-quantum security measures. Education received particular attention because infrastructure cannot be expanded sustainably without enough physicists, engineers, mathematicians, computer scientists, and technicians. Publication in December 2025 lies at the boundary between the historical period examined in this book and the policy framework intended for the years that followed. It therefore serves as evidence that developments accumulated since the 1990s had become sufficiently coherent to justify an explicit national strategy. The strategy did not create Czech quantum science, but it institutionalised a technological agenda that earlier research communities had made possible.

Between 1993 and 2025, Czech quantum physics thus progressed from strong but largely discipline-specific research towards an increasingly interconnected technology ecosystem.

Quantum optics at Palacký University supplied internationally visible work on quantum information, photon states, measurement, communication, and non-Gaussian resources. The Czech Technical University developed theory and later a dedicated educational pathway extending from undergraduate study to doctoral research in quantum technologies. The Institute of Scientific Instruments contributed ion trapping, optical clocks, precision metrology, and expertise relevant to secure quantum communication. CZQCI transformed quantum-key research into a national networking project linked to EuroQCI, while earlier inter-city tests demonstrated that quantum links could operate on real optical infrastructure. Quantum sensing began to connect diamond materials, nanoscale fabrication, optical readout, and microscopic magnetic measurement. Quantum-materials programmes linked superconductivity, spintronics, photonics, and correlated matter with sustainable and information technologies. IT4Innovations added physical quantum-computing infrastructure through the twenty-four-qubit VLQ system integrated with the Karolina supercomputer in 2025. The National Initiative for Quantum Technologies and subsequent European projects provided coordination before a formal state strategy existed. By the end of 2025, the Czech quantum landscape therefore contained the principal components required for further development: fundamental science, specialist education, communications infrastructure, quantum computing, precision measurement, advanced materials, and European integration. The major achievement of the period was not the completion of a mature quantum industry, but the creation of a scientifically credible and increasingly coordinated foundation from which such technologies could develop.

Computational, Theoretical, and Data-Driven Physics

Computational, theoretical, and data-driven physics became an increasingly important foundation of Czech physical science between 1993 and 2025. The transformation reflected a wider change in physics from calculations performed on individual workstations towards numerical experiments executed on national and European computing infrastructures. Czech researchers entered this period with established schools in theoretical mechanics, quantum theory, nuclear theory, statistical physics, relativity, plasma theory, and computational solid-state physics. During the following three decades, these traditions became progressively connected with high-performance computing, large-scale simulation, distributed data processing, and machine learning. Numerical methods allowed physical systems to be studied in parameter regimes that could not be reproduced easily in laboratories or described adequately by analytic approximation alone. Supercomputers also became essential for interpreting experiments whose detectors or observatories generated data volumes too large for conventional local processing. The emergence of IT4Innovations National Supercomputing Center in Ostrava supplied Czech researchers with a domestic petascale platform and linked the country more closely with European computing initiatives. Computational work consequently expanded across materials physics, plasma research, nuclear physics, particle physics, astrophysics, and engineering applications. By 2025, theoretical reasoning, numerical simulation, and data-driven methods had become mutually reinforcing components of the Czech physics research ecosystem.

Theoretical physics remained the conceptual foundation of this development rather than being displaced by computation. At Charles University, the Institute of Theoretical Physics

maintained research in relativity, astrophysics and cosmology, quantum theory, theoretical atomic physics, mathematical statistical physics, and computational physics. The Nuclear Physics Institute of the Czech Academy of Sciences developed microscopic theories of nuclei and hypernuclei, hadron physics, mathematical physics, and calculations connected with electroweak processes. The Institute of Physics of the Czech Academy of Sciences supported theoretical work in electronic structure, correlated electrons, magnetism, superconductivity, and the quantum behaviour of materials. Masaryk University and Silesian University in Opava added strong programmes in theoretical astrophysics, gravitation, compact objects, and computational modelling. The Institute of Plasma Physics of the Czech Academy of Sciences combined plasma theory with transport, kinetic modelling, and integrated tokamak simulation. These institutions illustrate the breadth of Czech theoretical physics after 1993. Their research ranged from exact mathematical solutions to numerical calculations involving millions or billions of degrees of freedom. The resulting methodological spectrum allowed Czech physicists to select analytic, semi-analytic, stochastic, or numerical approaches according to the structure of the problem. Computation therefore extended theoretical physics by making more complex models tractable rather than replacing the need for physical interpretation.

The growth of computational physics depended strongly on the development of national electronic infrastructure. Before a dedicated national supercomputing centre existed, Czech researchers used university clusters, institutional servers, distributed grid systems, and foreign high-performance computing facilities. These resources were sufficient for many calculations but imposed practical limits on model size, spatial resolution, parameter exploration, and statistical sampling. The creation of IT4Innovations at VSB – Technical University of Ostrava, whose Czech name is Vysoká škola báňská – Technická univerzita Ostrava, during the early 2010s changed this situation substantially. The centre was designed not merely as a machine room but as a national competence centre combining hardware, software, parallel algorithms, data analysis, and specialist support. Its resources became available to academic teams through competitive open-access mechanisms. The arrival of dedicated supercomputing infrastructure therefore converted computation from a scarce institutional asset into a more broadly shared national research capability. This institutional change was especially important for physics because many of its most demanding problems are naturally parallelisable but require access to hundreds or thousands of processing cores.

The first major IT4Innovations system, Anselm, entered service in 2013 with a theoretical peak performance of approximately ninety-four teraflops. Although modest by later standards, it provided a valuable platform for Czech teams learning to scale scientific codes beyond local clusters. Salomon followed in 2015 with a theoretical peak performance of two petaflops and initially ranked fortieth in the TOP500 list of the world's most powerful supercomputers. Its introduction increased available national performance by more than an order of magnitude and opened much larger simulation campaigns. Barbora, installed in 2019, added approximately 849 teraflops of computing performance and provided another flexible production system. In the same year, an NVIDIA DGX-2 system was installed specifically for artificial-intelligence workloads. These successive platforms supported numerical physics, chemistry, engineering, materials modelling, data processing, and the development of scalable algorithms. Their scientific importance cannot be measured solely by peak floating-point performance because storage, interconnect speed, software libraries, scheduling, and user support determine how effectively applications can exploit the hardware. Czech researchers also had to rewrite or parallelise older codes so that calculations designed for a workstation could run efficiently on

distributed-memory architectures. The centre therefore stimulated methodological development as well as providing raw computational capacity. By the end of the 2010s, high-performance computing had become a routine part of research planning in several Czech physics communities.

The commissioning of the Karolina supercomputer in 2021 marked another substantial increase in national capability. Acquired in cooperation with the European High Performance Computing Joint Undertaking, Karolina reached a theoretical peak performance of about 15.7 petaflops. At installation it was the most powerful supercomputer in Czechia and appeared among the leading European systems in international rankings. Its architecture combines a large conventional processor partition with graphics-processing-unit accelerated nodes designed for simulations and data-intensive workloads. The accelerated section is particularly suitable for algorithms that perform many similar numerical operations in parallel. This architecture allowed traditional high-performance computing to converge increasingly with artificial intelligence and high-performance data analytics. Czech researchers could therefore use the same national facility for differential-equation solvers, atomistic simulations, Monte Carlo calculations, neural-network training, and large-scale inference. Karolina also became a practical platform for preparing codes for future exascale environments in which massive parallelism is unavoidable. Its installation moved Czech computational physics from early petascale access towards a much more mature European high-performance computing ecosystem.

National supercomputing capacity was complemented by participation in European infrastructures. Czechia joined the European High Performance Computing Joint Undertaking in 2018, allowing IT4Innovations to take part in the development of a coordinated continental supercomputing strategy. The centre subsequently joined the consortium operating the Large Unified Modern Infrastructure (LUMI) supercomputer, the large pre-exascale system installed in Kajaani, Finland. Czech researchers therefore gained access not only to domestic systems but also to computing resources significantly larger than those that could be justified nationally for every research problem. This arrangement mirrors the infrastructure logic familiar from particle accelerators and astronomical observatories. A strong national centre provides expertise and everyday access, while European participation supplies additional scale for exceptional calculations. IT4Innovations also became part of broader initiatives concerned with performance optimisation, data infrastructure, open science, and specialised computing architectures. These links positioned Czech computational scientists within European discussions about exascale software, energy efficiency, heterogeneous processors, and research-data management. Access to LUMI from 2021 further widened opportunities for simulations requiring very large processor counts or graphics accelerators. The model therefore combines national autonomy in computing with participation in shared European capacity.

The formation of e-INFRA CZ created a wider digital framework around supercomputing. The infrastructure integrates IT4Innovations with CESNET and the CERIT Scientific Cloud, usually abbreviated as CERIT-SC. Together they provide computing, high-speed networking, grid and cloud services, storage, identity management, and tools for handling large scientific datasets. Such integration is particularly important for contemporary physics because simulation and experiment increasingly produce workflows that extend beyond a single machine. A calculation may begin on a supercomputer, store intermediate results on distributed storage, transfer data across an academic network, and later be analysed interactively in a cloud

environment. Particle physics had already demonstrated this model through distributed grid computing for the Large Hadron Collider. Astrophysics, materials research, and computational plasma physics increasingly developed similar needs as datasets and simulations grew. e-INFRA CZ therefore made data movement and long-term storage part of the national computational research architecture rather than treating them as secondary information-technology services. This transition supported a more reproducible and collaborative form of computational science.

Materials physics became one of the most important beneficiaries of this expanded computing environment. Modern electronic-structure calculations solve approximations to the quantum-mechanical many-electron problem in order to predict bonding, magnetism, conductivity, optical behaviour, and other material properties. Density Functional Theory, usually abbreviated as DFT, became the standard first-principles framework for many Czech computational-materials projects. Researchers at the Institute of Physics, Charles University, Masaryk University, Palacký University, and IT4Innovations used DFT to study metals, semiconductors, magnetic systems, surfaces, interfaces, two-dimensional materials, and defects. Systems with strong electronic correlations required extensions such as dynamical mean-field theory, exact diagonalisation, or more specialised many-body methods. Each increase in physical realism generally raises computational cost because more atoms, orbitals, momentum points, or many-body states must be represented. High-performance computing therefore allows theorists to move from idealised unit cells towards larger defects, interfaces, nanostructures, and realistic temperature effects. The computational result is then compared with diffraction, photoemission, transport, magnetism, or spectroscopy to determine whether the model captures the actual material. This iterative link between calculation and experiment has become one of the defining methods of Czech condensed-matter physics. In this way, computational prediction increasingly became a practical guide for selecting experiments as well as a tool for explaining completed measurements.

The Modelling for Nanotechnologies Laboratory at IT4Innovations exemplifies the multiscale character of contemporary computational materials research. Its methods range from Hartree–Fock and post-Hartree–Fock calculations to DFT, many-body perturbation approaches, molecular dynamics, atomistic spin dynamics, and coarse-grained modelling. No single method is optimal for every physical scale, because accurate quantum calculations are computationally expensive while larger simulations often require simplified effective interactions. Researchers therefore combine techniques so that electronic structure determines parameters for atomistic models, which can then address longer length and time scales. Molecular dynamics follows the trajectories of atoms and can reveal diffusion, melting, defect motion, interfaces, and phase transformation. Spin-dynamics calculations can examine the collective evolution of magnetic moments in materials where temperature and magnetic order interact. Large-scale linear-scaling electronic-structure methods extend quantum calculations towards nanoparticles, nanowires, and other systems containing many more atoms than conventional calculations. The laboratory also develops and uses parallel algorithms so that these models can exploit thousands of processors efficiently, connecting fundamental many-body theory with practical material design.

A central challenge is the enormous gap between the accuracy of quantum-mechanical calculations and the system sizes required to reproduce many material processes. Direct DFT calculations may describe hundreds or thousands of atoms, but mechanical deformation, thermal transport, phase boundaries, or defect evolution can involve millions of atoms over

timescales far longer than first-principles dynamics can reach. Classical interatomic potentials make such simulations feasible by replacing explicit electronic calculations with much cheaper mathematical functions. Their weakness is that simple analytic forms may fail when local atomic environments differ substantially from the configurations used during fitting. Machine-learning interatomic potentials provide a newer compromise by learning complex energy landscapes from databases of high-quality quantum calculations. Czech researchers at IT4Innovations have developed and applied such approaches to magnetic and structural materials. The trained model can retain near-quantum accuracy over a selected configuration space while reducing the cost enough for much larger atomistic simulations. This strategy turns supercomputers into virtual laboratories where defects, high-temperature phases, interfaces, and transformation pathways can be explored systematically. It also illustrates how artificial intelligence can accelerate physics without replacing the underlying physical data from which the model learns. The approach is particularly powerful when the underlying training database is generated systematically and validated against independent configurations.

Data-driven materials research became increasingly visible during the early 2020s. Instead of using machine learning only as a black-box predictor, Czech groups also investigated interpretable models that expose relationships between structural descriptors and physical properties. A 2025 study involving researchers from Palacký University and IT4Innovations used machine learning to predict atomic-scale magnetic anisotropy in candidate quantum materials. The model was trained on relativistic electronic-structure calculations but used physically meaningful features that could be related to perturbative mechanisms governing anisotropy. Such approaches can screen large families of candidate structures much faster than performing the most expensive calculation independently for every material. The best candidates can then be returned to more accurate first-principles calculations or experimental synthesis. This hierarchical workflow reduces computational waste while retaining a physical basis for the final prediction. It is especially valuable in materials discovery because the combinatorial space of chemical composition, defects, surfaces, and interfaces is vastly larger than any experimental programme can sample exhaustively, encouraging Czech computational materials science to combine physical theory, high-performance computing, and machine learning in a single discovery cycle.

Plasma physics provides another field in which numerical modelling is indispensable because the relevant processes extend from microscopic particle collisions to metre-scale magnetic confinement. At the Institute of Plasma Physics, the Theory and Modelling Department investigates transport in the plasma core, pedestal, and Scrape-Off Layer, usually abbreviated as SOL. Researchers model Neutral Beam Injection and Electron Cyclotron Resonance Heating, runaway-electron dynamics, plasma equilibrium, and the interaction between plasma and material surfaces. Their work supports the COMPact ASSembly (COMPASS) tokamak and contributes to scenarios for COMPASS Upgrade, the Joint European Torus, the Axially Symmetric Divertor Experiment Upgrade, the Mega Ampere Spherical Tokamak Upgrade, the Tokamak à Configuration Variable, Japan Torus-60 Super Advanced, the International Thermonuclear Experimental Reactor, and a future demonstration fusion power plant. The modelling portfolio includes internationally developed software as well as Czech codes such as BIT1, BIT3, EBdyna, NUR, PLEQUE, SOLF1D, and SPICE. Different models operate at different levels of physical description, ranging from fluid transport to kinetic particle simulations. The choice of model depends on whether the problem concerns

macroscopic equilibrium, turbulent transport, individual particle distributions, collisions, or plasma-wall processes. High-performance computing allows these models to include finer spatial and temporal resolution and more complete physical interactions. Simulation thus provides a controlled environment in which proposed experiments can be tested numerically before scarce tokamak time is committed.

The BIT family of codes illustrates the computational intensity of kinetic plasma simulation. BIT1 is an electrostatic particle-in-cell and Monte Carlo code developed for fusion-relevant plasma-edge conditions. It follows charged particles, neutrals, impurities, collisions, and plasma-surface interactions in a self-consistent electrostatic environment. Particle-in-cell methods represent plasma through large ensembles of computational particles whose motion determines charge and current distributions on a spatial grid. Monte Carlo collision operators add stochastic interactions representing atomic, molecular, and Coulomb processes. Resolving the plasma sheath close to a wall requires very small spatial and temporal scales even when the physical system itself extends over much larger distances. Parallelisation is therefore necessary if realistic edge conditions are to be simulated without prohibitive run times. Czech developers optimised memory and computational performance and continued work towards multidimensional and exascale-capable versions. Training organised in Prague in 2025 used the Karolina supercomputer for hands-on BIT1 simulations, illustrating the direct connection between national high-performance computing and fusion modelling. Such codes allow plasma-material interaction to be explored numerically before or alongside expensive tokamak experiments.

Engineering simulation became equally important during the design of COMPASS Upgrade. The new tokamak requires magnetic coils, support structures, vacuum components, plasma-facing elements, cooling circuits, and power systems capable of surviving large electromagnetic and thermal loads. Finite Element Method calculations are used extensively by the Institute of Plasma Physics to predict stresses, deformations, heat flow, and structural response. The method divides a complex component into many smaller elements and solves approximate field equations across the resulting numerical mesh. Increasing mesh resolution improves the representation of complicated geometries but also increases memory and computational requirements. Electromagnetic simulations determine forces generated during high-current operation, while thermal models predict temperature gradients in components exposed to plasma heat. Mechanical calculations then test whether those loads exceed material limits or produce unacceptable deformation. Such numerical work reduces the number of costly prototype iterations and helps identify problems before manufacturing. COMPASS-U therefore demonstrates that theoretical and computational physics now participate directly in the engineering design of experimental infrastructure.

Nuclear physics also developed computational methods capable of connecting fundamental interactions with measurable properties of nuclei. The Department of Theoretical Physics at the Nuclear Physics Institute studies nuclear structure, hypernuclei, meson–baryon systems, and electroweak processes using sophisticated many-body calculations. Ab initio methods attempt to derive nuclear behaviour from interactions among nucleons rather than fitting each nucleus independently. Effective Field Theory provides a systematic framework for organising nuclear forces according to the relevant energy scale. Many-body calculations are required because the number of possible quantum configurations rises rapidly with the number of particles. Computational methods are applied to double-beta decay, hypernuclear structure, nuclear reactions, and processes relevant to astrophysics or fusion. These calculations

complement accelerator experiments by identifying which observables are most sensitive to competing theoretical descriptions. They are also important in searches for physics beyond the Standard Model, where theoretical nuclear uncertainties can limit the interpretation of precision measurements, making Czech nuclear theory another area in which computation directly extends the reach of fundamental physics.

Particle physics created one of the earliest large-scale data-driven environments in Czech science. Experiments at the European Organization for Nuclear Research generate datasets that cannot be stored and analysed at a single site. Czech computing centres became part of the Worldwide Large Hadron Collider Computing Grid, allowing collision data and simulations to be processed through distributed resources. High-throughput computing is especially important because particle-physics analyses often require millions or billions of statistically independent simulated events rather than one enormous tightly coupled calculation. The HTCondor workload-management system is used to distribute such jobs across clusters and other available resources. Researchers at the Nuclear Physics Institute and Institute of Physics participate in this computational infrastructure for A Large Ion Collider Experiment (ALICE) and ATLAS (A Toroidal LHC Apparatus), with LHC denoting the Large Hadron Collider. Simulation reproduces particle interactions with detectors, while reconstruction software converts electronic signals back into tracks, energies, particle identities, and collision observables. Statistical inference then compares measured distributions with Standard Model predictions or candidate signals. This chain demonstrates that modern experimental particle physics is inseparable from software, distributed computing, and numerical modelling. The scale of this work also strengthened domestic expertise in scientific software engineering and reproducible statistical analysis.

Computational astrophysics addresses a different class of multiscale problems because astronomical systems cannot normally be manipulated experimentally. Czech researchers therefore use simulations to connect fundamental laws with observations of stars, galaxies, accretion flows, plasma, and large-scale cosmic structure. At Masaryk University, numerical work includes stellar winds, circumstellar discs, supernova interactions, galaxy atmospheres, black-hole feedback, and cosmological simulations. Multidimensional hydrodynamic codes can follow shocks and material flows produced when winds or supernova ejecta interact with an inhomogeneous environment. Particle-based and magnetohydrodynamic methods are needed when magnetic fields or collisionless plasma effects become important. Synthetic observations then convert simulated density, temperature, velocity, and chemical composition into quantities that can be compared directly with X-ray, optical, or radio measurements. This comparison is essential because a physically correct simulation does not necessarily resemble the underlying state in an obvious way after instrumental response and projection are included. Czech high-energy astrophysics increasingly uses such mock observations when testing models of hot gas in galaxies and clusters. Computation therefore acts as the laboratory in which astrophysical scenarios are evolved before being confronted with the sky.

Black holes and compact objects create particularly demanding theoretical problems because general relativity, plasma physics, radiation, and extreme gravity can interact within the same system. Czech theoretical groups in Prague, Brno, and Opava study particle motion, accretion, gravitational radiation, and electromagnetic processes around black holes and neutron stars. Some problems admit exact or semi-analytic solutions, preserving the long Czech tradition in mathematical relativity. Others require numerical integration of relativistic equations or large-

scale simulations of plasma and radiation. Particle-in-cell methods can model kinetic processes in compact-object magnetospheres, while relativistic hydrodynamics describes matter moving close to the speed of light. N-body calculations follow the gravitational interaction of many stars in dense clusters and galactic nuclei. Numerical waveform models are increasingly important in gravitational-wave astronomy because observations must be compared with theoretical signals generated by compact binaries. Czech workshops and emerging research initiatives during 2025 explicitly connected artificial intelligence with gravitational-wave data analysis and source modelling. Computational relativity therefore provides another area where traditional theoretical physics is converging with data-intensive methods. These methods are especially valuable when direct analytic solutions cease to exist but clear physical invariants and asymptotic limits remain available for validation.

Cosmological simulations extend the scale of numerical physics from individual objects to the evolution of large portions of the Universe. They begin with initial density fluctuations inferred from cosmological theory and follow the growth of structure under gravity over billions of years. Dark matter can be represented with very large N-body calculations, while baryonic gas requires hydrodynamic equations, cooling, star formation, and feedback prescriptions. Synthetic galaxies and clusters can then be compared with observations from X-ray, optical, radio, and millimetre surveys. Researchers at Masaryk University use state-of-the-art cosmological simulations and produce mock X-ray observations for comparison with existing and future space telescopes. The comparison helps identify observational selection effects and determine whether apparent structures in images correspond to real physical features. Machine learning is also being explored for classifying galaxy clusters and analysing the large-scale structure of the Universe. Such methods become increasingly useful as surveys produce samples far larger than can be inspected manually, placing Czech computational astrophysics within the wider transition from modelling a few idealised systems towards statistically comparing simulated universes with large observational datasets.

Solar and stellar physics provide further examples of numerical modelling connected closely to observation. Magnetohydrodynamic calculations are used to study magnetic reconnection, flares, prominences, coronal structures, turbulence, and the solar wind. Radiative-transfer models determine how the physical conditions in a stellar or solar atmosphere produce the spectral lines measured by telescopes. Non-equilibrium ionisation and non-Maxwellian particle distributions can be important when energetic events drive plasma far from thermal equilibrium. Stellar-atmosphere calculations similarly require large atomic databases and iterative numerical solutions to determine radiation fields, level populations, temperature, and outflow properties. Czech researchers use these methods to interpret observations of hot stars, stellar winds, binaries, and solar eruptions. Numerical models also make it possible to test which physical mechanism is consistent with time-dependent spectral variations. Theoretical prediction and observational diagnosis therefore operate as an iterative cycle. Computational astrophysics in Czechia is not restricted to spectacular cosmological simulations but is embedded in everyday interpretation of stellar and solar data. The same computational tools also help researchers design future observations by identifying which wavelengths, cadences, or spectral diagnostics are most sensitive to competing models.

Machine learning and artificial intelligence became increasingly visible in Czech physics during the 2010s and especially the first half of the 2020s. Their growth was enabled partly by graphics-processing-unit hardware and by the accumulation of large labelled datasets from experiments, simulations, and astronomical surveys. In particle and astroparticle physics,

neural networks can classify collision events or infer hidden shower properties from complex detector signals. In astronomy, machine learning is used for transient searches, classification of variable objects, analysis of galaxy clusters, and extraction of patterns from multi-wavelength surveys. In materials science, regression and classification methods accelerate screening of candidate compounds and learn surrogate models for expensive electronic-structure calculations. Spectroscopy groups at the Institute of Physics also began using machine learning to deconvolve complex photoelectron spectra. The common advantage is the ability to identify high-dimensional correlations that would be difficult to encode through simple analytic cuts. The common danger is that an apparently accurate model may exploit spurious correlations or fail when applied outside the domain represented by its training data. Czech researchers therefore increasingly combined machine learning with physical constraints, interpretability, calibration, and conventional simulation rather than treating artificial intelligence as a substitute for theory.

The Pierre Auger Observatory provides a particularly clear example of this hybrid methodology. Extensive air showers generate complicated time-dependent signals across many surface-detector stations, while fluorescence measurements provide a more direct but much smaller sample of longitudinal shower profiles. Deep neural networks can be trained on simulated and hybrid events to infer the atmospheric depth of shower maximum from the much larger surface-detector dataset. In 2025, the Pierre Auger Collaboration published results extending event-by-event mass-sensitive inference towards the highest observed cosmic-ray energies. Czech members of the collaboration participated in the wider detector, simulation, and analysis environment supporting this work. The method increased the statistical reach of composition studies while remaining dependent on calibration against physically interpretable observables. Differences among hadronic-interaction models still have to be propagated into the final uncertainty. Machine learning therefore amplifies the scientific value of the detector but does not remove the need for detailed shower physics. This example captures the broader Czech approach to data-driven physics, in which algorithms are most powerful when embedded inside a validated physical measurement framework. Similar principles are increasingly applicable to detector reconstruction and anomaly searches in other large physics experiments.

Artificial intelligence also changed the computational workflow itself rather than only the analysis of experimental data. Surrogate models can approximate expensive simulations and allow large parameter spaces to be explored before a smaller number of high-fidelity calculations are performed. Reduced-order models compress the behaviour of complex systems into a smaller set of variables that can be evaluated rapidly. Neural networks can assist optimisation of laser-plasma acceleration, predict material properties, or identify configurations worthy of more costly quantum calculations. Automated workflows can generate simulation inputs, submit jobs to supercomputers, analyse outputs, and select the next calculations adaptively. This approach is particularly attractive when each first-principles calculation takes many hours or when experimental beam time is scarce. IT4Innovations explicitly developed research at the intersection of high-performance computing, high-performance data analytics, and artificial intelligence. Its accelerated computing systems provided the graphics-processing-unit capacity required for large training tasks, making the integration of these methods into physics both a scientific and an infrastructural development.

The increasing sophistication of computational methods also placed greater emphasis on validation and reproducibility. A numerical model can produce visually convincing output even

when assumptions, boundary conditions, or numerical errors make the result physically misleading. Czech computational groups therefore compare simulations with analytic limits, benchmark problems, independent codes, and experimental measurements whenever possible. Convergence studies test whether increasing spatial, temporal, or basis-set resolution changes the result significantly. Uncertainty quantification distinguishes numerical error from uncertainty in physical parameters or experimental inputs. Version control, structured workflows, and shared repositories make it easier to reproduce calculations after software has changed. Large infrastructures also require explicit management of data provenance because a result may depend on many terabytes of intermediate files and hundreds of software dependencies. These practices became increasingly important as machine learning introduced additional choices concerning training data, architecture, and hyperparameters. Reproducible computation consequently became part of scientific methodology rather than merely good programming practice. Open software and archived metadata also make it easier for international collaborators to test or extend a Czech computational result.

Education adapted gradually to the growing centrality of computation. Physics students increasingly learned programming, numerical methods, statistical analysis, and data visualisation alongside analytical mechanics, electromagnetism, quantum theory, and laboratory techniques. Specialist courses at Czech universities introduced high-performance computing, computational physics, machine learning for astronomy, quantum simulation, and numerical methods for many-body systems. IT4Innovations offered training in parallel programming, accelerator architectures, performance optimisation, data analytics, and scientific use of its supercomputers. Such training is necessary because obtaining access to a powerful machine does not automatically make a calculation efficient. Researchers must understand domain decomposition, memory hierarchy, message passing, vectorisation, graphics-processing-unit programming, and the scaling behaviour of their codes. Computational competence therefore became a practical experimental skill analogous to learning how to operate a spectrometer or detector. By 2025, a new generation of Czech physicists was being trained to move more easily among theory, software, simulation, and data analysis. This shift changed the profile of physics training by making algorithmic judgement part of scientific judgement.

Between 1993 and 2025, computational, theoretical, and data-driven physics therefore developed from a collection of specialised methods into a common infrastructure underlying much of Czech physical research. Established theoretical schools in quantum physics, relativity, nuclear theory, statistical physics, condensed matter, and plasma science supplied the conceptual models that computation made increasingly realistic. IT4Innovations transformed the national scale of numerical work through Anselm, Salomon, Barbora, specialised artificial-intelligence hardware, and the Karolina petascale system. Participation in EuroHPC and the LUMI consortium connected Czech users with still larger European resources, while e-INFRA CZ integrated computing with networks, clouds, grids, and data storage. Materials researchers used electronic-structure theory, molecular dynamics, spin dynamics, and machine-learning potentials to bridge atomic and engineering scales. Plasma physicists developed and applied kinetic, fluid, equilibrium, and finite-element simulations for COMPASS, COMPASS-U, ITER-related research, and plasma–material interaction. Nuclear theorists used many-body and ab initio methods, while particle physicists relied on distributed computing and large Monte Carlo datasets. Astrophysicists simulated stars, supernovae,

black holes, galaxies, cosmic plasma, and large-scale structure before comparing synthetic observables with telescope data. Machine learning increasingly accelerated classification, inference, surrogate modelling, and materials discovery while remaining dependent on physical validation. The principal achievement was therefore not any single computer or algorithm, but the integration of mathematical theory, scalable computation, and data-intensive inference into the everyday practice of Czech physics.

Part Three

Leading Institutions and Scientific Schools of Czech Physics

Prague Physics School: The Czech Academy of Sciences, Charles University, and Czech Technical University

The term Prague Physics School is best understood as an analytical description of a dense institutional ecosystem rather than the official name of a single organisation. Between 1993 and 2025, that ecosystem was centred on the Institute of Physics of the Czech Academy of Sciences (FZU, from the Czech name Fyzikální ústav), the Faculty of Mathematics and Physics of Charles University, and the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague (CTU). Together these institutions covered an unusually broad range of modern physics, from elementary particles and quantum fields to solids, lasers, optics, and quantum technologies. Their proximity within one metropolitan research environment encouraged movement of students, shared appointments, joint laboratories, common seminars, and collaborative grant projects. The three institutions also occupied complementary positions within the Czech research system, with FZU oriented primarily towards research, Charles University combining fundamental research with mathematically rigorous university education, and the Czech Technical University linking physics more explicitly with engineering and technological implementation. This division of roles did not produce rigid boundaries, because all three institutions engaged in both fundamental and applied work. Large international collaborations further connected Prague groups at the European Organization for Nuclear Research, major neutron and synchrotron facilities, laser infrastructures, and other international laboratories. The resulting network became one of the main reasons why Prague retained its position as the dominant geographical centre of Czech physics after the dissolution of Czechoslovakia. Its importance lay less in institutional centralisation than in the sustained interaction of several scientifically autonomous but closely interconnected schools.

The Prague concentration of physics rested on foundations established long before 1993, but the independent Czech Republic changed the institutional conditions under which those traditions operated. Charles University provided the oldest academic lineage and preserved strong schools in theoretical, nuclear, particle, optical, and condensed-matter physics. The Czech Technical University contributed a distinctive physical-engineering tradition through the Faculty of Nuclear Sciences and Physical Engineering, which had been founded in 1955 and transferred from Charles University to the technical university in 1959. The Institute of Physics inherited major research programmes in solid-state physics, elementary particles, optics, and materials from the Czechoslovak Academy of Sciences. After 1993, all three institutions adapted to competitive grant systems, international evaluation, European research programmes, and much greater mobility of researchers. Their laboratories became progressively more dependent on international infrastructures that no national institution could reproduce alone. At the same time, new domestic facilities in Prague and the surrounding region allowed the metropolitan research community to host experiments of much greater scale. Cooperation became especially visible in particle physics, spintronics,

laser science, nanotechnology, and quantum research. The resulting structure combined historical continuity with a flexible division of scientific labour. By the 2020s, Prague physics functioned as an interconnected metropolitan research environment rather than as a collection of isolated institutional departments.

FZU became the largest research institute of the Czech Academy of Sciences and the principal non-university centre of physical research in Prague. Its scientific structure covered elementary-particle physics, condensed matter, solid-state physics, optics, laser science, and a wide range of materials-oriented research. Laboratories at Na Slovance and Cukrovarnická preserved complementary traditions in high-energy physics, theory, magnetism, semiconductors, crystallography, functional materials, and surface science. The Institute also developed major facilities outside the historic central Prague campuses, most notably Extreme Light Infrastructure (ELI) Beamlines and High average power pulsed LASErs (HiLASE) in Dolní Břežany. This expansion changed FZU from a predominantly institute-based research organisation into the operator of national and European-scale infrastructures. Its researchers worked simultaneously on fundamental questions such as particle interactions or emergent magnetic order and on technologies such as detectors, nanofabrication, laser systems, and advanced materials. Open-access laboratories further allowed university and industrial users to work with equipment concentrated at FZU. The Institute therefore became a central bridge between the academic, infrastructure, and technological dimensions of the Prague Physics School.

The elementary-particle programme at FZU illustrates especially clearly how Prague research became embedded in global experimental physics after 1993. Czech groups entered the post-Czechoslovak period with experience from international accelerator experiments and rapidly consolidated their position within the European Organization for Nuclear Research, commonly abbreviated as CERN. FZU researchers participated in experiments at the Large Hadron Collider and in earlier CERN programmes, contributing to detector construction, calibration, computing, data analysis, and physical interpretation. Work within ATLAS, whose name expands as A Toroidal LHC Apparatus, became one of the principal channels through which Prague physicists studied proton collisions at the highest accelerator energies. FZU also participated in A Large Ion Collider Experiment, commonly abbreviated as ALICE, where high-energy nuclear collisions are used to investigate strongly interacting matter under extreme conditions. The scientific programme included Higgs-boson physics, top-quark processes, electroweak measurements, searches for phenomena beyond the Standard Model, and studies of the quark–gluon plasma. Detector research strengthened domestic expertise in silicon sensors, radiation monitoring, electronics, and high-throughput data acquisition. Prague computing resources became part of the distributed infrastructure required to process Large Hadron Collider data. The same international projects trained students from Charles University and the Czech Technical University, making CERN a shared educational environment for the metropolitan physics community. Collaboration across institutional boundaries was therefore built into the practical organisation of high-energy physics. Particle physics became one of the clearest examples of a Prague school whose real laboratory extended far beyond Czech territory.

Charles University supplied much of the academic and theoretical depth that supported this particle-physics ecosystem. Its Institute of Particle and Nuclear Physics combined experimental high-energy research with nuclear physics, phenomenology, quantum field theory, detector methods, and advanced data analysis. Students received systematic training

in quantum mechanics and quantum field theory before specialising in experimental or theoretical problems. Research projects were connected with CERN and other major international facilities, allowing university education to move directly into collaboration-scale science. The Institute also linked particle physics with nuclear structure and the study of finite interacting quantum systems. This combination was valuable because experimental techniques, statistical methods, and theoretical concepts often move between nuclear and particle physics. Joint supervision and collaboration with FZU reduced the separation between Academy research and university teaching. Prague consequently developed a pipeline in which students could enter major international experiments before completing doctoral training. Charles University thus functioned not only as an educational institution but as an active component of the capital's high-energy research school.

The Czech Technical University added a more explicitly engineering-oriented branch to Prague particle and nuclear physics. Its Faculty of Nuclear Sciences and Physical Engineering, commonly abbreviated as FNSPE, combines deep mathematical preparation with experimental and technological training. The Department of Physics participates in nuclear and particle physics, mathematical physics, quantum information, plasma physics, and tokamak research. Students in nuclear and particle physics learn detector principles, data analysis, computation, and the theoretical structure of the microworld while collaborating with external research institutes. FNSPE researchers participate in international particle experiments and cooperate with CERN, the Czech Academy of Sciences, and other major laboratories. The faculty's engineering orientation is especially relevant to detector construction because a successful particle experiment requires electronics, mechanics, radiation-resistant materials, control systems, and software as well as theoretical physics. This practical competence complements the larger experimental groups at FZU and Charles University. The faculty also integrates particle physics with dosimetry, radiation applications, nuclear engineering, and accelerator-related technologies. The result is a distinctive educational model in which fundamental physics is treated as inseparable from the instrumentation required to measure it. Within the Prague Physics School, FNSPE therefore serves as an important bridge between frontier experiments and the engineering capabilities needed to build them.

Condensed-matter physics provides an equally important axis of cooperation among the three institutions. FZU maintains major programmes in electronic structure, magnetism, superconductivity, ferroics, semiconductors, thin films, crystallography, nanostructures, and functional materials. Charles University contributes strong research on intermetallic compounds, rare-earth and actinide systems, low-temperature physics, magnetic multilayers, surfaces, and computational materials science. FNSPE complements these programmes through solid-state engineering, diffraction methods, semiconductor technology, superconductivity, optical materials, and the physical properties of technologically relevant solids. Researchers across Prague therefore address related material systems from different methodological positions. A crystal may be synthesised or patterned at one institution, measured by diffraction or spectroscopy at another, and interpreted theoretically within a collaborating group. This circulation of samples, methods, and researchers reduces duplication while increasing the range of techniques available to individual projects. The Prague condensed-matter environment consequently combines the breadth of a large research institute with university specialisation and engineering implementation.

The Department of Condensed Matter Physics at Charles University exemplifies the university side of this metropolitan materials school. Its research encompasses atomic and electronic structure, thin films, magnetic multilayers, intermetallic compounds, nanocrystalline materials, low-temperature phenomena, diffusion, and phase transitions. X-ray, synchrotron, and neutron scattering are used together with magnetic, transport, thermodynamic, and computational methods. Rare-earth and actinide materials have provided a long-running platform for investigating the competition among magnetism, electronic correlations, and superconductivity. External pressure, magnetic field, and temperature are employed as controlled variables for exploring complex phase diagrams. The department also works on modern low-dimensional and surface systems rather than restricting itself to classical bulk solids. Computational materials science supports interpretation of electron structure and links experimental observations with microscopic models. Access to international neutron and synchrotron facilities gives students experience with infrastructure that would be impossible to reproduce inside one university. Collaboration with FZU is particularly natural in magnetism, spintronics, superconductivity, structural analysis, and nanoscience. These overlaps encourage joint projects without erasing the independent scientific identity of the university department. Charles University thus sustains one of the core research and educational traditions on which Prague condensed-matter physics depends.

FZU contributes the widest experimental and theoretical range within the same field. Its condensed-matter and solid-state laboratories span magnetic and superconducting materials, dielectrics, semiconductors, structural analysis, crystal growth, functional alloys, surface science, and nanoscale systems. The Institute's crystallographic groups developed methods and software used internationally for complex and modulated structures. Its semiconductor laboratories connect epitaxial growth with transport, optical spectroscopy, nanofabrication, and device physics. Magnetic research developed from classical materials studies towards spintronics, antiferromagnetic devices, and eventually altermagnetism. Functional-material programmes link microscopic phase transformations with shape-memory effects, magnetocaloric behaviour, and engineering applications. Open-access facilities for nanostructures and nanomaterials allow these research programmes to share expensive fabrication and microscopy tools. Theoretical groups provide electronic-structure and many-body calculations that guide or interpret experiments. FZU therefore supplies the Prague school with a broad institutional framework in which fundamental condensed-matter concepts can develop into materials and devices.

The interaction between FZU and Charles University became particularly visible in spintronics. Prague researchers investigated magnetic semiconductors, spin-orbit phenomena, antiferromagnetic order, ultrafast magnetic dynamics, and electrical control of magnetic states. The Laboratory of OptoSpintronics developed as a joint environment linking the Faculty of Mathematics and Physics with the Institute of Physics. This collaboration combined epitaxial materials and nanofabrication with ultrafast optical spectroscopy and transport measurements. Theoretical analysis of relativistic spin-orbit effects further connected experimental observations with crystal symmetry and electronic structure. During the 2010s, the Prague network became internationally prominent through electrical switching of antiferromagnetic order in copper manganese arsenide. During the 2020s, related theoretical work contributed to the formulation of altermagnetism as a distinct symmetry class of magnetic matter. Experimental confirmation required cooperation with synchrotron and photoemission laboratories abroad, but much of the conceptual and materials expertise

remained concentrated in Prague. This trajectory shows how a local institutional network can influence an international research field even when crucial measurements are geographically distributed. It also demonstrates that theoretical, optical, materials, and device physics were increasingly difficult to separate within the Prague research environment.

Theoretical physics forms another historical pillar of the Prague school. At Charles University, the Institute of Theoretical Physics serves as a major centre for teaching and fundamental research in relativity, astrophysics, quantum theory, mathematical physics, and statistical physics. Its work preserves the tradition of using rigorous mathematical structures to formulate physical questions before numerical approximation is introduced. FZU contributes complementary theory in particle physics, cosmology, condensed matter, magnetism, superconductivity, and quantum materials. The Czech Technical University develops mathematical physics and computational approaches closely connected with nuclear, particle, plasma, and engineering problems. These groups differ in institutional culture but share common methods based on symmetry, quantum theory, field theory, statistical mechanics, and numerical modelling. Seminars and doctoral supervision provide channels through which theoretical ideas circulate among institutions. The resulting theoretical landscape supports both highly abstract research and direct interpretation of major experiments.

Relativity and gravitation at Charles University illustrate the long-term value of a strong theoretical school inside a wider experimental metropolis. Prague researchers have worked on exact solutions of Einstein's equations, gravitational radiation, black holes, cosmology, lensing, and relativistic astrophysics. These subjects connect the university's mathematical traditions with observational questions investigated at the Astronomical Institute and other Czech institutions. The creation of the Albert Einstein Centre for Gravitation and Astrophysics in 2014 strengthened cooperation among several Prague and national groups. Although the centre extends beyond the three institutions considered here, it exemplifies the network logic characteristic of Prague theoretical physics. Fundamental work in relativity also contributes to the interpretation of gravitational-wave and high-energy astrophysical observations. Numerical methods have become increasingly important, but analytic structure remains central to understanding the limits and invariants of calculations. The coexistence of mathematical and computational approaches allows Prague researchers to work across the full chain from formal theory to observable predictions. This culture of theoretical depth influences other fields, including particle theory and quantum information. It also reinforces the role of Charles University as a training centre for physicists who later move into Academy institutes or international laboratories. The Prague school therefore retains a distinctive identity in which theoretical sophistication is treated as an enabling component of experimental science rather than a separate intellectual activity. This continuity has been one of the stabilising features of the metropolitan physics environment since 1993.

Optics and photonics provide another field in which the three Prague institutions developed complementary roles. FZU maintains a Division of Optics and operates or co-operates major laser infrastructures, including the Prague Asterix Laser System (PALS), HiLASE, and ELI Beamlines within the wider Prague region. Charles University develops optical spectroscopy, quantum optics, optoelectronics, ultrafast phenomena, and light–matter interaction in its Department of Chemical Physics and Optics. FNSPE contributes laser physics, photonics, X-ray optics, holography, optoelectronics, and nanophotonic structures through its Department of Laser Physics and Photonics. These programmes range from fundamental studies of

ultrafast electron dynamics to the design of laser sources and optical devices. Shared interests in semiconductors, magnetic materials, nanostructures, and plasma create numerous points of contact with condensed-matter and particle research. Prague optics therefore cannot be separated cleanly into university, Academy, and engineering branches. Its strength comes instead from the availability of several complementary experimental cultures within a small geographical area. This structure became increasingly important as optics moved towards quantum, nanoscale, and high-field regimes.

At Charles University, the Department of Chemical Physics and Optics provides a particularly broad interface between optical physics and other disciplines. Its teaching and research cover laser spectroscopy, optoelectronics, nonlinear phenomena, molecular physics, quantum chemistry, and ultrafast processes in solids. The Quantum Optics and Optoelectronics group studies strong-field electron dynamics, high-harmonic spectroscopy, ultrafast electron microscopy, and quantum interactions between free electrons and photons. Other groups investigate optical spectroscopy of molecular and biological systems and theoretical quantum processes. This breadth allows optical methods to be applied to problems originating in condensed matter, chemistry, biophysics, and quantum information. Femtosecond and attosecond techniques make it possible to follow electronic processes before slower structural relaxation dominates the response. Terahertz spectroscopy probes lower-energy collective dynamics in semiconductors and nanostructures. Magneto-optical experiments provide a direct bridge to spintronics and magnetic materials. The university programme therefore combines fundamental optical science with applications in optoelectronics, photovoltaics, and information processing. Cooperation with FZU strengthens access to materials preparation, nanofabrication, and complementary spectroscopy. The resulting Prague environment allows a single physical problem to be approached through both ultrafast optical measurement and detailed materials characterisation.

