

CHART Roadmap 2025 – 2032

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1 Purpose and Scope

This updated Roadmap for Swiss Accelerator Research and Technology (CHART) presents the view of the Swiss accelerator science and technology community that designs, builds and operates accelerator-based infrastructures serving a wide range of fields such as particle physics, photon, neutron and life sciences including medicine. The Roadmap addresses the research and technology infrastructure needs of these accelerator driven research fields in the next decade. These infrastructures are long-term in nature, often take decades to build, and are being exploited over decades as well. It is therefore important for communities that use such facilities to agree on priorities and future needs in order to pool resources in the best possible way. This roadmap process will help to establish the needs of the various scientific communities.

CERN belongs to the handful of top scientific organizations having a worldwide impact, which goes way beyond particle physics, and benefits all areas of natural sciences as well as industry. CERN is, as one of the most acknowledged Brands, recognized by the broad public. CERN's construction projects have also strongly contributed to technical innovations in many fields, such as superconductivity and detectors, and thus benefited industry directly and indirectly. Technology transfer to industry is a central mission of CERN and all institutions of the ETH Domain.

With the Large Hadron Collider (LHC) and its planned Upgrades, CERN is set to remain the world leader in the field of high energy physics until the 2030's and it is attracting the best scientists from all over the world. To maintain and further strengthen Europe's prime position beyond the present LHC Physics Program, the preparations for a new world-class high-energy physics research infrastructure have started, as called for by the 2013 update of the European Strategy for Particle Physics (CERN-Council-S/106), stating inter alia that:

"Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the

LHC running at 14 TeV will be available and that CERN should undertake design studies for accelerator projects in a global context with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D program including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide."

Defending CERN's unique role at the high-energy physics frontier is of utmost importance for Europe as a whole and for Switzerland, as one of the host countries. Therefore, Switzerland and France, together with their European partners, are strongly promoting the first steps to secure the competitiveness of CERN at the high-energy physics frontier against other initiatives worldwide. CERN is conducting a Feasibility Study of the Future Circular Collider and the mid-term review of this study was presented to the CERN Council at its dedicated Session in February 2024. The Council expressed its appreciation of the impressive progress and is looking forward to receiving the final report in 2025. CERN Council concluded that there were no technological or scientific show-stoppers that would hinder the realisation of the proposed FCC project.

CHART, the Swiss Center for Accelerator Research and Technology, was founded to support the future oriented accelerator project Future Circular Collider (FCC) at CERN and the development of advanced accelerator concepts in Switzerland beyond the existing technology. However, the proposed CHART program has a strategic character not only for CERN but also for Switzerland. Today CERN has to dedicate major part of its resources to the next project HL-LHC. It is the mission of CHART to support CERN for the phase beyond HL-LHC, the realization of FCC.

Securing the leading role of CERN in this type of research (without being the acknowledged world leader in this field, CERN will eventually lose its "raison d'être") is a long-term exercise. In order to reach the technical standards for a successful extrapolation of the necessary

new installation, research and development of accelerator technology needs to be intensified.

For these reasons, CHART was founded in 2016. The first phase of CHART was realised between 2016 and 2018. The second phase of CHART was then launched in 2018 and is coming to its conclusion in 2024. During CHART Phase 2, more than 20 projects financed by CHART funds were able to present excellent and important results. For more information, please visit the CHART (<https://chart.ch>) Reports and News pages.

The mission-oriented nature of CHART was highlighted in a report recently published by the Swiss Science Council (Mission-oriented Research and Innovation in Switzerland, SSC Report 1/2023): *"The Swiss Accelerator Research and Technology (CHART) programme is a good example of a mission-oriented programme. It aims at supporting the Future Circular Collider at CERN. In this case the receiver of the results is CERN. Such initiatives benefit both science and Switzerland."*

This updated Roadmap at hand was established under the auspices of CHART and covers specifically the period of 2025 to 2032. In view of the long-term nature of these activities it is foreseen to periodically update this Roadmap beyond 2032.

The CHART Council consists of one representative of each participating institution governs CHART. Chaired by H.-R. Ott (SCNAT), the members are: M. Benedikt (CERN), Ch. Theiler (EPFL), R. Wallny (ETHZ), M. Seidel (PSI) and G. Iacobucci (Uni Genève). Principal Investigators of the CHART Projects form the Executive Board, chaired by L. Rivkin from PSI, the Host Organisation. More details on the structure, projects and outcomes of CHART can be found on CHART Website (<https://chart.ch/>). The members of the CHART Roadmap Editorial Board are B. Auchmann, M. Calvi, P. Craievich, T. Pieloni, L. Rivkin (Chair), M. Seidel, and C. Senatore.