FNSPE adds an engineering dimension to this optical landscape. Its Department of Laser Physics and Photonics develops solid-state lasers, nonlinear and diffractive optics, holography, X-ray photonics, nanophotonics, and precision optical instrumentation. Research on laser-active materials links spectroscopy with crystal physics and the development of practical radiation sources. X-ray photonics extends the programme into extreme-ultraviolet lithography, microscopy, radiography, and plasma diagnostics. Nanophotonic research addresses photonic crystals, metamaterials, plasmonic systems, and increasingly quantum optical structures. The department also develops detectors and timing technologies relevant to space research and precision measurement. Cooperation with ELI Beamlines and HiLASE provides access to high-power systems and connects student projects with large research infrastructure. The faculty therefore translates optical principles into devices and technologies while retaining a substantial fundamental component. This combination makes FNSPE an important technological counterpart to the more research-oriented optical programmes at FZU and Charles University.

Quantum research became a particularly visible area of convergence during the 2010s and 2020s. Charles University brought together quantum optics, quantum information, many-body physics, superconducting nanostructures, quantum materials, and emerging quantum sensing. FNSPE developed research and formal study pathways in quantum information, quantum communication, photonic quantum technologies, and mathematical physics. FZU contributed quantum materials, spintronics, nanostructures, superconductivity, quantum transport, and advanced optical platforms. These programmes did not arise from a single

national initiative but from older disciplinary strengths that gradually became connected by the language of quantum technology. Shared laboratories and collaborative projects increasingly linked optical, condensed-matter, and information-theoretical approaches. The Prague environment therefore contained several possible physical implementations of quantum functionality rather than committing to one platform. This diversity became an advantage as European quantum programmes expanded during the 2020s. It allowed the metropolitan research community to participate in quantum technology without abandoning its long-standing foundations in materials, optics, and mathematical physics. This diversity also creates multiple entry points for students and researchers moving between fundamental and application-oriented quantum work. Prague's quantum profile therefore grew through convergence among established disciplines rather than through institutional replacement.

Charles University illustrates this diversification particularly well. Its quantum activities extend from precision theoretical calculations and quantum optics to superconducting systems, ultrafast electronics, open quantum systems, and quantum information thermodynamics. The Faculty of Mathematics and Physics developed an explicit Quantum Technologies framework that connects groups from several departments rather than placing all activity inside one institute. Quantum optics researchers study the interaction of light with matter on ultrafast timescales and explore free-electron and photon dynamics. Condensed-matter theorists investigate quantum dots, superconducting hybrid systems, transport, and decoherence. Emerging quantum-sensing work uses solid-state defects and nanoscale materials as possible probes of magnetic and other physical quantities. These themes create natural cooperation with FZU groups in diamond, nanofabrication, spintronics, and superconductivity. The university's role is therefore both disciplinary and integrative. By the middle of the 2020s, quantum research had become a visible umbrella connecting fields that had previously been administered separately. This institutional reorganisation reflects a wider transformation in physics from studying quantum phenomena towards deliberately engineering quantum states and devices.

The Czech Technical University responded to the same transformation by making quantum technologies an explicit part of its educational and research profile. FNSPE offers quantum-oriented study at bachelor, master's, and doctoral levels within a curriculum that combines physics, mathematics, optics, information, and engineering, while the Department of Physics addresses quantum information and communication together with mathematical, particle, and plasma physics. The Department of Laser Physics and Photonics contributes quantum photonic structures, correlated and entangled photons, nanophotonics, and single-photon technologies. The Department of Solid State Engineering adds materials, semiconductors, superconductivity, sensors, and photonic components. This distribution ensures that quantum technology is treated as a systems field rather than only as an abstract information theory. Students encounter both the mathematical description of quantum states and the hardware required to generate, manipulate, and measure them. The engineering context also encourages attention to reliability, fabrication, electronics, and integration. CTU consequently complements the stronger fundamental emphasis of Charles University and the research-infrastructure capabilities of FZU. The three institutions together create a Prague environment in which quantum science can move from formal theory to materials and ultimately towards technological implementation.

Large research infrastructures amplify this institutional complementarity. FZU's ELI Beamlines and HiLASE centres give Prague researchers access to advanced laser systems, secondary

radiation sources, ultrafast methods, and materials-processing technologies. CzechNanoLab provides open-access nanofabrication and characterisation that can support university projects as well as Academy research. CERN and other international particle facilities extend the experimental reach of local high-energy groups. Synchrotron, neutron, and high-magnetic-field infrastructures provide similar extensions for condensed-matter physics. University researchers therefore do not need to reproduce every expensive capability inside their own departments. Instead, they can combine local laboratories with national and international shared facilities. This infrastructure-based model became one of the defining organisational features of Prague physics after 2010.

The educational consequences of this network are substantial because Prague students can encounter several institutional cultures during a single degree. A Charles University student may perform thesis research at FZU, participate in an experiment at CERN, and use a technical method developed at CTU. A FNSPE student may receive mathematical and engineering training at CTU while conducting detector, laser, or materials work with an Academy institute. Doctoral candidates employed in FZU groups can simultaneously be enrolled at a Prague university and participate in international collaborations. This arrangement allows specialised research institutes to contribute directly to university education without becoming degree-awarding institutions themselves. It also gives universities access to infrastructure whose scale would be difficult to support from teaching budgets. Seminars, summer schools, joint doctoral projects, and co-authored publications reinforce these connections. Students become accustomed early to research that crosses formal institutional boundaries. The metropolitan concentration therefore increases the effective diversity of training available to each institution. It also helps Prague retain young researchers by offering multiple career routes without requiring immediate relocation to another scientific centre. International mobility remains important, but it operates from a strong domestic institutional base. The Prague Physics School is thus reproduced not only through publications but through the circulation and training of successive generations of physicists.

The relationship between fundamental and applied physics is another characteristic feature of the Prague school. FZU pursues fundamental questions in particle interactions, magnetism, quantum materials, and light–matter physics while also developing detectors, optical systems, functional materials, and nanotechnologies. Charles University retains a strong emphasis on fundamental understanding but connects spectroscopy, materials, and quantum physics with optoelectronic, biomedical, and information-related applications. FNSPE begins from an explicitly physical-engineering mission and therefore integrates theory with instrumentation, materials, nuclear technology, lasers, and data processing. These institutional orientations overlap sufficiently that fundamental discoveries can migrate towards technological development without requiring an entirely separate research ecosystem. Conversely, engineering problems often generate new questions for basic physics. Detector radiation damage, optical-component limits, semiconductor defects, or quantum decoherence are examples in which practical constraints expose underlying physical mechanisms. This feedback prevents applied research from becoming merely routine technical work. It also prevents fundamental physics from becoming disconnected from the instrumentation that makes new observations possible.

Industrial connections strengthened this fundamental–applied continuum during the 2010s and 2020s. FZU laboratories cooperate with companies in optics, microscopy, semiconductor technologies, materials, sensing, and laser processing. HiLASE provides an especially visible

interface through laser shock peening, micromachining, optical-component testing, and high-average-power laser development. FNSPE maintains an engineering culture in which research projects frequently involve external laboratories or industrial partners. Charles University has expanded structures for technology transfer while retaining fundamental physics as the core mission of its Faculty of Mathematics and Physics. Prague-based companies and national firms can therefore access knowledge generated across several scientific institutions rather than relying on a single university interface. Researchers also benefit because industrial requirements impose demanding standards for repeatability, reliability, scale, and cost. These requirements can reveal weaknesses in prototypes that appear successful under purely academic conditions. The interaction is consequently bidirectional rather than a simple transfer of finished inventions from science to industry. It contributes to an innovation environment in which advanced physics supports high-value engineering while practical challenges feed back into research programmes. By 2025, this relationship had become especially important in photonics, nanotechnology, advanced materials, detectors, and quantum-related technologies.

Internationalisation is equally central to the identity of the Prague Physics School. Particle physicists work in collaborations whose membership extends across dozens of countries, making multilingual and multi-institutional research routine. Condensed-matter researchers use European neutron, synchrotron, and high-field facilities and cooperate with specialised materials laboratories abroad. Optical and laser scientists participate in European infrastructures and transnational-access programmes. Quantum researchers join networks focused on communication, sensing, information processing, and advanced materials. These collaborations expose Prague students to scientific standards and methods that cannot be learned solely inside national institutions. They also allow Czech groups to specialise rather than attempt to reproduce every technique locally. International mobility therefore reinforces rather than weakens the Prague school because researchers return with methods and networks that become embedded in local laboratories. The capital's institutional density makes it easier to absorb these external influences across several organisations at once.

The ability of Prague institutions to sustain different research scales is another source of resilience. A theoretical project may require little more than individual expertise and computing access, while a particle experiment may involve thousands of collaborators and decades of detector development. A spectroscopy laboratory can investigate a precisely defined material system with a small team, whereas ELI Beamlines operates as an international user infrastructure. The Prague ecosystem accommodates all of these modes without forcing them into one organisational model. Charles University is particularly suited to investigator-led theoretical and experimental groups embedded in teaching. FZU can maintain specialised laboratories and infrastructures whose primary mission is research continuity over long periods. FNSPE can organise projects around engineering systems, instrumentation, and technically intensive education. Collaboration allows each model to contribute where it is strongest. This institutional diversity helps protect the research community from excessive dependence on any single funding mechanism or scientific fashion. It also makes interdisciplinary projects easier because an appropriate partner can often be found within the same metropolitan environment. The result is a research school whose coherence comes from interaction rather than administrative uniformity.

Scientific visibility during the 2010s and 2020s illustrates the effectiveness of this structure. Prague groups contributed to Large Hadron Collider physics, including measurements

associated with the Higgs boson, top quarks, heavy-ion collisions, and precision tests of the Standard Model. Condensed-matter researchers achieved international prominence in antiferromagnetic spintronics and helped establish the concept of altermagnetism. Crystallographers at FZU developed structural methods and software used by researchers far beyond Czechia. Optical groups advanced ultrafast spectroscopy, spin dynamics, laser technologies, and nanoscale light–matter interaction. Theoretical physicists maintained internationally connected programmes in relativity, quantum systems, many-body physics, and particle theory. These achievements arose from different institutions but often depended on overlapping personnel, students, facilities, and collaborations. The Prague Physics School therefore cannot be represented adequately by a single flagship result or discipline. Its strength lies in producing internationally competitive research across several branches of physics at the same time.

The metropolitan school also demonstrates how scientific specialisation can coexist with a coherent educational culture. Charles University emphasises deep conceptual training and the connection between mathematics and physical theory. FNSPE emphasises similarly strong mathematics but couples it more directly to engineering systems, instrumentation, and technological application. FZU provides an environment in which students encounter professional research laboratories whose activities are not constrained by a teaching timetable. Moving among these settings teaches researchers to translate between theoretical, experimental, and engineering languages. Such translation is essential in fields such as particle detectors, quantum devices, nanotechnology, and high-power lasers. Joint projects also expose students to different standards of documentation, software development, laboratory safety, and project management. The resulting competence is broader than disciplinary knowledge alone. It prepares graduates for academic research, large infrastructures, high-technology industry, and scientific computing. The Prague school therefore functions as a training ecosystem as much as a research concentration. This educational dimension helps explain its continuity across institutional reforms and changing scientific priorities.

By 2025, the Prague Physics School had become one of the clearest examples of the polycentric organisation of Czech science, with FZU supplying the largest concentration of dedicated physics research and operating facilities ranging from nanolaboratories to European-scale laser infrastructure. Charles University preserved the strongest connection between fundamental physics, mathematical depth, and advanced university education across particle, condensed-matter, theoretical, optical, and quantum fields. The Czech Technical University contributed a distinctive physical-engineering model linking the same fundamental disciplines with detectors, materials, lasers, nuclear technologies, and device development. None of the three institutions alone reproduces the entire scientific profile of the metropolitan school. Their importance lies instead in the way their capabilities overlap sufficiently to sustain collaboration while remaining different enough to provide genuine complementarity. Particle physics shows this through shared participation in international experiments and the training of detector specialists. Condensed-matter and quantum research show it through joint laboratories, materials exchange, theoretical cooperation, and access to common nanofabrication and spectroscopy tools. Optics demonstrates the same pattern through the interaction of university spectroscopy, Academy laser science, and engineering photonics. Theoretical physics supplies a common conceptual foundation that connects these experimental domains. The Prague Physics School therefore represents a

mature research ecosystem in which institutional diversity, international integration, and the continual exchange between fundamental and applied physics became mutually reinforcing features of Czech science between 1993 and 2025.

Institute of Physics of the Czech Academy of Sciences as a Centre of National and International Research

The Institute of Physics of the Czech Academy of Sciences, known as FZU from its Czech name *Fyzikální ústav*, became the principal institutional centre of Czech physics between 1993 and 2025. It combined fundamental research with technologically oriented work across elementary-particle physics, condensed matter, solid-state physics, optics, laser science, plasma-related research, and advanced materials. This breadth distinguished FZU from more specialised institutes because several branches of modern physics could interact within one organisation. The Institute also developed and operated research infrastructures whose users extended far beyond its own staff. Its Prague laboratories maintained long-standing strengths in materials, crystallography, semiconductors, magnetism, theory, and high-energy physics. New facilities in Dolní Břežany, including Extreme Light Infrastructure (ELI) Beamlines and High average power pulsed LASErs (HiLASE), added high-power laser science and large-scale international user research to this established profile. FZU researchers simultaneously participated in experiments at major foreign infrastructures, particularly the European Organization for Nuclear Research, commonly abbreviated as CERN, and global astroparticle observatories. The result was an institution that connected national scientific continuity with the increasingly distributed organisation of international physics. By 2025, FZU functioned not merely as a large Czech research institute but as an institutional bridge linking domestic laboratories, European infrastructures, multinational collaborations, universities, and advanced technological development.

The historical structure of FZU explains why it could sustain such a broad scientific profile after the establishment of the independent Czech Republic. The Institute of Physics of the Czechoslovak Academy of Sciences was formally established in 1954 from earlier laboratories devoted to experimental, theoretical, and nuclear physics. A major enlargement occurred in 1979 when the existing Institute was combined with the Institute of Solid State Physics, creating much of the thematic breadth associated with the modern organisation. The political changes after 1989 altered the management, international contacts, and scientific freedoms under which the Institute operated. From 1993 it continued within the newly constituted Academy of Sciences of the Czech Republic and had to adapt to the financial and institutional conditions of an independent state. Competitive grant funding and international evaluation progressively became normal components of research planning. On 1 January 2007, the Institute acquired the legal form of a public research institution. European Structural and Investment Funds later enabled expansion on a scale that would have been difficult to finance from ordinary institutional resources alone. These investments supported new laboratories as well as the ELI Beamlines and HiLASE centres. The post-1993 history of FZU was therefore characterised by institutional continuity accompanied by a substantial increase in internationalisation, infrastructure scale, and technological ambition.

The internal organisation of FZU reflected the diversity of physical questions addressed within the Institute. Its major scientific units included the Division of Elementary Particle Physics, the Division of Condensed Matter Physics, the Division of Solid State Physics, and the Division of Optics, alongside the later laser centres and specialised research infrastructures. These divisions contained departments working on theory, experiments, materials preparation, structural analysis, spectroscopy, detector development, and technological applications. Their coexistence allowed the same institution to study matter from elementary-particle scales to macroscopic functional materials. It also reduced the separation between physics concerned with fundamental laws and research intended to create new devices or materials. A semiconductor project, for example, could require crystal growth, nanofabrication, microscopy, electronic transport, optical spectroscopy, and theoretical modelling. High-energy physics similarly combined fundamental questions with detector engineering, electronics, distributed computing, and radiation-resistant technologies. FZU therefore operated through a matrix of specialised departments whose methods frequently overlapped. This organisational breadth became particularly valuable as modern physics grew more interdisciplinary during the 2000s and 2010s.

FZU also occupied a distinctive place in the Czech national research system because it was simultaneously a research employer, infrastructure operator, and partner of universities. The Institute does not replace university physics departments, but many of its scientists supervise master's and doctoral students enrolled at Charles University, the Czech Technical University in Prague, and other Czech universities. Students can therefore receive formal university education while conducting research in specialised FZU laboratories. Joint seminars, collaborative grants, shared laboratories, and co-authored publications reinforce these connections. The Laboratory of Nanostructures and Nanomaterials provides open access to users from universities and research organisations that do not possess equivalent fabrication or microscopy systems. HiLASE similarly works with academic and industrial users requiring high-average-power laser technologies. ELI Beamlines attracts international teams whose experiments also involve Czech university researchers and students. The Institute therefore enlarges the effective experimental capacity of the national university system without duplicating degree programmes. This relationship has been especially important in fields whose instrumentation is too expensive or specialised for every university to maintain independently. FZU's national role is consequently defined as much by the research opportunities it provides to the wider community as by the publications generated by its own employees.

Elementary-particle physics has been one of the most internationally oriented components of FZU since the beginning of the period considered in this book. Czech high-energy physicists entered the 1990s with experience from experiments at CERN and the Deutsches Elektronen-Synchrotron, usually abbreviated as DESY. FZU groups contributed to the H1 experiment at the Hadron-Electron Ring Accelerator through silicon tracking, readout electronics, detector calibration, and physics analysis. Such work established technical competence that was later transferred to the much larger experiments of the Large Hadron Collider, commonly abbreviated as the LHC. Czech membership of CERN from 1993 provided an institutional framework for long-term participation in these collaborations. FZU became one of the principal Czech organisations involved in the preparation and scientific exploitation of LHC experiments. Its researchers contributed not only to analysis but also to detector components, electronics, software, and distributed computing. This pattern is important because

participation in modern collider physics requires responsibility for hardware and operations as well as publication of physical results. FZU's particle-physics programme therefore developed through sustained technical commitments inside multinational collaborations rather than through occasional access to foreign accelerators. The Institute became part of the international experimental system on which contemporary high-energy physics depends. The programme also created durable institutional links with accelerator laboratories that outlasted individual detector projects.

The ATLAS experiment became the largest single focus of FZU participation at the LHC. ATLAS, whose name expands as A Toroidal LHC Apparatus, is a general-purpose detector designed to investigate proton collisions over a very wide range of physical processes. Prague groups participated in detector preparation and in work associated with silicon tracking, calorimetry, forward detectors, radiation monitoring, electronics, and software. FZU physicists also developed analysis expertise in top-quark processes, electroweak interactions, Higgs-boson physics, forward physics, and searches for phenomena not described by the Standard Model. The discovery of a Higgs-like boson by ATLAS and the Compact Muon Solenoid experiment in 2012 was a collaboration-wide achievement to which Czech groups contributed through the broader detector and analysis programme. Subsequent work shifted from discovery towards precision determination of Higgs properties and increasingly stringent tests of the Standard Model. FZU researchers also participated in detector upgrades required for higher collision rates and radiation doses. These activities trained engineers and physicists in silicon sensors, fast electronics, mechanical integration, calibration, and large-scale data processing. The ATLAS programme therefore illustrates how a fundamental question about the origin of particle masses generated technological competence with relevance far beyond one physics measurement. Within FZU, it also connected theoretical interpretation, experiment, instrumentation, and computing.

A Large Ion Collider Experiment, commonly abbreviated as ALICE, provided FZU with a complementary route into high-energy nuclear physics. ALICE studies collisions of heavy nuclei in order to investigate strongly interacting matter at temperatures and energy densities where quarks and gluons are no longer confined inside individual hadrons. FZU researchers contributed to software, detector-related work, distributed data processing, and analyses of the particles produced in these collisions. The scientific questions differ from those of ATLAS because the emphasis is on the collective properties of the quark–gluon plasma and the dynamics of Quantum Chromodynamics. Participation therefore broadened the Institute's high-energy programme beyond proton-collision searches and precision measurements. FZU groups also maintained involvement in other CERN and international experiments concerned with forward physics, fixed-target studies, and specialised particle measurements. This diversity is important because methods developed in one experiment can later be transferred to another detector environment. It also provides students with several routes into experimental particle physics rather than concentrating national expertise in a single collaboration.

Computing became an inseparable component of this particle-physics programme. LHC experiments generate data volumes that cannot be processed or stored permanently at CERN alone. The Worldwide LHC Computing Grid distributes data and processing tasks among centres in many countries. FZU helped build Czech computing capacity within this architecture and developed expertise in grid middleware, workload management, storage, monitoring, and large-scale analysis. Researchers could therefore analyse collider data in Prague while

participating in a computational system distributed across continents. The same infrastructure also supported detailed Monte Carlo simulations needed to compare detector observations with theoretical predictions. Distributed computing changed the practical meaning of international participation because access to data no longer depended on physical presence at the accelerator site. It also strengthened domestic scientific software engineering and created links with national e-infrastructure providers. FZU's experience in this area later became relevant to other data-intensive fields, including astroparticle physics and computational materials science. High-energy computing thus became both a service to experiments and a research competence of the Institute in its own right.

FZU's international experimental role extends beyond accelerator physics into astroparticle research. Czech teams participate in the Pierre Auger Observatory in Argentina, where ultra-high-energy cosmic rays are studied through the extensive air showers they create in the atmosphere. FZU groups have contributed to detector operation, atmospheric monitoring, electronics, simulations, and analyses of cosmic-ray composition and arrival directions. The Institute also became a central Czech participant in the Cherenkov Telescope Array and later the Cherenkov Telescope Array Observatory. These projects required optical design, mirror technologies, atmospheric characterisation, simulation, and gamma-ray data analysis. The research links high-energy particle physics with astrophysics because the objective is to identify natural cosmic accelerators and understand interactions at energies that can exceed those of terrestrial colliders. Participation in Auger and CTA strengthened the Institute's experience of long-lived collaborations with distributed technical responsibilities. It also broadened the meaning of FZU particle physics from accelerator collisions to naturally occurring high-energy phenomena.

Condensed-matter physics forms another major pillar of FZU and is institutionally broader than any single materials class. Research covers electronic structure, magnetism, superconductivity, dielectric and ferroic materials, strongly correlated systems, thermoelectric phenomena, and functional alloys. Experimental work spans electrical transport, magnetometry, calorimetry, terahertz spectroscopy, diffraction, and measurements under varying temperature, pressure, and magnetic field. Theoretical groups use first-principles electronic-structure methods and many-body approaches to interpret these observations. An important characteristic of the Institute is the ability to prepare or grow many of the materials that it subsequently studies. This reduces the separation between sample synthesis and physical characterisation. It also allows defects, composition, strain, and microstructure to be treated as controlled experimental variables rather than unknown imperfections. Shared experimental platforms encouraged researchers to treat these phenomena as interconnected manifestations of collective behaviour in solids. Condensed-matter research at FZU consequently ranges from fundamental questions about collective quantum states to materials with direct technological functionality.

The Division of Solid State Physics complements this work through particularly strong traditions in crystallography, semiconductors, surfaces, optical materials, and structural characterisation. Czech crystallographers at FZU developed the JANA family of software for solving and refining conventional, modulated, composite, twinned, and magnetic structures. The software became internationally used because many complex crystals cannot be described adequately within ordinary three-dimensional periodic crystallography. Electron-diffraction methods further extended structural analysis towards crystals too small for conventional single-crystal X-ray techniques. FZU researchers combined X-ray, neutron, and

electron diffraction with transmission electron microscopy and other local methods. Structural information could therefore be correlated directly with electrical, magnetic, mechanical, or optical properties. Semiconductor research added epitaxial growth, defect analysis, surface science, and spectroscopy to this methodological portfolio. Crystal growth and luminescence studies supported research on scintillators and optical materials. The Solid State Physics programme thus provided both internationally visible methodological contributions and the detailed materials knowledge required by other branches of the Institute. International workshops around the JANA software further spread this methodological expertise to crystallographers outside Czechia.

Semiconductor and nanoscale research became increasingly integrated through the Laboratory of Nanostructures and Nanomaterials, commonly abbreviated as LNSM. FZU founded LNSM in 2008 by connecting laboratories with complementary capabilities in thin-film deposition, nanostructure fabrication, microscopy, and materials analysis. The infrastructure offers open access rather than restricting advanced equipment to researchers employed by the Institute. Molecular Beam Epitaxy, Chemical Vapour Deposition, lithography, ion processing, electron microscopy, and scanning-probe methods allow materials to be prepared and examined across several length scales. Researchers study compound semiconductors, diamond, carbon nanomaterials, two-dimensional materials, magnetic heterostructures, and nanoelectronic systems. Device preparation makes it possible to test theoretical ideas through direct electrical or optical measurements. The same infrastructure has supported spintronic research and the development of quantum and sensing applications. LNSM later became the Prague node of CzechNanoLab in cooperation with CEITEC Nano in Brno. This development turned a collection of specialised laboratories into part of a distributed national infrastructure for nanofabrication and nanoscale characterisation. It also illustrates FZU's wider strategy of combining its own research with access services for the national scientific community. This open-access model also helped smaller research groups participate in nanoscale experiments without having to duplicate expensive fabrication equipment.

Functional materials provide another example of the Institute's movement between fundamental and applied physics. FZU researchers investigate shape-memory alloys, controlled microstructures, functional composites, diamond-based materials, and systems whose properties can be modified by temperature, stress, magnetic field, or electric field. Shape-memory research focuses particularly on martensitic transformations and superelastic nickel–titanium alloys. Detailed experiments combine thermomechanical loading with X-ray diffraction, neutron diffraction, electron microscopy, resistometry, and digital image correlation. These measurements reveal how microscopic structural rearrangements generate macroscopic strain and recoverable deformation. Theoretical models then help explain the relationship between phase transformation, microstructure, and mechanical response. Applications include medical devices, actuators, aerospace components, and smart structures. The same department studies controlled grain boundaries and microstructures in structural metallic materials. FZU therefore uses functional-material research to connect solid-state physics with engineering design while retaining a strong emphasis on microscopic mechanisms.

Dielectric, ferroelectric, and ultrafast materials research provides a further bridge between classical solid-state physics and modern photonics. FZU groups investigate lattice dynamics, phase transitions, relaxor ferroelectrics, multiferroics, metamaterials, semiconductors, and low-dimensional systems. The Laboratory of Terahertz Spectroscopy uses electromagnetic

radiation between the microwave and infrared regions to probe low-energy excitations and ultrafast charge dynamics. Terahertz measurements are particularly sensitive to carrier transport, phonons, superconducting gaps, and collective modes. Time-resolved techniques allow photoexcited carriers and transient states to be followed on picosecond and sub-picosecond timescales. Research therefore links condensed matter with optics and provides tools relevant to semiconductor devices, photovoltaics, superconductivity, and switchable materials. This methodological overlap is characteristic of FZU because organisational divisions often share physical techniques and target systems. The Institute's breadth makes it possible for a spectroscopic method developed in one field to become useful in another. Such cross-fertilisation is one reason why the division between solid-state, condensed-matter, and optical research at FZU has remained scientifically productive rather than restrictive. The terahertz programme consequently illustrates how one experimental method can serve several scientific communities inside the same institute.

Spintronics became one of the clearest examples of FZU producing internationally influential condensed-matter research. Early work on diluted magnetic semiconductors connected semiconductor physics with magnetism and provided expertise in epitaxial growth, transport, and spin-dependent phenomena. Researchers including Tomáš Jungwirth and international collaborators developed theoretical descriptions of carrier-mediated ferromagnetism and spin-orbit effects. The programme gradually shifted towards mechanisms capable of controlling magnetic order through electrical currents. Work on the spin Hall effect and spin-orbit torques provided the conceptual foundation for this transition. The combination of materials growth, device fabrication, transport measurements, and theory made it possible to test these mechanisms in real structures. FZU also maintained close collaboration with Charles University and the University of Nottingham, creating a wider Prague-international spintronics network. By the early 2010s, this research had positioned the Institute to address the much less explored problem of electrically controlling antiferromagnets. Spintronics therefore evolved at FZU through continuity of expertise rather than through a sudden change of research direction.

The antiferromagnetic spintronics programme produced a sequence of influential theoretical and experimental results. In 2014, Jakub Železný, Tomáš Jungwirth, and collaborators predicted current-induced relativistic Néel-order fields in crystals where local inversion asymmetry generates opposite effective fields on the two magnetic sublattices. This mechanism offered a practical route to manipulating compensated magnetic order electrically. In 2016, an international team demonstrated room-temperature electrical switching of the antiferromagnet copper manganese arsenide, written as CuMnAs, in thin-film devices. The stored state could be written and read electrically without relying on the net magnetisation characteristic of ferromagnetic memories. Later experiments demonstrated multilevel operation and switching driven by very short electrical pulses. These results established antiferromagnetic materials as active components for spintronic device concepts rather than merely as passive layers coupled to ferromagnets. FZU's contribution combined theory, materials expertise, nanofabrication, transport measurement, and international collaboration. The programme became one of the most visible examples of Czech condensed-matter research influencing an emerging global field. The achievement also demonstrated the practical value of combining symmetry-based theory with epitaxial growth and microfabricated transport devices.

During the 2020s, FZU researchers played a similarly important role in the theoretical and experimental development of altermagnetism. Libor Šmejkal, Jairo Sinova, Tomáš Jungwirth, and collaborators developed a symmetry-based description of compensated magnetic materials whose electronic bands exhibit alternating spin splitting in momentum space. The work showed that zero net magnetisation does not necessarily imply the spin-degenerate electronic structure associated with conventional antiferromagnets. In 2022, publications in *Physical Review X* established the new magnetic class and the term altermagnetism. The concept predicted strong spin-dependent transport while retaining many advantages of compensated magnetic order. International experiments in 2024 provided direct evidence for the predicted spin splitting in manganese telluride and expanded the observable phenomenology of the new phase. FZU researchers participated in these studies with collaborators from several European institutions. The rapid international growth of the field demonstrated the Institute's ability to contribute not only measurements but also a new conceptual framework for magnetic materials. Altermagnetism consequently became one of the strongest examples of FZU shaping the terminology and research agenda of contemporary condensed-matter physics. It also reinforced the importance of close interaction between theory and experiment within the Institute. The speed with which the concept moved from symmetry classification to experimental verification gave the research exceptional international visibility.

Optics has constituted another major scientific division of FZU throughout the post-1993 period. Research includes optical and biophysical systems, nonlinear optics, laser–matter interaction, thin films, spectroscopy, nanophotonics, optical materials, and low-temperature plasma-related technologies. Optical methods are used both to study fundamental interactions and to characterise materials developed elsewhere within the Institute. Spectroscopic techniques provide information about electronic states, defects, lattice excitations, and ultrafast processes. Nanophotonic research investigates how light can be confined or enhanced by structures whose dimensions are comparable to or smaller than its wavelength. Applied optical work extends towards sensors, imaging, environmental monitoring, and technologically useful thin films. FZU's optical research is also connected with Palacký University through the Joint Laboratory of Optics in Olomouc. This partnership broadens the Institute's national reach beyond its Prague sites. The optical division therefore forms another interface through which fundamental physics, instrumentation, and practical applications are combined.

High-power laser physics developed from these optical foundations but eventually required dedicated research centres. The Prague Asterix Laser System, commonly abbreviated as PALS, became the first major example of this expansion after the transfer of the ASTERIX IV iodine laser from Germany. FZU and the Institute of Plasma Physics established the PALS Research Centre jointly in 1998. The reconstructed laser entered operation in Prague in 2000 and provided kilojoule-class pulses for experiments on laser-produced plasma, X-ray emission, shock waves, and energetic particles. PALS became part of Laserlab-Europe and operated as an international user facility. The project gave Czech researchers practical experience in running a high-power laser infrastructure for external users. It also strengthened expertise in target physics, plasma diagnostics, optics, and high-energy-density science. These capabilities provided an important institutional and technical background for the much larger laser projects constructed during the 2010s.

HiLASE represented a different technological direction within FZU laser research. The centre was established in 2011 and its facility in Dolní Břežany was inaugurated in 2014. Its mission focuses on high-average-power pulsed lasers, particularly diode-pumped solid-state systems capable of combining substantial pulse energy with repeated operation. The BIVOJ system demonstrated pulse energies above one hundred joules at ten hertz and established internationally recognised performance records in its laser class. The PERLA family of thin-disk systems developed high-average-power picosecond sources suitable for precise materials processing. HiLASE uses these lasers for research on laser shock peening, micro- and nanomachining, optical damage, functional surfaces, and other advanced technologies. Industrial cooperation is therefore built directly into the centre's scientific model. At the same time, the development of laser architecture, thermal management, nonlinear optics, and beam control remains a fundamental research task. HiLASE shows how FZU expanded beyond laboratory-scale optics into a centre capable of developing complete laser technologies with scientific and industrial users.

ELI Beamlines represented a still larger transformation because FZU became responsible for implementing a pan-European-scale laser facility in Czechia. The Institute submitted the Czech candidacy during the preparatory phase of ELI and received the mandate to implement the Beamlines pillar in 2009. European funding enabled construction of the centre in Dolní Břežany during the following decade. The facility was designed around several ultrashort high-power laser systems covering high repetition rates, petawatt peak powers, and kilojoule-class pulse energies. Its scientific programme includes relativistic laser–matter interaction, plasma physics, particle acceleration, X-ray generation, laboratory astrophysics, materials research, and biomedical applications. The project required FZU to develop capabilities in systems engineering, radiation protection, vacuum technology, large-scale procurement, international recruitment, and facility management. This represented a qualitatively different institutional challenge from operating conventional research departments. ELI Beamlines therefore changed not only the scale of Czech laser science but also the managerial and organisational competencies of FZU. The Institute moved from participating in foreign large infrastructures to hosting and constructing one of European significance. The project therefore expanded FZU's responsibilities from scientific research into the long-term governance of a complex research infrastructure.

ELI Beamlines subsequently evolved from a construction project into an international user facility. External research teams can apply for access to laser systems and experimental end stations through competitive calls. Experiments combine primary laser pulses with secondary X-ray, electron, proton, ion, and other sources generated by intense laser–matter interaction. This enables research communities outside traditional laser physics to use the facility for materials, chemistry, biology, medicine, and astrophysics. The creation of the Extreme Light Infrastructure European Research Infrastructure Consortium, abbreviated as ELI ERIC, in 2021 provided a long-term European legal framework for the distributed infrastructure. Czechia became the host Member State and the statutory seat was placed at Dolní Břežany. Agreements subsequently integrated ELI Beamlines into the common ELI ERIC operating structure from the beginning of 2023. FZU therefore played a central role in bringing the facility from national implementation into European governance. This institutional transition is significant because the long-term scientific value of a large facility depends on stable user access and international management after construction funding has ended.

Research infrastructure at FZU is not limited to the large laser centres. LNSM and CzechNanoLab provide open-access nanofabrication and characterisation, while specialised laboratories support crystallography, materials analysis, spectroscopy, microscopy, and detector development. The infrastructure model allows expensive scientific equipment to serve researchers from other institutions rather than remaining confined to one department. This improves utilisation and encourages cooperation among universities, Academy institutes, and companies. Users also gain access to experienced technical staff who maintain complex instruments and develop measurement protocols. Such arrangements are particularly important in nanotechnology and advanced materials, where a complete experimental workflow may require several tools costing millions of euros. FZU's infrastructure portfolio therefore spans very different scales, from atomic-resolution microscopy to multi-petawatt laser systems. The common principle is that scientific capability is organised as a service to a broader research community as well as an internal asset. This model has helped transform the Institute into a national hub whose impact cannot be measured solely by the size of its own research staff. The infrastructure portfolio also supports contract research and methodological development for external users whose needs differ from those of FZU's own projects.

The relationship between fundamental and applied research is especially visible in FZU's materials and laser programmes. Semiconductor and diamond research can address basic questions about electronic states while simultaneously supporting sensors, optoelectronics, or quantum technologies. Shape-memory alloys provide a similar connection between martensitic phase transitions and medical or engineering devices. Spintronics starts from quantum transport and magnetic symmetry but aims at electrically controllable information functions. HiLASE translates laser physics into surface treatment, precision processing, and optical-component testing. ELI Beamlines develops extreme-field methods while also exploring secondary sources relevant to imaging, radiobiology, and advanced materials. These programmes demonstrate that application at FZU generally develops from a detailed understanding of physical mechanisms rather than from routine engineering alone. Industrial collaboration can therefore generate new scientific questions concerning damage, reliability, defects, heat transport, or device stability. The Institute's applied research is strongest where technological requirements and fundamental physics remain mutually dependent.

Internationalisation altered the composition and working culture of FZU as much as its scientific agenda. Major experiments and infrastructures require researchers to work in teams distributed across institutions and countries, often for many years. FZU scientists participate in CERN collaborations, the Pierre Auger Observatory, the Cherenkov Telescope Array Observatory, European laser networks, synchrotron programmes, and numerous materials and quantum projects. The Institute also recruits foreign researchers into its Prague and Dolní Břežany laboratories. ELI Beamlines in particular developed as an international workplace because specialised expertise in petawatt lasers and secondary sources could not be supplied from the domestic labour market alone. European framework programmes and mobility schemes further increased exchanges of doctoral students, postdoctoral researchers, and senior scientists. International collaboration therefore became an ordinary mode of research rather than an exceptional activity. This environment also strengthened English as the working language of many scientific teams and exposed younger researchers to global standards of project management and publication. FZU's national significance consequently rests partly on its ability to import expertise and embed it within Czech institutions. This international

environment also made the Institute an entry point through which specialised expertise could become established permanently in Czechia.

Education and researcher formation remain important even though FZU is not a university. Scientists supervise doctoral and master's theses, teach specialised courses, and involve students in experimental campaigns. Young researchers can move from local laboratories to CERN, synchrotrons, laser facilities, or astroparticle observatories through the Institute's collaborations. Large infrastructures provide training in technical disciplines that are rarely available through classroom education alone, including vacuum engineering, radiation safety, detector operation, cryogenic systems, high-power optics, and distributed computing. FZU also participates in programmes designed to attract international doctoral and postdoctoral researchers to Czechia. Open-science activities expose secondary-school and university students to active research groups before they enter permanent scientific careers. The combination of education and infrastructure helps preserve specialist knowledge across generations. This is especially important for experiments whose construction and operation extend over decades. FZU therefore contributes to human-capital formation as part of its research mission rather than treating training as an activity separate from scientific production.

Between 1993 and 2025, the Institute of Physics of the Czech Academy of Sciences developed into one of the clearest institutional expressions of Czech integration into international physical science. Its particle physicists became long-term participants in CERN experiments and global astroparticle observatories while maintaining detector and computing responsibilities in Czechia. Condensed-matter and solid-state groups preserved strong national traditions in materials, crystallography, semiconductors, magnetism, superconductivity, and spectroscopy while moving towards nanostructures and quantum materials. Spintronics produced internationally influential results in antiferromagnetic switching and helped generate the new field of altermagnetism during the 2020s. Optical research expanded into high-power laser science through PALS, HiLASE, and ultimately ELI Beamlines. The Laboratory of Nanostructures and Nanomaterials and CzechNanoLab strengthened the Institute's function as an open-access technological platform. ELI Beamlines changed FZU's international position by making it an implementing and host institution for a European-scale user infrastructure rather than only a participant in facilities located abroad. Applied programmes in advanced materials and laser technologies increased interaction with high-technology industry without displacing the Institute's fundamental research mission. University cooperation ensured that these capabilities contributed directly to the education of new generations of Czech physicists. The distinctive achievement of FZU therefore lies in the simultaneous maintenance of several scientific scales, from fundamental theory and laboratory experiments to multinational detectors and pan-European laser infrastructure. By 2025, it had become both a central national institution and an active organisational node of the international physics system.

Řež Nuclear Research Centre: Nuclear Physics, Accelerators, and European Research Infrastructure

The Řež nuclear research centre is best understood as a geographically concentrated research ecosystem whose principal academic physics institution is the Nuclear Physics Institute of the Czech Academy of Sciences (NPI CAS). Between 1993 and 2025, this site north of Prague became one of the most important Czech centres for nuclear physics, accelerator science, neutron research, radiation applications, and nuclear analytical methods. Its scientific identity combined fundamental investigations of nuclei and nuclear reactions with practical uses of charged particles, neutrons, radionuclides, and ionising radiation. NPI CAS operated several accelerators of different types and energy ranges, while also using neutron beams from the LVR-15 research reactor operated by Research Centre Řež. The resulting environment allowed nuclear structure, nuclear astrophysics, materials science, dosimetry, radiopharmaceutical research, and cultural-heritage analysis to share a common experimental base. A central organisational achievement of the post-1993 period was the development of the Centre of Accelerators and Nuclear Analytical Methods (CANAM) as an open-access infrastructure. The Institute simultaneously expanded Czech participation in major European projects including the European Spallation Source (ESS), the Facility for Antiproton and Ion Research (FAIR), and the Système de Production d'Ions Radioactifs Accélérés en Ligne (SPIRAL2). These projects transformed Řež from a primarily national nuclear-physics centre into a node of a distributed European research landscape. By 2025, the combination of domestic accelerators, neutron instrumentation, international in-kind contributions, and specialised applications made the Řež centre one of the clearest examples of Czech integration of fundamental nuclear science with research infrastructure and technological use.

The institutional history of nuclear physics at Řež long predates the establishment of the independent Czech Republic. A Nuclear Physics Institute of the Czechoslovak Academy of Sciences was founded at Řež in 1955 as a major national institution for nuclear research. It was subsequently renamed the Nuclear Research Institute as its activities broadened alongside the development of the Czechoslovak nuclear-power programme. In 1972, the organisation was divided so that the larger applied-research component passed to the Czechoslovak Commission for Atomic Energy, while the part focused principally on basic science remained within the Academy as the Nuclear Physics Institute. The applied Nuclear Research Institute was later privatised in 1992, creating an institutional distinction that remained important after the dissolution of Czechoslovakia. In 1993, NPI became one of the institutes of the newly constituted Academy of Sciences of the Czech Republic. The former Institute of Radiation Dosimetry was incorporated into NPI in 1994, broadening the Institute's work on ionising radiation, protection, and biological effects. The Laboratory of Neutron Activation Analysis also joined the Institute during the same period and strengthened its analytical capabilities. In 2007, NPI was transformed into a public research institution under the new Czech legal framework for research organisations. The post-1993 development of Řež should therefore be understood as the modernisation of a mature nuclear-science complex rather than the creation of a new institution from the beginning.

NPI CAS developed a scientific structure that covered both the fundamental and applied sides of nuclear science. Its departments included theoretical physics, heavy-ion physics, nuclear reactions, neutron and ion methods, accelerators, radiation dosimetry, and radiopharmaceutical research. Theoretical groups addressed nuclear structure, hypernuclei,

hadron physics, electroweak processes, and mathematical aspects of quantum theory. Experimental groups studied nuclear reactions, exotic nuclei, nuclear astrophysics, heavy-ion collisions, neutron interactions, and radiation effects. Accelerator specialists operated and upgraded machines while designing beam transport, target stations, and irradiation systems. Neutron physicists used diffraction, scattering, and activation methods to investigate materials and nuclear properties. Dosimetry and radiopharmaceutical programmes extended the same physical knowledge towards medicine, radiation protection, environmental studies, and space research. This breadth made NPI a multidisciplinary nuclear-physics institution whose common methodological core was the controlled production, detection, and interpretation of ionising radiation.

CANAM became the principal framework through which NPI organised its domestic accelerator and neutron capabilities as shared research infrastructure. The name expands as Centre of Accelerators and Nuclear Analytical Methods and reflects an emphasis on both beam production and the analytical techniques made possible by those beams. CANAM was included in the Czech Roadmap of Large Infrastructures for Research, Experimental Development and Innovation for the period beginning in 2010. Its facilities were supported through targeted national funding and later continued within the institutional framework of NPI CAS. The infrastructure is organised around five laboratories associated with distinct accelerator or neutron systems. The Laboratory of Cyclotrons and Fast Neutron Generators operates the U-120M and TR-24 cyclotrons and their associated target stations. The Laboratory of Tandetron operates the Tandetron 4130 MC for ion-beam analysis, implantation, and related experiments. The Neutron Physics Laboratory uses dedicated instruments on horizontal channels of the LVR-15 reactor, while the Laboratory of Microtron operates the MT-25 electron accelerator. The fifth component is the Laboratory of Accelerator Mass Spectrometry, which introduced the MILEA system for ultra-sensitive isotope measurements. Together these laboratories give CANAM access to ion, electron, photon, thermal-neutron, and fast-neutron beams over complementary energy ranges. Its open-access organisation allows Czech and foreign academic users to propose experiments while also permitting proprietary research and specialised industrial services.