2 Findings and Recommendations

The CHART Collaboration supports future accelerator based projects in Switzerland. The Future Circular Collider (FCC) at CERN is the main focus, but the know-how in accelerator science and technology available is also an important driver for present and future accelerator driven research infrastructures in Switzerland.

Accelerator science and technology R&D in Switzerland, fully embedded in an international context, reflects the priorities formulated in the European Strategy for Particle Physics (ESPP) as well as in the SCNAT Roadmaps for 2025 – 2028 period. CHART is actively contributing to the Accelerator R&D Roadmap by the Laboratories Directors

Group (LDG) as part of the ESPP.

Particle Physics - future of CERN: CHART recommends continuing support for a future large collider project at CERN in the years to come. It furthermore states that building up on existing expertise in accelerator science and related fields that are essential for the successful realization of such a project should be a national priority.

High Field Magnets development: CHART views superconducting high-field magnets as the key enabling technology for future accelerators of hadrons and muons. Moreover, the technology makes more compact accelerator systems possible, such as medical accelerators and gantry magnets. CHART recommends a continued and unrelenting push for innovation in low- and high-temperature superconducting magnet technology to achieve respective performance and cost targets.

Photon Science – future of PSI: CHART recommends further development of unique sources of synchrotron radiation by upgrading and expanding the existing flagship facilities SLS and SwissFEL. CHART further recommends the development of compact accelerator based photon sources relevant both for photonics research and industrial applications, as for example EUV lithography.

Neutrons and muons at PSI: CHART strongly supports further development of intense sources of neutrons and muons at PSI. Unique expertise at PSI and CERN forms the basis for accelerator R&D that is highly relevant to neutron scattering, precision physics with low energy muons and possible future very high-energy muon collider.

Advanced acceleration methods: laser and plasma acceleration constitute innovative developments of relevance to compact photon sources and medical applications.

Education: strengthening the attractiveness of accelerator science and technology to future generations of bright young students and researchers is of utmost importance. Involvement of students at all levels in CHART projects will help this goal. CHART academic partners are considering establishing additional professorships in this field.

Energy efficient accelerators: CHART gives high priority to the development and realization of sustainable concepts, in particular for the next generation of large accelerator-based facilities. This includes conceptual and technological advancements to maximize facility performance per grid power, as well as the efficient use of sparse natural resources.

3 Update on CHART Activities

3.1 Superconducting Magnets

The goal of an energy-frontier proton-proton collider in the 100 TeV range requires the development of superconducting magnets that produce magnetic fields well beyond those attained in the LHC. One of the objectives set in the ESPP Accelerator R&D Roadmap released in 2022 is to demonstrate Nb₃Sn magnet technology for large-scale deployment, which has motivated intense R&D on magnets and conductors. Moreover, the ESPP requests intense study of high-temperature superconductor (HTS) magnet technology for its applicability in a proton-proton collider. Research on the latter topic has enabled synergistic activities in CHART such as a no-insulation HTS solenoid for positron production in the FCC-ee injector and a demonstration of energy-saving magnet systems for the FCC-ee short straight sections. Beyond collider applications, CHART research on HTS bulk undulators has seen significant progress.

3.1.1 High-field magnets

The Magnet Development Laboratory: In August of 2020, the construction of the MagDev Laboratory, a 400 m² extension to the WLHA hall at PSI West, was completed. Major infrastructure items such as winding machines, furnaces, and an autoclave are installed, commissioned, and in regular use. All other laboratory infrastructure is designed for flexibility and the continuous evolution of workplaces and methodologies. Moreover, with local mobile workstations for all mechanics, technicians, engineers, and PhDs on the shop floor, there are no barriers to communication, and new ideas flow quickly

and unhindered.

Figure 1 shows the MagDev Laboratory at handover (left) and in May 2024 (right). Infrastructure items such as the programmable semi-automatic winding setup, 3D scanning metrology, experimental furnaces with Lab4.0 recording and control of process values and exhaust gas diagnostics, and a highly flexible custom-built autoclave all enable a wider range of materials and processes, inviting researchers to experiment with new ideas and materials.

Stress Managed Nb₃Sn Technology for FCC-hh: In 2022/23, the canted-cosine-theta stress-managed Nb₃Sn magnet CD1 (Canted Dipole 1), designed and built by a CHART project in 2017-2019, was tested and achieved 10 T field in the aperture or 91% of maximum performance at 1.9 K and 100% maximum cable performance at 4.5 K, albeit after a prolonged training campaign of over 80 quenches. This result demonstrated the ability of stress-managed coil technology, i.e., coils wound into a metallic structure, to protect the brittle Nb₃Sn conductor throughout the manufacturing, cooling, and powering steps. In anticipation of the above result, the 'MagDev' project at PSI directed a fast-turnaround experimental campaign at the remaining problem of stress-managed magnets, the prolonged training, and tested a series of coil-impregnation materials in 22 samples under realistic conditions at the University of Twente. Wax and alumina-filled wax could be shown to fully eliminate training, and the material was successfully tested in a stress-managed racetrack coil in a high-field test facility at Brookhaven National Laboratory. After studying a variety of coil options, MagDev has settled on a stress-managed common coil magnet design with wide-bending-radius flat racetrack coils generating field in two apertures at once (hence the name 'common coils'). A subscale 5-T stress-managed common coil (SMCC) has been designed, built, and tested, showing no training at 4.5 K. The conceptual design of



Figure 1: MagDev Laboratory (PSI) at handover (left) and in May 2024 (right).

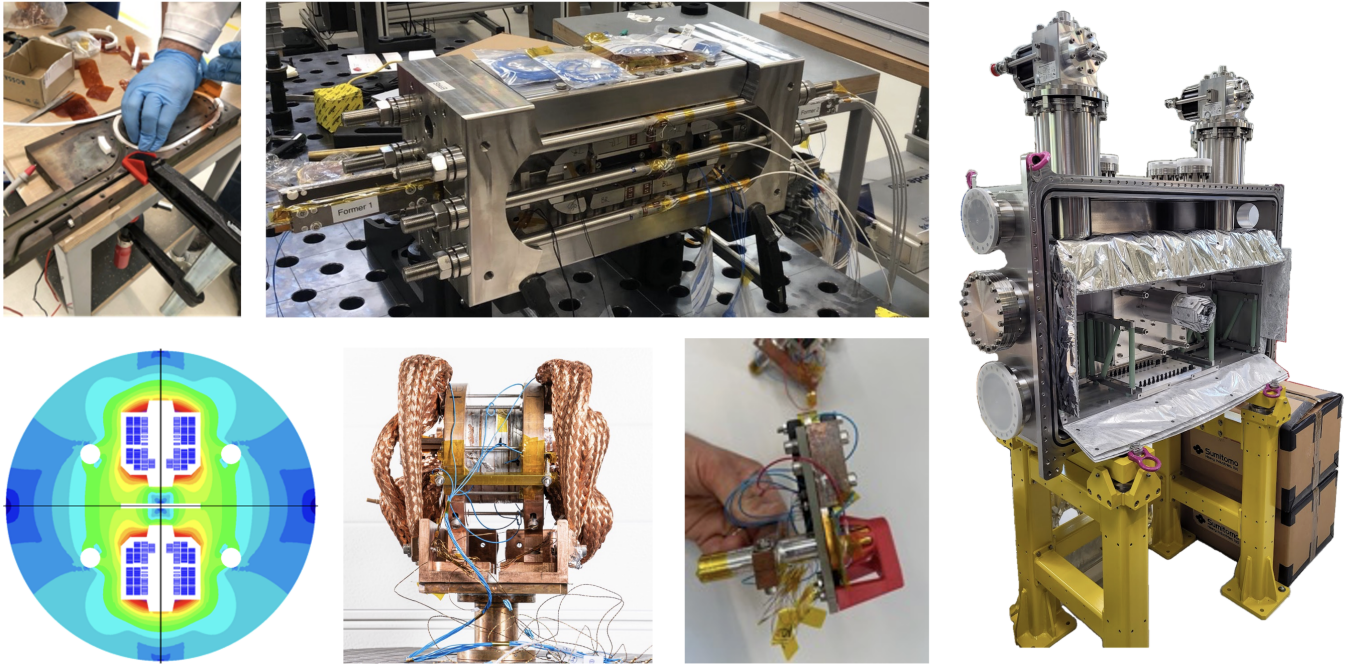


Figure 2: Magnets designed from 2021 to 2024 in the PSI MagDev laboratory. Top left: BigBOX Nb₃Sn stress-managed racetrack coil, tested in the Brookhaven background-field facility; Top middle: Nb₃Sn subscale stress-managed common coil (subSMCC) magnet, tested at CERN; Far right: Cryostat of the positron capture solenoid; Bottom left: electromagnetic model of a stress-managed asymmetric common coil (SMACC) cross-section; Bottom middle: conduction-cooled 18-T solenoid coil; Bottom right: HTS Model-validation coil with its instrumentation.

an innovative stress-managed asymmetric common coil (SMACC) for 14-T field at maximum performance is in progress. In an effort to strengthen trans-atlantic ties with the US Magnet Development Program, CHART MagDev has integrated a 20-T design study and contributes our experience with the stress-managed common coil design to the US program.