The U-120M cyclotron remained one of the central experimental machines of Řež throughout the entire period from 1993 to 2025. The isochronous accelerator had originally been commissioned in 1977 after being designed and manufactured at the Joint Institute for Nuclear Research in Dubna. During the 1990s, NPI specialists substantially reconstructed the machine so that it could accelerate and extract negative hydrogen and deuterium ions as well as operate with positive ions. Conversion to negative-ion acceleration between 1996 and 1998 increased extracted beam currents by approximately an order of magnitude. The cyclotron subsequently became a flexible multiparticle machine capable of accelerating protons, deuterons, helium-3 ions, and alpha particles over energy ranges extending to several tens of megaelectronvolts. Severe flooding in 2002 required extensive restoration and replacement of damaged subsystems, but operation was successfully re-established. Later upgrades improved cooling, controls, beam extraction, ion sources, and associated experimental lines. By the 2010s, the U-120M was no longer simply an inherited Czechoslovak accelerator but a repeatedly modernised national research instrument. Its longevity demonstrates how sustained technical renewal allowed an older accelerator to remain scientifically productive within a much more modern infrastructure environment.

The scientific value of U-120M derives from the variety of reactions and irradiation conditions that can be produced with its different ion species. Nuclear-reaction experiments use precisely controlled beams to measure cross-sections, reaction mechanisms, and properties of excited nuclei. Nuclear astrophysics benefits because selected reactions can be studied at laboratory energies and then related to processes responsible for nucleosynthesis in stars and explosive astrophysical environments. Helium-3 beams are particularly valuable because relatively few European accelerators can provide them with the required combinations of energy and intensity. The cyclotron also serves as a source of intense fast neutrons when charged particles strike specially designed production targets. These neutron fields support measurements of nuclear data, detector responses, radiation effects, and materials behaviour. Charged-particle activation is used to investigate production routes for radionuclides relevant to medicine and research. Irradiation stations also support tests of biological samples, semiconductor components, optical materials, and other systems whose response to ionising radiation must be characterised. Target design is therefore an essential part of the accelerator programme because beam energy, heat deposition, reaction products, and radiation fields all depend on target geometry and material. Beam-dynamics simulations complement these experiments by optimising acceleration and extraction before operating parameters are applied to the machine. The continuing use of U-120M thus illustrates how a medium-energy accelerator can support fundamental nuclear physics and a wide range of applications simultaneously. Its experimental flexibility became one of the technological foundations on which CANAM was built.

Fast-neutron research became one of the most distinctive applications of the Řež cyclotron programme. Neutrons interact with matter differently from charged particles because they penetrate deeply and are not repelled by atomic nuclei. Their energy-dependent reactions are important to fission systems, fusion technology, detector calibration, radiation transport, and nuclear-data libraries. U-120M target stations can generate quasi-monoenergetic or broad neutron spectra through reactions induced by protons or deuterons. NPI researchers measure neutron-production cross-sections and validate transport calculations using carefully characterised irradiation fields. Structural materials for future fusion facilities can be irradiated to study activation and damage under energetic neutrons. The Institute has also used CANAM fast-neutron generators within research related to the European Consortium for the Development of Fusion Energy (EUROfusion). Such experiments support validation, optimisation, and safety assessment for systems in which neutron transport determines both material lifetime and radiation environment. Fast-neutron capability therefore links the nuclear-reaction programme in Řež with European research on future fusion energy. It also provides a domestic test environment for detectors and materials before they are deployed at much larger international facilities.

The commissioning of the TR-24 cyclotron in 2015 added a modern high-current proton accelerator to the Řež complex. Manufactured by Advanced Cyclotron Systems in Canada, the machine provides proton energies from eighteen to twenty-four megaelectronvolts. Its external ion source and axial injection system enable beam currents reaching approximately three hundred microamperes. Negative hydrogen ions are accelerated and then converted into protons during extraction through a thin carbon foil. The extraction arrangement allows simultaneous delivery towards two irradiation branches and several target positions. This flexibility is valuable when different experiments or radionuclide-production tasks require dedicated target systems. The high beam current makes TR-24 particularly important for

production studies of medical radionuclides and for generation of intense secondary neutron fields. Its arrival therefore complemented rather than replaced U-120M by adding a different combination of beam intensity, energy range, and operational purpose.

The Tandetron 4130 MC introduced another important form of accelerator science into Řež when it was installed in 2005. It is a compact electrostatic tandem accelerator with a terminal voltage of up to approximately three megavolts. Negative ions are initially accelerated towards a positively charged terminal, stripped of electrons, and then accelerated a second time after becoming positively charged. The system can provide ion beams for elements ranging from hydrogen to heavy species such as gold, with energies determined by terminal voltage and final charge state. This versatility makes the Tandetron especially suitable for Ion Beam Analysis (IBA) and controlled implantation rather than for the same reaction studies as the cyclotrons. Available techniques include Rutherford Backscattering Spectrometry (RBS), Elastic Recoil Detection Analysis (ERDA), Particle-Induced X-ray Emission (PIXE), and Particle-Induced Gamma-ray Emission (PIGE). Channeling measurements reveal crystallographic order and lattice damage, while time-of-flight ERDA provides depth-resolved information about light elements. The nuclear microprobe focuses ion beams to micrometre or submicrometre dimensions so that spatially resolved composition can be mapped across heterogeneous samples. High-energy implantation allows ions to be deliberately introduced into solids in order to alter or investigate their physical properties. Complementary Atomic Force Microscopy (AFM) and deposition techniques make it possible to relate ion-beam results to surface morphology and nanostructure. The Tandetron therefore extended NPI from traditional nuclear experimentation towards a much wider field of materials analysis and modification.

Ion-beam methods became valuable precisely because they can provide quantitative information that is difficult to obtain by conventional chemical analysis alone, while Rutherford Backscattering Spectrometry can determine elemental composition and depth profiles in thin films without destroying the entire specimen. ERDA is particularly effective for detecting light elements such as hydrogen that are difficult to measure accurately by many electron-based methods. PIXE identifies trace elements from their characteristic X-ray emission and can be applied to very small regions through a focused microbeam. PIGE supplies complementary information by detecting gamma rays produced by nuclear reactions in the sample. These methods are used in semiconductor research, optics, nanoelectronics, bionics, wear-resistant coatings, nuclear materials, and space technology. Ion-beam writing can also create three-dimensional microstructures in polymers, glass, ceramics, and other materials. Cultural-heritage objects benefit because composition can often be determined with minimal sampling or through carefully controlled non-destructive measurements. Archaeological materials, pigments, historical metals, and environmental samples can therefore be studied using physical techniques originally developed for nuclear research. CANAM consequently became an interdisciplinary analytical centre rather than remaining limited to nuclear-structure physics.

Neutron science at Řež depends on a close institutional relationship between NPI CAS and Research Centre Řež, which operates the LVR-15 research reactor. LVR-15 is a light-water research reactor with a maximum thermal power of ten megawatts and several horizontal and vertical irradiation channels. NPI does not operate the reactor itself but uses its neutron beams through the Neutron Physics Laboratory within CANAM. Five neutron-scattering instruments are installed on four horizontal thermal-neutron channels for experiments in materials science and solid-state physics. Another channel supports Neutron Depth Profiling (NDP) and Prompt

Gamma Activation Analysis (PGAA). The reactor thus supplies particles while NPI provides specialised instrumentation, experimental expertise, data analysis, and scientific programmes. This division of responsibility is characteristic of the broader Řež research ecosystem, where several legally distinct organisations share a common physical and technological environment. Thermal neutrons are especially useful because they penetrate deeply into many materials and interact directly with atomic nuclei rather than predominantly with electron clouds. They are also sensitive to light elements and magnetic structures that can be difficult to study by X-rays. Neutron experiments therefore complement accelerator-based charged-particle analysis rather than duplicating it.

Neutron diffraction provides structural information by measuring how a beam is scattered by the periodic arrangement of nuclei in a crystalline material. Because neutron-scattering lengths do not vary monotonically with atomic number, neighbouring elements or different isotopes can sometimes be distinguished much more effectively than by X-ray diffraction. Neutrons also possess a magnetic moment and can therefore probe magnetic ordering inside solids. At Řež, diffraction instruments are used to study crystal structure, texture, phase transformations, residual stresses, and deformation processes. Small-angle and related scattering methods address larger structures such as precipitates, pores, magnetic domains, and nanoscale inhomogeneities. Engineering components can be measured non-destructively because neutrons penetrate millimetres or centimetres into many metals. In situ loading or heating allows structural changes to be followed while a material is undergoing conditions similar to processing or service. This is valuable for nuclear, aerospace, transport, and energy materials where internal stresses can strongly influence lifetime. Neutron activation analysis provides another route to elemental composition by identifying characteristic radiation from nuclei activated in a neutron field. Prompt gamma methods measure radiation emitted during neutron capture, whereas delayed activation techniques detect radioactive products after irradiation. NPI therefore uses the same reactor source for both fundamental scattering experiments and highly sensitive analytical applications. The resulting expertise prepared Czech neutron scientists for a much larger role in the European Spallation Source.

Czech participation in the European Spallation Source became one of the most important international extensions of the Řež neutron programme. The European Spallation Source, commonly abbreviated as ESS, is a European Research Infrastructure Consortium being constructed in Lund, Sweden. Instead of relying on a reactor, ESS generates neutrons when an intense proton beam strikes a heavy-metal target and ejects neutrons through the spallation process. The Czech Republic participated in the project from an early stage and organised its national contribution through ESS-Scandinavia-CZ under the leadership of NPI CAS. Czech commitments were structured largely as in-kind contributions rather than only direct financial payments. One major contribution concerns the Beamline for European Materials Engineering Research (BEER), developed jointly with German partners. Another concerns technological systems associated with cooling of the ESS neutron target. The programme gives Czech researchers access to a much more intense and versatile neutron source than could be constructed nationally. It also requires Czech engineers and physicists to meet the design, quality-assurance, and documentation standards of a large international infrastructure.

BEER represents the clearest scientific continuity between the domestic neutron school at Řež and the future experimental programme at ESS. The instrument is a time-of-flight neutron diffractometer designed specifically for materials engineering and in situ studies. Its very high neutron flux is intended to permit fast measurements during thermomechanical processing

rather than only before and after treatment. Researchers will be able to investigate phase transformations, residual stresses, texture evolution, precipitation, deformation mechanisms, and joining processes. Complex sample environments include furnaces, mechanical-loading systems, and equipment for reproducing manufacturing conditions. Czech scientists contributed substantially to the design of the instrument and to its neutron optics and experimental concept. NPI participates in construction together with Helmholtz-Zentrum Hereon and other ESS partners. The long flight path and time-of-flight method are intended to combine engineering-scale sample environments with detailed information about evolving crystal structures. The project transfers decades of Czech experience in engineering neutron diffraction into a much larger European source. BEER is therefore both an instrument delivered to an international facility and a strategic route through which Czech materials scientists obtain future beam access.

Participation in ESS also altered the institutional role of NPI within European neutron science. The Institute became a member of the League of Advanced European Neutron Sources (LENS) in 2022. This consortium coordinates strategic interests among major neutron facilities and strengthens cooperation in instrumentation, user access, training, and scientific planning. For NPI, membership connects the relatively compact LVR-15 neutron laboratories with the organisations operating Europe's largest sources. Domestic instruments remain valuable for method development, training, testing, and experiments that do not require the maximum available neutron flux. The European facilities provide access to specialised methods and performance ranges that cannot be reproduced in Řež. Czech neutron science therefore follows a layered infrastructure model in which local capability and international access reinforce one another. The same model is visible in the Institute's accelerator programme, where domestic machines support expertise later applied at FAIR and SPIRAL2.

The establishment of accelerator mass spectrometry in Řež added another major analytical capability during the early 2020s. The first Czech Accelerator Mass Spectrometry (AMS) laboratory entered routine operation at NPI in February 2022. Its central instrument is the Multi-Isotope Low-Energy Accelerator Mass Spectrometry system known as MILEA. The compact accelerator operates at a maximum terminal voltage of approximately three hundred kilovolts and measures extremely rare isotopes relative to abundant stable isotopes. The system was established through cooperation involving NPI, the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague, and the Institute of Archaeology of the Czech Academy of Sciences. Radiocarbon measurements use carbon-14 to determine the age of organic material and can work with samples much smaller than those required by traditional radiometric methods. MILEA is also configured for radionuclides including beryllium-10, aluminium-26, calcium-41, iodine-129, uranium isotopes, and plutonium. These isotopes support research in archaeology, environmental science, geology, nuclear safeguards, and studies of long-term radionuclide transport. Accelerator mass spectrometry therefore broadened the meaning of accelerator science at Řež from creating energetic beams for reactions to counting individual rare isotopes with exceptional sensitivity. It also strengthened cooperation between nuclear physics and fields whose research questions are historical, environmental, or geological rather than traditionally nuclear.

Radiocarbon dating became the most visible application of the new AMS capability. Carbon-14 is produced naturally in the atmosphere and becomes incorporated into living organisms through the carbon cycle. After an organism dies, exchange with the environment largely stops and the remaining carbon-14 decreases through radioactive decay. Measuring the isotope ratio

therefore provides chronological information when sample context and calibration are treated correctly. The Czech Radiocarbon Laboratory combines chemical preparation with accelerator measurement and statistical calibration of the resulting age. Archaeological specimens can be dated with much smaller samples than were practical with many older counting methods. Environmental studies can use modern carbon signals to trace carbon exchange, contamination, or movement through ecosystems. The broader MILEA isotope portfolio also permits investigations of cosmogenic nuclides and anthropogenic radionuclides. Such work illustrates how nuclear instrumentation can answer questions about human history and environmental change without being confined to nuclear-energy research.

Radiation dosimetry forms another major applied branch whose institutional integration into NPI dates from 1994. The Department of Radiation Dosimetry studies how ionising radiation deposits energy in matter and how that energy should be quantified for radiation protection and biological research. Dosimetry and microdosimetry investigate radiation fields on both macroscopic and microscopic scales because biological effect depends not only on total dose but also on the spatial distribution of energy deposition. Research includes low-dose exposure, environmental radioactivity, radiation transport, and the response of detector materials. Czech specialists also study cosmic radiation encountered at aviation altitudes and in space. Measurements on aircraft and spacecraft help estimate exposure to highly variable mixtures of neutrons, protons, heavy ions, and secondary particles. Such expertise connects Řež with international aviation, space, and radiation-protection programmes. The department also develops and characterises dosimetric materials and measurement methods. Collaboration with universities helps transfer these specialised techniques into professional training in radiation physics and protection. Nuclear physics is therefore translated into practical knowledge for occupational safety, medicine, and exploration beyond Earth.

Radiopharmaceutical research uses the accelerator infrastructure for another application in which nuclear reactions have direct medical significance. The Department of Radiopharmaceuticals develops production routes for radionuclides intended for diagnostic imaging and targeted therapy. Cyclotron irradiation allows specific isotopes to be produced by selecting projectile, energy, target material, and irradiation time. U-120M has been used to measure excitation functions that determine how efficiently a desired radionuclide is generated as beam energy changes. TR-24 provides higher proton currents suitable for studying production on targets designed to withstand substantial beam power. Research has included cyclotron-based production of technetium-99m and the preparation of other medically relevant radionuclides. The department also investigates labelling of monoclonal antibodies and their fragments so that a radionuclide can be delivered selectively to a biological target. Microfluidic systems are developed to automate chemical labelling while reducing reagent volumes and radiation exposure. This work requires close interaction among nuclear physics, radiochemistry, chemical engineering, and biomedical science. Although commercial radiopharmaceutical production was organisationally separated from NPI, research and development remained an important scientific activity of the Institute. Accelerator modernisation consequently created medical opportunities as well as new nuclear-physics experiments.

The MT-25 microtron adds electron beams to the particle portfolio of CANAM, even though the facility is physically located in Prague rather than at the Řež campus. It is a cyclic electron accelerator capable of providing variable energies up to approximately twenty-five megaelectronvolts. Electrons follow repeated orbits through a radio-frequency accelerating

cavity inside a magnetic field until they reach the selected energy. Extracted electron beams can be used directly for irradiation or converted into bremsstrahlung photon fields. Suitable targets can also produce secondary neutrons for specialised experiments. Applications include radiation testing, activation analysis, materials research, detector studies, and production or evaluation of selected radionuclides. The Microtron Laboratory demonstrates that CANAM is organisationally a distributed infrastructure rather than a facility confined entirely to one building or locality. It complements the ion accelerators because electrons and photons produce different interaction mechanisms and penetration depths. The inclusion of MT-25 therefore increases the range of radiation environments available to Czech and international users.

Fundamental nuclear physics at NPI also depends on theoretical work and participation in experiments outside Řež. The Department of Theoretical Physics investigates nuclear structure, hypernuclei, hadronic systems, electroweak reactions, and mathematical aspects of quantum physics. Such calculations interpret measurements from domestic accelerators but also address phenomena accessible only at larger international facilities. Heavy-ion physicists participate in A Large Ion Collider Experiment (ALICE) at the European Organization for Nuclear Research (CERN), where relativistic nuclear collisions create matter at extreme temperature and density. NPI participation therefore connects the moderate-energy machines at Řež with the high-energy frontier of nuclear and subnuclear physics. The Institute also takes part in the Karlsruhe Tritium Neutrino experiment (KATRIN), whose objective is a direct laboratory determination of the neutrino-mass scale. International projects broaden the scientific problems available to researchers without making domestic accelerator infrastructure redundant. Local facilities are crucial for detector development, nuclear-data studies, training, and experiments that can be performed efficiently without a large international accelerator. Theoretical, domestic experimental, and international programmes consequently form three mutually supporting layers of NPI research. This structure allows a relatively small national community to contribute to problems spanning nuclear structure, neutrino physics, hot nuclear matter, and astrophysical reactions.

SPIRAL2-CZ became a major example of how expertise from Řež could be converted into an in-kind contribution to a European accelerator facility. SPIRAL2 is an extension of the Grand Accélérateur National d'Ions Lourds, commonly known as GANIL, in Caen, France. It was designed to provide intense proton, deuteron, heavy-ion, neutron, and radioactive-ion beams for nuclear structure, reactions, astrophysics, and applications. NPI has cooperated with the SPIRAL2 programme as part of a European associated laboratory since 2008. Formal Czech participation developed further through projects supported from 2011 and through inclusion of SPIRAL2-CZ in the Czech large-infrastructure roadmap. Czech contributions include the R-OBOT production target, whose name derives from Řež – Other Beams Other Targets, together with radioisotope targets and detector systems. The Czech programme also supported equipment for the Neutrons for Science experimental area. Domestic U-120M measurements help develop reaction data and target concepts before systems are deployed at the larger French infrastructure. This relationship demonstrates how a national accelerator of moderate scale can serve as a development platform for components used internationally. SPIRAL2-CZ therefore extends the experimental reach of Czech nuclear astrophysics and exotic-nuclei research while preserving a strong technological role for the Řež laboratory. It also provides mobility and training opportunities for Czech students and researchers working within an international accelerator environment.

The Facility for Antiproton and Ion Research, usually abbreviated as FAIR, represents an even larger international commitment coordinated nationally by NPI CAS. FAIR is being constructed next to the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany, and is centred on the powerful SIS100 synchrotron. Czechia became an associated member of FAIR in March 2019 after years of scientific cooperation with GSI and the developing FAIR collaborations. FAIR-CZ is coordinated by NPI and connects Czech participation in nuclear physics, hadron physics, nuclear astrophysics, biophysics, and radiobiology. Czech scientists are involved in the Compressed Baryonic Matter programme, including the High Acceptance Di-Electron Spectrometer (HADES) and the Compressed Baryonic Matter (CBM) experiment. They also participate in antiProton ANnihilation at DArmstadt (PANDA), Nuclear Structure, Astrophysics and Reactions (NuSTAR), and Atomic, Plasma Physics and Applications (APPA). These programmes address dense nuclear matter, exotic hadrons, radioactive nuclei, nucleosynthesis, atomic physics, plasma conditions, and radiation effects. FAIR-CZ therefore gives Czech researchers access to experimental conditions far beyond the capabilities of domestic accelerators. The programme simultaneously obliges the national community to contribute technologically to construction rather than acting only as a future user. This reciprocity is central to the European large-infrastructure model adopted by NPI.

Czech in-kind contributions to FAIR illustrate the technological breadth that grew around the NPI-led programme. The national consortium has supplied or developed components for the electromagnetic calorimeter of HADES and the Forward Spectator Detector of CBM. Czech industry and research institutions contributed lead-tungstate crystals for the electromagnetic calorimeter associated with PANDA. Detector modules were prepared for GADAST within the NuSTAR programme, supporting experiments with exotic nuclei. Vacuum and beamline components were developed for the APPA and CBM areas. By 2024, Czech teams had also completed a specially engineered support platform designed for a load of approximately one hundred tonnes in the CBM experimental hall. These contributions required mechanical design, radiation-resistant materials, detector physics, precision manufacturing, structural modelling, and international quality assurance. NPI coordinated work involving the Czech Technical University in Prague, Charles University, Silesian University in Opava, Palacký University Olomouc, and industrial partners. The FAIR programme consequently functions as a national network rather than as an NPI-only experiment. Its construction phase already generated engineering competence before the full scientific programme of the new accelerator had begun. By 2025, FAIR-CZ had become one of the principal mechanisms connecting the Řež nuclear school with future European heavy-ion and hadron research.

Nuclear applications at Řež also support research on energy technologies beyond traditional fission physics. Fast-neutron irradiation and activation measurements provide data needed to estimate how structural materials behave in intense radiation fields. Such data are important for fusion concepts because high-energy neutrons can displace atoms, activate components, and alter mechanical properties. NPI participation in EUROfusion uses CANAM facilities to validate calculations and test materials relevant to future fusion installations. Experiments connected with the International Fusion Materials Irradiation Facility – DEMO Oriented Neutron Source (IFMIF-DONES) investigate neutron transport and material responses under fusion-relevant conditions. Similar activation methods help assess materials intended for reactors, accelerators, and other radiation environments. These programmes draw directly on the Institute's ability to produce characterised neutron fields and to measure induced radioactivity. They also require evaluated nuclear data because engineering predictions are

only as reliable as the reaction probabilities used in transport codes. NPI therefore contributes to energy research through measurement and validation rather than through reactor operation itself. This distinction is important because the scientific role of the Institute is centred on physics, nuclear data, instrumentation, and material response.

Open access became an important principle in the modern operation of CANAM and changed the relationship between the Řež facilities and the wider research community. External academic users can submit proposals for beam time at the cyclotron, Tandetron, neutron, and microtron laboratories. Scientific access is evaluated according to feasibility and the requirement that results from supported experiments enter the public domain. Industrial users can obtain proprietary access when confidentiality or application-specific services are required. This model allows specialised equipment to serve researchers in materials science, chemistry, biology, electronics, archaeology, environmental studies, and engineering. Facility scientists provide more than beam delivery because experiments often require target preparation, detector selection, calibration, radiation-safety procedures, and specialised analysis. Students consequently encounter a research environment in which nuclear techniques are applied to problems originating in several different disciplines. Cooperation with the Czech Technical University in Prague is especially important because NPI researchers teach and supervise students in nuclear and physical engineering. The Institute also maintains international mobility programmes that place junior researchers at facilities such as FAIR and other European laboratories. Open access and researcher mobility therefore help convert expensive nuclear infrastructure into a wider scientific and educational resource. They also ensure that specialist knowledge remains active between major international experimental campaigns.

The transformation of Řež after 1993 can consequently be described as a movement from an established national nuclear centre towards a multi-layered European research node. U-120M preserved and modernised a domestic accelerator tradition while continuing to support nuclear reactions, nuclear data, neutron generation, and radionuclide research. Tandetron added sophisticated ion-beam analysis and implantation in 2005, and TR-24 substantially increased high-current proton capability from 2015. Neutron instruments at LVR-15 maintained Czech competence in diffraction, scattering, activation, and materials analysis. CANAM integrated these machines with the MT-25 microtron and, from 2022, the MILEA accelerator mass spectrometer under a shared infrastructure model. Radiopharmaceutical research, dosimetry, cultural-heritage analysis, environmental studies, and materials modification demonstrated the technological and interdisciplinary reach of nuclear methods. ESS-Scandinavia-CZ carried domestic neutron expertise into construction of the BEER engineering diffractometer and associated European source technology. SPIRAL2-CZ connected Řež accelerator and target expertise with radioactive-ion and neutron research in France, while FAIR-CZ integrated the Czech community into one of Europe's largest emerging accelerator infrastructures. These programmes show that the principal achievement of the Řež nuclear research centre lies not in any single accelerator but in maintaining a continuous chain from local experimentation to international facility construction and scientific use. By 2025, NPI CAS had therefore become both a national laboratory with distinctive experimental capabilities and a coordinating institution through which Czech nuclear physics participated in the future architecture of European research.

Prague Plasma and Fusion School: From CASTOR and COMPASS to COMPASS Upgrade

The Prague plasma and fusion school represents a continuous scientific tradition that developed from experimental plasma physics into a nationally coordinated programme of magnetic-confinement fusion research. Its institutional centre is the Institute of Plasma Physics of the Czech Academy of Sciences, commonly abbreviated as IPP CAS. Between 1993 and 2025, the Institute linked domestic tokamak experiments with increasingly integrated European research on controlled thermonuclear fusion. The sequence from CASTOR through COMPASS to COMPASS Upgrade, usually written COMPASS-U, provides the clearest expression of this institutional and scientific continuity. Each device corresponded to a different stage in the development of Czech fusion capabilities, from small-scale edge-plasma studies to ITER-relevant confinement experiments and then to a purpose-built high-field machine. Prague researchers simultaneously developed diagnostics, theory, numerical modelling, power systems, plasma-facing components, and experimental methods required by contemporary tokamak physics. Their work became progressively embedded in the European Atomic Energy Community, the European Fusion Development Agreement, and later the European Consortium for the Development of Fusion Energy, known as EUROfusion. This integration allowed Czech teams to contribute to major European tokamaks while preserving an experimental base in Prague. By 2025, the Prague school had become a specialised European centre focused particularly on edge plasma, plasma exhaust, advanced confinement, disruptions, diagnostics, and technologies relevant to the International Thermonuclear Experimental Reactor and a future demonstration fusion power plant, commonly referred to as DEMO.

The institutional roots of this school reach back to the creation of the Institute of Vacuum Electronics of the Czechoslovak Academy of Sciences on 1 January 1959. The new institute incorporated specialists from earlier vacuum-electronics research, including groups concerned with accelerators, electron beams, and plasma phenomena. In 1963, it was renamed the Institute of Plasma Physics, reflecting the increasing importance of ionised matter as its central scientific subject. During the 1960s, Prague researchers developed recognised work on beam–plasma interaction, wave processes, and plasma instabilities. Experimental programmes were accompanied by theoretical studies of wave transformation and collective plasma behaviour, establishing a tradition in which theory and measurement developed together. Magnetic confinement was only one branch of the Institute's early work, because thermal plasma, plasma chemistry, and beam physics also became important. This diversity proved valuable later because fusion research requires knowledge of diagnostics, materials, high-current engineering, vacuum systems, and plasma–surface processes as well as confinement theory. The Institute's pre-1993 experience therefore created a reservoir of expertise that survived the political and institutional transformation following the end of Czechoslovakia. After 1993, the principal challenge was not to create a fusion programme from nothing but to adapt an existing school to new funding structures and to a rapidly internationalising European research environment. The long institutional memory of IPP CAS became one of the reasons Prague could move from a small tokamak to increasingly ambitious fusion infrastructure.

The CASTOR tokamak formed the experimental backbone of Prague magnetic-confinement research during the first phase of the independent Czech Republic. The machine had originally been constructed in Moscow as the small TM-1 tokamak and was transferred to the Prague institute during the 1970s. It entered operation there in 1977 under the designation TM-1-MH, with the suffix referring to microwave heating. A substantial refurbishment in 1985 introduced a new vacuum vessel and a feedback system for controlling plasma position. At that stage the device received the name CASTOR, meaning Czech Academy of Sciences TORus. Its circular plasma had a major radius of about 0.4 metres and supported discharges lasting only tens of milliseconds. These modest parameters nevertheless allowed highly flexible experiments in edge plasma, turbulence, electric fields, waves, and plasma control. CASTOR therefore remained scientifically productive throughout the 1990s and into the first years of the twenty-first century.

CASTOR was particularly well suited to detailed measurements at the boundary of magnetically confined plasma. Arrays of Langmuir probes could be inserted into the relatively accessible edge region to determine electron temperature, density, plasma potential, fluctuations, and particle transport. Czech researchers developed probe concepts that allowed local electric fields and plasma flows to be reconstructed with unusually high temporal resolution. Experiments investigated how turbulent structures move particles across magnetic surfaces and therefore degrade confinement. External biasing was used to modify the radial electric field and examine whether shear flows could suppress turbulent transport. Microwave diagnostics and other non-invasive techniques complemented local probe measurements and helped connect edge behaviour with global discharge conditions. Lower-hybrid waves provided another tool for studying heating, current-related phenomena, and wave–plasma interaction. The device was sufficiently small that diagnostic arrangements could be modified repeatedly without the long engineering cycles typical of larger European tokamaks. This flexibility made CASTOR an effective methodological laboratory in which new ideas could be tested before being transferred elsewhere. It also trained researchers to think of the plasma edge not as a peripheral region but as a controlling element of overall tokamak performance. The resulting expertise later became one of the strongest scientific continuities between CASTOR, COMPASS, and COMPASS-U.

CASTOR also functioned as an educational instrument and as a meeting point for the Czech plasma community. Students from the Czech Technical University in Prague and other institutions could participate directly in experiments rather than encountering tokamak physics only through lectures or remote datasets. The short discharges and accessible diagnostics made it possible to connect theoretical concepts with measurements during practical training. Young researchers learned vacuum practice, pulsed power, control systems, data acquisition, probe physics, and plasma diagnostics on the same machine. International visitors could test instrumentation or participate in focused experiments without the organisational barriers associated with a reactor-scale facility. This educational role helped preserve a national pool of specialists during the financially difficult transformation of Czech science in the 1990s. It also created continuity between senior researchers trained during the Czechoslovak period and students who entered fusion research after independence. By the beginning of the 2000s, however, CASTOR's small size and circular plasma limited its ability to address the diverted high-confinement regimes becoming central to European fusion research. The next stage therefore required not simply another upgrade but a machine capable of reproducing physical conditions more directly related to ITER.

European integration was the decisive institutional change that made this transition possible. At the end of 1999, the Institute of Plasma Physics signed a Contract of Association with the European Atomic Energy Community, commonly abbreviated as Euratom, with the explicit purpose of integrating Czechia into the European fusion programme. The resulting EURATOM–IPP.CR Association made IPP the national coordinator of Czech magnetic-fusion research and of cooperation with the other European associations. Related agreements opened structured participation in the European Fusion Development Agreement, usually abbreviated as EFDA, and in the common exploitation of the Joint European Torus, known as JET. Czech researchers also gained access to European mobility schemes and specialised high-performance computing for fusion applications. This arrangement changed the scale at which national research programmes were formulated because projects increasingly had to contribute to objectives agreed across Europe. Experiments in Prague could be compared systematically with results from larger machines, while Czech diagnostics and researchers could be deployed abroad. The association also exposed younger scientists to laboratories whose heating power, plasma current, and pulse duration greatly exceeded CASTOR's capabilities. European peer review and programme coordination encouraged the Prague group to identify areas in which a medium-sized national device could make a distinctive contribution. Edge plasma and plasma exhaust emerged as particularly promising specialisations because they could be studied with dense diagnostics and flexible experimental access. The institutional integration of 1999 therefore prepared both the scientific and political conditions for acquiring a more advanced tokamak. It marked the point at which Czech fusion research became structurally embedded in a long-term European programme rather than relying primarily on bilateral cooperation.

The wider research profile of IPP CAS reinforced this fusion programme even when particular laboratories were not devoted directly to magnetic confinement. Thermal-plasma groups developed plasma torches, coatings, and materials-processing technologies that required detailed understanding of high-temperature ionised matter. Materials specialists investigated structures and surfaces capable of operating in severe thermal environments. The joint Prague Asterix Laser System, established with the Institute of Physics of the Czech Academy of Sciences, added experience with high-energy-density plasma and sophisticated plasma diagnostics. Optical and spectroscopic expertise supported the measurement culture needed for fusion experiments. Engineering groups developed power supplies, vacuum technologies, cooling systems, and control methods applicable across several plasma platforms. These parallel activities broadened the technical base available when the Institute began planning a new tokamak. They also encouraged a conception of fusion as a multidisciplinary systems problem rather than as confinement physics alone. The Prague fusion school consequently grew inside a larger plasma-science institution whose capabilities could be redirected towards increasingly complex experimental infrastructure. This breadth became especially important during the transfer and reconstruction of COMPASS.

In 2004, the United Kingdom Atomic Energy Authority and the European fusion programme formally offered the COMPASS-D tokamak to IPP CAS. The machine had previously operated at the Culham Science Centre and possessed a diverted plasma geometry much closer to modern reactor-oriented tokamaks than CASTOR. Czech authorities decided in 2005 to accept the device with government support. The transfer required dismantling the British installation, transporting its major components to Prague, constructing a new experimental building, and designing new power and auxiliary systems. European preferential support helped finance the project within the Euratom framework. CASTOR was therefore withdrawn from the Institute at

the end of 2006 so that personnel and resources could concentrate on the new machine. The older tokamak was transferred to the Czech Technical University in Prague, where it later continued as the educational tokamak GOLEM. The succession preserved experimental continuity while clearly separating advanced research at IPP from hands-on university training.

COMPASS arrived in Prague in October 2007 and was installed in a purpose-built experimental hall beside the former CASTOR site. The transfer was much more than a relocation because substantial parts of the machine's supporting infrastructure had to be designed or rebuilt by the Czech team. New electrical power systems, vacuum equipment, controls, diagnostics, neutral-beam heating, and data acquisition gradually transformed the inherited device into a modern Prague research facility. The first high-temperature plasma after reinstallation was produced on 9 December 2008. Official test operation began on 19 February 2009, when discharges with plasma current around one hundred kiloamperes were demonstrated publicly. Commissioning of diagnostics, control systems, and power supplies continued from 2009 through 2011. Regular scientific exploitation began in 2012 after the experimental platform had matured sufficiently for systematic research campaigns. The rapid reconstruction strengthened Czech engineering competence because the team had to understand the entire tokamak rather than only individual diagnostics. It also created a younger generation of specialists experienced in machine operation, plasma control, auxiliary heating, and experimental planning. COMPASS thus represented an institutional upgrade as much as an improvement in plasma parameters. The project demonstrated that a Czech research institute could take responsibility for rebuilding and operating a complex fusion device within the coordinated European programme.

COMPASS occupied a distinctive position because it was a relatively compact tokamak capable of producing shaped diverted plasmas and high-confinement operation. Its major radius was approximately 0.56 to 0.60 metres, while its plasma shape was roughly one tenth of ITER dimensions on a linear scale. The similarity of the magnetic configuration was scientifically more important than the absolute size of the machine. Diverted plasmas allowed particles and heat leaving the confined region to be directed towards specific target surfaces, reproducing the basic topology required in reactor-oriented devices. The machine could also be heated by neutral-beam injection, enabling plasma conditions inaccessible through ohmic heating alone. Its relatively small dimensions kept experiments flexible and made dense diagnostic coverage practical. This combination allowed Prague researchers to examine local processes in detail while remaining connected to ITER-oriented questions. COMPASS therefore filled an intermediate niche between small university tokamaks and the largest European fusion facilities. Its value depended on physical similarity, diagnostic accessibility, and experimental flexibility rather than on competing directly with larger devices in plasma energy.

Diagnostics became one of the strongest technical specialisations of the COMPASS programme. Magnetic coils reconstructed plasma equilibrium and recorded rapid fluctuations associated with instabilities. High-resolution Thomson scattering measured electron temperature and density profiles without inserting a probe into the hot plasma. Microwave interferometry and reflectometry provided additional information about density and edge structures. Visible, ultraviolet, and X-ray spectroscopy identified impurities and characterised radiation from different plasma regions. Infrared thermography measured surface temperatures and therefore helped reconstruct heat loads on divertor components. Fast cameras recorded visible structures that evolved too rapidly for ordinary imaging. Langmuir

probes and ball-pen probes supplied exceptionally detailed local measurements in the edge and Scrape-Off Layer, usually abbreviated as SOL. Neutral-particle analysers and detectors of energetic radiation extended this diagnostic set towards fast ions and runaway electrons. Many instruments were developed or substantially modified in Prague rather than purchased as closed commercial systems. This culture of diagnostic development became transferable because Czech systems and expertise could later be deployed in experiments on other European tokamaks. Dense diagnostic coverage consequently became one of the scientific reasons why a modestly sized machine could produce results relevant to much larger facilities.

A major milestone came on 29 November 2012 when COMPASS achieved the high-confinement regime known as H-mode after injection of approximately 210 kilowatts of neutral-beam heating. The transition was marked by a characteristic drop in hydrogen-alpha radiation together with increases in plasma density and stored energy. An ohmically heated H-mode was also obtained during controlled current ramp-down the following day. H-mode is central to reactor-oriented fusion because an edge transport barrier reduces energy losses and substantially improves overall confinement. ITER is designed around operating regimes that rely heavily on this improved confinement, so the achievement confirmed that COMPASS could reproduce one of the most important qualitative states required for ITER-related research. In 2013, the Prague team also obtained Type-I Edge Localised Modes, usually abbreviated as ELMs. These instabilities periodically release particles and energy from the H-mode pedestal and can create damaging transient loads on plasma-facing surfaces. COMPASS could thus investigate both the benefit of enhanced confinement and one of the principal difficulties generated by the same edge transport barrier. The result moved Prague research beyond generic tokamak operation into a set of problems explicitly connected with the reactor-relevant plasma edge and made direct comparison with larger European H-mode experiments substantially more meaningful. H-mode operation therefore became a defining scientific transition in the history of the Prague fusion school.

The plasma edge and SOL became the signature research domain of COMPASS during its mature operating phase. Energy and particles that escape the closed magnetic surfaces must cross these regions before reaching the divertor or other material structures. Their transport determines both how well the hot core is insulated and how severe the thermal load on reactor components becomes. Czech researchers measured turbulent fluctuations, radial electric fields, flows, density profiles, and heat transport with high spatial and temporal resolution. Probe systems were combined with optical and infrared diagnostics to relate local plasma behaviour to actual energy deposition on surfaces. Experiments examined how plasma shape, density, heating, and magnetic configuration changed the width of the exhaust channel. The goal was not only to describe turbulence but to identify conditions in which sufficient core confinement could coexist with tolerable divertor loading. This focus gave Prague a recognisable niche within the European fusion programme. It also created the scientific rationale for designing COMPASS-U around much higher reactor-relevant power fluxes.

Magnetic perturbations provided another route through which COMPASS contributed directly to preparations for ITER. No large tokamak can be constructed with perfectly symmetric magnetic coils, so small engineering deviations generate error fields that perturb the confined plasma. These imperfections can degrade performance or trigger instabilities if they exceed acceptable limits. COMPASS possessed a flexible system of additional coils capable of deliberately imposing controlled magnetic perturbations. Researchers could therefore reproduce selected classes of error fields and study how plasma response depended on their

amplitude and geometry. Results from these experiments contributed to determining tolerances for magnetic-field errors and to developing methods for compensating them. Such information is important to ITER because the size and complexity of its superconducting magnet system make post-construction mechanical correction extremely difficult. The Prague experiments thus translated a relatively small machine into a controlled testbed for an engineering problem affecting the world's largest tokamak. This type of work illustrates why relevance to ITER does not require duplication of ITER's absolute plasma dimensions. Carefully scaled experiments can isolate a mechanism, validate models, and provide limits that inform design or operation of a much larger device.

Disruptions and runaway electrons formed another increasingly important component of the Prague programme. A disruption is a rapid loss of plasma confinement that can convert magnetic and thermal energy into intense mechanical and thermal loads. During this process, the induced electric field can accelerate a fraction of the electron population to relativistic energies. These runaway electrons can remain concentrated in a narrow beam and damage plasma-facing components if they strike the wall. COMPASS allowed researchers to generate, diagnose, and perturb runaway populations under controlled conditions. Hard X-ray detectors, magnetic diagnostics, imaging, and other measurements were used to determine when the electrons formed and how they were lost. Experiments examined the influence of externally imposed magnetic perturbations and plasma conditions on runaway confinement. The Prague programme also investigated forces and asymmetries associated with disruptions themselves. These questions became progressively more important as ITER planning intensified because disruption energies scale strongly with machine size and plasma current. Czech results therefore contributed to the wider international effort to develop avoidance, prediction, and mitigation strategies. The experience also shaped the diagnostic and modelling programme planned for COMPASS-U, where higher current and magnetic field make these topics even more demanding.

Theory and numerical modelling provided continuity between experiments on COMPASS and preparations for machines that did not yet exist. The Theory and Modelling Department at IPP CAS studies transport in the plasma core, pedestal, and SOL together with auxiliary heating and runaway-electron dynamics. Researchers use internationally developed simulation packages as well as in-house codes such as BIT1, BIT3, EBdyna, NUR, PLEQUE, SOLF1D, SPICE2, and SPICE3. Particle-in-cell calculations describe kinetic phenomena that cannot always be represented adequately by fluid equations. Fluid and reduced models allow much larger spatial and temporal scales to be explored at manageable computational cost. Equilibrium and transport calculations help design discharges before experimental time is committed. Comparisons with measured COMPASS data provide tests of whether the numerical description captures relevant edge and exhaust physics. The same validated tools can then be applied cautiously to COMPASS-U, ITER, and DEMO parameter regimes. Czech modellers also participate in EUROfusion theory programmes and the European Theory and Advanced Simulation Coordination framework. Their work extends to JET, ASDEX Upgrade, MAST Upgrade, the Tokamak à Configuration Variable, and JT-60SA. Direct involvement with International Tokamak Physics Activity groups and ITER research networks further connects Prague modelling with global fusion planning. Theoretical work is therefore one of the principal mechanisms through which results from a medium-sized Czech experiment can contribute to the design and interpretation of much larger future facilities.

The reorganisation of European fusion research into EUROfusion from 2014 strengthened this multilateral structure. IPP.CR became the Czech Research Unit within the consortium and IPP CAS remained the leading national institution for magnetic-fusion research. Czech Technical University in Prague, Charles University, the Research Centre Řež, the Nuclear Physics Institute, and the University of West Bohemia participate in the wider Czech contribution. The national programme therefore extends beyond one institute even though its experimental tokamak centre is located at IPP. EUROfusion coordinates work around a common roadmap leading from present experiments through ITER towards DEMO. Czech groups contribute to work packages on experiments, modelling, diagnostics, plasma-facing technologies, materials, training, and future facility development. Access to European devices allows questions beyond COMPASS capability to be studied without abandoning a strong domestic experimental programme. Conversely, Prague diagnostics and specialised edge-plasma expertise contribute to the common European knowledge base. The organisational model therefore combines national specialisation with shared continental infrastructure.

Experiments on other European tokamaks became an ordinary part of Prague fusion research. Czech scientists worked on JET in the United Kingdom before the completion of its experimental programme and participated in campaigns on ASDEX Upgrade in Germany. They also use the Tokamak à Configuration Variable in Switzerland and the WEST tokamak in France, among other facilities. Each machine provides a different combination of magnetic field, wall material, size, heating power, and plasma geometry. Cross-machine comparison allows researchers to determine which observations reflect general plasma physics and which depend mainly on a particular device. Prague specialists contribute edge diagnostics, experimental proposals, modelling, data interpretation, and studies of disruptions or runaway electrons. The same researcher can therefore work on a flexible domestic tokamak and on a larger foreign device within a single EUROfusion programme. This mobility helps maintain scientific continuity during periods when the Prague machine is being rebuilt. It also ensures that COMPASS-U is designed by a community familiar with the strengths and limitations of several existing tokamaks. International participation consequently reinforces rather than replaces the role of Prague as a national fusion centre. The school is European in operational practice while remaining institutionally rooted in Czech laboratories.