No-Insulation High-Field Solenoids: To initiate HTS magnet-R&D in the 'MagDev' project, PSI entered into a collaboration and licensing agreement with Tokamak Energy Ltd, a compact-fusion company in the UK, for the construction of a solder-impregnated no-insulation high-field solenoid. For pre-tinning of tapes, MagDev was supported by experts from EPFL SPC. In addition to building the solenoid, MagDev upgraded the cryogen-free test station at PSI for magnet tests up to 2 kA, and could produce 18 T field in the aperture.

Positron Capture Solenoid: The solder-impregnated no-insulation technology was applied for the design and construction of an innovative positron-capture solenoid for the FCC-ee injector's positron source; see Sec. 3.3. The standalone conduction-cooled magnet produces 15 T in a 72-mm warm aperture. The large stored energy is managed in case of a power-outage by a 200-kg thermal buffer from cast lead. HTS technology in the capture solenoid replaces conventional pulsed resistive magnets,

and promises to increase the capture efficiency by a factor ten. The magnet system will be commissioned in early 2025.

HTS Model-Validation Coils: In view of considerable uncertainties in numerical modeling techniques for parasitic screening currents in ReBCO tapes, MagDev is building a series of small-scale coils for model validation. The coils use different types of insulated cable made from ReBCO tape (4-mm double stacks, single-tape double pancake, ribbon-type cable) in order to extract information on relative performance, and to collect measurement data that can be used in the validation of numerical models. Three small-scale coils have been tested to date. Tests will continue at University of Twente over the summer.

3.1.2 Energy-saving magnet systems

For FCC-ee, CHART studies high-temperature superconducting (HTS) magnet systems as an alternative to normal-conducting arc quadrupoles and sextupoles. The goal of the study is to demonstrate the extent to which power can be saved in all FCC-ee operation modes using relatively low-field (3-4 T) HTS magnets at intermediate temperatures (40 K). The project is a light-pole project for the development of energy-efficient magnets, requiring innovation in cryogenics, low-loss powering, simple and

reliable protection within the cold system, and compact partially-insulated coils. The project went through extensive canvassing studies, setting up an expenditure model over the FCC-ee life time and optimizing the sum of capital expenditure and operating expenditure to derive an optimal compromise between operating temperature and coil size for every given technology stack. Today, two sub-scale sextupole demonstrators, one canted-cosine-theta, and one cosine theta are being wound and the validation of splicing, impregnation, and assembly procedures are under way; see Fig. 3.

3.1.3 Undulators

At the end of 2019, CHART council approved a project to develop a High Temperature Superconducting Undulator using ReBCO materials. The project focused on a staggered array design, utilising bulk or tape-stacked REBCO magnetized by a high-field solenoid exceeding 10 Tesla. Initial design phases involved complex computer simulations to address the challenging field cooling magnetization process.

A short sample program (see Fig. 4) began in collaboration with the University of Cambridge, where their facility was upgraded with new measuring equipment designed by PSI to accurately assess the magnetic profile of the undulators. Initial prototypes were simple and low-cost to demonstrate field strength. Subsequently, more advanced devices were developed to manage premature quenching and improve field quality. Various manufacturers supplied ReBCO bulks and tapes, and innovative techniques were used for precise shaping and assembly within a copper

matrix, potentially warranting a patent.

The project achieved excellent results, with record-breaking undulator magnetic fields documented in international journals, positioning PSI as a leader in this technology. A full-scale prototype is nearly complete (see Fig. 5) and will be tested at PSI's laboratory in 2025. It will then be installed in the new Swiss Light Source ring in 2026 to power the flagship beamline I-TOMCAT for microscopic tomography, achieving a Technology Readiness Level of 7. This technology is expected to be ready for industrial production, potentially refurbishing many hard x-ray beamlines at synchrotron facilities to enhance their performance.

For manufacturing the prototype, a strategic partnership has been formed with Fermi National Accelerator Laboratory, setting the stage for future collaborations.

3.1.4 Enabling technologies

In the following, we list CHART activities that develop technologies enabling the design and construction of more robust, efficient, and sustainable superconducting magnets.