Education became another defining function of the Prague school because fusion development requires technical expertise sustained over several decades. CASTOR already trained students in direct tokamak experimentation before its transfer from IPP. At the Czech Technical University, the former CASTOR machine continued as GOLEM and developed into a dedicated educational tokamak that can be operated locally or remotely. Students can initiate discharges, analyse diagnostic signals, and connect basic plasma theory with the behaviour of an operating magnetic-confinement device. The Faculty of Nuclear Sciences and Physical Engineering also developed specialised study in Plasma and Thermonuclear Fusion Physics. Its curriculum covers plasma theory, tokamak physics, diagnostics, computational methods, inertial fusion, and materials science. Collaboration with IPP allows students to move from GOLEM-scale experiments towards participation in research associated with COMPASS and COMPASS-U. EUROfusion mobility further opens access to foreign laboratories during master's and doctoral training. Prague thus developed an educational ladder extending from a university tokamak to national infrastructure and then to major European machines. This structure is important because ITER and DEMO will require researchers who understand both physical principles and complex experimental technology.

COMPASS itself became an important international training platform during its operational lifetime. Summer and winter schools allowed young researchers from many countries to participate in real experimental campaigns. More than three hundred students from roughly thirty countries took part in these programmes over the years of Prague operation. Participants encountered plasma control, diagnostics, experimental planning, data processing, and the collaborative organisation of tokamak research. A medium-sized machine is particularly suitable for education because students can understand a larger fraction of the experimental system than is possible on a facility with thousands of specialised subsystems. At the same time, COMPASS operated in regimes sufficiently advanced to make the training relevant to larger European devices. International schools therefore combined education with genuine research rather than presenting simplified demonstrations. The programme strengthened Prague's reputation as a place where fusion specialists could acquire practical tokamak experience. It also created international professional networks that persisted as former students moved to other fusion laboratories.

The final experimental discharge of COMPASS took place on 20 August 2021 after approximately twelve years of operation in Prague. More than twenty-one thousand high-temperature plasma discharges had been carried out during that period. The machine had progressed from commissioning to H-mode, ELM physics, detailed edge studies, disruption research, magnetic-perturbation experiments, and advanced diagnostics. Its supporting infrastructure was repeatedly upgraded, including the addition of stronger auxiliary heating towards the end of operation. Closure was planned because the same experimental site was required for construction of COMPASS-U. The decision therefore represented a transition in scientific strategy rather than abandonment of domestic tokamak research. COMPASS had also created the team capable of specifying the physics and engineering requirements of its successor. Diagnostics, software, control concepts, and modelling expertise could be retained even when much of the physical machine was removed. European collaborations ensured that researchers continued experimental work abroad during the construction interval. The end of COMPASS thus marked completion of one institutional generation and the beginning of another.

The conceptual development of COMPASS-U began while COMPASS was still scientifically productive. Radomír Pánek and colleagues presented the design publicly at the Symposium on Fusion Technology in Prague in 2016. The project formally started on 1 December 2017 and was supported through Czech and European structural funding. Its purpose was not to construct the largest possible tokamak but to occupy a missing experimental regime in the European fusion portfolio. The design combines compact size with a toroidal magnetic field reaching 5 tesla and plasma current up to 2 megaamperes. High magnetic field allows reactor-relevant dimensionless parameters and intense exhaust conditions to be approached without building an ITER-sized device. The machine is designed for high plasma density and strong auxiliary heating from neutral beams and electron-cyclotron systems. Several plasma shapes can be produced, including lower single null, double null, negative triangularity, and snowflake configurations. A replaceable divertor design allows different exhaust concepts to be tested within the same basic machine. The conceptual strategy was shaped by the experience gained from detailed edge measurements on COMPASS and from Czech participation in other EUROfusion devices. It was also intended to restore a high-field experimental capability that had become scarce in the European programme. The project therefore translates the scientific

specialisation developed on COMPASS into a device constructed specifically around future fusion questions.

COMPASS-U is designed as a high-field experimental facility rather than as a power-producing reactor. Its current engineering specification gives a major radius of about 0.894 metres and a minor radius of approximately 0.27 metres. The nominal toroidal field can reach 5 tesla, while the plasma current can reach 2 megaamperes. Initial auxiliary heating includes several megawatts of Neutral Beam Injection and an Electron Cyclotron Resonance Heating system, with higher powers envisaged in later phases. The first wall and vacuum vessel are designed for elevated-temperature operation around 300 degrees Celsius and potentially up to 500 degrees Celsius. The plasma-facing environment is fully metallic, using tungsten and tungsten-coated nickel-based alloys in relevant regions. High field and compact geometry produce narrow exhaust channels and very large divertor heat fluxes. These conditions are scientifically valuable because power exhaust is one of the unresolved barriers between successful plasma confinement and a practical fusion power plant. COMPASS-U is therefore intended to reproduce selected reactor-relevant stresses while retaining the diagnostic access and flexibility of a medium-sized experiment.

The divertor lies at the centre of this scientific mission. A fusion plasma must maintain temperatures high enough for nuclear reactions while simultaneously preventing escaping heat and particles from destroying surrounding surfaces. The divertor receives a large share of this exhaust along magnetic field lines and therefore operates in one of the harshest environments inside a tokamak. COMPASS-U is designed with a closed and well-diagnosed divertor in order to reach high plasma and neutral densities. Researchers will study detachment, a regime in which radiation and atomic processes dissipate energy before the plasma reaches the solid target. The system is intended to compare conventional divertor geometries with advanced configurations such as the snowflake. Negative-triangularity plasmas provide another option for changing edge stability and confinement. Replaceable cassettes make it possible to test different plasma-facing concepts without reconstructing the entire tokamak. This flexibility directly reflects the EUROfusion objective of identifying exhaust solutions relevant to ITER and especially to DEMO. Plasma exhaust is therefore not a secondary engineering topic within COMPASS-U but one of the principal scientific reasons for the device's existence. The Prague school has consequently moved from diagnosing the plasma edge on CASTOR to constructing an entire tokamak around the unresolved physics of that boundary.

Plasma-facing materials form the complementary technological side of this problem, and the COMPASS-U first wall is designed around metallic surfaces with tungsten used in the most strongly exposed components. Tungsten has a very high melting point and relatively low sputtering under many relevant conditions, but impurities entering the plasma can radiate strongly and reduce confinement. The device is therefore intended to investigate the coupled behaviour of plasma and wall rather than simply to test whether a material survives. Design studies envisage heat loads of approximately twenty megawatts per square metre during routine high-load divertor operation, with substantially higher local transients possible in demanding conditions. Detachment, strike-point motion, and alternative magnetic geometry will be required to reduce the thermal burden on target surfaces. Hot-wall operation changes hydrogen recycling and impurity behaviour, bringing the surface environment closer to future reactor conditions. COMPASS-U also reserves a role for liquid-metal divertor concepts, which EUROfusion has considered as one possible route towards more resilient power exhaust. Liquid surfaces may redistribute heat and renew themselves, but they introduce difficult

questions involving evaporation, magnetohydrodynamics, contamination, and fuel retention. Prague therefore provides a potential European test environment in which conventional tungsten and more experimental liquid-metal strategies can be compared. Such work is particularly relevant to DEMO, whose continuous power-handling requirements will be substantially more demanding than those of present experimental tokamaks.

Building COMPASS-U required IPP CAS to become a large systems-engineering organisation as well as a plasma-physics laboratory. The tokamak uses powerful copper magnetic coils that are cooled towards cryogenic temperatures to reduce electrical resistance during high-field pulses. A massive support structure must withstand the electromagnetic forces generated by currents and fields far above those of COMPASS. The cryostat, vacuum vessel, coil systems, auxiliary heating, cooling circuits, power supplies, control systems, diagnostics, and protection systems all have to function as one integrated machine. The electrical infrastructure uses flywheel generators and specialised converters capable of delivering very high pulsed power. Finite Element Method simulations are used extensively to predict mechanical stress, thermal behaviour, and electromagnetic loads before components are manufactured. Civil reconstruction of the experimental hall accompanied development of the tokamak itself. The first major phase of those building works was completed in 2023. Manufacturing of the large steel support structure proceeded internationally during 2024 and 2025. Several major power-supply components had already been delivered and installation work advanced in parallel with mechanical construction. In April 2025, external experts reviewed the final design of the first-wall limiters and the preliminary design of the tungsten divertor without identifying fundamental obstacles. These milestones show that the Prague school had moved from adapting a transferred machine to engineering a complex high-field tokamak largely around its own scientific requirements.

The relationship between Prague research and ITER is based on specialised contribution rather than an attempt to reproduce the international reactor experimentally. COMPASS provided data on H-mode, pedestal physics, magnetic error fields, disruptions, and edge transport under conditions that could be compared with other tokamaks. Its additional magnetic coils allowed controlled studies that informed understanding of field-error tolerances and compensation procedures relevant to ITER. Czech theory groups participate directly in International Tokamak Physics Activity activities and in research networks linked to the ITER Organization. COMPASS-U is intended to extend this contribution into high-field, high-density, high-power-exhaust conditions while retaining experimental flexibility. The ITER project's revised baseline adopted in 2024 places the Start of Research Operation in the 2030s, meaning that preparation remains an active scientific process rather than a completed design phase. Models of edge transport, disruption mitigation, wall interactions, and advanced operating regimes will continue to require validation before and during ITER operation. Prague researchers can contribute to this process through both their own device and experiments on other EUROfusion machines. The national role is therefore to provide specialised physical knowledge, diagnostics, models, and trained personnel that feed into the wider international programme.

DEMO gives the Prague programme an even longer technological horizon because it is intended to move beyond ITER's experimental objectives towards the demonstration of fusion electricity and reactor technologies. Questions of steady or repeated power exhaust become more severe when a device must operate for energy production rather than for limited experimental campaigns. Plasma-facing components must tolerate intense heat and neutron exposure

while minimising impurity contamination and fuel retention. Advanced confinement regimes must provide high performance without producing unacceptable transient loads. Disruptions and runaway electrons have to be avoided or mitigated with exceptional reliability. Remote maintenance, materials lifetime, tritium management, and efficient energy conversion introduce additional systems requirements beyond the plasma itself. COMPASS-U addresses only a subset of these challenges, but its high-field design is deliberately concentrated on several that are among the most difficult experimentally. Its closed divertor, hot wall, advanced plasma shapes, high exhaust power density, and provision for liquid-metal studies all connect directly with this reactor-oriented research agenda. EUROfusion gives Czech groups a framework in which results from Prague can be combined with materials studies, systems modelling, and experiments performed elsewhere. The Prague school therefore contributes to DEMO through specialisation rather than by attempting to build every reactor technology nationally. This distributed model is characteristic of European fusion science, where individual facilities are designed to close particular knowledge gaps within a common roadmap. Prague's long-developed expertise in edge physics and diagnostics gives it a clear place within that division of scientific labour.

Between 1993 and 2025, the Prague plasma and fusion school consequently passed through a coherent sequence of scientific and institutional transformations. CASTOR preserved national experimental continuity and developed strong expertise in edge diagnostics, turbulence, electric fields, and student training during the first post-Czechoslovak decade. Association with Euratom in 1999 embedded the Czech programme in coordinated European fusion research and opened systematic access to JET, common computing, and researcher mobility. The transfer of COMPASS from Culham moved Prague into diverted, H-mode-capable tokamak research directly connected with ITER-oriented questions. Its operation from 2008 to 2021 produced more than twenty-one thousand discharges and established recognised work on the pedestal, SOL, magnetic perturbations, disruptions, runaway electrons, and plasma exhaust. EUROfusion subsequently placed these activities within a roadmap extending from present experiments through ITER towards DEMO. The transfer of CASTOR to the Czech Technical University as GOLEM preserved an educational tokamak alongside the increasingly advanced research programme at IPP. COMPASS-U transformed the next stage from adaptation of an imported device into the design and construction of a new high-field machine around specifically selected European research gaps. By 2025, engineering work on the new tokamak had reached major structural, power-system, and plasma-facing-component milestones while Czech researchers continued experiments and modelling across the wider EUROfusion network. Prague had therefore become a centre where national scientific tradition, advanced engineering, European integration, and training were organised around a common long-term fusion objective. The evolution from CASTOR through COMPASS to COMPASS-U is consequently not merely a sequence of machines but the institutional history of how Czech fusion science positioned itself within preparations for ITER and the development path towards DEMO.

Dolní Břežany Laser Cluster: ELI Beamlines and HiLASE

The Dolní Břežany laser cluster emerged during the 2010s as one of the most significant transformations in the institutional geography of Czech physics. Its core consists of two complementary centres operated by the Institute of Physics of the Czech Academy of Sciences: ELI Beamlines and the High average power pulsed LASErs Centre, commonly known as HiLASE. Located a few kilometres south of Prague, the two facilities brought together high-energy, high-peak-power, high-average-power, ultrafast, and industrially oriented laser research within one compact scientific environment. ELI Beamlines was created as the Czech pillar of the pan-European Extreme Light Infrastructure, whereas HiLASE was designed to develop advanced diode-pumped laser technologies with strong links to industrial applications. Their scientific missions therefore overlap in laser engineering and light–matter interaction but differ in the combinations of pulse energy, repetition rate, peak power, and application for which the systems are optimised. This complementarity allowed Dolní Břežany to develop into more than a collection of individual laser laboratories. It became a research ecosystem in which laser source development, plasma physics, secondary radiation generation, materials science, precision manufacturing, and technology transfer could interact. The cluster also attracted international researchers and strengthened cooperation between Czech laboratories and major laser centres abroad. By 2025, Dolní Břežany had become one of the clearest examples of Czechia hosting research infrastructure whose scientific significance extended well beyond the national scale.

The creation of this cluster was rooted in the European effort to construct a new generation of ultra-intense laser infrastructure. The Extreme Light Infrastructure project entered the roadmap of the European Strategy Forum on Research Infrastructures in 2006 and was conceived as a facility too large and technologically demanding for a conventional national laboratory. During the preparatory phase, European partners examined scientific concepts and possible host countries for several complementary pillars. In October 2009, the Czech Republic, Hungary, and Romania received the mandate to implement separate but coordinated ELI facilities. The Czech proposal was led by the Institute of Physics, which planned a centre focused on high-energy beamlines and laser-driven secondary sources. In November 2009, the Institute submitted the formal project application to the Czech Ministry of Education, Youth and Sports. The European Commission approved financing for ELI Beamlines in April 2011, and the project budget of approximately €278 million was signed later that year. Construction documentation and scientific engineering proceeded in parallel because the building had to satisfy exceptional requirements for vibration, radiation shielding, vacuum systems, clean environments, and beam transport. Excavation began in 2012 and major building construction followed in 2013. The project therefore combined European infrastructure policy, Czech public investment, and a major institutional expansion of the Institute of Physics.

HiLASE arose from a related but more application-oriented strategy for strengthening Czech laser technology. The project application for HiLASE was approved in September 2011, marking the formal establishment of the centre. Construction began in 2012 in Dolní Břežany close to the emerging ELI site. The building was completed in 2014 and the centre was ceremonially inaugurated on 24 September of that year. Its mission was to develop high-average-power diode-pumped solid-state lasers capable of delivering energetic pulses repeatedly and with high beam quality. This technological emphasis addressed an important limitation of many

traditional high-energy lasers, which could produce exceptional single pulses but only at low repetition rates. HiLASE therefore targeted the region between laboratory-scale ultrafast sources and industrial systems requiring reliable, repeated operation. The proximity of HiLASE and ELI Beamlines created the physical basis for a laser cluster with complementary scientific and technological functions.

The relationship between peak power, pulse energy, pulse duration, and repetition rate is central to understanding why the two centres are complementary. Peak power describes how much energy is delivered per unit time during an individual pulse and can reach petawatt values when tens or hundreds of joules are compressed into femtoseconds. Average power instead measures energy delivered over many pulses and becomes crucial when a process must be repeated rapidly or applied over a large surface. ELI Beamlines was designed principally to reach extreme peak powers and intensities while also pushing selected systems towards high repetition rates. HiLASE focuses more strongly on energetic pulses at high average power and on the engineering required for stable repeated operation. These regimes create different thermal, optical, and mechanical problems inside a laser system. An optic that survives a single extreme pulse may still fail when exposed to thousands or millions of pulses because heat accumulates and microscopic defects grow. Conversely, an industrially efficient high-average-power source may not reach the field strengths required for relativistic laser–matter interaction. The Dolní Břežany cluster therefore spans several dimensions of laser performance rather than pursuing a single numerical record. This breadth supports research from fundamental high-field physics to manufacturing and surface engineering. It also allows technology developed for one operating regime to inform solutions needed in another.

ELI Beamlines reached its first major construction milestone in 2015. The initial construction phase was completed on 30 June, and the facility was formally inaugurated on 19 October. Completion of the building did not mean that the research infrastructure was scientifically finished because complex laser chains and experimental stations still had to be installed and commissioned. The facility entered trial operation in 2018 and gradually opened individual systems to external researchers. Its design centres on four principal laser systems, conventionally labelled L1 through L4. These systems cover different combinations of pulse duration, repetition rate, energy, and peak power so that users can select the source appropriate to a particular experiment. The architecture also includes beam transport, target chambers, radiation shielding, diagnostics, and secondary photon or particle sources. This systems approach distinguishes a research infrastructure from a single high-power laser. ELI Beamlines was conceived from the beginning as a user facility in which the laser is the driver for a much wider experimental environment.

The L1 system, known as ALLEGRA, represents the high-repetition end of the ELI Beamlines portfolio. It was developed largely by the Czech ELI team and uses Optical Parametric Chirped Pulse Amplification, usually abbreviated as OPCPA, driven by a diode-pumped ytterbium-doped yttrium aluminium garnet thin-disk pump laser. The system is capable of operating at kilohertz repetition rates while producing ultrashort pulses with terawatt-class peak power. Such repetition rates are scientifically valuable because they generate large datasets rapidly and permit signal averaging in experiments where a single shot would be statistically insufficient. ALLEGRA supports high-harmonic generation, plasma-based X-ray sources, ultrafast spectroscopy, and studies of materials and molecules. The E1 experimental hall uses synchronised optical, extreme-ultraviolet, and X-ray pulses to examine processes unfolding on femtosecond timescales. Researchers can therefore investigate structural dynamics,

electronic excitation, chemical reactions, and radiation-induced changes before slower thermal processes obscure the initial state. High repetition also encourages development of automated targets and diagnostics capable of operating continuously rather than being reset manually after every pulse. This operational philosophy is important for translating extreme-laser science from spectacular single events into statistically robust measurement programmes. The L1 system consequently demonstrates that the scientific frontier in laser physics depends not only on maximum pulse energy but also on reliability and repetition. Its in-house development also strengthened Czech expertise in OPCPA, thin-disk pumping, synchronisation, and ultrafast beam diagnostics. These competences became part of the technological base of the wider Dolní Břežany cluster.

The L2 system extends this concept towards higher-energy ultrashort pulses while retaining an unusually high repetition rate. Its design uses OPCPA combined with a gas-cooled ytterbium-doped solid-state pump architecture. Cooling the active medium is essential because high repetition continuously deposits heat that would otherwise distort the optical wavefront and reduce beam quality. The resulting source is intended for strong-field experiments, laser–plasma interaction, and generation of energetic secondary particles and radiation. One associated experimental area is TERESA, whose name expands as TEstbed for high REpetition-rate Sources of Accelerated particles. TERESA was created to study laser-driven particle sources under conditions where targets, diagnostics, and data acquisition must work repeatedly rather than as isolated single-shot experiments. This is technologically important because practical applications of laser acceleration will require stable operation and controlled particle output. The L2 programme therefore connects high-field plasma physics with the engineering problem of turning an intense laser interaction into a reproducible source. Lessons from this work are relevant to imaging, irradiation, materials studies, and future compact accelerator concepts. The system also occupies an intermediate regime between ALLEGRA's very high repetition and the much higher pulse energies of the petawatt-class beamlines.

The L3 system is the High-Repetition-Rate Advanced Petawatt Laser System, commonly abbreviated as HAPLS. It was developed in cooperation with Lawrence Livermore National Laboratory in the United States and transferred to ELI Beamlines as a major international technology project. HAPLS combines a diode-pumped pump laser with titanium-doped sapphire amplification to generate ultrashort petawatt-class pulses. Its design was notable because petawatt peak power had traditionally been associated with comparatively low shot rates. Operating at several shots per second makes it possible to accumulate data far faster than on earlier petawatt facilities. This capability is particularly important for particle acceleration, high-field physics, and experiments that require systematic scanning of parameters. The system also demonstrates how ELI Beamlines became a platform for integrating Czech infrastructure with advanced technology developed through international partnerships. HAPLS therefore contributed both scientific capability and experience in transferring complex laser technology across national laboratories.

The L4 system, known as ATON, occupies the high-energy end of ELI Beamlines. Its architecture uses OPCPA preamplification followed by amplification in neodymium-doped glass, enabling pulse energies on the kilojoule scale. Unlike a lower-energy high-repetition source, L4 is designed to combine enormous pulse energy with compression to ultrashort duration. This combination produces multi-petawatt peak powers and creates electromagnetic fields strong enough to drive highly nonlinear and relativistic interactions with

matter. The system can support experiments in high-energy-density physics, plasma optics, laboratory astrophysics, energetic particle generation, and extreme-condition materials science. Its beam can also be divided into components with different temporal formats so that experiments can combine nanosecond, picosecond, and femtosecond interactions. This flexibility is valuable when a target must first be compressed or magnetised and then interrogated with a second ultrashort pulse. During a test campaign in September 2025, ATON delivered 786 joules compressed to 154 femtoseconds. The corresponding peak power reached 5.1 petawatts, while the pulse energy was reported as the highest achieved worldwide at the multi-petawatt power level at that time. The result marked one of the most visible technical milestones reached by the Czech ELI facility before the end of the period covered by this book. It also demonstrated that the cluster could contribute directly to the international technological frontier of extreme-power lasers.

The scientific importance of petawatt lasers lies in the intensity reached when an ultrashort pulse is focused onto a microscopic target area. Electrons in the target can be accelerated to relativistic velocities within a fraction of an optical cycle. The resulting plasma can generate energetic electrons, ions, X-rays, gamma rays, and high-order harmonics. These secondary sources extend the facility from laser physics into accelerator science and radiation science. Laser-driven particle acceleration is attractive because the accelerating electric fields in a plasma can greatly exceed those sustainable in conventional radio-frequency cavities. The challenge is to convert this exceptional gradient into beams with sufficient stability, energy spread, repetition rate, and control for reproducible science. ELI Beamlines therefore combines laser development with target engineering, beam transport, dosimetry, diagnostics, and detector systems. The objective is not merely to maximise intensity but to transform extreme optical fields into usable experimental tools. This distinction is essential for understanding the infrastructure's role as a multidisciplinary user facility.

The experimental halls at ELI Beamlines were organised around different scientific uses of these laser systems and the secondary sources they produce. E1 focuses on material, molecular, and biomolecular applications using ultrafast optical, extreme-ultraviolet, and X-ray techniques. E2 is devoted to hard X-ray science and laser-driven electron acceleration capable of producing femtosecond X-ray or gamma-ray pulses. E3 contains the Plasma Physics Platform for high-energy-density matter, warm dense matter, plasma optics, laboratory astrophysics, and ultra-high-intensity interaction. E4 houses ion-acceleration experiments centred on the ELI Multidisciplinary Applications of laser-Ion Acceleration beamline, known as ELIMAIA. E5 is dedicated to electron acceleration and laser-driven X-ray sources. These halls show that the facility's scientific output cannot be reduced to the characteristics of the primary lasers themselves. Each beamline contains target systems, transport optics, diagnostics, shielding, sample environments, and data-acquisition technologies tailored to a different class of experiments. The same laser pulse can therefore become a probe of chemical dynamics, a driver of plasma acceleration, or a source of radiation for materials research depending on the experimental configuration. The infrastructure model is consequently based on converting extreme light into multiple forms of scientific access.

ELIMAIA provides a particularly clear example of this conversion from laser pulse to user-oriented secondary beam. Its name expands as ELI Multidisciplinary Applications of laser-Ion Acceleration and describes a beamline designed to deliver laser-accelerated ions to experiments rather than merely observe their production at the target. The system includes laser contrast enhancement, an interaction chamber, ion transport, diagnostics, dosimetry,

and an in-air sample irradiation station. Such elements are necessary because particles emerging directly from a laser target may have broad energy distributions, strong divergence, and substantial shot-to-shot variation. Transport and selection systems must therefore shape the beam before many applications become feasible. Dosimetry is especially important when biological or materials samples are irradiated because the deposited dose has to be known quantitatively. ELIMAIA consequently joins high-field plasma physics with accelerator engineering and radiation metrology. Potential applications include radiobiology, detector testing, materials irradiation, and studies of novel approaches to particle-beam therapy. The scientific programme remains exploratory because conventional accelerators still provide much more mature beam quality for many applications. Nevertheless, the beamline allows users to test where the distinctive temporal or spectral properties of laser-driven ions may offer advantages. Its development demonstrates the broader ELI strategy of turning extreme laser interactions into reproducible sources for external scientific communities. The approach also creates technological knowledge relevant to future compact accelerator systems.

Laboratory astrophysics is another field in which ELI Beamlines creates experimental conditions unavailable in ordinary laboratories. Astrophysical objects such as supernova remnants, stellar interiors, accretion environments, and magnetised shocks contain plasmas at extreme temperature, pressure, and magnetic field. Direct replication of an entire astronomical object is impossible, but selected dimensionless parameters and physical processes can be reproduced on a much smaller scale. High-energy laser pulses can rapidly heat or compress matter, generating shocks and plasma flows that are diagnosed with optical, X-ray, or particle techniques. External pulsed magnetic fields can add another important control variable. Comparing the measurements with radiation-hydrodynamic or magnetohydrodynamic simulations allows models used in astrophysics to be tested experimentally. The E3 Plasma Physics Platform was designed to support precisely such high-energy-density and laboratory-astrophysics studies. This programme connects Dolní Břežany with theoretical astrophysics and plasma physics far beyond the traditional boundaries of laser science.

Materials research provides an equally important but methodologically different use of the facility. Ultrafast X-ray diffraction can follow atomic rearrangements while a material is being excited, transformed, or damaged. Time-resolved spectroscopy tracks changes in electronic structure before the system relaxes towards thermal equilibrium. Coherent diffractive imaging can reconstruct microscopic structures without relying on conventional optical lenses. Hard X-ray pulses can penetrate samples and reveal transient states inaccessible to surface-sensitive probes. Optical pump and X-ray probe schemes separate excitation from measurement by controlling the delay between two ultrashort pulses. This allows a physical process to be reconstructed as a sequence of time slices rather than inferred only from its initial and final states. Such experiments are relevant to semiconductors, magnetic materials, functional solids, molecular systems, and radiation chemistry. ELI Beamlines therefore provides a bridge between extreme-laser technology and condensed-matter or chemical physics.

HiLASE addresses a different technological frontier by emphasising energetic pulsed lasers that can operate repeatedly at high average power. Diode pumping improves electrical efficiency and permits more controlled thermal management than traditional flashlamp pumping in many solid-state laser architectures. The centre concentrated particularly on cryogenically cooled multi-slab lasers and thin-disk systems. These geometries are designed

to remove heat while preserving beam quality as repetition rate and pulse energy increase. The engineering challenge becomes progressively more severe as the average optical power reaches the kilowatt range. Thermal gradients can distort the wavefront, stress optical materials, and reduce the lifetime of coatings or gain media. Reliable operation therefore requires advances in cooling, pump optics, amplification, diagnostics, controls, and component testing. HiLASE treats these problems as research subjects rather than as secondary engineering details. Its central objective is to make high-performance lasers usable repeatedly and predictably enough for scientific and industrial processes. The centre's scientific identity is consequently defined by the interaction between laser architecture and application requirements. That approach complements ELI Beamlines, where the highest priority is access to extreme intensity and high-energy ultrashort interactions.

The BIVOJ laser became the best-known embodiment of the HiLASE high-energy programme. It was developed through a Czech-British collaboration with the Central Laser Facility of the Science and Technology Facilities Council in the United Kingdom. Construction began in Britain in 2013, after which the system was transferred and recommissioned in Dolní Břežany. BIVOJ uses a Master Oscillator Power Amplifier architecture with cryogenically cooled ytterbium-doped yttrium aluminium garnet slab amplifiers. Its central objective was to combine pulses of approximately one hundred joules with a repetition rate of ten hertz. In 2016, the Czech-British team achieved 105 joules in ten-nanosecond pulses at ten hertz, corresponding to average output at the kilowatt level. This was reported as a world record for a high-energy laser of that class. On 26 January 2021, BIVOJ surpassed its earlier result and operated for an hour above 145 joules, with a maximum pulse energy of 146.5 joules at ten hertz. The improvement raised average power to approximately 1.45 kilowatts while preserving the combination of high pulse energy and repeated operation. The achievement confirmed HiLASE as an internationally competitive centre for diode-pumped high-energy laser engineering.

BIVOJ is scientifically significant because high pulse energy and high repetition are usually competing design requirements. Large pulse energy requires a substantial volume of stored energy in the laser medium and can create strong thermal and mechanical stress during extraction. High repetition rate gives the system less time to remove deposited heat before the next pulse arrives. Cryogenic cooling improves thermal conductivity and alters the spectroscopic properties of the ytterbium-doped gain medium in ways that facilitate efficient amplification. Multi-slab architecture distributes the amplification and thermal load across several elements rather than concentrating them in a single large crystal. Beam shaping is also required because local hot spots can damage optical surfaces even when average energy remains within nominal limits. Long-duration tests therefore matter as much as record single-shot performance when the intended use is repeated industrial or scientific processing. The 2021 result showed that BIVOJ could maintain very high energy over an extended operating period rather than producing only an isolated maximum pulse. This distinction makes the system relevant to applications requiring many controlled shots on a component. It also provides a development platform for the next generation of high-average-power laser architecture. Experience with BIVOJ has consequently influenced both HiLASE source development and the design of application stations built around it. The system demonstrates how laser engineering converts a physical performance record into a practical experimental capability.

The PERLA family represents the ultrashort high-average-power branch of HiLASE technology. These systems use thin-disk architectures and are designed to produce picosecond pulses with high beam quality and high repetition rates. Short pulses concentrate energy in time while limiting the duration over which heat can diffuse into the surrounding material. This makes them especially suitable for precision micromachining and controlled surface modification. HiLASE developed PERLA largely in-house, strengthening domestic competence in laser design rather than relying only on imported systems. A commercial PERLA 100 unit was delivered to a customer in 2020. The achievement showed that technologies developed in a research centre could be transferred into a product configured for an external user. PERLA also became the basis for experiments in parallel multi-beam processing. By combining high-quality pulses with diffractive optical elements, researchers could divide one incoming beam into thousands of controlled processing spots.

Parallel processing allowed HiLASE to demonstrate how high-average-power lasers can overcome the productivity limits of conventional serial micromachining. In 2021, researchers used 40,401 simultaneous beams in a laser multi-beam nanostructuring experiment. The same research direction produced laser-induced periodic surface structures on stainless steel at a reported rate of 1,909 square centimetres per minute. This performance exceeded the previous reported record by more than thirty per cent. Laser-induced periodic surface structures alter the optical, wetting, tribological, or biological behaviour of a surface without adding a separate coating. Potential applications therefore include antibacterial surfaces, optical functions, authenticity protection, friction control, and other forms of surface engineering. The result is important not merely because it set a numerical record but because productivity is one of the central barriers separating laboratory nanostructuring from industrial manufacturing. Splitting a high-quality beam into many parallel interaction points provides one route to using the available average laser power more efficiently. The work also demonstrated the importance of combining source development with beam-shaping optics and process engineering. HiLASE consequently became a site where advances in laser architecture could be tested immediately against manufacturing-relevant performance.

Laser Shock Peening, commonly abbreviated as LSP, became another principal industrial application developed at HiLASE. The process directs energetic laser pulses onto a material surface in conditions that generate a rapidly expanding plasma and a strong mechanical shock wave. The shock creates deep compressive residual stresses that can improve resistance to fatigue and stress-corrosion cracking. Unlike ordinary thermal surface treatment, the desired effect is primarily mechanical rather than the result of melting a thick surface layer. BIVOJ provides the pulse energies and repetition rates needed to treat substantial metallic areas within experimentally useful times. A robotic application station allows complex components to be positioned accurately under the laser beam. HiLASE researchers investigate how pulse shape, overlap, energy, material condition, and component geometry affect the final residual-stress profile. Applications are relevant to aerospace, power engineering, transport, tooling, and other industries in which fatigue life determines component reliability. The centre has also tested steels relevant to nuclear-reactor components, where resistance to stress-corrosion cracking is especially important. LSP therefore illustrates how a laser system developed through fundamental optical engineering can produce a direct materials-engineering capability. Its development also creates research questions concerning shock propagation, plastic deformation, microstructure, and long-term material stability.

Laser-Induced Damage Threshold testing provides a third major industrial and scientific application at HiLASE. High-power laser facilities depend on mirrors, windows, crystals, coatings, and other optical components that must survive repeated exposure without catastrophic degradation. A microscopic defect or contamination particle can absorb energy locally and initiate damage at intensities far below the theoretical limit of the ideal material. Damage behaviour may also change with pulse duration, wavelength, repetition rate, temperature, and accumulated shot number. HiLASE therefore uses its laser systems to determine how candidate optical components behave under realistic high-power operating conditions. The resulting measurements are relevant both to the centre's own source development and to manufacturers supplying optics for other facilities. Testing at unusual combinations of pulse energy and repetition rate can reveal failure mechanisms that are not visible with conventional commercial lasers. This knowledge feeds back into coating design, polishing, cleaning, quality control, and lifetime prediction.

The coexistence of ELI Beamlines and HiLASE creates scientific synergies that neither centre could reproduce as effectively in isolation. Both require advanced optical coatings, precision beam diagnostics, reliable vacuum and control systems, high-damage-threshold components, and specialised laser engineers. Knowledge gained from high-average-power operation at HiLASE is relevant to the long-term reliability of repetitive systems at ELI Beamlines. Conversely, the extreme-field requirements of ELI stimulate research on optics and diagnostics that can influence lower-energy but high-duty-cycle systems. The two centres also share a regional workforce and help create a critical mass of specialists who can move among laser development, experimental physics, and applications. Students can encounter both the fundamental physics of extreme light and the engineering constraints of industrially useful sources within the same locality. International visitors may collaborate with separate teams while remaining within one scientific cluster. This concentration improves the visibility of Czech laser science when partnerships or European projects require several complementary competencies. It also encourages suppliers and technology companies to regard Dolní Břežany as a sustained market for advanced optical and engineering solutions rather than as the site of one temporary construction project. The cluster effect is therefore organisational and economic as well as scientific.

The establishment of Brain4Industry in 2021 represented one effort to strengthen this translation from research capability to manufacturing innovation. The initiative brought together HiLASE, the Institute of Physics, the Institute of Thermomechanics, regional innovation organisations, and industrial partners. Its purpose was to provide companies with access to advanced manufacturing technologies, digitalisation, additive methods, simulation, and specialised expertise. HiLASE contributed laser processing and surface-engineering capabilities within this broader technological environment. The same period also saw the creation of the Hi-Beams spin-off in cooperation with an industrial partner specialising in physical vapour deposition coatings. The company aimed to commercialise laser-based methods for tool and surface treatment. Such initiatives demonstrate that technology transfer from the cluster can occur through collaborative research, service provision, training, licensing, or dedicated companies. They also create feedback because industrial users expose research teams to problems of throughput, reproducibility, cost, and component geometry that are less prominent in laboratory demonstrations. The innovation function of the cluster therefore depends on sustained interaction with users rather than simply on ownership of powerful lasers. The aim is to convert unique beam parameters into processes that can be

integrated into real production or testing environments. This applied dimension differentiates the Dolní Břežany ecosystem from laser centres devoted exclusively to fundamental high-field physics.

Open access is the corresponding mechanism through which the cluster serves external scientific users. HiLASE has offered competitive open-access beamtime since 2017, initially through Laserlab-Europe and later through programmes including Lasers4EU, Re-MADE, and RIANA. Researchers from other countries can therefore use specialised lasers and application stations without their institutions having to construct equivalent systems. ELI Beamlines launched its first external commissioning call in 2019 for experiments in the E1 hall. The user programme subsequently expanded to multiple laser systems and experimental platforms under a common ELI access framework. Proposals are evaluated through international peer review with scientific excellence as the principal criterion. By 2025, ELI had progressed through repeated calls involving researchers from dozens of countries and hundreds of proposed experiments across its facilities. This user model changes the role of Czech staff because they must operate complex systems reproducibly for experiments designed by outside teams. It also exposes the facility to a much wider range of scientific questions than an internal research programme could generate. International user access is therefore one of the principal mechanisms through which investment in Dolní Břežany produces scientific effects across Europe.

The creation of the Extreme Light Infrastructure European Research Infrastructure Consortium, commonly abbreviated as ELI ERIC, gave this user model a durable institutional framework. The European Commission granted ELI the legal status of an ERIC on 30 April 2021. The Czech Republic and Hungary became host countries, while Italy and Lithuania joined them as founding members. Germany and Bulgaria initially participated as observers, and Bulgaria became a full member at the beginning of 2025. The statutory seat of ELI ERIC was established at the ELI Beamlines site in Dolní Břežany. This gave Czechia a particularly visible position in the governance of a pan-European research infrastructure. ELI Beamlines was subsequently integrated into the ERIC operating structure, creating unified access and management with the other participating ELI facility. The legal transition was important because construction funding alone cannot guarantee the long-term operation of an expensive international laser centre. ERIC status creates a mechanism through which participating states share governance, scientific strategy, and operating responsibilities. It also moves ELI conceptually closer to other European organisations whose facilities serve multinational scientific communities. For Czech science, hosting the statutory seat demonstrated that the country's role had shifted from recipient of European structural investment towards co-governance of an international research infrastructure. The Dolní Břežany cluster therefore acquired an institutional significance extending beyond the technical specifications of its lasers.

International partnerships were essential to the formation of both centres and remained central to their operation. ELI Beamlines involved laboratories and suppliers from several countries in the design of lasers, experimental systems, diagnostics, and control technologies. HAPLS was developed through cooperation with Lawrence Livermore National Laboratory, while other systems drew on European and Czech expertise in diode pumping, OPCPA, and high-energy amplification. HiLASE developed BIVOJ through a long-term partnership with the Central Laser Facility of the United Kingdom's Science and Technology Facilities Council. European projects later supported the transformation of HiLASE into a centre of excellence and expanded transnational access. Scientific users bring further international networks every time

an experiment is approved at either facility. These collaborations make Dolní Břežany a point of circulation for engineers, physicists, students, and specialised technical knowledge. They also reduce the risk that a national facility develops around locally isolated standards or methods. International integration therefore became part of the operating logic of the cluster rather than an additional diplomatic function. At the same time, the presence of major infrastructure in Czechia gives domestic researchers opportunities that previously required long stays at foreign laser laboratories.

By the end of 2025, the Dolní Břežany laser cluster had completed a transition from construction-driven projects towards sustained scientific and technological operation. ELI Beamlines had developed four major laser systems and a set of experimental platforms for photons, electrons, ions, plasma, materials, and biomolecular research. The L4 ATON milestone of 5.1 petawatts showed that the facility could reach the extreme-power regime that originally motivated the European project. Repeated international user calls demonstrated that the centre was increasingly functioning as an infrastructure for external science rather than primarily as a development laboratory. ELI ERIC provided a multinational governance framework and placed its statutory seat in Czechia. HiLASE had meanwhile established internationally competitive high-average-power laser technology through BIVOJ and the PERLA family. Its records in energetic ten-hertz operation and high-throughput nanostructuring demonstrated two different routes towards increasing laser productivity. Industrial programmes in Laser Shock Peening, micromachining, and optical-damage testing translated source development into materials and manufacturing applications. Open-access schemes connected both centres with users who could not reproduce these laser parameters within their own institutions. Regional initiatives and spin-offs extended the cluster into innovation and technology transfer. The combined result was an internationally significant Czech laser centre in which extreme-light science, laser engineering, European infrastructure, and industrial application developed as mutually reinforcing activities.

The broader significance of Dolní Břežany for Czech physics lies in the institutional model that the cluster established. Before the 2010s, Czech laser science was internationally active but was based mainly on university laboratories, Academy institutes, the Prague Asterix Laser System, and participation in foreign facilities. ELI Beamlines and HiLASE created a new scale of domestic infrastructure that could attract international users rather than only send Czech researchers abroad. The two centres also demonstrated that very different laser strategies can coexist productively within one national institution. ELI pursues extreme intensity, ultrashort duration, high-energy secondary sources, and large-scale fundamental experiments. HiLASE pursues high average power, reliability, industrial process development, and laser architectures capable of repeated energetic operation. Their shared location generates technical, educational, and economic interactions without requiring the scientific missions to become identical. The cluster consequently embodies the wider transformation of Czech physics from national scientific continuity towards participation in and hosting of European-scale research infrastructure. By 2025, Dolní Břežany had become not merely a site containing powerful lasers but a durable research ecosystem linking fundamental science, advanced engineering, international access, and innovation.

Brno Physics and Nanotechnology School: Masaryk University, Brno University of Technology, and CEITEC

The Brno Physics and Nanotechnology School emerged between 1993 and 2025 as one of the most distinctive regional concentrations of Czech research outside Prague. Its institutional core was formed by Masaryk University, Brno University of Technology (BUT), and the Central European Institute of Technology (CEITEC). These organisations developed complementary strengths in condensed matter, nanophysics, microscopy, materials science, photonics, semiconductor physics, and advanced instrumentation. Masaryk University contributed long-established university traditions in solid-state and theoretical physics, optical spectroscopy, X-ray methods, and semiconductor structures. Brno University of Technology added a particularly strong physical-engineering culture linking fundamental physics with surfaces, nanostructures, optics, microscopy, and technological development. CEITEC provided the shared large-scale research infrastructure that allowed these traditions to operate with modern clean rooms, nanofabrication equipment, electron microscopes, and advanced analytical systems. The resulting ecosystem was not based on a single dominant laboratory but on interactions among university departments, shared facilities, research groups, and high-technology companies. This arrangement encouraged movement between fundamental questions about matter and practical problems in electronics, microscopy, sensing, energy, and manufacturing. By 2025, Brno had become a major Czech centre in which condensed-matter physics and engineering were integrated through research infrastructure at the micro- and nanoscale.

The roots of this school predate CEITEC and are closely connected with the development of physics at both major Brno universities. At Masaryk University, the Faculty of Science maintained departments concerned with condensed matter, plasma physics and technology, theoretical physics, astrophysics, and related experimental methods. The Department of Condensed Matter Physics became especially important for research on optical and structural properties of solids, semiconductors, insulators, and layered systems. Brno University of Technology developed a different but complementary profile within the Faculty of Mechanical Engineering. Its Institute of Physical Engineering traces its modern form to 1994, when the Physical Engineering study programme was added to the earlier Optical Engineering tradition of the Department of Physics. The institute gradually expanded into surface physics, nanostructures, optics, micromechanics, technical acoustics, electron microscopy, and nanotechnology. This combination gave Brno both a university physics tradition oriented towards fundamental properties and an engineering tradition oriented towards fabrication, instrumentation, and applications. Cooperation between the two universities was therefore scientifically natural even before a common large research centre existed. The formation of CEITEC after 2011 provided an institutional mechanism for deepening this interaction and for concentrating expensive equipment in shared facilities. Brno physics consequently developed through convergence of older academic traditions rather than by replacing them with an entirely new organisational model.

Condensed-matter physics at Masaryk University provides one of the clearest examples of this continuity. Researchers study metals, semiconductors, insulators, superconductors, polymers, and multilayer systems through their optical, electronic, and structural properties. Optical spectroscopy from the far-infrared to the ultraviolet is used to identify electronic excitations, lattice vibrations, and their interactions. X-ray diffraction and reflectometry reveal

crystal structure, strain, interfaces, film thickness, and the structural quality of layered materials. Low-dimensional semiconductor structures have remained a particular area of interest because confinement and interfaces can strongly modify their electronic and optical behaviour. High-temperature superconductors and other strongly correlated oxides provide a contrasting class in which collective electronic interactions dominate the physical response. Experimental work is supported by theoretical groups using models of correlated electrons, magnetism, and superconductivity. The department therefore links traditional solid-state physics with the newer questions of quantum materials and nanoscale heterostructures.

Theoretical condensed-matter physics at Masaryk University developed in close contact with these experiments. Researchers use microscopic models to investigate transition-metal oxides, unconventional superconductivity, frustrated magnetism, spin-orbit coupling, and excitonic phenomena. Effective Hamiltonians such as Hubbard, t–J, and spin models provide simplified descriptions of strongly interacting electrons whose exact many-body behaviour is generally inaccessible. Analytical diagrammatic techniques are combined with numerical exact diagonalisation, Quantum Monte Carlo, and dynamical mean-field theory. These methods allow theorists to calculate optical spectra, magnetic correlations, phase transitions, and response functions that can be compared with experiment. High-performance computing becomes necessary when the number of quantum states grows too rapidly for direct calculation. The resulting work connects Brno condensed-matter physics with national supercomputing resources and international computational collaborations. Theory also helps identify which experimental observables are most sensitive to competing microscopic mechanisms. This interaction is particularly important in materials where several forms of order, such as magnetism and superconductivity, coexist or compete. Theoretical and experimental groups can therefore approach the same material from complementary directions without reducing the problem to either measurement or computation alone. Such integration became one of the characteristic methodological features of the Brno school.

X-ray science provided another long-standing strength at Masaryk University. The X-ray Structure Analysis group studies crystalline and amorphous materials, single crystals, thin films, multilayers, and nanostructures. Its methods include conventional and grazing-incidence diffraction, reflectometry, small-angle scattering, and X-ray spectroscopy. These techniques are especially valuable for determining strain, texture, interface roughness, composition, and nanoscale ordering without destroying the sample. The group combines experimental measurements with scattering theory and develops its own analytical software for interpreting complex data. Synchrotron experiments extend the available photon flux, energy range, and spatial or temporal resolution beyond what can be achieved with laboratory sources. Film-growth activity allows structural measurements to be connected directly with the conditions under which a material was prepared. This capability supports research on semiconductors, oxides, magnetic layers, and other functional thin-film systems. X-ray physics therefore provides a bridge between materials preparation, condensed-matter theory, and nanoscale characterisation in Brno.

Semiconductor physics became an important point of contact between Masaryk University, Brno University of Technology, CEITEC, and regional industry. Masaryk University's Department of Condensed Matter Physics maintained research on low-dimensional semiconductor structures and operated a clean-room facility used particularly for education in semiconductor technologies. Optical spectroscopy and X-ray methods provided detailed information about the electronic and structural properties of epitaxial and layered systems. At Brno University of

Technology, the Institute of Physical Engineering developed a long tradition of cooperation with semiconductor companies and research on surfaces, crystal defects, nanostructures, and analytical instrumentation. CEITEC Nano added a facility in which deposition, lithography, microscopy, surface analysis, and device fabrication could be carried out under one roof. By the 2020s, Brno teams were working on gallium nitride and other materials relevant to power electronics and energy-efficient semiconductor devices. European projects connected local researchers with manufacturers and technology centres working on advanced gallium-nitride integrated circuits. Transmission electron microscopy was used to examine dislocations whose movement and density can limit device performance. Nanofabrication allowed prototype structures to be produced and then inspected using the same infrastructure. Semiconductor research therefore linked fundamental defect physics with industrial questions of efficiency, reliability, and manufacturability. The field also became strategically important as European policy increasingly emphasised domestic semiconductor capability. By 2025, Brno possessed a research and educational chain extending from semiconductor physics to chip-oriented technological training.

The Institute of Physical Engineering at Brno University of Technology became one of the principal institutional carriers of this applied-physics tradition. Its research is organised around surface physics and nanostructures, optics and precision mechanics, micromechanics of materials, and related forms of instrumentation. Surface groups investigate adsorption, thin-film growth, interactions of atoms and molecules with solids, and the fabrication of nanoscale structures. Nanophotonics research examines how metallic and dielectric nanostructures manipulate optical fields, including plasmonic and metasurface effects. Nanoelectronics groups investigate graphene and other two-dimensional systems as potential elements of sensors and future electronic devices. Nanomagnetism research addresses spin waves, magnetisation dynamics, and spintronic phenomena in patterned structures. Advanced microscopy and spectroscopy provide the methods needed to correlate local structure with these electronic, optical, or magnetic properties. The institute therefore treats nanotechnology as a physical-engineering discipline in which fabrication, characterisation, modelling, and device concepts must remain closely connected. Its students are trained in the same laboratories in which research projects are carried out, reinforcing the link between education and the Brno technology ecosystem. This model made the institute a natural academic partner for CEITEC Nano when the new research infrastructure was established. It also positioned Brno University of Technology to translate fundamental surface and nanoscale physics into technologically relevant methods.

The Central European Institute of Technology transformed the scale of this regional collaboration after its approval in 2011. CEITEC was created as a consortium linking Masaryk University, Brno University of Technology, other Brno universities, and research institutes of the Czech Academy of Sciences. Its original scientific design deliberately connected life sciences with advanced materials and technologies rather than building a centre around one traditional academic discipline. European Structural Funds provided more than five billion Czech crowns for laboratories and equipment during the establishment phase. Construction began in 2012 at the Masaryk University campus in Bohunice and the Brno University of Technology campus at Pod Palackého vrchem. Shared core facilities were central to the organisational concept because expensive instruments were intended for use across research groups and institutional boundaries. For physics and nanotechnology, the most important development was the creation of CEITEC BUT laboratories devoted to advanced nanotechnologies,

microtechnologies, and materials. CEITEC therefore altered Brno science by combining new infrastructure with a consortium model that encouraged interdisciplinary and interinstitutional research.

CEITEC Brno University of Technology became the part of the consortium most directly associated with nanophysics and advanced materials. Since 2011, its research has been organised around advanced nanotechnology and microtechnology, advanced materials, and technical cybernetics with instrumentation and systems integration. These broad areas accommodate research on low-dimensional materials, epitaxial structures, nanomagnetism, spintronics, molecular nanostructures, ceramics, polymers, biomaterials, coatings, and analytical instrumentation. The structure allows physicists to work alongside materials scientists, chemists, electrical engineers, and specialists in imaging or control systems. Research groups can therefore approach a nanostructure not only as a physical system but also as a material to be fabricated, measured, integrated, and potentially applied. This organisation differs from a conventional physics department because the research programme is built around shared problems and technologies rather than classical disciplinary divisions. The CEITEC model also makes it easier to establish groups around emerging topics without having to create an entirely new faculty structure. International recruitment increased the diversity of the scientific staff and introduced methods developed in laboratories outside Czechia. Common infrastructure allows these teams to share clean rooms, microscopes, deposition systems, spectrometers, and computing resources. The resulting environment significantly strengthened Brno's ability to undertake experiments requiring several expensive techniques in sequence. It also made the city attractive for collaborative projects whose partners needed a combination of fabrication and characterisation rather than one isolated instrument.

CEITEC Nano became the technological core of this development. The facility reached full operation in 2016 and was described as the largest clean-room nanocentre in the Czech Republic. Its laboratories provide nanofabrication, nanocharacterisation, structural analysis, and X-ray computed tomography in a single site. Clean-room areas reduce airborne contamination to levels appropriate for processes in which a microscopic dust particle could destroy a nanoscale device. Users can deposit thin films, pattern structures lithographically, etch or modify them, and then examine the resulting material with complementary analytical tools. The infrastructure supports multiple material classes rather than being restricted to silicon or one semiconductor technology. It is also designed for both academic and industrial users, making open access part of its operational model. Researchers can therefore construct an experimental workflow extending from raw material to functional nanodevice without moving between unrelated laboratories. This integration is one of the principal reasons CEITEC Nano became central to the Brno physics school.

Nanofabrication at CEITEC Nano combines bottom-up and top-down approaches. Molecular Beam Epitaxy, magnetron sputtering, Chemical Vapour Deposition, Plasma-Enhanced Chemical Vapour Deposition, and electrochemical methods allow atoms or molecules to assemble into controlled films and nanostructures. Researchers investigate the early stages of growth because nucleation, surface diffusion, and substrate interactions often determine the later physical properties of a material. Semiconductor nanowires, nanotubes, quantum dots, ultrathin layers, and two-dimensional materials can therefore be studied as growth processes rather than only as finished specimens. Top-down fabrication uses electron-beam lithography, focused-ion-beam processing, and scanning-probe techniques to define

structures with characteristic dimensions reaching the tens of nanometres scale. Optical lithography remains efficient for larger features and for process steps that do not require the finest resolution. Combining both approaches allows self-organised structures to be incorporated into deliberately patterned devices. Electrical contacts can then connect nanoscale regions to macroscopic measurement equipment. This chain is indispensable for nanoelectronics, nanophotonics, spintronics, and sensor research. CEITEC Nano therefore acts simultaneously as a fabrication laboratory and as a platform for experimental device physics.

Microscopy became one of the defining strengths of the Brno school because the city developed both a major research community and an unusually dense industrial base in electron instrumentation. Scanning Electron Microscopy allows surface morphology and microstructure to be examined over large areas with nanometre-scale detail. Transmission Electron Microscopy can resolve internal structures, interfaces, defects, and in favourable conditions individual atomic columns. Scanning Transmission Electron Microscopy combines a focused probe with several detectors to generate structural and chemical maps. Energy-Dispersive X-ray Spectroscopy identifies elemental composition, while Electron Energy Loss Spectroscopy provides information about chemistry, bonding, and electronic excitations. Focused Ion Beam systems can cut site-specific cross-sections and prepare thin lamellae for transmission microscopy. CEITEC Nano installed a high-performance TITAN Themis transmission electron microscope that entered research use in 2016. The instrument became central to studies of semiconductors, nanomaterials, interfaces, structural defects, and advanced functional materials. Researchers can correlate electron images with X-ray, scanning-probe, electrical, and optical measurements performed elsewhere in the same infrastructure. Brno's microscopy ecosystem is strengthened further by the presence of major manufacturers including Thermo Fisher Scientific, TESCAN, and Delong Instruments. Academic groups interact with these companies in instrument development, testing, methodology, and specialised applications. Electron microscopy consequently serves in Brno not only as a characterisation method but also as a field of technological innovation in its own right.

The relationship between microscopy and semiconductor physics became especially visible in research on gallium nitride. Gallium nitride is a wide-band-gap semiconductor capable of operating at higher electric fields and temperatures than many conventional silicon devices. Its properties make it attractive for power conversion, telecommunications, electric vehicles, and energy-efficient electronics. Device performance, however, can be degraded by dislocations and other crystallographic defects generated during epitaxial growth. Brno researchers use transmission electron microscopy to locate these defects and study how they evolve under processing or external stimuli. In the European ALL2GaN project, teams from Brno University of Technology and the local microscopy industry worked on methods relevant to gallium-nitride integrated circuits. The project connected fundamental defect analysis with the practical requirement to transfer advanced characterisation into industrial environments. This type of collaboration illustrates the Brno school's ability to connect atomic-scale physics with strategic semiconductor technology.

Surface science provides another foundation for Brno nanophysics. Ultra-High Vacuum systems allow surfaces to be prepared and investigated before contamination from ordinary atmosphere changes their atomic or electronic structure. Researchers study adsorption, self-assembly, thin-film growth, graphene, and molecular structures using complementary

microscopies and spectroscopies. Scanning Tunnelling Microscopy can map conducting surfaces through the quantum tunnelling current between a sharp tip and the sample. Low-Energy Electron Microscopy observes surface processes over larger fields while retaining sensitivity to nanoscale structure and crystallography. X-ray Photoelectron Spectroscopy identifies elemental composition and chemical states close to the surface. Angle-Resolved Photoemission Spectroscopy provides information about electronic band structure and the momentum of electrons emitted from a crystalline surface. At CEITEC, molecular nanostructures are assembled deliberately on metals, graphene, and other substrates in order to investigate self-organisation and functional properties. The same systems can serve as model platforms for molecular electronics, spintronics, catalysis, and two-dimensional materials research. Surface physics therefore connects fundamental studies of atomic interactions with the design of structures whose function depends almost entirely on interfaces. This tradition also reflects the historical strength of Brno University of Technology in developing specialised surface-analysis instrumentation.

Nanomagnetism and spintronics broadened the Brno programme from electronic and structural properties towards controlled magnetic functionality. CEITEC researchers study how spatial confinement, interfaces, strain, electrical current, temperature gradients, and ultrafast optical pulses influence nanoscale magnetic order. Patterned nanomagnets can exhibit switching behaviour and collective excitations very different from those of bulk magnetic materials. Spin waves, or magnons, are studied as potential carriers of information that could complement charge-based electronics. Their use is attractive because information encoded in collective magnetic excitations may reduce some forms of resistive energy loss associated with conventional current flow. Brno groups also investigate antiferromagnetic and other magnetic materials whose rapid dynamics may be useful for future spintronic devices. Nanolithography creates magnetic structures with controlled dimensions, while magnetic-force and magneto-optical microscopy visualise their resulting states. X-ray microscopy and spectroscopy at international synchrotrons extend these measurements to element-specific and ultrafast regimes. Electrical transport provides another route for detecting magnetic switching or magnetoresistive effects. The research therefore requires an integrated combination of fabrication, microscopy, optics, electronics, and theoretical interpretation. This is precisely the kind of interdisciplinary problem for which CEITEC Nano was designed. These experiments also connect Brno researchers with international synchrotron and high-field facilities needed to probe magnetic order beyond the capabilities of local laboratories.

Photonics and nanophotonics form a second major technological axis within Brno University of Technology. Researchers investigate how light interacts with metals, dielectrics, semiconductors, and engineered nanostructures at dimensions smaller than or comparable with an optical wavelength. Metallic structures can support plasmonic resonances that concentrate electromagnetic fields into very small volumes. Dielectric resonators and metasurfaces provide alternative methods for shaping phase, polarisation, and propagation while avoiding some metallic losses. Photoluminescent nanostructures allow optical emission to be modified through changes in local electromagnetic environment. Near-field techniques reveal optical behaviour below the diffraction-limited resolution of conventional microscopes. These effects are relevant to sensors, integrated optics, information processing, spectroscopy, and advanced imaging. The Institute of Physical Engineering combines nanophotonic research with theoretical modelling and nanoscale fabrication. CEITEC Nano supplies the lithography and microscopy required to test whether the manufactured structure corresponds to the

optical design. Photonics in Brno therefore develops through the same fabrication–characterisation cycle that supports nanoelectronics and spintronics.

Experimental biophotonics extends this optical expertise into imaging systems for complex and living samples. CEITEC BUT groups develop advanced light microscopy, quantitative imaging, and optical methods in which physical instrumentation is tailored to biological or biomedical questions. Such work illustrates the genuinely interdisciplinary character of the Central European Institute of Technology. Optical systems must be designed according to principles of diffraction, coherence, polarisation, detector noise, and computational reconstruction. At the same time, samples may impose requirements concerning low phototoxicity, speed, three-dimensional resolution, and compatibility with living cells. Engineering a useful microscope therefore requires collaboration among physicists, optical engineers, biologists, and software specialists. The physical principles remain those of modern optics, but the research question is no longer defined by physics alone. This kind of boundary-crossing work was one of the institutional goals built into CEITEC from its foundation. Brno photonics consequently became part of a wider ecosystem extending from nanostructured optical materials to biological imaging.

Magneto-optical and terahertz spectroscopy added another specialised branch to the Brno research environment. CEITEC BUT developed high-frequency Electron Paramagnetic Resonance and related magnetic-resonance methods for studying spin systems, molecular magnets, graphene, and low-dimensional materials. The FRASCAN instrumentation programme created specialised spectrometers rather than relying exclusively on commercially available systems. One system covers a broad frequency range extending roughly from one hundred to five hundred gigahertz and can operate under strong magnetic fields and cryogenic conditions. A later instrument combines Electron Spin Resonance with Nuclear Magnetic Resonance for experiments using dynamic nuclear polarisation. Such equipment makes it possible to investigate quantum spin dynamics and electronic states that are difficult to access with conventional spectroscopy. The group also combines magnetic resonance with terahertz and magneto-optical methods. Two-dimensional materials and single-molecule magnets provide experimental platforms relevant to electronics, sensing, and future quantum technologies. The programme illustrates Brno's continuing tradition of treating instrument construction as part of physics rather than merely as technical support. The combination of custom instrumentation and quantum-sensitive spectroscopy strengthened Brno's position at the boundary between condensed-matter physics and emerging quantum technologies.

Materials research at CEITEC BUT extends well beyond systems traditionally classified as condensed matter. Research groups work on ceramics, polymers and composites, biomaterials, coatings, low-dimensional materials, bioelectronic systems, and plasma technologies. These fields differ greatly in application but share a need to connect composition and microstructure with physical properties. Advanced ceramics require control of grain structure, porosity, defects, and phase composition. Polymer composites depend on interfaces between chemically and mechanically different constituents. Functional coatings derive much of their behaviour from surfaces only micrometres or nanometres thick. Low-dimensional materials can change their electronic and optical properties when reduced to sheets, wires, or other constrained geometries. Microscopy, spectroscopy, diffraction, tomography, and mechanical testing therefore provide a common experimental language across these programmes. CEITEC's organisational structure encourages methods developed

for one material class to migrate into another, reinforcing the integration of physics and materials engineering.

X-ray computed tomography adds three-dimensional internal imaging to the predominantly surface and nanoscale methods of the Brno school. Unlike conventional radiography, computed tomography reconstructs a volume from many projections recorded as the sample is rotated relative to an X-ray beam. Laboratory microtomography can reveal pores, cracks, inclusions, interfaces, and complex internal geometries without destroying the object. Higher-resolution systems extend this method towards structures measured in micrometres or below. In situ sample environments allow heating, mechanical loading, humidity, or other external conditions to be applied during measurement. Researchers can therefore observe how damage develops rather than simply comparing a pristine specimen with a failed one. This approach is useful for composites, additively manufactured materials, biological specimens, electronic components, and industrial parts. CEITEC Nano includes X-ray tomography within the same user infrastructure as nanofabrication and microscopy. The combination allows a specimen to be investigated hierarchically from centimetre-scale internal structure down to nanoscale defects in selected regions. Multi-scale imaging consequently became another area in which Brno linked instrumentation development with materials physics.

Open access changed the role of CEITEC Nano from that of an institutional laboratory to that of national research infrastructure. Academic groups from Czechia and abroad can apply to use equipment even when they do not belong to Brno University of Technology. Industrial users can likewise access selected processes, measurements, or expert services. Trained researchers are encouraged to operate equipment themselves where appropriate, which develops practical competence rather than creating a purely service-based relationship. The facility therefore combines expert support with a self-service model characteristic of major international nanotechnology centres. Shared use reduces duplication of expensive systems and increases the range of methods available to smaller research groups. It also encourages projects that would otherwise be impossible because one laboratory rarely possesses every deposition, lithography, microscopy, and spectroscopy method required. The national importance of the Brno node increased further when it became part of CzechNanoLab together with the Laboratory of Nanostructures and Nanomaterials at the Institute of Physics in Prague. This distributed infrastructure links the two largest Czech concentrations of nanofabrication and nanocharacterisation. CEITEC Nano thus connects the Brno school not only internally but also with the broader national architecture of Czech nanoscience. The model demonstrates how infrastructure can integrate institutions without eliminating their individual scientific identities.

Education is deeply embedded in this infrastructure-based model. Masaryk University students in condensed-matter physics receive training in optical spectroscopy, X-ray analysis, semiconductor structures, theoretical models, and experimental laboratory work. Brno University of Technology offers Physical Engineering and Nanotechnology as a dedicated interdisciplinary study programme. Students encounter surface science, two-dimensional materials, nanoelectronics, nanophotonics, micromagnetism, biophotonics, electron microscopy, spectroscopy, and X-ray tomography within one educational framework. CEITEC laboratories give students access to research instruments that would be unusual in ordinary university teaching facilities. Thesis projects can therefore move directly into contemporary research on nanostructures, semiconductors, spin systems, optical devices, or advanced materials. Industrial collaboration adds practical exposure to reliability, reproducibility,

process control, and technological constraints. This educational integration helps Brno sustain a workforce able to operate sophisticated infrastructure and contribute to high-technology companies. It also makes the regional research system less dependent on importing every specialist from abroad. The Brno school is consequently reproduced through a training pipeline that is as interdisciplinary as its research.

The local electron-microscopy industry gives this training an unusually direct relationship with high-technology manufacturing. Brno hosts major producers and developers of scanning and transmission electron microscopes, including Thermo Fisher Scientific, TESCAN, and Delong Instruments. University researchers collaborate with these companies on detection methods, instrument prototypes, in situ techniques, and specialised applications. The Institute of Physical Engineering previously participated in development of an Ultra-High Vacuum Scanning Electron Microscope with TESCAN. Research around advanced surface and microscopy techniques also contributed to the creation of the Brno spin-off NenoVision. CEITEC receives instruments, expertise, and collaborative opportunities from companies whose engineers work on the same classes of problems studied academically. Companies, in turn, gain access to researchers testing demanding materials and experimental configurations. Students trained in CEITEC and university laboratories enter a labour market in which microscopy competence has immediate regional relevance. This circulation of people and knowledge helps explain why microscopy became a defining technological identity of the Brno research environment.

International collaboration expanded this regional ecosystem far beyond South Moravia. Masaryk University groups use synchrotron facilities for advanced X-ray scattering and cooperate with foreign laboratories studying superconductors, oxides, and semiconductor heterostructures. CEITEC researchers perform magnetic X-ray microscopy and spectroscopy at international photon sources and collaborate with universities across Europe, Asia, and the Americas. Surface scientists work with laboratories specialising in graphene, molecular self-assembly, and low-dimensional electronic structure. Electron microscopists participate in European semiconductor projects and compare methodologies with leading instrument centres. CEITEC's international recruitment strategy also brought researchers trained abroad into Brno-based groups. Training schools expose students to Molecular Beam Epitaxy, Metalorganic Vapour Phase Epitaxy, Pulsed Laser Deposition, X-ray diffraction, Transmission Electron Microscopy, and Atomic Force Microscopy within a common programme. In 2025, Masaryk University and CEITEC BUT jointly hosted an international training school that combined these growth and characterisation techniques. The programme also included contributions from industrial partners such as Thermo Fisher Scientific and onsemi. Such events show how the Brno school functions as an international training location rather than merely sending its researchers to foreign centres. Internationalisation therefore reinforced local infrastructure by increasing both the variety of users and the technical standards expected from shared facilities. The resulting network positioned Brno as a participant in European nanoscience rather than a purely national centre.

The expansion of semiconductor research during the 2020s brought several of these institutional strands together. European concern about dependence on non-European chip manufacturing increased interest in materials, fabrication, characterisation, and specialist education. Brno University of Technology responded by strengthening collaboration among physical engineering, microelectronics, information technology, and CEITEC Nano. CEITEC's clean rooms provide a platform where students and researchers can fabricate and test

semiconductor structures while learning the physical basis of processing steps. The Institute of Physical Engineering contributes expertise in surfaces, crystal defects, microscopy, and materials, whereas electrical-engineering groups address device and circuit design. Projects on gallium nitride connect Brno microscopy with power electronics and the European effort to improve energy efficiency. Beyond conventional Complementary Metal–Oxide–Semiconductor technology, CEITEC groups explore magnonics, spintronics, two-dimensional systems, and other possible information-processing concepts. This diversity allows fundamental research to coexist with strategic semiconductor training rather than forcing the infrastructure to imitate an industrial fabrication plant. The Brno model therefore contributes to semiconductor capability by specialising in research, characterisation, and advanced concepts where university infrastructure can provide distinctive value. By 2025, this field had become one of the clearest examples of interaction among physics, engineering, European policy, and regional industry.

The development of Brno physics between 1993 and 2025 also demonstrates how infrastructure can reshape the relationship between scientific disciplines. Before CEITEC, condensed-matter physics, optics, materials engineering, microscopy, and semiconductor technology already existed in separate university units. The new infrastructure did not erase these traditions but created laboratories in which researchers from different backgrounds could work on the same physical object. A magnetic heterostructure may require epitaxial growth, lithography, electron microscopy, magnetic imaging, terahertz spectroscopy, and theoretical modelling. A gallium-nitride device may similarly combine semiconductor growth, defect microscopy, electrical characterisation, and engineering analysis. Nanophotonic structures require electromagnetic design, nanoscale fabrication, surface inspection, and optical measurement. None of these problems fits comfortably inside a single conventional department. Shared infrastructure therefore changed interdisciplinarity from an administrative ambition into a practical requirement imposed by the research workflow. CEITEC's consortium structure further encouraged cooperation across universities and research institutes. Masaryk University supplied fundamental condensed-matter, theoretical, optical, and X-ray expertise, while Brno University of Technology supplied fabrication, instrumentation, engineering, and application-oriented strengths. The result was a regional scientific school defined less by institutional uniformity than by the ability to assemble complete experimental chains. This organisational capability became one of Brno's principal competitive advantages in contemporary materials and nanophysics.

By 2025, the Brno Physics and Nanotechnology School had therefore matured into a polycentric research ecosystem with a recognisable international profile. Masaryk University preserved strong programmes in condensed matter, semiconductor structures, optical response, X-ray physics, and many-body theory. Brno University of Technology developed physical engineering across surfaces, nanostructures, nanoelectronics, nanophotonics, nanomagnetism, optics, microscopy, and materials mechanics. CEITEC converted these disciplinary strengths into shared infrastructure capable of supporting research from atomic structure to functional devices. CEITEC Nano provided clean-room fabrication, electron and probe microscopy, structural analysis, spectroscopy, and X-ray tomography within an open-access environment. The presence of a major electron-microscopy industry gave Brno an unusual feedback loop between academic methodology and commercial instrumentation. Semiconductor projects connected defect physics and nanofabrication with European concerns about power electronics and technological sovereignty. Photonics, magnetic

resonance, spintronics, molecular surface science, and two-dimensional materials broadened the school's scientific range beyond conventional solid-state physics. Interdisciplinary education ensured that these capabilities were transferred to students trained to move between physics and engineering. The central achievement of the Brno school was therefore not a single instrument or discovery but the construction of a research environment in which fundamental condensed-matter physics, nanotechnology, microscopy, materials science, photonics, and semiconductor engineering became mutually reinforcing parts of one regional innovation system.

Czech Astronomy and Astrophysics: Ondřejov, Prague, Brno, and Opava

The Czech astronomical and astrophysical community developed between 1993 and 2025 as a distributed national school whose principal centres were Ondřejov, Prague, Brno, and Opava. The Astronomical Institute of the Czech Academy of Sciences provided the largest dedicated research base and operated the country's principal professional observatory at Ondřejov. Charles University sustained major traditions in stellar astronomy, celestial mechanics, relativistic astrophysics, and the theoretical foundations of gravitation. Masaryk University in Brno combined stellar astrophysics with high-energy studies, X-ray astronomy, numerical modelling, and increasingly ambitious space-based experiments. Silesian University in Opava developed a distinctive school of relativistic astrophysics centred on black holes, neutron stars, cosmology, and computational methods. These institutions differed in size and historical origin, yet they were connected through shared students, national grants, observatory access, seminars, and international collaborations. The Czech astronomical system therefore remained polycentric rather than being concentrated entirely in Prague or within a single Academy institute. International membership in the European Southern Observatory and participation in major ground-based and space missions progressively expanded the observational reach available to all of these schools. By 2025, Czech astronomy combined domestic telescopes and long theoretical traditions with systematic access to some of the world's most advanced observatories and international scientific infrastructures.

The Astronomical Institute of the Czech Academy of Sciences, commonly abbreviated as ASU from its Czech name *Astronomický ústav*, occupies the central institutional position in Czech professional astronomy. Its modern institutional history combines two older traditions, one associated with astronomical work in Prague and another with the private observatory established by Josef Jan Frič in Ondřejov in 1898. The Ondřejov observatory was donated to the Czechoslovak state and Charles University in 1928 and later became part of the national astronomical research system. In 1953, the relevant observatory organisations were merged into the institution that became the modern Astronomical Institute. After the dissolution of Czechoslovakia, the Institute continued within the newly constituted Academy of Sciences of the Czech Republic and later the Czech Academy of Sciences. Most of its research infrastructure is located at Ondřejov, about thirty-five kilometres southeast of Prague, while a separate scientific workplace remains in Prague at Spořilov. The Institute is organised around four broad scientific departments devoted to solar physics, stellar physics, interplanetary matter, and galaxies and planetary systems. This structure allows it to cover subjects extending from solar eruptions and meteoroids to exoplanets, galaxies, black holes, and relativistic processes. The Institute also operates technical groups responsible for instrumentation,

telescope maintenance, software, data archives, and observational support. Its role after 1993 was therefore both scientific and infrastructural, because it sustained the national observational base while connecting Czech astronomers with international facilities.

Ondřejov Observatory provides the clearest physical expression of this national role. Its largest optical instrument is the Perek two-metre telescope, which entered service in 1967 and remained the largest optical telescope in Czechia throughout the period covered by this book. The telescope has been used primarily for stellar spectroscopy and is equipped with spectrographs and a photometric camera. Electronic detectors replaced photographic recording before the creation of the independent Czech Republic, and Charge-Coupled Device technology became standard from 2000. A major modernisation in 2019 replaced much of the old coudé optical path with optical fibres leading from the primary focus to the spectrographs. This change increased throughput and extended observations towards fainter targets. The telescope is used not only by Astronomical Institute researchers but also by scientists and students from Czech universities and foreign partner institutions. Its persistence as a national facility demonstrates how carefully modernised medium-sized telescopes can remain scientifically useful even in an era dominated by international observatories with much larger apertures.

The Stellar Department at Ondřejov developed a research profile linking traditional spectroscopy with contemporary stellar and exoplanetary astrophysics. One long-standing area concerns hot massive stars, their atmospheres, winds, circumstellar material, binaries, and short-lived evolutionary phases. Researchers combine observations with radiative-transfer and stellar-atmosphere modelling in order to understand how radiation, chemical composition, rotation, and mass loss shape these stars. Binary and multiple systems provide additional information because orbital dynamics make stellar masses and other fundamental parameters measurable with high precision. During the 2010s, exoplanet research became a more explicit part of the department's programme. The Perek telescope was adapted for radial-velocity follow-up and for the characterisation of candidates discovered by missions such as Kepler, K2, and the Transiting Exoplanet Survey Satellite. Robotic telescopes including D50 and BART added flexible monitoring of variable and transient sources. Astroinformatics also became increasingly important as survey and space-mission datasets grew beyond the scale manageable by traditional manual analysis. The department consequently evolved from a primarily spectroscopic stellar school into a broader programme combining stars, planets, transients, and data-intensive astronomy. This transition was achieved without abandoning the observational traditions on which the Ondřejov school had originally been built. The coexistence of legacy instruments and modern data analysis became one of the characteristic strengths of Czech stellar astronomy.

Solar physics forms a second major research tradition at the Astronomical Institute. Ondřejov researchers investigate the structure and dynamics of the solar atmosphere, flares, prominences, magnetic reconnection, energetic particles, and the heliosphere. Ground-based solar observations provide rapid temporal coverage of phenomena that can change on timescales of seconds or minutes. Spectroscopic and radio measurements are combined with theoretical models of magnetohydrodynamics, radiative transfer, and non-equilibrium plasma processes. International space missions greatly expanded this work by providing access to ultraviolet, extreme-ultraviolet, coronagraphic, and in-situ measurements beyond the capabilities of ground observatories. Czech scientists participate in Solar Orbiter research, including scientific exploitation of instruments observing the corona and solar-wind source

regions. They also use observations from missions and observatories operated by the European Space Agency, the National Aeronautics and Space Administration, and other international partners. Solar physics therefore illustrates how a domestic observational programme can remain productive by being embedded in a multi-platform international research environment. The Prague and Ondřejov school contributes particularly through interpretation, modelling, spectroscopy, and long-term expertise in dynamic solar plasma.

Millimetre and submillimetre astronomy provided another route through which the Czech astronomical community entered a highly international observational regime. The Atacama Large Millimeter/submillimeter Array, commonly abbreviated as ALMA, operates in northern Chile as a partnership involving the European Southern Observatory and organisations in North America and East Asia. Czech researchers gained access to ALMA through the country's membership in the European Southern Observatory. A Czech node of the European ALMA Regional Centre was established at the Astronomical Institute in 2016. The node provides support for preparation of proposals, calibration, reduction, imaging, and interpretation of ALMA data. It also developed a particular specialisation in solar observing, a technically demanding mode because the Sun is enormously brighter than most astronomical sources for which interferometric arrays are designed. ALMA observations of the solar chromosphere provide temperature-sensitive measurements at spatial scales inaccessible to many traditional radio instruments. Czech solar physicists contributed to the early scientific exploitation of these observations and to the transfer of expertise across the European ALMA community. The same support infrastructure can serve researchers working on stellar, Galactic, and extragalactic projects. The ALMA node therefore strengthened national competence not by constructing a Czech radio array, but by embedding data expertise inside a global observatory. This arrangement is typical of modern astronomy, where scientific competitiveness increasingly depends on the ability to transform internationally acquired data into rigorous physical results. It also made Ondřejov an access and training point for a facility located on another continent.

The Department of Interplanetary Matter maintains one of the most distinctive observational programmes at Ondřejov. Its researchers study meteoroids, fireballs, meteorites, asteroids, and the physical processes that occur when small Solar System bodies enter planetary atmospheres. The European Fireball Network provides a coordinated system of stations for recording bright meteors over a large geographical area. Precise trajectories reconstructed from multiple cameras can determine atmospheric entry paths and, in favourable cases, predict regions where meteorites may have reached the ground. Photometry and spectroscopy supply information about fragmentation, radiation, composition, and the physical strength of meteoroids. Czech researchers have used this approach to connect recovered meteorites with pre-atmospheric orbits, providing unusually direct links between laboratory material and Solar System dynamics. The group also cooperates with fireball-network projects outside Europe, including observational systems in Australia. Asteroid research complements meteor work through light curves, shape reconstruction, binary-system studies, rotational dynamics, and estimates of bulk properties. A dedicated 0.65-metre telescope at Ondřejov supports photometric asteroid monitoring. International observations from much larger telescopes are then combined with these national datasets when higher angular resolution or sensitivity is required.

One internationally visible example of this strategy came from physical characterisation of large main-belt asteroids. Czech researchers participated in observations with the Spectro-

Polarimetric High-contrast Exoplanet REsearch instrument at the Very Large Telescope. The adaptive-optics images resolved the shapes of dozens of large asteroids at unprecedented detail. Combining these observations with light curves and dynamical information improved estimates of three-dimensional shape, density, and internal structure. Such work helps distinguish between intact differentiated bodies, collisionally reaccumulated objects, and other evolutionary outcomes. It also demonstrates how expertise developed with modest national instruments can contribute directly to programmes on one of the world's most advanced optical telescopes. The Czech asteroid school therefore depends on continuity between long-term photometric monitoring and episodic access to international high-resolution facilities. This combination of temporal coverage and observational power is more valuable scientifically than either component alone.

The Department of Galaxies and Planetary Systems extends the Astronomical Institute's research from nearby Solar System dynamics to the largest gravitationally bound systems and relativistic compact objects. Research includes galaxy evolution, environmental effects on galaxies, active galactic nuclei, black holes, relativistic astrophysics, astrodynamics, and space geodesy. One major theme concerns galaxies moving through hot intracluster gas and the resulting ram-pressure stripping of their interstellar medium. Multi-wavelength observations reveal where gas is removed, where star formation is triggered or suppressed, and how environment changes the long-term evolution of galaxies. Numerical modelling is used to interpret these processes and connect individual systems with the broader physics of galaxy clusters. Another branch studies accretion flows and radiation near black holes, where general-relativistic effects strongly modify spectra and timing signals. Czech researchers developed transfer-function methods and relativistic models used to calculate how radiation from accretion discs is shifted, lensed, and time-delayed before reaching an observer. These calculations are relevant to interpretation of X-ray spectra from stellar-mass and supermassive black holes. Astrodynamics provides a further connection to planetary and satellite motion, including gravitational perturbations and precise orbit determination. The breadth of the department illustrates how the Czech Academy astronomical school joins observation, relativistic theory, and numerical modelling within one institutional structure. Cooperation with Charles University is especially strong in gravitation and relativistic astrophysics, where personnel and intellectual traditions have long overlapped.

Charles University provides the oldest university-based astronomical school in Czechia and remained a central training institution throughout 1993–2025. The Astronomical Institute of Charles University belongs to the Faculty of Mathematics and Physics and conducts research in stellar astrophysics, asteroid studies, celestial mechanics, and related areas. Its stellar programme includes spectroscopic and photometric studies of binaries, multiple systems, hot stars, and Be stars. Researchers use Ondřejov telescopes as well as foreign observatories, making the Academy facility an important practical extension of university education. Asteroid researchers developed sophisticated inversion methods for reconstructing rotation states and three-dimensional shapes from light curves. The Database of Asteroid Models from Inversion Techniques became a recognised resource for making such models available to the international community. Celestial-mechanics research examines gravitational and non-gravitational forces affecting small bodies, including thermal effects that can alter asteroid orbits over long timescales. The institute therefore links observational astronomy with mathematical dynamics rather than separating them into independent schools. Students

receive training that connects theoretical foundations with direct experience of real astronomical observations.

Relativity and gravitation at Charles University form another major component of the Prague astrophysical tradition. The Institute of Theoretical Physics developed internationally recognised work on exact solutions of Einstein's equations, black holes, gravitational radiation, cosmology, and mathematical aspects of general relativity. Jiří Bičák and collaborators helped preserve and extend a Prague school whose emphasis combined mathematical rigour with astrophysical interpretation. Research addresses stationary and dynamical space-times, perturbations, gravitational lensing, higher-dimensional gravity, and the behaviour of fields in strong gravitational environments. Numerical methods became increasingly important for problems that cannot be treated by exact analysis. The detection of gravitational waves after 2015 gave renewed observational relevance to questions that Prague theorists had studied for decades. Charles University researchers consequently interacted more closely with astrophysical communities interpreting compact-object mergers and relativistic transients. The same theoretical environment supports doctoral training in astronomy, astrophysics, and theoretical physics. The university therefore supplies a conceptual framework extending from classical celestial mechanics to contemporary relativistic astrophysics. That breadth has made it an important connecting institution among the Czech national schools.

The Albert Einstein Centre for Gravitation and Astrophysics, established in 2014, formalised part of this national theoretical network. It brought together leading groups from Charles University, the Astronomical Institute and Institute of Mathematics of the Czech Academy of Sciences, and Silesian University in Opava. The centre focused on general relativity, gravitation, relativistic astrophysics, black holes, cosmology, gravitational waves, and related mathematical problems. Its structure is significant because it did not attempt to move researchers into a single institution. Instead, it linked established teams that retained their own university or Academy identities. This model matched the historical organisation of Czech theoretical astrophysics, in which strong groups were geographically distributed but intellectually connected. Researchers maintained international collaborations with institutions including the Albert Einstein Institute in Germany, the University of Cambridge, and the Perimeter Institute in Canada. Joint seminars and projects helped transmit expertise between Prague and Opava. The centre also reinforced the visibility of Czech gravitation research at a time when gravitational-wave astronomy was rapidly becoming an observational discipline. Its existence shows that national scientific schools can be strengthened through coordination without administrative centralisation. Relativistic astrophysics consequently became one of the clearest fields in which Prague and Opava functioned as parts of a common Czech research network. The network also provided a route through which students could encounter both mathematical general relativity and its applications to observable compact objects.

Czech membership in the European Southern Observatory, commonly abbreviated as ESO, transformed the observational opportunities available to these national schools. An accession agreement was signed in Prague on 22 December 2006, and Czechia became a full ESO Member State on 30 April 2007. The country was the first ESO member from Central and Eastern Europe. Membership opened competitive access to facilities including the Very Large Telescope, the Atacama Pathfinder EXperiment, and the European share of ALMA. It also gave Czech scientists opportunities to participate in future instrumentation and in planning for the Extremely Large Telescope. Observing proposals from Czech institutions entered the same

peer-review system used by astronomers from the other member states. This changed the scale of feasible research because projects could be designed around instruments far beyond the capability of domestic observatories. ESO membership therefore became an institutional watershed comparable in importance to the modernisation of Ondřejov itself.

The significance of ESO membership was not limited to access to telescope time. Czech astronomers became eligible for fellowships, studentships, technical positions, advisory roles, and participation in instrument consortia. National industry also gained opportunities to compete for contracts connected with observatory construction and high-technology procurement. Researchers from Ondřejov, Charles University, Brno, and other Czech centres could develop projects assuming access to European facilities as a normal component of their scientific strategy. This encouraged greater specialisation because national groups no longer needed to reproduce every observational capability domestically. At the same time, local telescopes retained value for long monitoring campaigns, target selection, student training, and follow-up observations. The international and domestic layers therefore became complementary rather than mutually exclusive. Czech involvement with ESO also increased the importance of data archives because observations obtained by one team can later support independent research by another. Training in proposal preparation, calibration, reduction, and advanced statistical analysis became increasingly important components of astronomical education.

The PLATOSpec project illustrates how Czech astronomy moved from using ESO facilities towards contributing new instrumentation at an ESO site. The project refurbished the 1.52-metre telescope at La Silla Observatory in Chile and equipped it with a modern high-resolution spectrograph. The revived facility is intended particularly for ground-based support of exoplanet missions, including the European Space Agency's PLAnetary Transits and Oscillations of stars mission. Czech researchers lead the project through the Astronomical Institute with international partners. The telescope began renewed operation during the early 2020s, while the PLATOSpec spectrograph reached its first observational milestones in 2024. Radial-velocity measurements from the instrument can help determine masses and reject false planetary candidates identified through transit photometry. Spectroscopy also yields stellar properties needed to interpret the planets correctly. The project therefore combines instrument development, stellar astrophysics, and exoplanet science. It also provides a dedicated bridge between a Czech research group and a major international observatory site. PLATOSpec demonstrates a more mature form of international participation in which Czech astronomers help create an observational capability rather than only apply for time on existing instruments. Such projects strengthen technical expertise that can later contribute to larger European instrumentation programmes.

Masaryk University in Brno developed a complementary astrophysical school within its Department of Theoretical Physics and Astrophysics. One major group studies stellar atmospheres, winds, circumstellar media, chemically peculiar stars, variable stars, multiple systems, and open clusters. Theoretical modelling is especially important because radiative transfer and hydrodynamics determine how hot stars lose mass and how their observable spectra are formed. Brno researchers have developed numerical models of stellar winds that relax the assumption of local thermodynamic equilibrium. These calculations connect atomic physics with the global evolution of massive and chemically peculiar stars. Observational work uses domestic and international telescopes, including the Perek telescope at Ondřejov. Masaryk University also operates its own observatory at Kraví hora in Brno with a 0.6-metre

reflector for research and education. Variable-star and cluster studies provide opportunities for long-term photometric monitoring that do not require the largest international telescopes. The Brno stellar school therefore combines theory, targeted observation, and systematic analysis of stellar populations. Its combination of local observation and detailed radiation-hydrodynamic modelling gives Brno a distinctive place within the wider Czech stellar-astrophysics network.

A second Masaryk University group developed high-energy astrophysics into a major Brno research direction during the late 2010s and 2020s. Its programme studies the hot gaseous atmospheres of massive galaxies and galaxy clusters, accreting supermassive black holes, and gamma-ray bursts. X-ray imaging and spectroscopy are combined with radio interferometry and observations at other wavelengths. One central question concerns how energy released by active galactic nuclei prevents or regulates cooling of the surrounding hot plasma. Researchers compare observations with numerical simulations in order to determine how black-hole feedback influences galaxy evolution. Cluster outskirts and the cosmic web provide another target because much of the ordinary matter in the Universe resides in diffuse hot gas that is difficult to detect. Brno scientists participate in scientific preparation for advanced X-ray observatories and use archived observations from major space missions. Machine-learning methods are also being explored for galaxy, cluster, and large-scale-structure studies. High-energy astrophysics consequently added extragalactic and cosmological dimensions to a Brno school previously identified more strongly with stellar theory.