Cryogenic Power Supplies: In a conduction-cooled magnet system, the largest heat load on the cryogenic system (e.g., cryocoolers) comes from the electrical powering leads. The 'FCC-ee CPES' project has studied cryogenic power supplies, i.e., DC/DC converters that use thermally efficient high-voltage/low-current leads. The power is converted to high-current/low-voltage inside the cryostat. Through topological optimization and judicious selection of components, the CPES project has been able to reduce

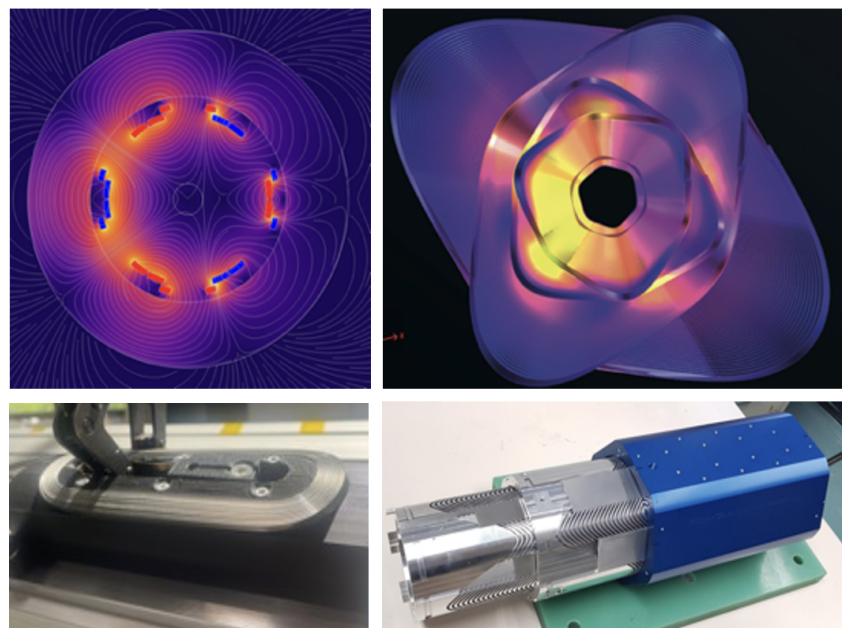


Figure 3: Top: Design of superconducting nested sextupole and quadrupole magnets for the FCC-ee; a cosine-theta design on the left, and a canted-cosine-theta design on the right. Bottom: Winding of cosine-theta test coil and the canted-cosine theta sextupole subscale demonstrator.

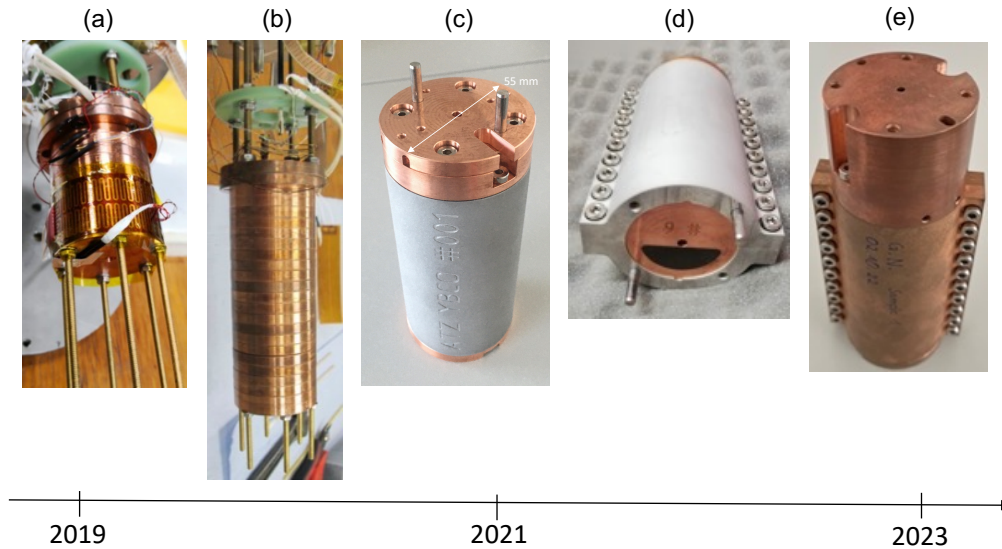


Figure 4: The evolution of the short prototype assemblies: (a) The initial prototype developed at the university, featuring custom-grown bulks and a 6 mm aperture for easier magnetic assessment. (b) A university sample with the standard 4 mm aperture and 20 bulks. (c) The first industrial prototype, featuring a closed aluminum shrinking cylinder. (d) An industrial prototype equipped with two aluminum half-shells. (e) Our current baseline design prototype, with copper half-shells, achieving a record undulator field of 2.1 T.

by a factor of four the heat-load due to powering as compared to conventional optimized leads.