Gamma-ray bursts created a particularly innovative connection between Brno astrophysics and small-satellite technology. Traditional high-energy missions require substantial budgets because gamma-ray detectors, spacecraft systems, launch arrangements, and ground operations all contribute to cost. Miniaturised CubeSat platforms offer a different strategy in which several relatively inexpensive satellites can monitor large fractions of the sky. Masaryk University researchers became involved in the CAMELOT initiative and in demonstration missions designed to detect gamma-ray bursts from low Earth orbit. GRBAlpha and VZLUSAT-2 showed that compact detectors can contribute scientifically useful high-energy observations. A network of small satellites could in principle localise transients by comparing the arrival times of the same burst at spatially separated spacecraft. This is especially relevant to multi-messenger astronomy because short gamma-ray bursts may accompany mergers of neutron stars detected through gravitational waves. The Brno programme therefore links high-energy astrophysics with detector engineering, spacecraft technology, timing analysis, and international mission coordination. Such projects also create an observational role for a national university that does not operate a large space agency of its own. The result is a form of astrophysical specialisation based on distributed low-cost instrumentation rather than ownership of a flagship satellite.

Silesian University in Opava represents a younger institutional centre but one with a highly distinctive theoretical profile. Astronomy and relativistic astrophysics developed in Opava before the creation of an independent Institute of Physics, initially within the Faculty of Philosophy and Science. On 1 January 2020, the Institute of Physics in Opava became an independent constituent part of Silesian University. Its research is organised particularly through centres devoted to theoretical physics and astrophysics and to computational physics and data processing. Core subjects include strong gravitational fields, black holes, neutron stars, cosmology, quantum field theory, particle physics, and multimessenger astrophysics.

Computer simulation and analysis of large datasets complement analytic work. The institute also connects fundamental research with applied programmes involving environmental monitoring and data processing. This structure gave Opava a scientific identity different from the observational focus of Ondřejov or the broad university physics environment in Prague. Its comparative advantage lies in concentrated expertise in relativistic and computational problems.

Black-hole and neutron-star physics became the most internationally recognisable component of the Opava school. Researchers study orbital motion, accretion structures, oscillations, magnetic fields, radiative processes, and the observational signatures of strong gravity. Relativistic frequency models are used to interpret quasi-periodic oscillations observed in X-ray binaries and other compact systems. Calculations examine how the geometry of space-time changes particle trajectories and affects the frequencies generated near compact objects. Alternative gravitational theories and modified space-times are also investigated as theoretical tests of the assumptions underlying general relativity. Neutron-star research addresses compactness, rotation, magnetic environments, and energetic radiation. These problems frequently require a combination of analytic relativistic mechanics and numerical simulation. Observational datasets from X-ray and other high-energy missions provide constraints against which theoretical models can be tested. The Opava programme therefore connects abstract gravity with measurable signals rather than treating relativistic space-times as purely mathematical constructions. Participation in international collaborations broadens access to both data and specialised theoretical expertise.

Cosmology and multimessenger physics broadened the Opava research agenda beyond individual compact objects. Researchers investigate inflationary models, dark matter, dark-energy phenomena, gravitational fields in galaxies and clusters, and possible observational tests of non-standard physics. The interaction of strong electromagnetic and gravitational fields is particularly relevant near black holes and neutron stars. Multimessenger astrophysics introduces additional carriers of information, including gravitational waves, neutrinos, cosmic rays, and high-energy photons. Theoretical predictions can therefore be compared with several independent observational channels rather than with electromagnetic spectra alone. Opava's computational centre supports numerical work and the processing of complex or large datasets required by these comparisons. The Institute is a member of the International Center for Relativistic Astrophysics Network, commonly abbreviated as ICRANet. This membership connects the relatively small Czech centre with a global community specialising in relativistic astrophysics. International links help compensate for the absence of a major local observatory by making theory, simulation, and collaborative data analysis the primary routes to frontier research. The annual RAGtime workshop in Opava reinforces this role by bringing together researchers working on black holes, neutron stars, gravitation, and related problems. Training within this environment allows students to enter an international speciality while remaining based at a regional Czech university.

The relationship among Prague, Ondřejov, Brno, and Opava is therefore characterised more by scientific complementarity than by duplication. Ondřejov supplies the principal domestic professional observatory and strong observational schools in the Sun, stars, meteors, asteroids, galaxies, and exoplanets. Charles University provides university-based astronomy together with a major tradition in celestial mechanics and mathematical relativity. Masaryk University combines stellar modelling with increasingly strong high-energy and space-based astrophysics. Opava concentrates on relativistic theory, compact objects, cosmology,

simulation, and multimessenger problems. Students and researchers move among these centres through doctoral supervision, joint grants, telescope access, seminars, and national research networks. The Albert Einstein Centre made this circulation explicit in gravitation, while Ondřejov observing facilities create practical links between the Academy and universities. International observatories then provide an external layer of infrastructure shared by all Czech institutions. This structure reduces the need for each centre to maintain identical equipment or expertise. It also allows a relatively small national community to cover a broad range of contemporary astrophysics without losing specialised scientific identities.

International space missions became increasingly important to this distributed Czech system during the 2000s and 2010s. Solar physicists work with data from Solar Orbiter and other heliophysics missions. Stellar and exoplanet groups use Kepler, K2, the Transiting Exoplanet Survey Satellite, Gaia, and related catalogues while preparing for the PLATO mission. High-energy researchers exploit X-ray observations from XMM-Newton, Chandra, and other orbiting observatories. Gamma-ray burst studies connect Czech teams with international satellite networks and with gravitational-wave follow-up campaigns. Space missions alter the organisation of research because instrument data are often archived and made accessible to a wider community after proprietary periods. Scientific success therefore depends heavily on calibration knowledge, software, statistical inference, and the ability to combine heterogeneous datasets. Czech universities increasingly trained students in these data-intensive methods. Astroinformatics consequently developed as a cross-cutting competence connecting traditional observation with computational physics. By 2025, access to space-based data had become as routine for Czech astrophysicists as use of domestic optical telescopes. This shift also increased the value of reproducible pipelines and long-term digital archives as scientific infrastructure in their own right.

Ground-based international observatories remained equally important because they provide capabilities unavailable from space or from Czech national instruments. ESO's Very Large Telescope supports high-resolution spectroscopy, adaptive-optics imaging, interferometry, and observations extending from the optical into the infrared. ALMA provides submillimetre interferometry with angular resolution sufficient to resolve structures in protoplanetary discs, stellar atmospheres, galaxies, and the solar chromosphere. The Atacama Pathfinder EXperiment gives complementary access to wider-field submillimetre observations. La Silla continues to host productive medium-sized telescopes and became the site of the Czech-led PLATOSpec project. Future access to the Extremely Large Telescope promises another large increase in collecting area and angular resolution. Czech teams also use non-ESO facilities when particular wavelengths or observing modes are required. This distributed access allows science programmes to be designed around physical questions rather than around the limitations of one national observatory. The price of this flexibility is strong competition for observing time and a need for highly developed proposal-writing and data-analysis skills. National schools therefore remain essential because they provide the expertise needed to exploit international infrastructures successfully. Ondřejov and university observatories retain a complementary role by enabling training, monitoring, method development, and observations that would be inefficient on the largest facilities. Modern Czech astronomy consequently operates through a hierarchy of instruments ranging from university telescopes to globally shared observatories.

Education and researcher formation are fundamental to the persistence of these astrophysical schools. Charles University provides comprehensive programmes in astronomy, astrophysics,

theoretical physics, gravitation, and computational methods. Masaryk University integrates astrophysics into its physics curriculum and allows students to work directly with stellar, X-ray, and space-mission projects. Silesian University trains students in theoretical and applied physics with unusually strong exposure to relativity and computational astrophysics. Academy researchers at Ondřejov supervise university theses and host observational workshops in which students prepare, execute, reduce, and interpret genuine telescope observations. The Perek telescope therefore functions as both a scientific instrument and a national training facility. International mobility allows doctoral students to spend time at ESO sites, partner universities, and specialised observatories abroad. Conferences and workshops organised in Czechia bring foreign specialists into direct contact with domestic students. This educational circulation helps small groups remain internationally connected even when permanent staffing is limited.

The development of astronomical instrumentation also became more important within the Czech community after ESO membership. PLATOSpec is the clearest recent example, but Czech researchers also contribute software, data-processing methods, detector concepts, and observational support to other projects. The ALMA Regional Centre node converts technical knowledge of interferometric calibration into a national service. Ondřejov engineers maintain and repeatedly modernise the Perek telescope and its spectrographs rather than treating the facility as technologically static. Small-satellite projects in Brno require compact radiation detectors, electronics, timing systems, and spacecraft integration. Fireball-network stations rely on automated optical cameras, precise timing, meteorological resilience, and rapid data transfer. These activities broaden the meaning of an astronomical school beyond researchers who interpret celestial phenomena. Engineers, programmers, data specialists, and instrument scientists become part of the same research ecosystem. Participation in international observatory construction and future space missions can therefore generate technological competence even when the final facility is located outside Czechia. Czech astronomy increasingly reflects this systems character, in which instruments, software, physical theory, and observation are mutually dependent. The resulting expertise also strengthens connections with optics, electronics, aerospace engineering, and high-performance computing.

The period from 1993 to 2025 transformed the international position of Czech astronomy without eliminating the national scientific traditions from which it developed. The Astronomical Institute preserved Ondřejov as the country's principal professional observatory while modernising its stellar, solar, meteor, asteroid, galactic, and relativistic programmes. Charles University maintained a broad academic school spanning stellar astronomy, celestial mechanics, asteroid science, gravitation, and cosmology. Masaryk University expanded from strong stellar and theoretical work towards high-energy astrophysics, X-ray studies, numerical modelling, and CubeSat-based gamma-ray astronomy. Silesian University in Opava consolidated a distinctive relativistic and computational school and gained an independent Institute of Physics in 2020. National collaboration became particularly visible through shared training, the Albert Einstein Centre, use of Ondřejov instruments, and common participation in international projects. Czech accession to the European Southern Observatory in 2007 gave all of these centres systematic access to world-leading ground-based infrastructure. The ALMA Regional Centre node, PLATOSpec, Solar Orbiter participation, international asteroid programmes, and small-satellite missions show that Czech astronomers increasingly contributed expertise and instrumentation as well as scientific users. The domestic

observatory system continued to provide long-baseline monitoring, method development, rapid follow-up, and education that complement international facilities. The Czech astronomical landscape therefore developed as a layered system in which local instruments, national scientific schools, European observatories, and space missions served different but mutually dependent functions. This structure allowed a relatively small research community to remain scientifically broad while developing internationally recognisable specialisations. By 2025, Ondřejov, Prague, Brno, and Opava together formed a mature national astrophysical network whose strength lay precisely in combining distinct institutional traditions with sustained international observatory participation.

Regional Physics Centres and the Polycentric Development of Czech Physical Science

The regional development of Czech physics between 1993 and 2025 did not follow a simple model in which Prague and Brno accumulated all major research capacity. Important university and technology centres also emerged or expanded in Olomouc, Plzeň, Ostrava, Liberec, Pardubice, Zlín, and several other regional cities. These centres generally developed around areas where local academic traditions intersected with industrial structure, specialised instrumentation, or new European research funding. Optics and quantum science became particularly strong in Olomouc, plasma and thin-film physics in Plzeň, high-performance computing and energy-oriented nanotechnology in Ostrava, and nanofibrous materials in Liberec. Pardubice contributed a distinctive school of chalcogenide and functional materials, while Zlín strengthened polymer and soft-material research. The resulting map of Czech physics was therefore increasingly polycentric rather than organised solely through the capital and one secondary metropolitan centre. Regional universities did not duplicate the full disciplinary breadth of the largest Academy institutes, but instead concentrated resources where they could achieve critical mass. Their research frequently crossed the conventional boundaries between physics, materials science, chemistry, electrical engineering, mechanical engineering, and information technology. By 2025, this network of specialised regional centres had become an important structural feature of Czech physical science and its innovation system.

The expansion of regional research capacity accelerated particularly after Czech accession to the European Union in 2004 and the later availability of structural funding for research infrastructure. Universities outside Prague used these programmes to modernise laboratories, establish new research centres, and recruit specialists from abroad. The process changed the role of regional universities because research ceased to be confined primarily to teaching departments with modest local instrumentation. New centres were designed around clean rooms, electron microscopes, deposition systems, laser laboratories, high-performance computers, advanced spectroscopy, and pilot-scale engineering facilities. Their missions commonly combined fundamental research with technology transfer and cooperation with companies located in the surrounding industrial regions. This applied orientation did not eliminate basic physics, because many projects still depended on understanding electronic structure, optical response, plasma processes, surfaces, defects, or quantum behaviour. Instead, the regional model often made fundamental and applied work more tightly connected

than in institutions organised around traditional academic disciplines. European and national grants also encouraged interregional cooperation by requiring teams to combine specialised capabilities rather than reproduce identical equipment at several universities. Open-access infrastructure gradually made some regional laboratories available to researchers from the entire country. International partnerships further reduced the intellectual distance between regional Czech centres and large research universities abroad. The polycentric development of Czech physics therefore reflected both deliberate regional investment and the increasing technological complexity of contemporary research.

Olomouc provides one of the clearest examples of a regional scientific centre built around a strong disciplinary specialisation. Palacký University, re-established after the Second World War and substantially modernised after 1990, developed a particularly visible profile in optics, quantum physics, particle physics, and advanced materials. The Faculty of Science opened a new modern complex at the Envelopa site in 2009, giving several physical and natural-science departments significantly improved research space. Its Department of Optics had already accumulated more than four decades of experience in theoretical and experimental optical research. The Joint Laboratory of Optics, founded in 1985 as a common workplace of Palacký University and the Institute of Physics of the Czech Academy of Sciences, added another institutional layer. During the 2010s, the Regional Centre of Advanced Technologies and Materials strengthened nanomaterials, optical technologies, and experimental particle physics in the city. These structures meant that Olomouc could sustain research extending from single photons and wave optics to nanostructured materials and astroparticle detectors. The city therefore developed a scientific identity in which fundamental optical physics and technological instrumentation reinforced one another.

The Department of Optics at Palacký University became one of the principal Czech centres for quantum and modern optical physics. Its research programme encompasses quantum information processing, quantum tomography, quantum communication, non-classical light, quantum optomechanics, wave-front sensing, digital holography, non-diffracting beams, optical signal processing, and spectroscopy. Theoretical groups analyse how information can be encoded, transmitted, transformed, and measured using quantum states of light. Experimental laboratories generate entangled photon pairs, detect individual photons, stabilise interferometers, and implement elementary quantum operations. These activities produced a research environment in which foundational tests of quantum theory coexist with technological questions about secure communication and metrology. The department also developed strong traditions in vortex and structured beams, where the spatial form of optical fields becomes an experimentally controllable degree of freedom. Digital and computational optical methods connect these experiments with image reconstruction and precision measurement. Students can enter research through programmes in optics and optoelectronics, general and mathematical physics, and specialised experimental laboratories. European and national projects during the 2020s supported work on quantum key distribution, quantum memories, optical quantum networks, super-resolution imaging, and non-Gaussian quantum states. Olomouc therefore became one of the few Czech regional centres where quantum technologies emerged directly from a long-established optical school. Its success also demonstrates that internationally competitive fundamental physics need not be concentrated in the largest metropolitan universities.

Quantum optics in Olomouc illustrates how regional specialisation can produce a research profile with international reach. Researchers investigate quantum interference, teleportation,

quantum measurement, quantum-state estimation, quantum memories, and the suppression of noise in optical communication. Single-photon experiments require sources and detectors whose performance is sensitive to loss, timing, polarisation, and background counts. These practical constraints make the laboratory an environment where abstract information theory is continually tested against real optical systems. The resulting work has contributed to protocols for optical quantum gates, secure communication, non-classical state preparation, and advanced metrology. Collaboration with European partners connects the university to the wider development of quantum networks and photonic information processing. The same expertise also supports national initiatives in quantum communication that require trained specialists in light sources, detectors, and optical channels. Education and research are closely coupled because students can work with single-photon experiments during advanced study. The Olomouc school therefore shows how a regional university can maintain a highly specialised fundamental programme while contributing to an emerging technological field.

The Joint Laboratory of Optics gives the Olomouc school an unusually broad bridge between fundamental optics and applied physical instrumentation. As a shared workplace of Palacký University and the Institute of Physics of the Czech Academy of Sciences, it links university teaching with the research infrastructure of the Academy. Its activities include quantum and nonlinear optics, laser and optical technologies, wave and statistical optics, holography, optical coatings, particle physics, and astroparticle physics. Researchers design and construct optical devices rather than limiting their work to the interpretation of measurements made elsewhere. Thin-film technologies allow reflective, antireflective, and other functional optical surfaces to be prepared and tested for demanding applications. Applied projects have included multilayer optical systems developed with Czech industrial partners, demonstrating how surface physics and optical engineering can move into commercial products. The laboratory also contributes to the Pierre Auger Observatory through optical expertise associated with fluorescence telescopes used to detect ultra-high-energy cosmic rays. Related experience has supported work for the Cherenkov Telescope Array through mirrors, site characterisation, and atmospheric-monitoring systems. This means that an Olomouc laboratory concerned with precision optics can contribute directly to experiments located in Argentina, the Canary Islands, and other international sites. The same facility trains students in applied physics, nanotechnology, instrumental physics, and optoelectronics. Its scientific reach therefore extends from the quantum scale to astronomical and astroparticle instrumentation. The Joint Laboratory of Optics is consequently an important example of regional Czech physics functioning through institutional partnership rather than through a single university department.

Materials research added a second major dimension to the Olomouc physics environment. The Regional Centre of Advanced Technologies and Materials was established in 2010 and developed strong programmes in nanomaterials, low-dimensional systems, functional surfaces, magnetic materials, catalysts, and advanced characterisation. Its work often occupied the boundary between physics and chemistry because nanoscale electronic, magnetic, and optical properties depend directly on chemical composition and surface structure. Graphene and related two-dimensional materials became particularly important platforms for studying controlled functionalisation and unusual magnetic or electronic behaviour. Electron microscopy, spectroscopy, magnetic measurements, and computational modelling were combined to connect atomic structure with observable properties. In January 2021, several Palacký University research teams were integrated into the Czech Advanced

Technology and Research Institute, commonly abbreviated as CATRIN. CATRIN brought together nanotechnology and new materials with biomedical and plant research in a deliberately interdisciplinary university institute. This organisational change broadened the possible applications of nanoscale physics towards energy, environmental technologies, sensing, and biomedicine. Olomouc thus developed complementary strengths in quantum and optical physics around the Department and Joint Laboratory of Optics and in advanced materials through CATRIN, demonstrating how disciplinary methods can support interdisciplinary scientific problems. By 2025, the city's evolution had made it an important national centre for quantum optical science and materials-oriented nanotechnology while exemplifying the wider Czech strategy of building regional capacity around specialised research concentrations.

Plzeň developed a different regional model based on applied physics, plasma technologies, materials, and close interaction with engineering. The Department of Physics at the University of West Bohemia traces its independent institutional history to 1963, when it was created as a department of technical physics. Its research role expanded strongly after the establishment of the Faculty of Applied Sciences in 1990. New study programmes connected physics with engineering rather than treating the discipline solely as general scientific education. The department developed research in plasma physics, plasma chemistry, thin-film physics, and solid-state physics. Doctoral training in plasma and thin-film physics supported the creation of specialist research groups. This profile was well matched to the industrial environment of Plzeň, where materials processing and engineering remained economically important. The regional school consequently evolved around physical technologies that could connect microscopic processes with manufacturing.

Plasma-assisted deposition became one of the most characteristic fields of the Plzeň physics school. Researchers use direct-current, radio-frequency, microwave, continuous, and pulsed discharges to create thin films with controlled composition and microstructure. The plasma supplies energetic particles that can activate chemical reactions, modify surfaces, or sputter atoms from a target onto a substrate. Film properties are then determined by a combination of deposition energy, reactive gases, substrate temperature, stress, and microstructural evolution. Research therefore requires both plasma diagnostics and detailed characterisation of the resulting solid material. Hard coatings, optical layers, photovoltaic materials, and functional films provide technologically relevant experimental systems. Surface texture and tribological behaviour are important because a film only a few micrometres thick can determine friction, wear, corrosion resistance, or optical response of a much larger component. The Department of Physics combines this work with education in applied physics and physical engineering. Students can participate in research projects while learning vacuum technology, plasma physics, materials analysis, and computational modelling. This integration of education with experimental technology helped create a continuing regional pool of specialists. Plzeň's plasma school therefore occupies a different niche from the fusion-oriented plasma research in Prague, with its principal strength lying in controlled surface processing and the physics of technologically useful thin films.

The New Technologies – Research Centre, commonly abbreviated as NTC, expanded the scale and interdisciplinarity of this work from 2000 onwards. NTC was created as a university research centre intended to develop industrially relevant technologies while maintaining a substantial basic-research component. Its laboratories address advanced and quantum materials, infrared technologies, energy systems, biomechanics, polymer systems, and

computational modelling. The centre became particularly important because it assembled researchers from physics, mechanical engineering, materials science, electronics, and computation within one organisation. Rather than focusing on a single instrument, NTC built a chain extending from theoretical prediction and material preparation to measurement, prototype development, and industrial validation. International recruitment also increased the scientific diversity of the centre. Cooperation with companies in transport, machinery, energy, and manufacturing anchored the research in the technological structure of western Czechia. At the same time, participation in European projects connected Plzeň with research groups in Germany, France, and other countries. NTC consequently became the main institutional mechanism through which applied physics at the University of West Bohemia moved beyond the scale of an individual academic department.

The CENTEM project, implemented from 2011 to 2014 within NTC, provided an important infrastructure upgrade for materials and physical technologies in Plzeň. Its five research programmes covered surface morphology and modification, advanced polymer technologies, laser processing and materials analysis, polymer composites, and materials for photovoltaics, photonics, and microsystems. Substantial investment in new instrumentation allowed researchers to study structure, surfaces, thermal behaviour, and optical or electronic properties with much greater precision. Laser systems were developed for heat treatment, welding, cutting, coating, micromachining, and surface structuring. Infrared thermography and spectroscopy supplied non-contact methods for measuring temperature fields and photothermal properties. These capabilities were particularly valuable for manufacturing because they allowed processes to be monitored while they were operating rather than only inspected afterwards. Materials research also moved increasingly towards quantum and emergent properties during the 2020s. NTC teams combined first-principles calculations with photoemission, electron microscopy, tribology, and other experimental methods to investigate advanced functional systems. Research on materials such as manganese telluride and related compounds connected the regional centre with contemporary spintronics and altermagnetism. The Plzeň school therefore broadened from classical applied plasma physics into a modern programme encompassing quantum materials and computational design. Its continuing industrial orientation ensured that this expansion remained connected to devices, surfaces, energy, and manufacturing technologies. By 2025, NTC represented one of the strongest regional Czech examples of fundamental materials physics operating inside an applied research institution.

Ostrava followed another trajectory shaped by the industrial transformation of the Moravian-Silesian region. VSB – Technical University of Ostrava historically developed around mining, metallurgy, mechanical engineering, and energy technologies, disciplines in which physical modelling and materials characterisation are essential. After 1993, the decline and restructuring of heavy industry created pressure to diversify the region towards higher-value scientific and technological activities. The university responded by expanding research in computational science, nanotechnology, energy, advanced materials, and information technologies. Several of these programmes were deliberately organised as research infrastructures serving users outside the university itself. This transformed Ostrava from a regional technical university centre into a host of national-scale scientific facilities. Physics entered this model through computational modelling, materials science, magneto-optics, nanostructures, and later quantum computing. The regional scientific identity therefore

became closely tied to infrastructure capable of serving both academic research and industrial innovation.

The most consequential of these developments was the creation of the IT4Innovations National Supercomputing Center. Since 2013, IT4Innovations has operated the principal Czech supercomputing systems and made them available to research teams from universities, institutes, and industry. The Anselm supercomputer provided the first major national platform, followed by the two-petaflop Salomon system in 2015. Barbora entered operation in 2019 and added 849 teraflops of performance, while a specialised NVIDIA DGX-2 system expanded capacity for artificial intelligence. The Karolina supercomputer, commissioned in 2021 in cooperation with the European High Performance Computing Joint Undertaking, reached a theoretical peak performance of about 15.7 petaflops. Its accelerated nodes made the centre suitable for machine learning as well as conventional simulation. Czech researchers consequently gained domestic access to calculations that previously required foreign supercomputing allocations or much smaller university clusters. Materials physics, plasma modelling, astrophysics, engineering, molecular simulation, and data analysis all benefited from this infrastructure. IT4Innovations also became part of the LUMI consortium, giving Czech researchers access to one of Europe's largest pre-exascale systems. The centre therefore changed the regional and national geography of computational physics by placing a strategic research infrastructure in Ostrava rather than Prague or Brno. Its development shows that polycentric science can arise from digital infrastructure as effectively as from traditional laboratories. By 2025, Ostrava had become one of the most important European-facing Czech centres for computationally intensive research.

The scientific importance of IT4Innovations extends beyond providing processor time. Research groups at the centre develop parallel algorithms, modelling methods, data analytics, artificial intelligence, and computational approaches to advanced materials. The Modelling for Nanotechnologies Laboratory uses electronic-structure theory, molecular dynamics, spin dynamics, and machine-learning potentials to study matter across several length scales. Such work connects the centre directly with condensed-matter and materials physics rather than positioning supercomputing as a purely generic service. High-performance data analytics supports large datasets that cannot be treated efficiently through traditional serial workflows. Researchers also collaborate with industrial partners on optimisation, virtual prototyping, and predictive modelling. The installation and inauguration of the twenty-four-qubit VLQ quantum computer in 2025 added another technological layer to this regional infrastructure. VLQ uses superconducting qubits and is integrated conceptually with the European High Performance Computing environment through the LUMI-Q consortium. Its immediate scientific importance lies in experimentation with hybrid quantum–classical workflows rather than in replacing conventional supercomputers. Hosting the system gave Ostrava a direct role in the emerging European quantum-computing landscape and demonstrated how sustained specialisation in computational technologies could elevate a regional centre to strategic international importance.

Materials and nanotechnology form the second major physical-science axis at VSB – Technical University of Ostrava. The Nanotechnology Centre operates within the Centre for Energy and Environmental Technologies and focuses on the synthesis, modification, and detailed characterisation of advanced materials. Electron microscopy, spectroscopy, thermal analysis, and electrochemical methods are used to connect nanoscale structure with functional behaviour. Research is strongly oriented towards energy storage and conversion, reflecting

both European decarbonisation priorities and the industrial history of the region. Nanostructured electrodes, composites, coatings, and functional surfaces provide platforms for studying electrochemical and transport processes. The centre also conducts research in magneto-optics, plasmonics, spintronics, and molecular modelling. These topics connect applied energy research with more fundamental questions about electronic and optical states. Instrument-driven characterisation is therefore not separated from materials design but used iteratively to improve it. The NanoOstrava conference series further created an international meeting point for nanotechnology, energy materials, and advanced characterisation. Ostrava's materials school consequently combines regional industrial relevance with research areas that belong to the international frontier of nanoscience. It also provides an example of how a historically heavy-industrial region can redirect materials expertise towards low-carbon and high-technology applications.

Interdisciplinary energy research further distinguishes the Ostrava regional model. The Centre for Energy and Environmental Technologies combines nanotechnology with work on energy transformation, environmental protection, and sustainable industrial processes. Physical methods are used to analyse materials intended for batteries, membranes, coatings, thermal systems, and chemically demanding environments. Machine learning increasingly assists microscopy and materials evaluation, including automated interpretation of images from scanning electron microscopes. High-performance computing can then connect these experimental observations with simulations of material behaviour or process optimisation. This combination of experiment and computation is particularly useful for systems that degrade gradually under heat, corrosion, or repeated electrochemical cycling. Regional industrial partners provide real operating conditions against which laboratory models can be tested. European cooperation brings additional expertise in corrosion, hydrogen, energy storage, and environmental technology. The resulting research is difficult to classify as physics, chemistry, or engineering alone because the relevant problems cut across all three disciplines. Ostrava therefore illustrates how regional applied physics can develop through mission-oriented research without losing a rigorous physical basis in measurement and modelling. The city's post-industrial transformation gave this orientation a particularly strong economic and societal context. By 2025, energy, computation, nanotechnology, and advanced materials had become mutually reinforcing pillars of the Ostrava research environment.

Liberec developed another distinctive regional specialisation around fibres, polymers, textiles, surfaces, and nanomaterials. The Technical University of Liberec was founded in 1953 in a region whose economy had long depended on textile, glass, mechanical, chemical, and automotive industries. Its research therefore developed from the beginning in close interaction with production technologies and material performance. The Faculty of Textile Engineering became especially important because it linked textile science with polymer physics, mechanics, measurement, and later nanotechnology. Research on nonwoven materials provided a natural route towards structures in which fibre diameter became progressively smaller. The university also built strong engineering programmes in machinery, mechatronics, and material processing. This combination allowed physical understanding of electric fields, polymer solutions, flow, and surface behaviour to be transformed into manufacturing technology. Liberec's regional school consequently became an example of applied physics emerging from a traditional industry rather than from a conventional physics department.

Nanofibre research became the most internationally visible result of this development. Researchers at the Faculty of Textile Engineering developed needleless electrospinning

methods capable of producing nanofibrous webs at a scale far beyond the throughput of conventional single-needle laboratory systems. The Nanospider technology was created at the university in cooperation with an industrial partner and provided a practical route to mass production of nanofibres. Electrospinning uses a strong electric field to draw extremely fine jets from a polymer liquid and transform them into fibres with diameters that may reach the submicrometre scale. Removing the dependence on individual spinning needles enabled many jets to form simultaneously from a free liquid surface. This changed the technology from a mainly experimental method into a process with realistic industrial productivity. Research then expanded towards control of fibre diameter, orientation, porosity, mechanical properties, and surface functionality. Liberec groups also investigated direct-current and alternating-current electrospinning, coaxial fibres, centrifugal methods, and hybrid production routes. Applications include filtration, tissue engineering, acoustic materials, protective systems, membrane separation, and composite reinforcement. The physical problem therefore links electrohydrodynamic instability with polymer chemistry and manufacturing engineering. Student laboratories and pilot lines allow the same principles to be investigated from fundamental mechanism to scalable production. Nanofibres consequently became the clearest example of a Czech regional university converting physical research into a technology with international industrial impact while giving Liberec a specialised scientific identity complementary to the nanofabrication centres in Prague and Brno.

The Institute for Nanomaterials, Advanced Technologies and Innovation, commonly known as CxI, broadened this technological base beyond textile engineering. CxI combines more than six decades of university experience in mechanical and materials engineering with newer research in nanomaterials, environmental technologies, and system integration. Its laboratories synthesise nanoparticles, modify nanofibres, develop functional membranes, and analyse materials using advanced microscopy and chemical methods. Environmental applications include water treatment, remediation, gas filtration, and removal of micropollutants. These projects exploit the large surface area and tunable chemistry of nanoscale materials rather than treating nanotechnology as miniaturisation alone. CxI also cooperates extensively with companies and provides accredited analytical services. The institute therefore integrates research, testing, and technological implementation within one regional organisation. This applied structure makes it a counterpart to more fundamentally oriented nanophysics centres elsewhere in Czechia.

Advanced materials research at CxI adds surface and plasma physics to the Liberec profile. Thin layers and coatings are produced or modified using plasma-based technologies in order to control wear, friction, corrosion, and other surface properties. Microscopy and microanalysis determine chemical composition, microstructure, phase distribution, and failure mechanisms. Tribological measurements connect these structural observations with friction and mechanical durability. Nanoparticles and nanofibres can be incorporated into composite structures whose properties depend strongly on interfaces between dissimilar components. Surface functionalisation also changes wetting, adhesion, biological interaction, or filtration performance without altering an entire bulk material. Researchers therefore move between scales ranging from nanoscale coatings to full engineering components. The same institute develops mechatronic and system-integration technologies, creating links between materials and intelligent machines. This breadth reflects the structure of the Liberec regional economy, where automotive, textile, glass, and environmental technologies all demand specialised materials. Physical research is consequently evaluated not only through

publications but also through prototypes, patents, contract research, and industrial implementation. The Liberec school thus demonstrates how nanotechnology can become a unifying methodological layer across several branches of applied engineering while showing how regional industrial context can determine which areas of physics achieve long-term critical mass.

Pardubice provides a further example of specialised regional materials physics centred on optical, electronic, and nanostructured solids. The University of Pardubice developed internationally recognised research on chalcogenide glasses, amorphous thin films, layered semiconductors, non-silicate glasses, and related functional materials. Chalcogenides are especially important because their high refractive indices, infrared transparency, and photosensitivity make them useful for photonics and optoelectronics. Researchers investigate relationships among chemical composition, atomic structure, thermal stability, optical response, and electrical properties. Thin films can be prepared by thermal evaporation and other deposition methods and then modified through light or controlled heating. These transformations allow refractive index, chemical resistance, or phase structure to be engineered for specific functions. The Centre of Materials and Nanotechnologies, commonly abbreviated as CEMNAT, was founded in 2013 to integrate this expertise with broader research in nanostructures and advanced materials. Its programme covers photonics, electronics, photovoltaics, catalysis, and chemically active surfaces. Open-access operation allows external academic and industrial users to employ the centre's synthesis and characterisation capabilities. In the 2023–2026 national roadmap, CEMNAT was recognised as a large research infrastructure. The Pardubice school therefore demonstrates how a university with strong chemical-technology traditions can also sustain significant physical research on optical and electronic materials. Its contribution further broadens the geographical distribution of Czech photonics and nanoscience beyond the major optics centres in Prague and Olomouc.

Zlín adds a different materials tradition based on polymers, soft matter, composites, and the physical behaviour of complex macromolecular systems. Tomas Bata University emerged in a region historically shaped by rubber, plastics, footwear, and chemical manufacturing. The Centre of Polymer Systems began as a major regional research project in 2011 and moved into a purpose-built high-technology building in 2015. Its teams conduct both fundamental and applied research on polymer materials and associated processing technologies. Mechanical, electrical, rheological, surface, and structural properties must be understood if a polymer system is to perform reliably in real applications. Nanofillers and composite architectures add additional length scales whose interfaces often dominate macroscopic behaviour. Research therefore connects polymer physics with chemistry, materials engineering, processing, and device requirements. Applications extend into plastics, rubber, medicine, cosmetics, and other industrial sectors. The Zlín centre illustrates how physical materials research can develop from a regional manufacturing tradition and then diversify into modern functional systems. Together with Pardubice, it confirms that Czech regional physics includes important centres whose institutional home may be materials or chemical technology rather than a department explicitly named physics.

The regional centres also changed the national organisation of research infrastructure. During the 1990s, highly specialised instruments were more likely to be concentrated in the Academy of Sciences or the largest university faculties. European structural investment during the following two decades created major equipment bases in Olomouc, Plzeň, Ostrava, Liberec, Pardubice, Zlín, and other regions. This reduced the need for researchers to relocate

permanently to Prague in order to gain access to advanced laboratories. At the same time, the cost and complexity of equipment encouraged open-access models in which instruments were shared among institutions. CATRIN, CEMNAT, IT4Innovations, CxI, and other centres therefore became nodes in a national network rather than purely local assets. Digital infrastructure made this network still more distributed because computation could be accessed remotely. International facilities added another layer by allowing regional groups to use CERN, synchrotrons, neutron sources, astronomical observatories, and European computing systems. The resulting research geography is best described as interconnected polycentrism rather than decentralisation in isolation. Regional specialisation works because laboratories can obtain complementary methods elsewhere while preserving a distinctive local competence, so a strong optics group does not need its own supercomputer and a computational centre does not need to duplicate every experimental characterisation method. This division of scientific labour allowed Czech physics to broaden geographically without fragmenting into disconnected local communities.

University education was one of the principal mechanisms sustaining this polycentric system. Palacký University trains specialists in optics, quantum science, applied physics, and nanotechnology who can move directly into its research laboratories. The University of West Bohemia combines applied physics and physical engineering with doctoral work on plasma and thin films. VSB – Technical University of Ostrava links computational technologies and materials research with engineering education and, by 2025, was preparing specialised training associated with quantum computing. The Technical University of Liberec integrates polymer physics, nanofibre production, materials characterisation, and industrial technology within its engineering programmes. Pardubice and Zlín similarly embed physical understanding of materials within chemistry- and technology-oriented degrees. Students therefore encounter physics in several institutional forms rather than through a single national curriculum model. Regional companies provide thesis topics, internships, testing problems, and employment opportunities that keep a portion of this trained workforce outside the capital. International mobility remains important, but regional laboratories give researchers a credible domestic base to which they can return. This circulation helps transfer methods acquired abroad into local universities and strengthens their ability to recruit foreign researchers. The polycentric system is consequently reproduced through people as much as through instruments. Its long-term sustainability depends on whether specialised educational programmes remain connected to active research and regional technological demand.

Industrial cooperation is another common feature linking otherwise very different regional schools. Olomouc optics works with companies producing optical components and applies coating and metrology expertise to real devices, while Plzeň research centres cooperate with machinery, transport, automotive, and energy companies on surfaces, thermal diagnostics, laser processing, and functional materials. Ostrava combines supercomputing and materials science with industrial modelling, corrosion studies, energy technologies, and digital innovation, whereas Liberec converts nanofibre, coating, membrane, and mechatronic research into applications for filtration, medicine, textiles, environmental engineering, and automotive systems. Pardubice materials research connects photonics and electronic materials with industrially relevant deposition and characterisation. Zlín's polymer research remains closely linked to plastics, rubber, and processing technologies. These relationships do not imply that regional research is less fundamental than work in larger academic centres. Instead, technological problems frequently expose unresolved questions about interfaces,

defects, heat transport, charge motion, optical response, or mechanical failure. Industrial cooperation can therefore generate basic physical problems while also imposing requirements of reproducibility, cost, scale, and reliability. The regional centres are particularly effective when they preserve this two-way exchange rather than becoming purely contract-testing laboratories. Their development after 1993 shows that applied physics can serve simultaneously as a source of scientific questions and as a mechanism for regional economic transformation. This interaction with industry is one of the major structural differences between the Czech regional schools and institutions focused almost exclusively on fundamental research.

Internationalisation ensured that regional specialisation did not become provincial isolation. Olomouc groups participate in CERN, the Pierre Auger Observatory, the Cherenkov Telescope Array Observatory, European quantum programmes, and international optical collaborations. Plzeň researchers work through European projects on advanced materials, quantum materials, energy technologies, and cross-border cooperation with Germany. Ostrava's IT4Innovations belongs to EuroHPC structures and the LUMI consortium and coordinates the multinational LUMI-Q quantum-computing project. Liberec researchers cooperate internationally on nanofibres, environmental technologies, advanced materials, and industrial processing. Pardubice materials scientists maintain collaborations with universities and institutes in France, Germany, Japan, Canada, and other countries. These partnerships provide access to facilities, specialist methods, doctoral networks, and research cultures that no regional centre could reproduce alone. They also increase the visibility of Czech universities outside the two largest national metropolitan research hubs. European programmes often reinforce domestic connections because Czech institutions must assemble complementary national consortia before entering larger international projects. Regional centres therefore participate simultaneously in local industry, national infrastructure, and European scientific networks. This multi-level integration is a defining feature of Czech physical science by the mid-2020s. It allows a geographically dispersed system to behave scientifically as a connected research environment rather than as a collection of isolated provincial laboratories.

Between 1993 and 2025, the regional development of Czech physics thus produced a diverse network of specialised scientific centres whose collective importance exceeded the role of any single university. Olomouc became a major national centre for optics, quantum information, optical technologies, astroparticle instrumentation, and advanced nanomaterials. Plzeň built a distinctive applied-physics school around plasma processing, thin films, laser technologies, infrared diagnostics, and increasingly advanced quantum materials. Ostrava transformed computational science into national research infrastructure through IT4Innovations while simultaneously developing energy-oriented nanotechnology, materials characterisation, and quantum-computing capability. Liberec converted textile and polymer expertise into internationally recognised nanofibre technology and expanded this base through CxI into surfaces, coatings, environmental nanotechnology, and advanced engineering. Pardubice developed an important photonic and electronic materials school centred on chalcogenides and the open-access CEMNAT infrastructure. Zlín reinforced the physical study of polymers and complex material systems through a research centre closely connected with regional industry. These centres did not replace Prague, Brno, or the major institutes of the Czech Academy of Sciences. Instead, they added specialised capabilities that made national research more resilient, technologically diverse, and geographically distributed. Their growth was supported by European integration, infrastructure investment, international collaboration,

and close ties between universities and regional economies. The resulting polycentric structure allowed Czech physical science to combine metropolitan centres of fundamental research with regional schools distinguished by optics, materials, computation, applied physics, and interdisciplinary technology, and by 2025 this distributed architecture had become one of the characteristic institutional features of contemporary Czech physics.

Czech Physics within European and Global Research Infrastructures

The integration of Czech physics into European and global research infrastructures became one of the defining institutional changes of the period from 1993 to 2025. After the dissolution of Czechoslovakia, international facilities increasingly provided Czech researchers with access to experimental conditions that could not be created economically within a medium-sized national research system. Particle accelerators, astronomical observatories, neutron sources, laser facilities, fusion devices, cosmic-ray observatories, and supercomputers became extensions of domestic laboratories rather than occasional foreign destinations. Czech institutions responded by building national infrastructures whose purpose was to organise participation, maintain technical contributions, train users, and represent the country in multinational collaborations. This model altered the meaning of scientific capacity because competitiveness depended not only on equipment located inside Czechia but also on guaranteed access to shared instruments abroad. It also encouraged specialisation, since Czech groups could concentrate on detectors, optics, diagnostics, materials, software, or theory without reproducing an entire international facility. Mobility of students, engineers, and senior researchers became a normal component of experimental work. Participation in governance and in-kind construction contributions gave Czech organisations responsibilities beyond the role of external users. By 2025, the international infrastructure network had become a structural component of Czech physics across high-energy physics, astronomy, fusion, nuclear science, laser research, astroparticle physics, and computational science.

The national framework for this participation developed through the Czech Roadmap of Large Research Infrastructures and related programmes of the Ministry of Education, Youth and Sports. The roadmap linked domestic facilities with Czech participation in infrastructures located abroad and gave both forms of activity a common strategic language. National nodes such as CERN-CZ, AUGER-CZ, CTA-CZ, FAIR-CZ, ESS-Scandinavia-CZ, and SPIRAL2-CZ were therefore treated as components of the Czech research system even when the principal experimental site lay in Switzerland, Argentina, Chile, Spain, Germany, Sweden, or France. Funding supported membership fees, operational costs, travel, detector development, computing, and the preparation of in-kind contributions. This structure helped institutions plan participation over periods much longer than ordinary research grants. It also created formal responsibility for coordinating users from several universities and institutes rather than leaving international access to isolated personal contacts. Czech participation increasingly included representation in councils, scientific committees, technical boards, and experiment management structures. The resulting model combined national funding with European or global governance. It reduced the distinction between infrastructure located inside and outside the country because both required long-term commitments of staff, equipment, and operating resources. Large research infrastructures consequently became instruments of both science policy and scientific internationalisation.

The European Organization for Nuclear Research, commonly known as CERN, provided the earliest and most influential example of this model after 1993. The former Czech and Slovak Federal Republic had been a CERN Member State from 1 January 1992, and the newly independent Czech Republic became a Member State on 1 July 1993. Membership gave Czech scientists stable access to CERN accelerators and formal representation in the organisation's governance. It also required the country to contribute financially to the shared laboratory and to accept responsibilities associated with long-term experiments. Czech participation was organised nationally through CERN-CZ, with the Institute of Physics of the Czech Academy of Sciences as a principal coordinating institution and with major contributions from universities and the Nuclear Physics Institute. The infrastructure supported detector construction, maintenance, upgrades, computing, and data analysis carried out both at CERN and in Czech laboratories. This organisation transformed CERN from a foreign accelerator visited by individual researchers into a permanent component of Czech particle and nuclear physics. The relationship also gave younger physicists a predictable route from university training into large international collaborations.