Cryogenics Concepts: To substitute normal-conducting magnets with superconducting magnets in an accelerator, the superconducting-magnet system must be highly reliable and efficient. To this end, as part of the 'FCC-ee HTS4' project, alternative cooling techniques are being studied analytically and experimentally. In collaboration with industry, cryo coolers with inverter technology are used for the first time on a superconducting magnet system, promising to keep power consumption to a minimum. At the same time, an innovative centralized cooling system based on a commercially available liquid-hydrogen distribution line is being developed, which could provide important cost savings and dependability benefits.

Model-Based Systems Engineering: The ever-growing complexity of superconducting-magnet technology requires modeling and management tools that ensure traceability, repeatability, and flexibility over prolonged periods of times and in multi-disciplinary and globally distributed teams of engineers. In the 'MagNum' project at ETHZ D-ITET, a novel implementation of the model-based systems engineering paradigm has been established that is particularly well-suited to the combination of in-house created tools, commercial software, measurement data, and other sources of information more.

Soft-Materials R&D: The development of novel impregnation systems for Nb₃Sn magnets that feature an increased resistance to cracking at cryogenic tempera-

tures has been the primary focus of the 'MagRes' project at ETHZ D-MAT Soft Materials Group. The group could demonstrate resin composition with 300% increased crack resistance while tuning the materials glass transition temperature and curing temperature in order to minimize thermal strain on the material during the cooling of a magnet. Lately, a novel resin was developed that will not bond to metallic surfaces, therefore potentially combining the advantages of wax impregnation (see above) with those of resins. The 'MagRes' project dove-tails into 'MagComp', which analyzes the Nb₃Sn coil composite experimentally and numerically and thereby provides crucial input into the design and analysis of accelerator magnets. 'MagComp' is closely coordinated with the 'MagNum2' project at ETHZ D-ITET and PSI, which implements multi-scale modeling approaches into magnet design and analysis. Finally, the 'MagMu' project explores, in the context of the muon collider, different implementations of smart insulation systems, i.e., insulation systems that can switch into conductors provide additional current paths in case of a local overheating. MagDev and MagMu benefit from exchanges with experts at the EPFL SPC SULTAN facility on the PSI campus.

Acoustic Instrumentation: Acoustic piezo-electronics sensors provide intuitive insight into the mechanical workings of a superconducting accelerator magnet under load. In collaboration with EMPA, software has been developed to isolate acoustic events, process them through specialized filters, and categorize them.

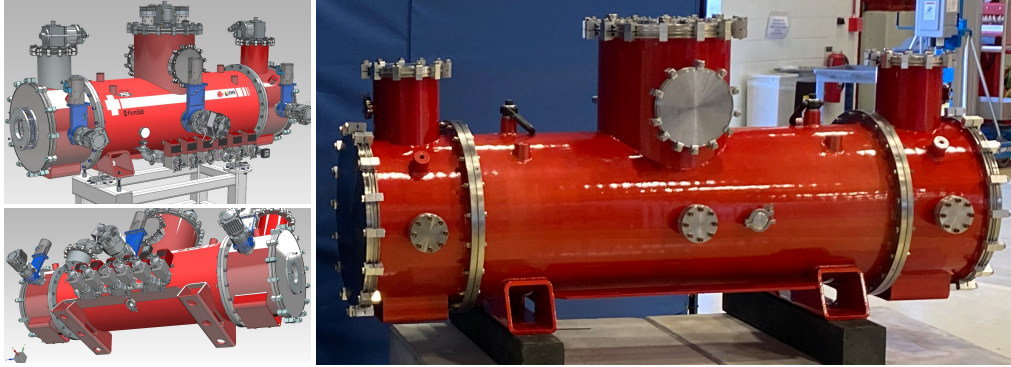


Figure 5: On the left is the cryostat design for the metre-long prototype, developed in collaboration with Fermilab. Cooling is achieved via conduction, utilising three cryocoolers: the central one for the superconducting solenoid and two side ones for the HTS insert, the undulator's core. On the right is a photograph of the vacuum vessel.

Additive Manufacturing: The 'MagAM' project with ETHZ D-MAVT pd|z explored the potential of additive manufacturing to enable functional designs of magnet components, e.g., add functionality such as shape compliance, improved surface bonding, or locally adjustable mechanical stiffness.

Numerical Models of HTS Coils: ReBCO tape conductor poses substantive challenges to numerical algorithms and tools to accurately capture electromagnetic/thermal transient phenomena such as screening currents, coupling currents, and quenches. PSI is working with multiple institutes and companies to create a simulation workflow that is both, computationally efficient and accurate. Collaborations have been initiated with COMSOL, Quanscient, Little Beast Engineering, and the Technical University of Darmstadt. Model and performance comparison has started among the three commercial products.

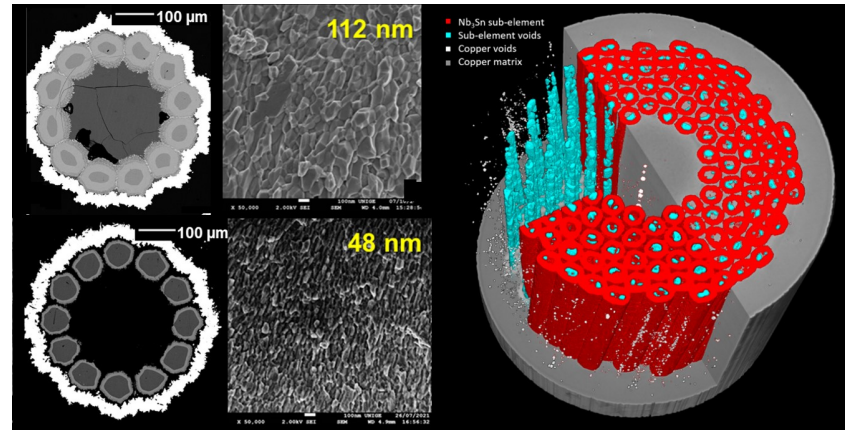
3.1.5 Conductors

Reaching the ESPP goal of a 100 TeV collider involves pushing Nb₃Sn magnet technology to its practical limits in terms of performance, towards an ultimate target of 16 T in a dipole configuration. The prime challenge to reach the ultimate target of 16 T in Nb₃Sn magnets is the development of conductors that exceed the performance of state-of-the-art Nb₃Sn wires in terms of both critical current density (J_c) and tolerance to mechanical stresses. Hence, the advancement of Nb₃Sn technology must build on novel processing routes scalable at the industry level and with a full control of the material at the nanoscale dimension, tailoring the vortex-pinning landscape to enhance J_c , and at the microscale dimension, linking the electromechanical behavior to the wire architecture. The CHART wire development (WireDev) project at the Uni-

versity of Geneva investigated methods for the inhibition of the grain growth in Nb₃Sn by means of nanoparticles – typically ZrO₂ or HfO₂ – that form through an internal oxidation process. The obtained multifilamentary test-wires exhibit average grain size ≤ 50 nm, i.e. two to three times smaller compared to the optimized industrial conductors. The resulting increase in grain boundary density combined to the presence of additional point-like pinning centers due to the oxide nanoparticles lead to a significant enhancement of J_c , which extrapolates beyond the target of 1500 A/mm² at 16 T and 4.2 K set for FCC-hh.

The other aspect where CHART focused its research on conductors concerns the tolerance to stress of Nb₃Sn wires. It appears clear from various conceptual studies that the design of a 16 T dipole entails electromagnetic stresses ranging from 150 to 200 MPa and, thus, it becomes crucial to establish precisely the mechanical limits at which Nb₃Sn can operate safely. Permanent reduction of the critical current occurs from the combination of the effects of cracks in the Nb₃Sn filaments and plastic deformation of the Cu matrix. In the frame of the CHART wire characterization (WireChar) project at the University of Geneva, a new method was developed to identify the dominant mechanism of degradation. The method builds on electromechanical measurements and a novel non-destructive and non-invasive tool to investigate wires' internal features that combines X-Ray tomography and deep learning networks. The analyses provided valuable insights into the failure mechanism of accelerator-grade Nb₃Sn wires relevant for magnet design, highlighting the dominant role of residual stresses due to the plastic strain in the Cu matrix, while acknowledging the potential variability in stress tolerance among wires produced with different technologies.

Figure 6: The two pictures on the left depict the cross section of the Nb₃Sn test-wires without internal oxidation (top) and with internal oxidation (bottom), respectively, produced at the University of Geneva. The two pictures at the center magnify the Nb₃Sn grain morphology at fractured surfaces, highlighting a pronounced grain refinement due to the internal oxidation (bottom) with respect to the reference wire (top). The picture on the right depicts a tomography reconstruction of an industrial Nb₃Sn wire analyzed by machine learning to identify specific features in its internal structure.



3.2 Beam Dynamics

Designing the next generation collider, whether hadronic or leptonic, presents significant challenges in beam dynamics. These studies are essential for determining project feasibility, identifying and mitigating potential issues, and proposing a robust operational scenario with precise technical tolerances and requirements to drive technological advancements. Since 2020, CHART has been deeply involved, through EPFL-LPAP and UniGe teams, in beam dynamics studies for the FCC-ee, FCC-hh, and exploring a future muon collider. Alongside advancing the FCC-ee design, a key focus is developing numerical tools for leptons and muons, previously non-existent before the CHART2 initiative. For the hadron collider FCC-hh, the LHC's experience, knowledge, and tools provide a solid foundation. However, the significant time gap since the LEP design has resulted in a lack of tools and expertise for leptons, while muons represent entirely new territory. Due to different timelines, priorities focus first on leptons, then hadrons, and only marginally on muons.