Czech groups became deeply involved in experiments at the Large Hadron Collider, commonly abbreviated as LHC, and in other CERN programmes. Researchers at the Institute of Physics, Charles University, the Czech Technical University in Prague, and the Nuclear Physics Institute contributed to A Toroidal LHC Apparatus, known as ATLAS, and to A Large Ion Collider Experiment, known as ALICE. Their responsibilities included silicon tracking, calorimetry, forward detectors, radiation monitoring, electronics, mechanics, detector control, software, and physics analysis. Czech teams also participated in fixed-target and specialised experiments addressing hadron structure, heavy-ion physics, nuclear reactions, and rare processes. These activities required detector components to be designed and tested domestically before installation at CERN. The national Tier-2 computing centre provided another shared instrument by processing and storing data within the Worldwide LHC Computing Grid. Students could therefore analyse CERN data in Czechia while remaining integrated into a collaboration whose detector and accelerator were located in Geneva. Technical groups developed expertise in radiation-hard sensors, vacuum engineering, cryogenics, cooling, high-speed electronics, and distributed computing. Such capabilities were transferable to medicine, space instrumentation, materials testing, and other branches of experimental physics. The Czech CERN programme thus demonstrates how participation in a multinational laboratory can generate domestic technological competence as well as access to frontier measurements. Its scientific value lies in the combination of shared instrumentation, local specialisation, and sustained international responsibility.

Mobility is inseparable from this mode of high-energy physics because detector construction and operation require researchers to work repeatedly at the host laboratory. Czech doctoral students and postdoctoral researchers spend periods at CERN taking shifts, commissioning instruments, attending collaboration weeks, and working with specialist teams from many countries. Engineers travel for installation and maintenance campaigns whose timing is determined by accelerator shutdowns rather than by university teaching calendars. Senior scientists participate in physics groups, editorial boards, management committees, and national representation. These movements create professional networks that often persist across several generations of experiments. Returning researchers bring software practices, quality-control procedures, and laboratory techniques back to Czech institutions. CERN also provides schools and training programmes in accelerator science, instrumentation,

computing, and theoretical physics. The international laboratory therefore functions simultaneously as an experimental facility and as an educational environment. Czech membership has consequently shaped the professional culture of particle physics as much as the individual measurements produced there.

Astronomy followed a comparable path through membership in the European Southern Observatory, commonly abbreviated as ESO. Czechia formally became ESO's thirteenth Member State on 30 April 2007 and the first member from Central and Eastern Europe. Membership gave Czech astronomers competitive access to facilities in Chile whose scale and observing conditions could not be reproduced at Ondřejov or any other domestic site. The Very Large Telescope opened high-resolution spectroscopy, adaptive-optics imaging, interferometry, and advanced optical and infrared observations to Czech teams. The Atacama Pathfinder EXperiment provided access to submillimetre astronomy, while ESO participation in the Atacama Large Millimeter/submillimeter Array connected Czech researchers with a global radio-interferometric facility. Membership also provided routes into the construction and scientific preparation of the Extremely Large Telescope. The effect was therefore broader than gaining additional telescope nights because Czech institutions entered a long-term European observatory system with common governance, fellowships, instrumentation, and data archives. ESO membership also placed Czech representatives in its governing and advisory bodies.

ESO membership changed the organisation of domestic astronomy by making international observational access a routine component of research planning. The Astronomical Institute of the Czech Academy of Sciences, Charles University, Masaryk University, and other institutions could design projects around instruments located in Chile while using Czech telescopes for monitoring, target selection, and follow-up observations. A Czech node of the European ALMA Regional Centre was established at the Astronomical Institute in 2016 to support proposal preparation, calibration, imaging, and interpretation of interferometric data. Its solar specialisation allowed Czech expertise to serve users beyond the national community. The PLATOSpec project at La Silla provided a further step from using international facilities towards leading a dedicated instrument on an ESO site. Czech scientists also became eligible for ESO fellowships, studentships, staff positions, advisory committees, and technical collaborations. Industrial organisations gained access to procurement opportunities associated with advanced observatory construction. The result was a scientific network in which domestic observatories, university groups, ESO facilities, and space missions complemented one another. International infrastructure thereby strengthened rather than displaced national astronomical schools.

The Extreme Light Infrastructure European Research Infrastructure Consortium, commonly abbreviated as ELI ERIC, reversed the usual geographical direction of internationalisation by placing the statutory centre of a European infrastructure in Czechia. The European Commission granted ELI ERIC legal status on 30 April 2021. The Czech Republic and Hungary became host countries and were joined by Italy and Lithuania as founding members. The statutory seat was established at ELI Beamlines in Dolní Břežany, south of Prague. This arrangement made Czechia responsible not only for contributing to a foreign facility but also for hosting the governance and part of the operation of a multinational organisation. ELI ERIC provides unified access to high-power and ultrafast laser facilities and coordinates their development for users from many countries. The Czech position therefore represents a significant change from the early 1990s, when internationalisation primarily meant

reconnecting national laboratories with established Western European centres. By the 2020s, Czech institutions were also capable of hosting infrastructure of direct European strategic importance.

ELI Beamlines demonstrates how international infrastructure can reorganise a national scientific centre around open user access. External teams apply competitively for beam time rather than relying on personal agreements with individual laboratory heads. Accepted experiments are supported by facility scientists responsible for laser operation, target areas, diagnostics, radiation safety, and data acquisition. Users may investigate laser-driven particle acceleration, high-energy-density plasma, ultrafast X-ray science, materials, molecular dynamics, or biomedical questions. The need to serve varied external projects forces the facility to maintain reproducible operating conditions and transparent technical specifications. International users also bring experimental concepts that would not necessarily arise within the Institute of Physics alone. The resulting scientific traffic turns Dolní Břežany into a meeting point for laser physicists, plasma researchers, chemists, materials scientists, engineers, and medical researchers. Training and mobility are therefore built directly into the user-facility model. ELI illustrates a mature stage of internationalisation in which Czech researchers both travel to foreign infrastructure and host foreign users within a Czech-based European organisation. This reciprocal movement is one of the clearest institutional achievements of Czech physics after 1993.

Fusion research developed through another form of European integration centred on common scientific programming. The Institute of Plasma Physics of the Czech Academy of Sciences signed an association agreement with the European Atomic Energy Community at the end of 1999. Czech researchers subsequently participated in coordinated European work around the Joint European Torus and other major tokamaks. From 2014, this cooperation was reorganised within the European Consortium for the Development of Fusion Energy, known as EUROfusion. The Institute of Plasma Physics leads the Czech Research Unit, while Research Centre Řež, the Nuclear Physics Institute, the Czech Technical University in Prague, Charles University, and the University of West Bohemia contribute to the wider national programme. EUROfusion coordinates experiments, theory, materials research, training, and engineering around a common roadmap. The Czech programme can therefore specialise in edge plasma, power exhaust, diagnostics, disruptions, modelling, and related topics while relying on other European facilities for complementary regimes. The framework makes European facilities part of a shared programme rather than isolated host laboratories.

The relationship with EUROfusion is also the principal route through which Czech plasma physics contributes to preparations for the International Thermonuclear Experimental Reactor and for a future demonstration fusion power plant, usually called DEMO. Experiments on COMPASS were designed partly around questions that could be compared with ITER-relevant H-mode plasmas, magnetic perturbations, runaway electrons, and exhaust physics. Czech researchers also work on devices such as ASDEX Upgrade, WEST, the Tokamak à Configuration Variable, and other European machines through coordinated campaigns. Theory groups participate in common modelling and validation activities that extend beyond any one national tokamak. The COMPASS Upgrade project is being built in Prague to address high-field and high-power-exhaust regimes that occupy a specific gap in the European experimental portfolio. Materials and neutron studies at other Czech institutions complement the confinement programme by addressing radiation and reactor-relevant technologies. Mobility through EUROfusion enables students and specialists to work at laboratories that possess systems

unavailable in Prague. This networked organisation allows a relatively small national fusion community to participate across the chain from present experiments to future reactor concepts. The European programme therefore acts simultaneously as research infrastructure, training system, and strategic planning framework.

Nuclear and hadron physics became similarly connected with the Facility for Antiproton and Ion Research, commonly abbreviated as FAIR, under construction in Darmstadt, Germany. In March 2019, the Czech Republic entered a formal associated relationship with FAIR through an agreement involving the Nuclear Physics Institute of the Czech Academy of Sciences. The national FAIR-CZ infrastructure coordinates participation by Czech institutes and universities in nuclear structure, hadron physics, high-density nuclear matter, biophysics, and radiobiology. Czech researchers contribute to the High Acceptance Di-Electron Spectrometer, the Compressed Baryonic Matter programme, the antiProton ANnihilation at DArmstadt experiment, Nuclear Structure, Astrophysics and Reactions, and Atomic, Plasma Physics and Applications. This breadth links domestic nuclear physics with a future accelerator complex whose energies, ion species, and antiproton capabilities cannot be reproduced at Řež. The national programme therefore extends the scientific reach of Czech accelerators without reducing the value of those domestic facilities. Local machines remain essential for detector testing, target development, nuclear data, training, and preparatory experiments. Formal involvement also positioned Czech scientists to influence experimental planning and technology choices before FAIR became fully operational.

FAIR participation illustrates the importance of in-kind contributions in contemporary research infrastructure. Czech teams do not simply purchase future beam time but design and supply parts of experiments and technical systems. Contributions have included equipment for electromagnetic calorimetry, spectator detection, detector modules for exotic-nuclei research, vacuum systems, and structural components. The work involves the Nuclear Physics Institute together with Charles University, the Czech Technical University, Silesian University in Opava, Palacký University, and industrial partners. Engineers must satisfy common standards for radiation tolerance, mechanical stability, documentation, safety, and integration with systems produced in other countries. Construction therefore generates scientific and engineering knowledge before the accelerator reaches full operation. Students can work on a component in Czechia and later follow it through installation, commissioning, and data taking in Germany. Industrial suppliers similarly gain experience with quality requirements associated with a major international laboratory. FAIR-CZ thus converts membership into a programme of technology development and human-capital formation. The infrastructure is valuable precisely because responsibility for construction is shared rather than outsourced entirely to the host country.

The European Spallation Source, commonly abbreviated as ESS, provides a parallel example in neutron science. The Czech Republic is one of the member states of ESS European Research Infrastructure Consortium and has participated in the project from an early stage. The Nuclear Physics Institute coordinates the national ESS-Scandinavia-CZ infrastructure. Czech financial responsibility has been designed to include a substantial proportion of in-kind contributions rather than cash alone. Roughly half of the Czech construction contribution has been associated with the Beamline for European Materials Engineering Research, known as BEER. The remaining major contribution concerns technological units connected with cooling of the neutron target system. This arrangement ensures that Czech participation creates technical

capability and future scientific expertise at home. It also gives the national neutron community a direct relationship with the construction and operation of instruments it intends to use.

BEER demonstrates how shared instrumentation can connect a domestic scientific school with a much larger European source. The instrument is a time-of-flight neutron diffractometer intended for engineering materials and in-situ or in-operando experiments. Czech researchers at the Nuclear Physics Institute developed the concept with German partners and contributed substantially to instrument construction. The scientific programme includes phase transformations, residual stresses, texture evolution, precipitation, deformation, and joining under controlled thermomechanical conditions. Many of these questions had already been studied with neutron instruments at the LVR-15 research reactor in Řež. ESS provides much higher flux and a different time-of-flight environment, allowing faster measurements and more complex sample conditions. Domestic facilities can therefore support method development and routine experiments, while BEER extends the accessible parameter range. The Czech contribution also gives engineers practical experience in neutron optics, instrument control, sample environments, and systems integration. Shared construction creates a community of users who understand the instrument before routine operation begins. ESS participation thus reinforces the national neutron school while embedding it within European materials research.

The Pierre Auger Observatory provides a contrasting global infrastructure because its principal detector covers about three thousand square kilometres in Argentina rather than being concentrated in one accelerator complex. Czech participation is organised through AUGER-CZ and involves the Institute of Physics, Charles University, and Palacký University. Czech researchers contributed to the construction and long-term operation of fluorescence telescopes used to observe ultraviolet light from extensive air showers. Fifteen of the observatory's fluorescence telescopes use Czech glass mirrors, and Czech teams assumed major responsibilities for operation and maintenance of the fluorescence system. They also developed atmospheric-monitoring instruments and optical methods necessary for accurate reconstruction of cosmic-ray events. Scientific work addresses the spectrum, mass composition, arrival directions, hadronic interactions, photons, and neutrinos at extreme energies. The infrastructure therefore joins detector engineering with astrophysics and particle physics. Long-term maintenance in a remote environment also requires a particularly strong culture of international logistical coordination.

The Auger model shows that international infrastructure can depend on distributed contributions rather than a single host-laboratory technology. Mirror development in Olomouc, detector and analysis expertise in Prague, computing services, and fieldwork in Argentina form one experimental chain. Czech students may therefore work on optics or data processing domestically before travelling to the observatory for detector shifts or maintenance. Instrument knowledge acquired at Auger was later transferred to gamma-ray astronomy and helped shape Czech contributions to the Cherenkov Telescope Array. Atmospheric-monitoring systems provide a particularly clear example because the same methods for characterising aerosols and clouds are relevant to several air-shower observatories. The collaboration also exposes Czech researchers to governance in a project involving institutions from many continents. Scientific papers are produced collectively, requiring internal review and common standards for statistical significance and systematic uncertainty. Such procedures influence the research culture of participating institutions even outside astroparticle physics. Pierre Auger therefore acts as both a detector and a long-term school in international experimental

collaboration. Its value to Czech science includes technology, data, networks, and training as well as access to rare cosmic-ray events.

The Cherenkov Telescope Array extended this experience into very-high-energy gamma-ray astronomy and evolved institutionally into the Cherenkov Telescope Array Observatory, commonly abbreviated as CTAO. Czech participation through CTA-CZ has included the Institute of Physics, Palacký University, Charles University, the Astronomical Institute, and supporting digital infrastructure. Optical specialists developed and tested mirror technologies drawing directly on experience from Pierre Auger. Czech teams also built all-sky cameras and robotic atmospheric-monitoring systems used in site characterisation and planned observatory operations. Scientists participated in simulations, calibration, scientific working groups, and organisational structures during the long preparatory phase. CTAO was formally established as a European Research Infrastructure Consortium on 7 January 2025. The Czech Republic became one of its founding members together with several European states and the European Southern Observatory. This legal status placed Czechia directly within the governance of the future observatory rather than leaving national groups as external contributors.

CTAO also demonstrates how research infrastructure increasingly links European governance with global scientific participation. Its northern array is being developed on La Palma in Spain, while the southern array is planned near the European Southern Observatory site at Paranal in Chile. The observatory is intended to serve a much wider scientific community than the original construction consortium by providing proposal-based access, data products, and analysis software. Czech groups therefore contribute to an infrastructure whose users will include astronomers who never participated in telescope construction. Optical and atmospheric systems supplied through national teams become part of a common observatory service rather than remaining the property of the laboratory that developed them. The transition from a collaboration-led project to an ERIC also creates long-term rules for governance, funding, data management, and user access. For Czech institutions, this evolution provides experience applicable to other international observatories and research organisations. It also strengthens links between astroparticle physics, conventional astronomy, optics, computing, and atmospheric science. By 2025, CTAO had become another example of Czech participation moving from preparatory scientific networking towards formal infrastructure co-governance.

Mobility across all of these infrastructures performs a scientific function that cannot be reduced to travel support. Large facilities concentrate specialised knowledge in particular locations, and many skills can be acquired only through direct work with the instrument. A doctoral student learning to calibrate a collider detector, align a Cherenkov telescope mirror, operate a neutron instrument, or diagnose a tokamak gains tacit knowledge that is difficult to reproduce from documentation alone. Short visits can support a single measurement, while longer secondments allow researchers to join development teams or assume coordination responsibilities. Returning scientists transfer this knowledge into national laboratories and university courses. Repeated mobility also creates trust among groups that must share unpublished data, common software, and technically sensitive information. International infrastructures therefore form professional networks whose members often collaborate again in later projects. The Czech scientific community benefits disproportionately from this circulation because its domestic institutions are too small to maintain every specialised technique independently. Mobility is consequently one of the mechanisms by which access to

a foreign instrument becomes lasting national competence. These exchanges also help younger scientists build international reputations early in their careers.

Shared instrumentation similarly changes the economics and organisation of physical research. A modern collider detector, multi-petawatt laser, neutron source, astronomical array, or fusion device may require investment far beyond the resources of a single national institution. International construction distributes these costs while allowing each partner to specialise in components for which it has established expertise. Czech laboratories have contributed silicon detectors, calorimeter components, optical mirrors, atmospheric monitors, neutron instruments, accelerator targets, vacuum systems, laser technology, computing, and specialised diagnostics. These contributions are scientifically important because the group that builds a subsystem usually acquires deep knowledge of its response and limitations. That knowledge later improves calibration, analysis, and interpretation of the data generated by the common facility. In-kind contributions also allow domestic companies to participate in demanding procurement chains. Quality standards developed for international infrastructure can then influence industrial production outside research. Shared instrumentation therefore links scientific access with technological learning.

Digital infrastructure created another form of shared instrument during the 2000s and 2010s. Particle physics introduced Czech researchers early to distributed grid computing because Large Hadron Collider data had to be processed across many national centres. The e-INFRA CZ environment later connected high-performance computing, cloud services, data storage, and academic networking on a broader scale. IT4Innovations joined the Large Unified Modern Infrastructure consortium, commonly known as LUMI, giving Czech users access to a European pre-exascale supercomputer located in Finland. The Karolina supercomputer in Ostrava was itself acquired in cooperation with the European High Performance Computing Joint Undertaking. These arrangements allowed simulations in materials science, plasma physics, astrophysics, and other fields to cross national hardware boundaries in much the same way as experimental research. Computing allocations became a form of transnational access comparable to beam time or telescope time. Researchers could migrate codes between national and European machines while receiving technical support through shared programmes. By 2025, computational infrastructure had therefore become part of the same internationalisation process that earlier transformed accelerator and observatory science. The installation of the VLQ quantum computer in Ostrava that year added an emerging quantum layer to this European digital ecosystem.

Other nuclear-physics collaborations further widened this infrastructure network beyond FAIR and ESS. The Système de Production d'Ions Radioactifs Accélérés en Ligne, commonly abbreviated as SPIRAL2, is a major extension of the Grand Accélérateur National d'Ions Lourds in Caen, France. The Nuclear Physics Institute has cooperated with SPIRAL2 since 2008 and coordinates the Czech SPIRAL2-CZ infrastructure. Czech in-kind contributions include production targets, radioisotope targets, germanium detection equipment, and systems for irradiation experiments. Domestic cyclotrons at Řež provide a platform for preparatory measurements relevant to nuclear astrophysics, activation, and neutron production. Czech researchers also participate in the Karlsruhe Tritium Neutrino experiment and in collaborations at other accelerator laboratories. These programmes demonstrate that internationalisation does not occur only through formal state membership in large organisations. Bilateral and multilateral laboratory partnerships can create equally durable experimental networks when they involve equipment, shared scientific programmes, and regular mobility. The Czech

nuclear community therefore operates through a layered system extending from CANAM at Řež to European and global accelerator infrastructures.

Laser science developed a similar transnational layer through European access programmes and laboratory networks. Before ELI Beamlines became fully operational, Czech researchers already used Laserlab-Europe to exchange expertise and provide access to facilities such as the Prague Asterix Laser System. HiLASE later offered transnational access through European projects, allowing foreign users to work with high-average-power laser systems in Dolní Břežany. Such programmes standardise proposal evaluation and make specialised equipment available independently of the user's national funding base. They also encourage laboratories to compare technical performance, safety procedures, and data-management practices. Czech laser groups gain from receiving external users because unusual experiments reveal limitations and new possibilities in the sources they operate. Researchers travelling abroad can access complementary pulse energies, wavelengths, diagnostics, or target capabilities. Networks therefore reduce the danger that a national laser centre becomes technically isolated despite possessing advanced hardware. This circulation of users and methods helped prepare Czech institutions for the more formal governance model of ELI ERIC. Transnational access consequently became an intermediate mechanism between bilateral cooperation and full membership in a European research organisation.

Participation in large infrastructures also changes how scientific quality is assessed and how research priorities are negotiated. Access to telescope time, neutron beams, laser systems, or supercomputers is frequently allocated through international peer review. Experimental collaborations require internal approval before major results are released and may subject analyses to repeated independent checks. Technical changes are evaluated through design reviews involving experts from institutions that did not build the original subsystem. Governing councils balance national financial responsibilities with the collective scientific mission of the infrastructure. Czech representatives therefore participate in decisions about strategy, upgrades, user policy, and long-term investment rather than only about individual experiments. This experience exposes national institutions to management practices developed for organisations much larger than ordinary university departments. It also requires Czech groups to articulate their scientific priorities in competition and cooperation with communities from other countries. International infrastructure thus becomes a mechanism of scientific governance as well as a collection of instruments.

The industrial dimension of international research infrastructures became increasingly visible during the 2010s and 2020s. Companies can supply precision mechanics, electronics, optics, vacuum systems, cryogenic equipment, software, specialised materials, and construction services to multinational facilities. Czech participation in CERN, FAIR, ESS, ESO, ELI, Pierre Auger, and CTA has created opportunities for domestic firms to qualify for such technically demanding work. Research institutes often act as intermediaries by developing prototypes or defining specifications together with industrial partners. Successful delivery requires documentation, traceability, quality assurance, and long-term maintenance at standards higher than those of many ordinary commercial projects. Companies can subsequently apply the acquired competence in other high-technology markets. The process also works in the opposite direction because industrial production methods can solve problems that research laboratories cannot address efficiently on their own. Hosting ELI Beamlines gives Czech suppliers particular access to a major infrastructure located domestically, while participation abroad exposes them to international procurement systems. Research infrastructures

therefore contribute to innovation partly through supply chains rather than only through scientific discoveries. Participation also familiarises Czech companies with international tendering and certification procedures.

The international infrastructure system also reshaped the geography of Czech physics by connecting regional centres directly with global projects. Palacký University in Olomouc contributes optics to Pierre Auger and CTAO rather than depending on Prague as an intermediary. The University of West Bohemia participates in EUROfusion and advanced materials projects linked to European facilities. IT4Innovations in Ostrava connects Czech computational physics directly with EuroHPC and LUMI. Silesian University in Opava contributes to FAIR and international astrophysics despite being geographically distant from the largest national laboratories. Brno groups use European synchrotrons, microscopy networks, and computing resources while also hosting CEITEC facilities for external users. These links mean that internationalisation and regionalisation are not opposing trends. Access to shared infrastructure can actually strengthen regional specialisation because researchers do not need to relocate permanently to the capital to use frontier instruments. The national system consequently becomes more polycentric while remaining scientifically interconnected. Large infrastructures provide the external framework within which this distributed domestic geography can function coherently. Such connections help regional institutions retain scientific autonomy while remaining integrated with the national community.

By 2025, the cumulative effect of these relationships was a profound change in what it meant for a physical instrument to be part of Czech science. CERN accelerators in Switzerland and France, ESO telescopes in Chile, the Pierre Auger Observatory in Argentina, FAIR in Germany, ESS in Sweden, and CTAO sites in Spain and Chile all formed part of the practical research environment of Czech institutions. EUROfusion linked Prague fusion research with tokamaks distributed across Europe and with the preparation of ITER and DEMO. ELI ERIC placed Czechia on the opposite side of this relationship by making Dolní Břežany the statutory seat and one of the operational centres of an international laser infrastructure. EuroHPC and LUMI extended the same model into computational science, where instrument access could be provided through networks rather than travel. SPIRAL2 and other laboratory collaborations added further layers of specialised access and in-kind development. The common mechanisms were shared financing, mobility, technical contribution, peer-reviewed access, data exchange, and multinational governance. Czech researchers increasingly built careers across these interconnected environments rather than within the boundaries of one institute. National laboratories remained essential because they provided training, prototypes, diagnostics, computing, and the specialist knowledge needed to exploit larger shared facilities. International infrastructure therefore did not weaken the national research system but became one of the principal ways in which that system accumulated capability. The transformation from post-1993 international reconnection to co-governance and hosting of major facilities is one of the clearest indicators of the maturation of contemporary Czech physics. By the end of the period, internationalisation had become an operating principle of Czech physics rather than a separate policy objective.

Conclusion

Physics in Contemporary Czechia, 1993–2025: From Scientific Continuity to a European Research and Innovation Ecosystem

The development of physics in Czechia between 1993 and 2025 is best understood not as a rupture with the Czechoslovak past but as a transformation of a strong inherited scientific system. The independent Czech Republic began with established institutes, university departments, observatories, accelerator laboratories, plasma facilities, and internationally recognised scientific schools. This inheritance supplied expertise in condensed matter, nuclear physics, plasma physics, optics, astronomy, theoretical physics, and instrumentation. It also preserved professional communities capable of maintaining complex experimental facilities during a period of institutional and economic change. The post-1993 system therefore did not need to create modern physics from an institutional vacuum. Its central task was to reorganise inherited capacities under new national conditions while reconnecting them more deeply with European and global science. Continuity was particularly visible in the Czech Academy of Sciences, Charles University, the Czech Technical University in Prague, Masaryk University, Palacký University, and the long-established research centres at Řež and Ondřejov. At the same time, continuity did not imply institutional immobility because laboratories, funding structures, research priorities, and forms of international cooperation changed substantially. The resulting trajectory combined preservation of scientific competence with gradual reorientation towards a more open, competitive, and infrastructure-intensive research system.

The dissolution of Czechoslovakia in 1993 was therefore a political and administrative watershed rather than the beginning of Czech physical science. Institutes of the former Czechoslovak Academy of Sciences were reorganised within the Academy of Sciences of the Czech Republic, later renamed the Czech Academy of Sciences. Universities adapted to new financing models, competitive grants, expanding doctoral education, and greater international mobility. Research institutes acquired new legal and managerial forms, while public research funding became progressively connected with evaluation and project competition. Several institutions also had to redefine their scientific missions in response to reduced central planning and stronger interaction with international partners. This transition was difficult because expensive experimental physics requires long-term continuity that cannot be reconstructed rapidly after institutional disruption. Czech physics nevertheless preserved its principal scientific schools and maintained enough technical capacity to modernise them during the following decades. The survival of this institutional base was one of the most important preconditions for later success in large European infrastructures. By the 2000s, the question was no longer whether Czech physics could preserve its inherited competence, but how that competence could be embedded in a new European research environment. Institutional modernisation after 1993 thus converted continuity into a platform for expansion rather than merely conserving the structures of the previous period.

European integration became the decisive external framework for the next stage of development. Czech membership in the European Organization for Nuclear Research from 1993 connected the national particle-physics community directly with one of the world's largest laboratories. Accession to the European Union in 2004 subsequently expanded

opportunities for research funding, infrastructure investment, mobility, and participation in framework programmes. Czech membership in the European Southern Observatory from 2007 transformed the observational possibilities of national astronomy. Fusion research became increasingly integrated through Euratom arrangements and later through the European Consortium for the Development of Fusion Energy. Nuclear physics entered long-term projects associated with the European Spallation Source, the Facility for Antiproton and Ion Research, and SPIRAL2. These links changed international cooperation from a set of bilateral contacts into a structural component of national scientific organisation. European integration therefore became an operating condition of Czech physics rather than an additional layer placed on top of domestic research.

The most profound institutional change was the transition towards an infrastructure-based model of science. In this model, scientific capability depends not only on individual laboratories or departments but on coordinated access to large instruments, specialised facilities, shared data systems, and international user programmes. Czech researchers increasingly worked with particle accelerators, neutron sources, high-power lasers, astronomical observatories, supercomputers, and tokamaks whose construction and operation exceeded the capacity of a single university. Domestic institutions responded by creating national research infrastructures and by formalising participation in facilities located abroad. The Czech Roadmap of Large Research Infrastructures provided an important policy framework for this transformation. Research teams had to learn how to operate within peer-reviewed access schemes, multinational governance structures, technical boards, and long-term upgrade cycles. Engineers and physicists became responsible for in-kind contributions whose quality had to satisfy international standards. Scientific success increasingly depended on instrumentation, software, data management, and project coordination as well as on the originality of a physical hypothesis. This infrastructure model also encouraged specialisation because Czech groups could contribute strongly in selected areas without reproducing the entire experimental chain nationally. It therefore allowed a medium-sized research system to participate in frontier science on terms that were more substantial than simple external access. By 2025, infrastructure participation had become one of the defining organisational principles of Czech physics.

This transformation is particularly visible in particle and nuclear physics. Czech groups at the Institute of Physics, Charles University, the Czech Technical University in Prague, and the Nuclear Physics Institute became long-term participants in major CERN experiments. Their work included detector construction, electronics, radiation monitoring, software, computing, data analysis, and physics interpretation. The national research system therefore contributed technical components and scientific labour rather than merely consuming data generated elsewhere. The same logic shaped FAIR-CZ, ESS-Scandinavia-CZ, SPIRAL2-CZ, and the accelerator programmes at Řež. Domestic facilities such as the U-120M cyclotron, TR-24 cyclotron, Tandetron, neutron instruments, and accelerator mass spectrometry remained important because they supported training, preparatory measurements, nuclear data, materials research, and technological development. International facilities extended this capability into energy and particle regimes that could not be reproduced nationally. The resulting system demonstrates how local infrastructure and international access can reinforce rather than replace one another.

Astronomy followed a comparable path of integration through a different technological model. Ondřejov remained the principal national professional observatory and preserved strong

schools in solar, stellar, meteor, asteroid, and relativistic research. Charles University sustained university-based astronomy and theoretical gravitation, while Brno and Opava developed distinctive astrophysical specialisations. Czech accession to the European Southern Observatory gave these national schools systematic access to facilities in Chile whose collecting area, angular resolution, and wavelength coverage greatly exceeded domestic possibilities. Participation in the Atacama Large Millimeter/submillimeter Array added another layer of international observational infrastructure. The Czech ALMA Regional Centre node showed that scientific value could also be created through data expertise, user support, and specialised calibration knowledge. Projects such as PLATOSpec demonstrated movement from external use towards Czech-led instrumentation at an international observatory site. Astronomy therefore became a clear example of how domestic continuity and international infrastructure can coexist within one research strategy. National telescopes retained their value for monitoring, rapid follow-up, education, and long-term programmes, while international observatories supplied capabilities impossible to reproduce at home.

Fusion research reveals the same evolution in an especially coherent institutional sequence. The Institute of Plasma Physics preserved a national experimental tradition through CASTOR during the 1990s and early 2000s. Association with Euratom at the end of 1999 integrated Prague more systematically into the European fusion programme. The transfer and reconstruction of COMPASS moved Czech research into diverted, H-mode-capable tokamak physics directly relevant to reactor-oriented questions. Prague teams developed strong expertise in edge plasma, transport, diagnostics, magnetic perturbations, disruptions, runaway electrons, and plasma exhaust. Participation in EUROfusion connected this domestic work with experiments on larger European machines and with common modelling programmes. COMPASS Upgrade represents the next stage because it is being constructed around high-field, high-power-exhaust conditions selected specifically for future fusion challenges. Its design reflects knowledge accumulated through both domestic experiments and European collaboration. Czech fusion research consequently moved from maintaining a small national tokamak to contributing specialised experimental capability to the European path towards the International Thermonuclear Experimental Reactor and a demonstration fusion power plant. The continuity from CASTOR to COMPASS and COMPASS Upgrade is therefore simultaneously scientific, technological, and institutional. It also shows how national specialisation can remain meaningful inside a strongly coordinated European programme. Fusion became one of the fields in which Czech physics developed a distinctive role that is internationally visible without attempting to reproduce every element of reactor science domestically. This specialised contribution is one of the clearest outcomes of the post-1993 transformation.

Laser physics provides the strongest example of Czechia moving from participation in foreign infrastructure towards hosting research facilities of European significance. The earlier Prague Asterix Laser System established important domestic competence in high-energy laser–plasma interaction. HiLASE then created a dedicated centre for high-average-power pulsed laser technologies in Dolní Břežany. ELI Beamlines expanded this development to petawatt and multi-petawatt regimes within the distributed Extreme Light Infrastructure. The creation of ELI European Research Infrastructure Consortium gave this development a durable European legal and governance framework. Its statutory seat in Dolní Břežany gave Czechia a role very different from that of a country whose researchers only travel abroad to use large instruments. Czech institutions now had to host international users, operate complex laser systems,

provide technical support, and contribute to multinational governance. This shift symbolises a wider maturation of the national research system.

The Dolní Břežany laser cluster also demonstrates why hosting infrastructure has scientific consequences beyond prestige. ELI Beamlines combines high-power ultrashort lasers with experimental stations for plasma, particles, X-rays, materials, molecular science, and biomedical research. HiLASE complements this orientation through high-average-power diode-pumped systems designed for repeated energetic operation and technological applications. The coexistence of the two centres creates a concentration of expertise in laser engineering, optics, target systems, diagnostics, radiation safety, materials processing, and control technologies. International users introduce scientific questions that would not necessarily emerge from an internal institutional programme. Industrial users impose requirements of reliability, throughput, component lifetime, and process reproducibility that feed back into laser development. The cluster therefore combines fundamental and applied research more tightly than a conventional academic laboratory. Achievements such as the BIVOJ high-energy high-repetition laser and the multi-petawatt ATON system placed Czech laser technology at the international frontier. At the same time, laser shock peening, micromachining, optical-damage testing, and surface structuring created direct routes towards industrial application. Dolní Břežany consequently became a visible example of a Czech research ecosystem in which scientific infrastructure, internationalisation, and innovation developed together. Its emergence marks one of the most substantial changes in the geography and scale of Czech physics since 1993.

Condensed-matter and materials physics provide a different example of national specialisation because their strength is distributed across several institutions. The Institute of Physics developed broad programmes in magnetism, superconductivity, semiconductors, crystallography, dielectric materials, functional alloys, surfaces, and nanostructures. Charles University sustained strong experimental and theoretical research on correlated systems, low-temperature physics, magnetism, and structural characterisation. Brno developed a complementary school based on Masaryk University, Brno University of Technology, and CEITEC. Regional centres in Plzeň, Olomouc, Ostrava, Pardubice, Liberec, and Zlín added further specialisations in thin films, nanomaterials, polymers, photonics, energy materials, and surface technologies. Shared infrastructures such as CzechNanoLab allowed expensive fabrication and microscopy resources to serve users across institutional boundaries. Czech materials physics therefore became increasingly polycentric rather than being dominated by one national laboratory. The field also illustrates how physics, chemistry, engineering, and nanotechnology became progressively more difficult to separate institutionally.

Spintronics and altermagnetism show how this distributed materials base could produce internationally distinctive scientific contributions. Czech researchers built long-term expertise in magnetic semiconductors, spin-orbit phenomena, antiferromagnetic materials, transport, and nanoscale device fabrication. Work on electrical control of antiferromagnetic order demonstrated that compensated magnetic materials could perform active information functions. Subsequent theoretical research identified symmetry principles that led to the formulation of altermagnetism as a distinct class of magnetic order. Experimental confirmation by international teams in 2024 gave the concept rapid global visibility. The significance of this development lies not only in the introduction of a new term but in the combination of symmetry theory, electronic structure, materials preparation, spectroscopy, and transport. Czech groups contributed at several stages of this process rather than entering

only after the field had been established elsewhere. Altermagnetism therefore became an example of a research direction in which Czech physicists helped shape the conceptual agenda of international condensed-matter physics. It also demonstrates the importance of long-term continuity, because the breakthrough emerged from expertise accumulated through earlier semiconductor and spintronic programmes. By 2025, the field had become one of the clearest cases of a Czech-originating contribution attracting broad worldwide scientific attention.

Quantum technologies provide another area in which older disciplinary strengths were recombined into a new national research direction. Optical quantum information in Olomouc developed from a long-established school of quantum and wave optics. Prague contributed quantum materials, superconductivity, spintronics, mathematical physics, quantum information, and emerging quantum sensing. Brno added nanofabrication, quantum materials, magnetic resonance, and low-dimensional systems. Ostrava supplied high-performance computing and, by 2025, a superconducting quantum computer integrated into a European computational project. National quantum communication initiatives connected these scientific capabilities with secure-network infrastructure. The resulting ecosystem remained heterogeneous, but that diversity was scientifically useful because quantum technology depends on several physical platforms rather than one universal device concept. Czech physics therefore entered the quantum-technology era through convergence of existing competencies rather than through the sudden creation of a single central programme. This pattern resembles the broader post-1993 evolution of the national research system.

Optics and photonics likewise illustrate continuity combined with diversification. Palacký University became internationally visible in quantum optics, photonic information processing, structured light, and advanced optical instrumentation. The Joint Laboratory of Optics linked university research with the Institute of Physics and contributed optical expertise to astroparticle experiments. Prague groups developed ultrafast spectroscopy, nonlinear optics, nanophotonics, laser physics, and optical materials. Brno strengthened photonics through nanofabrication, spectroscopy, and metasurface research. HiLASE and ELI Beamlines added research infrastructures operating at power and intensity regimes inaccessible to conventional university laboratories. Industrial cooperation created additional pathways into optical coatings, precision instrumentation, surface processing, and high-power laser components. Czech optics therefore expanded from a set of academic schools into a vertically connected system extending from quantum experiments to industrial laser technologies. The field is one of the strongest examples of how national specialisation can span fundamental physics, infrastructure, and application within the same research ecosystem.

Computational physics became the connective tissue linking many of these specialisations. The growth of national high-performance computing transformed what could be attempted in materials theory, plasma simulation, astrophysics, nuclear structure, and data-intensive experiment. IT4Innovations in Ostrava established a sequence of increasingly powerful supercomputers and connected Czech users to European systems such as LUMI. e-INFRA CZ integrated computing, networking, cloud services, and data storage into a broader national digital environment. Particle physics relied on distributed computing to process Large Hadron Collider data, while astrophysics increasingly depended on large digital archives and numerical models. Materials researchers combined electronic-structure theory, molecular dynamics, and machine-learning potentials. Plasma physicists used kinetic and fluid simulation to interpret COMPASS and design COMPASS Upgrade. Artificial intelligence entered

physical research principally as a tool for inference, classification, surrogate modelling, and accelerated analysis. By 2025, computation was no longer a specialised auxiliary method but an infrastructure underlying much of Czech experimental and theoretical physics.

The regional development of Czech physics strengthened this system by preventing frontier research from becoming excessively concentrated in Prague. Brno became a major centre for condensed matter, microscopy, nanotechnology, semiconductor physics, and photonics. Olomouc developed an internationally competitive profile in quantum optics, optical instrumentation, and advanced materials. Plzeň specialised in plasma processing, thin films, laser technologies, physical engineering, and functional materials. Ostrava combined supercomputing with energy-oriented materials, nanotechnology, and emerging quantum computing. Liberec turned polymer and textile expertise into internationally recognised nanofibre technologies. Pardubice developed important research in chalcogenide, photonic, and electronic materials, while Zlín built a strong polymer-systems research environment. These centres did not reproduce the entire disciplinary spectrum of Prague or the Czech Academy of Sciences. Instead, they strengthened the national system through focused areas in which local universities, infrastructure, and regional industry could interact. Polycentric development therefore became an important source of resilience and technological diversity.

The relationship between fundamental and applied physics changed substantially during the same period. In the early post-1993 transition, these categories were often treated institutionally as separate missions associated with universities, Academy institutes, or industrial research. The infrastructure model gradually made the boundary more porous. Detector physics at CERN produced technologies in sensors, electronics, radiation monitoring, and data acquisition. High-power laser research generated applications in surface treatment, materials testing, and precision manufacturing. Nanophysics combined questions about electronic or magnetic structure with device fabrication and industrial characterisation. Plasma physics connected confinement theory with materials, power systems, diagnostics, and reactor engineering. Semiconductor research linked defects, epitaxy, microscopy, and quantum transport with Europe's renewed concern about technological capacity. The most successful Czech programmes therefore tended to be those in which application generated new physical questions rather than replacing fundamental research with routine engineering. This interaction helped create a research and innovation ecosystem rather than a simple linear pipeline from laboratory discovery to commercial product. It also strengthened cooperation among universities, Academy institutes, research infrastructures, and companies.

Research infrastructures altered the professional culture of Czech physics as strongly as they altered its equipment base. Scientists increasingly had to work inside collaborations containing hundreds or thousands of researchers from many countries. Experimental results required common calibration procedures, internal review, shared software, long-term data stewardship, and coordinated publication rules. Engineers had to document components according to international standards and design them for integration with systems produced elsewhere. Doctoral students learned to divide their time between domestic institutions and facilities abroad. Senior researchers increasingly served on international boards, scientific committees, and infrastructure councils. These experiences encouraged professional practices that were less nationally bounded than those of the early 1990s. English became the routine working language of many teams even when their home institution remained entirely Czech. Internationalisation therefore changed everyday scientific behaviour as well as the formal structure of cooperation. The Czech research system became progressively embedded

in transnational professional communities whose standards influenced national laboratories in return. By 2025, this culture of distributed collaboration had become normal across much of experimental physics.

Mobility played a central role in this transformation because advanced instrumentation requires forms of practical knowledge that cannot be transmitted fully through publications. Czech researchers travelled to CERN, ESO sites, FAIR-related laboratories, EUROfusion tokamaks, synchrotrons, neutron sources, and astroparticle observatories. Foreign specialists came to Dolní Břežany, Prague, Brno, Olomouc, Ostrava, and other Czech centres as users, collaborators, or employees. These movements created scientific networks that often outlasted the particular grant or experiment that initiated them. Returning researchers brought methods, software practices, laboratory standards, and new questions back into national institutions. International facilities therefore acted as training environments as well as sources of data. The effect was particularly important for smaller regional centres that could gain direct access to frontier expertise without reproducing every technology locally. Mobility also made Czech scientific careers less dependent on permanent relocation abroad, because international work could be combined with a stable institutional base at home. The circulation of people thus became one of the mechanisms through which international infrastructure produced domestic scientific capacity. This circulation was as important to the modernisation of Czech physics as the construction of new buildings or purchase of new instruments.

The scale of Czech participation in global projects also changed the country's scientific position qualitatively. During the 1990s, many international links were primarily about regaining access to established laboratories and reconnecting scientific communities after decades of political separation. During the 2000s, Czech institutions increasingly became reliable partners responsible for subsystems, data analysis, and specialised technologies. During the 2010s, they helped construct large European infrastructures through in-kind contributions and national nodes. During the 2020s, Czechia also hosted facilities and governance structures of European significance. ELI ERIC is the most visible example because its statutory seat is located in Dolní Břežany. COMPASS Upgrade represents a different form of hosting by creating a specialised national machine intended to fill a recognised gap in the European fusion programme. IT4Innovations similarly turned Ostrava into a national and European computational node. This progression shows a movement from access, through participation, towards co-ownership and hosting. It is one of the most important indicators that the Czech research system matured institutionally between 1993 and 2025. The country increasingly contributed infrastructure value to Europe rather than only receiving access to facilities funded and operated elsewhere. This change does not eliminate dependence on international cooperation, but it makes that dependence more reciprocal.

The same evolution can be observed in scientific identity. Czech physics after 1993 did not become internationally visible by attempting to compete in every possible field. Its strongest results emerged from a limited number of areas supported by sustained institutional competence. High-intensity and high-average-power laser physics became one of these areas through PALS, HiLASE, and ELI Beamlines. Plasma and fusion research became another through the continuity from CASTOR to COMPASS and COMPASS Upgrade. Spintronics and altermagnetism provided a third, rooted in condensed-matter theory, magnetic materials, and nanoscale transport. Quantum optics in Olomouc, neutron and accelerator physics at Řež, microscopy in Brno, and astronomical specialisations at Ondřejov, Brno, and Opava added further recognisable strengths. These areas differ greatly in method, but all depend on long-

term accumulation of expertise rather than short-lived thematic fashion. National specialisation therefore developed through path dependence combined with selective modernisation. The strongest Czech contributions were usually those in which historical expertise could be connected to a new international problem or infrastructure.

The role of the Czech Academy of Sciences remained crucial throughout this transition. Its institutes preserved long-term research programmes that would have been difficult to maintain under short university funding cycles alone. The Institute of Physics provided national leadership in particle physics, condensed matter, materials, spintronics, optics, and major laser infrastructure. The Nuclear Physics Institute sustained accelerators, neutron methods, theoretical nuclear physics, dosimetry, and international infrastructure participation. The Institute of Plasma Physics preserved experimental fusion research and developed COMPASS Upgrade. The Astronomical Institute maintained the national professional observatory and broad research programmes from the Sun to galaxies and compact objects. Academy institutes also supplied open-access facilities that were used by university researchers and industrial partners. Their contribution was therefore not limited to the employment of full-time researchers. They formed much of the long-term institutional backbone on which infrastructure-based Czech physics was constructed.

Universities were equally important because they linked these research capacities to education and the renewal of scientific communities. Charles University remained central to theoretical physics, particle and nuclear physics, astronomy, condensed matter, optics, and quantum research. The Czech Technical University combined strong mathematics and physics with engineering, detectors, lasers, nuclear technologies, and plasma education. Masaryk University contributed condensed matter, astrophysics, materials, and theoretical research, while Brno University of Technology added nanotechnology, microscopy, photonics, and physical engineering. Palacký University established one of the country's strongest optical and quantum schools. Regional technical universities in Plzeň, Ostrava, Liberec, Pardubice, and Zlín developed specialised areas connected with materials, computation, energy, nanotechnology, and industrial physics. The university system therefore provided a geographically distributed training base for the national research infrastructure. Joint supervision and shared laboratories reduced the institutional distance between universities and the Czech Academy of Sciences. The result was a research system in which advanced facilities and formal education became increasingly interdependent. This educational dimension is essential because infrastructure without a continuing supply of trained researchers would have limited long-term value. By 2025, the circulation of students among universities, Academy institutes, and international facilities had become one of the central mechanisms reproducing Czech physics.

The period also demonstrates the importance of continuity in scientific schools while cautioning against interpreting them as closed national traditions. Prague, Brno, Olomouc, Ostrava, Plzeň, Opava, Liberec, and other centres developed distinctive profiles, but their researchers increasingly worked inside overlapping international networks. The Prague physics school is meaningful because of interaction among FZU, Charles University, the Czech Technical University, and external infrastructures rather than because it is administratively unified. The Brno school depends on cooperation among Masaryk University, Brno University of Technology, CEITEC, and regional microscopy industry. The astronomy network links Ondřejov, Prague, Brno, and Opava through shared scientific problems and international observatories. Regional centres draw strength from specialisation while depending on national

and European facilities for complementary methods. Scientific schools therefore became networked communities rather than geographically self-sufficient institutions. Their continuity lies in accumulated expertise, training practices, and research questions, not in isolation from external influence. This network character is one of the defining features of contemporary Czech physical science. It also explains how a relatively small country can sustain a disciplinary range extending from particle collisions and fusion plasmas to quantum optics and astrophysical cosmology.

The emergence of world-level Czech research directions should therefore be interpreted as the outcome of this institutional ecology rather than as a sequence of isolated breakthroughs. Multi-petawatt laser physics required decades of optical research, infrastructure investment, international recruitment, and European governance. COMPASS Upgrade depends on national plasma traditions, Euratom integration, EUROfusion participation, and engineering competence accumulated through earlier tokamaks. Altermagnetism emerged from long-term work in magnetism, spintronics, symmetry theory, materials preparation, and international spectroscopy. Similar chains can be identified behind advances in quantum optics, neutron instrumentation, microscopy, and computational materials science. Major achievements are consequently embedded in organisations, technical communities, and training systems that take decades to develop. This perspective is especially important when evaluating a period beginning in 1993, because many successful post-1993 programmes were possible only because earlier Czechoslovak institutions had preserved relevant expertise. Modernisation gave that expertise new organisational forms and access to wider resources. The relationship between continuity and innovation is therefore not contradictory but causal. Czech physics became internationally more innovative precisely because it was able to modernise a substantial inherited scientific base rather than having to reconstruct one from the beginning.

By 2025, the Czech research system had thus moved far beyond the post-Czechoslovak task of institutional stabilisation. It possessed nationally coordinated participation in CERN, ESO, EUROfusion, FAIR, ESS, the Pierre Auger Observatory, the Cherenkov Telescope Array Observatory, and other major infrastructures. It hosted ELI Beamlines within ELI ERIC and maintained nationally significant centres in accelerators, lasers, nanotechnology, microscopy, astronomy, plasma physics, and high-performance computing. It supported specialised regional schools rather than concentrating all advanced research in one city. It had developed open-access facilities that served universities, Academy institutes, foreign researchers, and industrial users. Czech scientists participated in international governance as well as in experiments and publications. Domestic companies could enter research-infrastructure supply chains requiring advanced optics, electronics, mechanical engineering, software, and materials. The national system had therefore become simultaneously more international and more internally differentiated. This combination is characteristic of a mature European research ecosystem.

The historical trajectory from 1993 to 2025 can therefore be summarised as a movement from inherited scientific continuity towards institutionalised European interdependence. The first achievement was preservation of the strongest components of the Czechoslovak scientific base during political and economic transformation. The second was institutional modernisation through competitive funding, new legal structures, infrastructure policy, and stronger university–Academy cooperation. The third was deep European integration through membership, joint programmes, multinational experiments, and research mobility. The fourth was adoption of an infrastructure model in which access, construction, governance,

computation, and shared instrumentation became central to scientific capacity. The fifth was the development of specialised national strengths rather than indiscriminate disciplinary expansion. The sixth was Czechia's transition from being primarily a user of large foreign facilities towards also hosting and co-governing European research infrastructure. These processes created the conditions for internationally visible contributions in high-intensity laser physics, fusion research, spintronics, altermagnetism, quantum optics, nuclear science, astrophysics, and computational physics. None of these outcomes can be attributed to a single reform or institution. They emerged from the cumulative interaction of historical continuity, European integration, infrastructure investment, education, mobility, and scientific specialisation. The Czech experience therefore provides a clear example of how a medium-sized national research system can increase international influence by combining selective excellence with deep participation in shared scientific institutions. By the end of 2025, Czech physics had become not simply a national collection of laboratories, but an active component of the European and global research and innovation ecosystem.

Chronological Timeline 1993–2025

Key Milestones in the Development of Physical Science in Czechia

Year	Key milestone	Significance for Czech physics
1993	Establishment of the independent Czech Republic and reorganisation of the national scientific system. The institutes of the former Czechoslovak Academy of Sciences continued within the newly constituted Academy of Sciences of the Czech Republic.	Preserved the principal Czechoslovak scientific schools in physics while creating the institutional basis for their development within an independent national research system.
1993	The Czech Republic became a Member State of the European Organization for Nuclear Research (CERN) on 1 July.	Established long-term Czech participation in European high-energy physics and provided stable institutional access to CERN accelerators, experiments, detector programmes, computing, and scientific training.
1994	The former Institute of Radiation Dosimetry was incorporated into the Nuclear Physics Institute of the Academy of Sciences at Řež.	Expanded the national nuclear-physics programme towards radiation dosimetry, radiation protection, environmental measurements, and studies of biological effects of ionising radiation.
1996–1998	Major reconstruction of the U-120M cyclotron at the Nuclear Physics Institute in Řež. The machine was adapted for acceleration and extraction of negative hydrogen and deuterium ions.	Increased beam intensity substantially and extended the useful lifetime of one of the country's principal accelerator facilities for nuclear reactions, radionuclide production, neutron generation, and materials research.
1997	Transfer of the ASTERIX IV high-energy iodine laser from the Max Planck Institute for Quantum Optics to the Institute of Physics of the Academy of Sciences.	Created the technological basis for the future Prague Asterix Laser System and significantly strengthened Czech high-energy laser and laser–plasma physics.
1998	Establishment of the Prague Asterix Laser System (PALS) Research Centre by the Institute of Physics and the Institute of Plasma Physics.	Created a national high-energy laser facility capable of supporting laser–plasma interaction, X-ray generation, high-energy-density physics, and international user experiments.
1999	The Institute of Plasma Physics signed the Euratom association agreement on 22 December.	Integrated Czech magnetic-confinement fusion research formally into the coordinated European fusion programme and opened systematic access to common European facilities and research programmes.

Year	Key milestone	Significance for Czech physics
2000	PALS entered scientific operation; the reconstructed laser was officially launched on 8 June.	Established Czechia as an internationally accessible centre for kilojoule-class laser research and provided experience later important for ELI Beamlines and other large laser projects.
2002	The major flood affecting the Řež research site damaged infrastructure associated with the U-120M cyclotron. Extensive reconstruction followed.	Demonstrated the institutional resilience of Czech accelerator science and led to modernisation of several technical systems during restoration.
2004	Czechia joined the European Union on 1 May.	Opened a new phase of integration into European Framework Programmes, infrastructure policy, researcher mobility, structural funding, and multinational research networks.
2004	The United Kingdom Atomic Energy Authority offered the COMPASS-D tokamak to the Institute of Plasma Physics in Prague.	Initiated the transition from the small CASTOR tokamak towards an advanced diverted device capable of addressing ITER-relevant plasma physics.
2005	The Czech government approved acceptance and reconstruction of COMPASS in Prague.	Established the institutional and financial basis for creating a substantially more advanced national fusion-research facility.
2005	Installation of the Tandetron 4130 MC at the Nuclear Physics Institute in Řež.	Added modern ion-beam analysis, implantation, nuclear microprobe methods, materials modification, and nanoscale analytical capabilities to the CANAM accelerator complex.
2006	The Extreme Light Infrastructure (ELI) entered the European Strategy Forum on Research Infrastructures roadmap.	Created the European strategic framework from which the later Czech ELI Beamlines facility developed.
2006	CASTOR ended operation at the Institute of Plasma Physics and was transferred to the Czech Technical University in Prague.	Preserved the former research tokamak as the educational GOLEM facility while IPP concentrated its resources on reconstruction of COMPASS.
2006	Czechia signed the agreement to join the European Southern Observatory on 22 December.	Prepared the national astronomical community for systematic access to world-leading optical, infrared, and submillimetre observatories.
2007	Czechia became a full Member State of the European Southern Observatory on 30 April.	Czech astronomers gained regular competitive access to the Very Large Telescope, La Silla facilities, APEX, the European share of ALMA, and later the Extremely Large Telescope programme.

Year	Key milestone	Significance for Czech physics
2007	COMPASS was transported from Culham to Prague and installed in a newly constructed experimental hall.	Marked the physical establishment of a new generation of Czech tokamak research.
2007	Academy institutes, including major physics institutes, completed transition to the legal status of public research institutions.	Modernised governance and provided a new legal framework for long-term research, infrastructure operation, employment, and project participation.
2008	The Laboratory of Nanostructures and Nanomaterials was established at the Institute of Physics.	Concentrated nanofabrication, semiconductor growth, microscopy, carbon and diamond research, and nanoscale characterisation within a shared infrastructure.
2008	First plasma in the reconstructed COMPASS tokamak on 9 December.	Demonstrated successful transfer and reconstruction of the British tokamak and opened the way towards systematic experimental operation in Prague.
2009	Public test operation of COMPASS began on 19 February.	Established Prague as an operational European tokamak centre with capabilities in plasma control, diagnostics, auxiliary heating, and edge physics.
2009	Czechia was selected to host the ELI Beamlines pillar of the Extreme Light Infrastructure.	Represented a major change in Czech scientific ambition, moving the country towards hosting a European-scale facility rather than only using large installations abroad.
2010	The first Czech Roadmap of Large Infrastructures for Research, Experimental Development and Innovation included major physics facilities such as CANAM.	Formalised the large-research-infrastructure model as a central component of Czech science policy and long-term research financing.
2010	The Regional Centre of Advanced Technologies and Materials was established at Palacký University Olomouc.	Strengthened regional research in nanomaterials, low-dimensional systems, optics, magnetism, advanced characterisation, and interdisciplinary technologies.
2011	The European Commission approved financing for ELI Beamlines.	Enabled construction of one of Europe's major high-power laser infrastructures at Dolní Břežany.
2011	HiLASE was formally established as a new laser research centre.	Added a complementary Czech specialisation in high-average-power diode-pumped solid-state lasers and industrial laser applications.

Year	Key milestone	Significance for Czech physics
2011	The Central European Institute of Technology (CEITEC) project was approved in Brno.	Created the foundation for a major interdisciplinary infrastructure in nanotechnology, microscopy, advanced materials, semiconductor research, and life sciences.
2011	Development of CENTEM at the University of West Bohemia strengthened applied materials physics in Plzeň.	Expanded regional capability in surface engineering, laser processing, polymers, photonics, photovoltaics, and materials characterisation.
2012	COMPASS achieved H-mode on 29 November.	Moved Prague fusion research into the high-confinement regime central to modern tokamak and ITER-oriented physics.
2012	Czech teams participated in the ATLAS and ALICE scientific programmes during the year in which the Higgs boson was discovered at the Large Hadron Collider.	Confirmed Czech integration into frontier particle physics at CERN and strengthened domestic expertise in detector technology, data analysis, and large-scale scientific collaboration.
2012–2013	Construction of the ELI Beamlines and HiLASE facilities advanced rapidly at Dolní Břežany.	Created the physical basis of what later became an internationally important Czech laser cluster.
2013	COMPASS obtained Type-I Edge Localised Modes in H-mode plasmas.	Enabled Prague researchers to study an ITER-relevant instability associated with the edge transport barrier and transient heat loads on plasma-facing components.
2013	The Anselm supercomputer entered operation at IT4Innovations in Ostrava.	Established the first major system of the future Czech national supercomputing centre and expanded domestic capacity for computational physics and engineering.
2013	The Centre of Materials and Nanotechnologies (CEMNAT) was founded at the University of Pardubice.	Strengthened Czech regional research in chalcogenides, photonics, thin films, electronic materials, photovoltaics, and nanostructures.
2014	HiLASE was formally inaugurated in Dolní Břežany on 24 September.	Established a dedicated national centre for high-average-power pulsed lasers, laser engineering, materials processing, and industrial applications.
2014	The Albert Einstein Centre for Gravitation and Astrophysics was established.	Strengthened cooperation among Czech groups in Prague and Opava working on general relativity, black holes, cosmology, gravitational physics, and relativistic astrophysics.

Year	Key milestone	Significance for Czech physics
2014	European fusion research was reorganised under EUROfusion.	The Czech fusion programme became part of a more integrated European roadmap leading from existing tokamaks towards ITER and DEMO.
2014	Prediction of current-induced relativistic Néel-order fields by Czech and international spintronics researchers.	Provided the theoretical mechanism that soon enabled electrical control of antiferromagnetic materials and helped establish Prague as a major centre of antiferromagnetic spintronics.
2015	The first construction phase of ELI Beamlines was completed in June and the centre was formally inaugurated on 19 October.	Established Czechia as host of one of the three principal European Extreme Light Infrastructure facilities.
2015	The TR-24 high-current proton cyclotron entered operation at Řež.	Expanded Czech capacity for medical radionuclide research, proton irradiation, neutron generation, and applied nuclear physics.
2015	The Salomon supercomputer entered operation at IT4Innovations.	Raised Czech national computing capacity to the petaflop scale and enabled much larger simulations in materials, physics, chemistry, and engineering.
2015	The European Spallation Source became a European Research Infrastructure Consortium with Czech participation in the project.	Strengthened Czech integration into European neutron science and prepared national contributions to the BEER engineering diffractometer and other systems.
2016	Electrical switching of the antiferromagnet CuMnAs was experimentally demonstrated by an international team with major Czech participation.	Established antiferromagnetic spintronics as a practical experimental field and became one of the most influential Czech-associated condensed-matter results of the decade.
2016	The BIVOJ laser at HiLASE achieved approximately 105 J at 10 Hz.	Set a world-leading performance benchmark for high-energy, high-repetition-rate diode-pumped solid-state lasers.
2016	CEITEC Nano entered full operation in Brno.	Created the largest Czech clean-room centre for nanofabrication and a major platform for electron microscopy, semiconductor physics, nanomagnetism, photonics, and materials research.
2016	The Czech node of the European ALMA Regional Centre was established at the Astronomical Institute.	Embedded Czech astronomers directly in the European support infrastructure for

Year	Key milestone	Significance for Czech physics
		ALMA, with particular expertise in solar observing and interferometric data analysis.
2016	Conceptual design of COMPASS Upgrade was presented internationally.	Defined the next generation of Prague tokamak research around high magnetic field, high plasma current, and reactor-relevant power exhaust.
2017	The COMPASS Upgrade project formally began on 1 December.	Started development of a purpose-built Czech high-field tokamak intended to fill a specialised role within the European fusion programme.
2018	ELI Beamlines entered trial operation and progressively commissioned its laser and experimental systems.	Marked the transition from construction towards operation as an international user facility.
2018	Czech involvement in the European High Performance Computing initiative expanded through EuroHPC.	Connected national supercomputing development more closely with Europe's emerging coordinated high-performance computing ecosystem.
2019	Czechia became an associated member of FAIR in March.	Formalised Czech participation in one of Europe's largest future accelerator infrastructures for nuclear, hadron, atomic, plasma, and applied physics.
2019	The Barbora supercomputer entered operation at IT4Innovations, together with strengthened hardware for artificial-intelligence workloads.	Expanded computational capacity and accelerated the convergence of high-performance computing, data analytics, and machine learning.
2019	ELI Beamlines launched its first external commissioning and user activities.	Began the transition from a nationally constructed project into an open international scientific infrastructure.
2019	Major modernisation of the Perek two-metre telescope at Ondřejov.	Improved optical throughput and spectroscopic capability, extending the useful scientific lifetime of Czechia's largest optical telescope.
2020	CzechNanoLab was established as a distributed national nanotechnology infrastructure linking the Institute of Physics in Prague and CEITEC Nano in Brno.	Integrated two of the country's strongest nanofabrication and characterisation centres into a common open-access platform.
2020	The Institute of Physics at Silesian University in Opava became an independent university unit on 1 January.	Consolidated Opava as a national centre for relativistic astrophysics, black-hole physics, cosmology, computational physics, and data processing.

Year	Key milestone	Significance for Czech physics
2020	An optical two-qubit gate resistant to selected decoherence effects was demonstrated by researchers associated with the Olomouc quantum-optics school.	Reinforced the international position of Czech quantum optics and photonic quantum-information research.
2021	ELI became the Extreme Light Infrastructure European Research Infrastructure Consortium on 30 April.	Converted ELI from a group of major national projects into a formally governed European research infrastructure, with its statutory seat at Dolní Břežany.
2021	BIVOJ reached a maximum pulse energy of 146.5 J at 10 Hz during sustained high-energy operation.	Established another world-leading benchmark for high-average-power laser technology at HiLASE.
2021	The Karolina supercomputer was commissioned at IT4Innovations.	Increased Czech national supercomputing capacity to approximately 15.7 petaflops of theoretical peak performance and added powerful GPU resources for artificial intelligence.
2021	The final COMPASS discharge was performed on 20 August after more than 21,000 plasma discharges in Prague.	Closed the COMPASS experimental era and released the site for construction of COMPASS Upgrade while preserving the scientific team and research programme.
2021	The Czech Advanced Technology and Research Institute (CATRIN) began operation at Palacký University.	Consolidated interdisciplinary research on nanomaterials, advanced functional materials, environmental technologies, and biomedical applications in Olomouc.
2021	An intercity quantum-key-distribution demonstration between Ostrava and the Polish border region strengthened Czech experimental quantum communication.	Signalled the transition of Czech quantum research from laboratory optics towards practical secure-network technologies.
2022	The first Czech accelerator mass spectrometry laboratory at Řež entered routine operation in February.	Introduced ultra-sensitive measurement of carbon-14 and other rare isotopes for archaeology, environmental science, geology, and nuclear applications.
2022	Theoretical formalisation of altermagnetism was published by researchers including Libor Šmejkal, Jairo Sinova, and Tomáš Jungwirth.	Identified a new class of compensated magnetic order with unconventional spin-split electronic structure and initiated a rapidly expanding international research field.
2022	The Nuclear Physics Institute joined the League of Advanced European Neutron Sources.	Integrated the Czech neutron-science community more closely with the strategic network of Europe's leading neutron facilities.

Year	Key milestone	Significance for Czech physics
2022	LUMI entered scientific operation, providing Czech researchers access through the international consortium.	Extended Czech high-performance computing from national petascale systems to one of Europe's most powerful pre-exascale machines.
2023	ELI Beamlines became operationally integrated into the common ELI ERIC structure.	Completed the transition from a Czech implementation project towards routine operation within a multinational European research infrastructure.
2023	Major civil-construction work for COMPASS Upgrade advanced in Prague.	Marked the transition of the project from design and preparation towards physical installation of a new-generation national tokamak.
2023	The Czech quantum-communication infrastructure programme expanded within the European Quantum Communication Infrastructure framework.	Connected Czech universities, research institutes, and the national academic network with Europe's emerging secure quantum-communication architecture.
2024	Direct experimental evidence for altermagnetic spin splitting was reported in manganese telluride by an international team with major Czech participation.	Provided decisive experimental support for the altermagnetic state and established the Czech-associated concept as one of the most visible new directions in contemporary magnetism.
2024	Manufacturing and installation preparations for the COMPASS-U support structure and major systems accelerated.	Demonstrated that the new Czech high-field tokamak had moved from conceptual development into large-scale engineering realisation.
2024	PLATOSpec achieved major commissioning milestones at the La Silla Observatory.	Strengthened Czech leadership in dedicated spectroscopic follow-up for exoplanet missions and deepened the country's role within the ESO observational ecosystem.
2024	Modernisation of CzechNanoLab received major new investment for fabrication and characterisation equipment.	Reinforced Prague–Brno cooperation in nanoscience and upgraded national capability in semiconductor, nanophysics, and advanced-materials research.
2025	The Cherenkov Telescope Array Observatory became a European Research Infrastructure Consortium on 7 January, with Czechia among the founding members.	Moved Czech participation in very-high-energy gamma-ray astronomy from project construction towards formal co-governance of a global observatory.
2025	External design review of the COMPASS-U first-wall limiters and preliminary tungsten divertor design was completed in April.	Confirmed the maturity of key plasma-facing components required for high-

Year	Key milestone	Significance for Czech physics
		power-exhaust and reactor-relevant fusion experiments.
2025	The VLQ superconducting quantum computer was inaugurated at IT4Innovations in Ostrava on 23 September.	Added a 24-qubit quantum-computing platform to the Czech and European high-performance computing ecosystem and opened a new phase of hybrid quantum–classical research.
2025	The L4 ATON laser at ELI Beamlines reached 5.1 PW during a September test campaign.	Placed the Czech ELI facility among the world's leading multi-petawatt laser centres and demonstrated the maturity of its high-energy ultrafast infrastructure.
2025	Machine-learning methods were applied increasingly to frontier physical research, including cosmic-ray composition, materials prediction, astronomy, microscopy, and computational modelling.	Demonstrated the emergence of data-driven physics as a cross-cutting national methodology rather than an isolated computational speciality.
2025	Czechia completed the 1993–2025 period as both a participant in and a host of major European research infrastructures.	The national system had evolved from post-Czechoslovak institutional continuity towards an integrated European research ecosystem encompassing CERN, ESO, ELI ERIC, EUROfusion, FAIR, ESS, CTAO, Pierre Auger, EuroHPC, and other international infrastructures.

Major Czech Physics Institutions and Research Infrastructures, 1993–2025

Major Research Institutions and University Centres

Institution	Location	Profile	Key research directions	Significance for Czech physics
Institute of Physics of the Czech Academy of Sciences (FZU)	Prague; Dolní Břežany	Largest specialised physics research institute of the Czech Academy of Sciences	Particle physics; condensed matter; solid-state physics; magnetism; spintronics; altermagnetism; semiconductors; crystallography; nanophysics; optics; laser physics; advanced materials	Principal national centre for fundamental and applied physics; major Czech participant in CERN and international experiments; operator of ELI Beamlines, HiLASE, and major nanotechnology facilities
Nuclear Physics Institute of the Czech Academy of Sciences (NPI CAS)	Řež near Prague; Prague	National centre for nuclear and accelerator physics	Nuclear structure and reactions; theoretical nuclear physics; neutron science; accelerator physics; ion-beam analysis; dosimetry; radionuclides; radiopharmaceutical research; accelerator mass spectrometry	Maintains the main Czech accelerator complex and coordinates Czech participation in FAIR, ESS, SPIRAL2, and other European nuclear infrastructures
Institute of Plasma Physics of the Czech Academy of Sciences (IPP CAS)	Prague	National centre for plasma physics and magnetic-confinement fusion	Tokamak physics; edge plasma; transport; turbulence; plasma exhaust; disruptions; runaway electrons; plasma diagnostics; modelling; plasma-facing materials; thermal plasma	Core of the Czech fusion programme; operated CASTOR and COMPASS; developing COMPASS Upgrade; national coordinator within EUROfusion
Astronomical Institute of the Czech Academy of Sciences (ASU CAS)	Ondřejov; Prague	Principal professional astronomical research institute in Czechia	Solar physics; stellar astrophysics; meteors and asteroids; galaxies; exoplanets; relativistic astrophysics; radio and submillimetre astronomy	Operates Ondřejov Observatory; central national astronomical institution; coordinates major links with ESO, ALMA, Solar Orbiter, and international observatories
Charles University – Faculty of Mathematics and Physics	Prague	Major research-intensive university centre for fundamental physics	Theoretical physics; gravitation; particle and nuclear physics; condensed matter; astronomy; astrophysics; optics; quantum physics; mathematical physics	One of the oldest and strongest Czech centres of university physics; provides theoretical depth and doctoral training across most major branches of physics
Charles University – Institute of Theoretical Physics	Prague	Specialised centre of fundamental theoretical physics	General relativity; gravitation; cosmology; quantum theory; mathematical physics; statistical physics; computational theory	Maintains the Prague theoretical-physics tradition and contributes strongly to Czech gravitation, cosmology, and mathematical physics

Institution	Location	Profile	Key research directions	Significance for Czech physics
Charles University – Institute of Particle and Nuclear Physics	Prague	University centre for experimental and theoretical particle and nuclear physics	CERN physics; nuclear structure; detector physics; high-energy data analysis; phenomenology; quantum field theory	Important training and research partner of FZU and CERN-CZ; connects university education directly with major international experiments
Charles University – Astronomical Institute	Prague	University astronomy and astrophysics centre	Stellar astrophysics; binaries; asteroids; celestial mechanics; orbital dynamics; observational astronomy	Provides a principal university training route into Czech astronomy and maintains close research links with Ondřejov
Czech Technical University in Prague – Faculty of Nuclear Sciences and Physical Engineering (FNSPE)	Prague	Physics and engineering faculty specialising in nuclear and advanced physical technologies	Nuclear and particle physics; quantum technologies; plasma physics; laser physics; solid-state engineering; dosimetry; mathematical physics	Distinctive Czech centre linking fundamental physics with engineering, instrumentation, nuclear technologies, and advanced technical education
Masaryk University – Department of Physics and related research groups	Brno	Major university physics centre in Moravia	Condensed matter; theoretical physics; astrophysics; semiconductor structures; X-ray science; plasma technologies; quantum materials	Principal academic physics centre in Brno; contributes strong theoretical, materials, stellar, and high-energy astrophysical programmes
Brno University of Technology – Institute of Physical Engineering	Brno	Applied and physical-engineering research centre	Surface physics; nanostructures; electron microscopy; nanoelectronics; nanophotonics; nanomagnetism; semiconductor physics; precision optics	Key institutional link between fundamental nanoscale physics, microscopy, engineering, and Brno's high-technology industrial environment
Central European Institute of Technology – CEITEC BUT	Brno	Interdisciplinary research institute for nanotechnology and advanced materials	Nanofabrication; nanophysics; microscopy; semiconductor materials; spintronics; nanomagnetism; photonics; low-dimensional materials	One of the principal Czech centres for interdisciplinary nano- and materials research; major open-access infrastructure for academic and industrial users
Palacký University – Department of Optics	Olomouc	Major national centre for modern and quantum optics	Quantum information; quantum communication; single-photon physics; quantum metrology; structured light; holography; optical imaging	Established Olomouc as an internationally recognised Czech centre of quantum optics and photonic technologies
Joint Laboratory of Optics, Palacký University and FZU	Olomouc	Joint university–Academy optics research centre	Quantum optics; nonlinear optics; optical coatings; laser technologies; holography; astroparticle instrumentation	Connects Olomouc optics with the Czech Academy of Sciences and contributes instrumentation to Pierre Auger and CTA
Czech Advanced Technology and Research Institute (CATRIN)	Olomouc	Interdisciplinary institute for advanced materials and nanotechnologies	Two-dimensional materials; functional nanomaterials; magnetic materials; surfaces; sensing; environmental and biomedical technologies	Extends the Olomouc research profile from optics towards advanced materials and interdisciplinary nanoscience

Institution	Location	Profile	Key research directions	Significance for Czech physics
University of West Bohemia – Department of Physics	Plzeň	Applied-physics university centre	Plasma physics; thin films; surface modification; solid-state physics; plasma chemistry; physical engineering	Core of the Plzeň school of plasma-assisted materials processing and applied physical technologies
New Technologies – Research Centre (NTC)	Plzeň	Interdisciplinary applied research centre	Advanced and quantum materials; laser processing; infrared technologies; computational modelling; surfaces; energy systems	Major regional centre connecting materials physics with engineering and industrial applications
IT4Innovations National Supercomputing Center	Ostrava	National high-performance computing centre	Computational physics; materials modelling; artificial intelligence; high-performance data analytics; parallel algorithms; quantum–classical computing	Provides Czech national petascale computing and access to European HPC infrastructure; central to computational and data-driven physics
VSB – Technical University of Ostrava – Nanotechnology Centre / CEET	Ostrava	Energy- and materials-oriented research centre	Nanomaterials; energy storage; surfaces; microscopy; magneto-optics; plasmonics; spintronics; environmental technologies	Connects nanophysics and materials characterisation with the industrial and energy transformation of the Moravian-Silesian region
Silesian University in Opava – Institute of Physics	Opava	Specialised theoretical and computational physics centre	Black holes; neutron stars; general relativity; cosmology; high-energy astrophysics; computational physics; multimessenger astronomy	Created a distinctive Czech regional school of relativistic astrophysics and strong-gravity physics
Technical University of Liberec – Faculty of Textile Engineering	Liberec	Applied-physics and materials centre rooted in fibre and textile science	Nanofibres; electrospinning; polymer physics; nonwoven materials; filtration; functional fibres	Internationally visible through development of scalable nanofibre technologies and their industrial applications
Technical University of Liberec – Institute for Nanomaterials, Advanced Technologies and Innovation (CxI)	Liberec	Interdisciplinary materials and engineering centre	Nanomaterials; coatings; membranes; plasma modification; environmental technologies; microscopy; mechatronics	Broadens the Liberec nanotechnology school beyond textiles towards advanced materials, environmental applications, and industrial research
University of Pardubice – Centre of Materials and Nanotechnologies (CEMNAT)	Pardubice	Research infrastructure for functional and photonic materials	Chalcogenide glasses; amorphous materials; photonics; thin films; semiconductors; photovoltaics; nanostructures	Maintains a distinctive Czech specialisation in chalcogenide, optical, and electronic materials
Tomas Bata University – Centre of Polymer Systems	Zlín	Research centre for polymer and soft-material systems	Polymer physics; composites; rheology; functional polymers; surfaces; processing technologies	Connects fundamental materials physics with the strong polymer and manufacturing traditions of the Zlín region

Major Research Infrastructures

Research infrastructure	Location / scope	Profile	Key research directions and capabilities	Significance for Czech physics
ELI Beamlines	Dolní Břežany	European high-power laser infrastructure hosted in Czechia	Petawatt and multi-petawatt lasers; ultrafast science; laser–plasma interaction; particle acceleration; high-energy-density physics; X-ray sources; materials and biomedical applications	One of the most important international research infrastructures ever established in Czechia; transformed the country into a host of European-scale extreme-light science
ELI European Research Infrastructure Consortium (ELI ERIC)	Statutory seat in Dolní Břežany; distributed European infrastructure	European governance and user-access framework for extreme-light facilities	International user access; coordination of high-power laser facilities; scientific networking; joint infrastructure development	Symbolises Czechia's transition from participant in foreign infrastructures to host and co-governor of a major European research organisation
HiLASE Centre	Dolní Břežany	High-average-power laser research and technology centre	Diode-pumped solid-state lasers; BIVOJ; PERLA; laser shock peening; micromachining; surface functionalisation; optical-damage testing	Internationally significant Czech centre for energetic repetitive lasers and industrial laser applications
Prague Asterix Laser System (PALS)	Prague	High-energy laser and laser-plasma facility	Kilojoule laser pulses; laser-produced plasma; X-rays; energetic particles; high-energy-density physics; laboratory astrophysics	Established the modern Czech high-energy laser tradition and provided experience later important for ELI and HiLASE
COMPASS	Prague	Research tokamak operated until 2021	H-mode; edge and Scrape-Off Layer physics; turbulence; magnetic perturbations; disruptions; runaway electrons; plasma diagnostics	Integrated Prague fusion research with ITER-oriented European science and prepared the scientific basis for COMPASS Upgrade
COMPASS Upgrade (COMPASS-U)	Prague	High-field tokamak under development by 2025	High magnetic field; high plasma current; power exhaust; advanced divertors; negative triangularity; plasma-facing materials; ITER- and DEMO-relevant conditions	Designed to occupy a specialised role in the European fusion programme and strengthen Prague as a major fusion research centre
GOLEM Tokamak	Czech Technical University, Prague	Educational tokamak derived from CASTOR	Plasma generation; magnetic confinement; diagnostics; remote experiments; student training	Preserves direct hands-on tokamak education and connects undergraduate and doctoral training with the Czech fusion research tradition
Centre of Accelerators and Nuclear Analytical Methods (CANAM)	Řež; Prague	National open-access accelerator and neutron infrastructure	Cyclotrons; Tandetron; Microtron; neutron methods; accelerator mass spectrometry; ion-beam analysis; irradiation	Principal national infrastructure for accelerator-based nuclear physics and analytical methods

Research infrastructure	Location / scope	Profile	Key research directions and capabilities	Significance for Czech physics
U-120M Cyclotron	Řež	Multiparticle isochronous cyclotron	Nuclear reactions; nuclear astrophysics; fast-neutron production; activation; radionuclide research	Long-serving experimental foundation of Czech accelerator nuclear physics
TR-24 Cyclotron	Řež	High-current proton cyclotron	Radionuclide production; medical isotope research; proton irradiation; secondary neutrons	Modernised Czech high-current accelerator capability and expanded nuclear applications
Tandetron 4130 MC	Řež	Electrostatic tandem ion accelerator	Rutherford Backscattering Spectrometry; Elastic Recoil Detection Analysis; Particle-Induced X-ray Emission; implantation; nuclear microprobe	Key national facility for ion-beam analysis, nanomaterials, semiconductor studies, and cultural-heritage research
MILEA Accelerator Mass Spectrometry Laboratory	Řež	Ultra-sensitive isotope measurement facility	Carbon-14; beryllium-10; aluminium-26; iodine-129; uranium and plutonium isotopes	Introduced modern accelerator mass spectrometry to Czechia and linked nuclear physics with archaeology, geology, environmental science, and safeguards
LVR-15 Research Reactor neutron instruments	Řež	Neutron source operated by Research Centre Řež with NPI instruments	Neutron diffraction; scattering; residual stress; activation analysis; depth profiling; materials research	Maintains domestic neutron-science capability and provides the expertise underpinning Czech participation in ESS
CzechNanoLab	Prague and Brno	Distributed national nanotechnology infrastructure	Nanofabrication; electron microscopy; scanning-probe microscopy; lithography; deposition; structural and chemical analysis	Integrates FZU and CEITEC Nano into a common national platform for nanoscale research
CEITEC Nano	Brno	Open-access clean-room and nanocharacterisation infrastructure	Epitaxy; deposition; lithography; electron microscopy; surface analysis; X-ray tomography; semiconductor fabrication	One of Czechia's most important infrastructures for nanophysics, semiconductor research, microscopy, and advanced materials
Ondřejov Observatory	Ondřejov	Principal Czech professional astronomical observatory	Stellar spectroscopy; solar physics; meteors; asteroids; exoplanets; robotic telescopes	Central domestic observing base for Czech astronomy and training
Perek Two-Metre Telescope	Ondřejov	Largest optical telescope in Czechia	High-resolution stellar spectroscopy; binaries; hot stars; exoplanet follow-up	Flagship domestic optical telescope and long-term national training and observational facility
Czech ALMA Regional Centre Node	Ondřejov	National support node for ALMA	Interferometric data reduction; user support; solar ALMA observations; calibration and imaging	Embeds Czech astronomy directly in the European ALMA support network

Research infrastructure	Location / scope	Profile	Key research directions and capabilities	Significance for Czech physics
PLATOSpec	La Silla Observatory, Chile; Czech-led project	High-resolution spectroscopic facility	Radial velocities; stellar characterisation; exoplanet confirmation; support for European space missions	Represents Czech movement from user access towards leadership of dedicated instrumentation at an ESO observatory site
CERN-CZ	Czech national network linked to CERN	National infrastructure for Czech participation in CERN	ATLAS; ALICE; detector technology; computing; software; high-energy and nuclear physics	Principal organisational framework connecting Czech particle physics with CERN
FAIR-CZ	Czech national network linked to FAIR, Darmstadt	National infrastructure for heavy-ion, hadron, atomic, plasma, and nuclear physics	HADES; CBM; PANDA; NuSTAR; APPA; detector and engineering contributions	Connects Czech nuclear and particle physicists with one of Europe's largest emerging accelerator infrastructures
ESS-Scandinavia-CZ	Czech national node linked to ESS, Lund	National infrastructure for European neutron research	BEER engineering diffractometer; neutron optics; materials research; target-system technologies	Extends Czech neutron science from Řež into the European Spallation Source
BEER – Beamline for European Materials Engineering Research	ESS, Lund; Czech-German contribution	Engineering neutron diffractometer	In-situ phase transformations; stress; texture; deformation; processing	Major Czech contribution to ESS and a strategic route for future materials research using high-flux neutrons
SPIRAL2-CZ	Czech national node linked to GANIL/SPIRAL2, France	Nuclear and radioactive-ion research infrastructure	Nuclear reactions; radioactive beams; neutron science; target systems; detector development	Extends Czech accelerator physics towards exotic nuclei and international nuclear astrophysics
AUGER-CZ	Czech national participation in Pierre Auger Observatory, Argentina	Ultra-high-energy cosmic-ray infrastructure	Cosmic-ray spectrum; composition; anisotropy; fluorescence detection; atmospheric monitoring	Major Czech contribution to global astroparticle physics and a source of expertise in large optical detector systems
CTA-CZ / CTAO participation	Czech national network; observatory sites in Spain and Chile	Very-high-energy gamma-ray astronomy	Cherenkov telescopes; mirrors; atmospheric monitoring; calibration; gamma-ray astrophysics	Connects Czech optics, astronomy, and astroparticle physics with the next generation of ground-based gamma-ray observatories
IT4Innovations – Karolina	Ostrava	National petascale supercomputer	Numerical modelling; materials simulation; plasma physics; astrophysics; machine learning; engineering computation	Core domestic computational infrastructure for Czech data-intensive and theoretical physics
LUMI access through IT4Innovations	Finland / European consortium	European pre-exascale supercomputing infrastructure	Large-scale simulation; GPU computing; artificial intelligence; computational materials and physics	Gives Czech researchers access to computing resources beyond national capacity and integrates them into EuroHPC

Research infrastructure	Location / scope	Profile	Key research directions and capabilities	Significance for Czech physics
VLQ Quantum Computer	Ostrava	Superconducting quantum-computing infrastructure	Hybrid quantum–classical algorithms; quantum software; experimental quantum computing	Introduced a domestic multi-qubit platform and connected Czech research with the emerging European quantum-computing ecosystem
e-INFRA CZ	National distributed infrastructure	Integrated digital research infrastructure	High-performance computing; grids; cloud services; high-speed networking; data storage	Provides the digital backbone supporting computational physics, large experimental collaborations, and national scientific data workflows

Taken together, these institutions and infrastructures demonstrate that Czech physics developed between 1993 and 2025 as a distributed but strongly interconnected national system. Prague and its surroundings retained the greatest concentration of Academy institutes and large physical infrastructures, Brno became a major centre of nanotechnology and microscopy, Olomouc developed exceptional strength in quantum optics, Ostrava became the centre of national supercomputing, and other regional universities established internationally relevant specialisations in materials and applied physics. At the same time, CERN-CZ, FAIR-CZ, ESS-Scandinavia-CZ, AUGER-CZ, CTA-CZ, EUROfusion, ESO participation, and European computing networks extended the effective boundaries of Czech scientific infrastructure far beyond the country's territory. The defining feature of the system by 2025 was therefore not institutional centralisation, but the integration of national laboratories, university schools, regional specialisations, open-access facilities, and European and global research infrastructures into a common research and innovation ecosystem.

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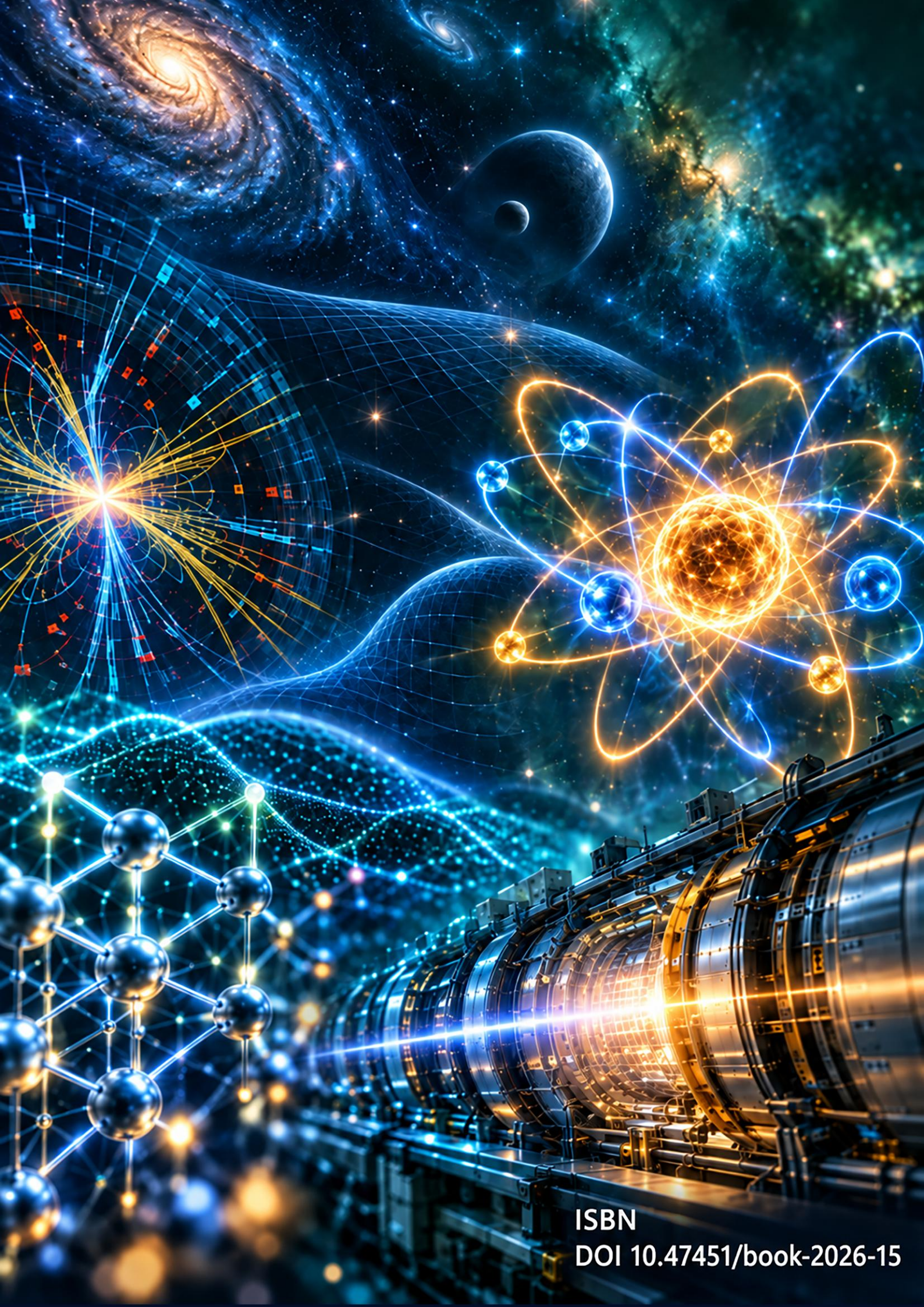
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