Beam Dynamics Studies for FCC-ee: A new software framework, XSUITE, has been developed with CHART's support to model colliding leptons in a potential 100 km synchrotron FCC-ee. This development incorporates several effects, including synchrotron radiation (SR) in magnets, beamstrahlung (BS, the self-emitted radiation due to beam deflection during collisions), and ba-bar scattering. The framework's flexibility allows for simulating beam trajectories over multiple turns with multiple collision points (four collision points for both FCC options), along with a comprehensive description of the accelerator lattice that includes magnetic errors, aperture limitations, and tuning capabilities. The studies will define magnet and component tolerances, support material choices, and establish a clear strategy for the machine protection system. Additionally, the framework considers several collective effects, such as beam-beam interactions, machine impedance, and electron cloud effects, crucial

for exploring and studying combined effects that typically limit collider intensity. This new framework also uses state-of-the-art programming languages and technologies, including machine learning (ML) and artificial intelligence (AI), making it a solid tool for future designs.

For the FCC-ee, a baseline scenario for physics operations has been proposed, modeled, and studied. Several challenges were identified, and mitigation strategies were applied where possible. The results have been summarized in the recently reviewed Mid Term Review Plan report presented to the CERN council. The EPFL-LPAP and UNIGE teams made significant contributions to key aspects of beam dynamics.

Optics and Performance Studies: A complete design of the magnetic lattice of the FCC-ee has been developed and provided with different options and improved performances. The optics called Global Hybrid Chromatic lattice (GHC) is based on the global correction of chromatic aberrations and uses the crab waist scheme to allow large beam-beam effects at the collision points.

Electron Cloud Effects: Secondary electrons emitted by the inner chamber surfaces can reach very high densities near the circulating beams, triggering fast instabilities. Studies of electron cloud build-up for different bunch spacings and intensities have defined the Secondary Electron Yield (SEY) requirements for the inner vacuum chamber materials to suppress electron multipacting effects. Various filling schemes and injection strategies to reduce electron multipacting have been proposed, studied, and included in the baseline scenario. A significant challenge identified in these collider feasibility studies is the extremely high density of photon electrons. Addressing this issue has necessitated a complete redesign of the photon absorbers.

Beam-Beam Effects and realistic lattice: Numerically studying the effects of electromagnetic collisions of two beams multiple times through a 100 km lattice, composed of several tens of thousands of elements, is now

feasible. This step allows for realistic simulations of the FCC-ee. The collision occurs using a modified crab waist scheme, with strong sextupoles on either side of each collision. BS and ba-bar scattering interleaving the collision add to the computational demands, requiring integration with the accelerator lattice and magnetic system. Studies have identified strong instabilities and sub-optimal lifetimes when imperfections exist in the lattice elements. To avoid loss of luminosity, top-up and bunch-to-bunch differences should be kept below 5%. Furthermore, BS has been modelled, serving as a starting point for the machine detector interface design (MDI). Thanks to these developments, for the first time, a complete simulation flow from collision to particle-matter interactions is possible within the software framework.

Polarization Studies: The center-of-mass energy calibration based on resonant depolarization of the stored beams is a cornerstone of the unique precision measurement program of FCC-ee. This method offers the potential to improve measurements of the Z and W boson mass and width, by one to three orders of magnitude. Such advancements will provide sensitivity to various new physics scenarios. Enhancing and maintaining polarized beams significantly impacts collider design. First studies of polarization for realistic lattice configurations have been enabled. Additionally, several techniques to increase polarization via harmonic spin matching bumps have been proven.

Alternative Optics with Nested HTS Magnets: Inspired by the rapid advancements in high-temperature superconductors (HTS), we collaborated with the PSI magnet team to develop an innovative lattice sequence and collider optics utilizing nested magnets. This design achieves a 17% reduction in synchrotron radiation, saving 8.5 MW of power per beam due to the increased filling factor from the dipole field. Furthermore, it is compatible and applicable to both the baseline GHC and the LCC alternative optics (Local Chromatic Correction) optics, which rely on normal conducting technology. With similar perfor-

mances.

Beam Dynamics Studies for FCC-hh: As part of the FCC integrated programme, a large hadron collider similar to the LHC is envisioned, utilizing the infrastructure of the lepton collider. This new collider aims to be three times larger and more powerful, capable of reaching a center-of-mass energy of 100 TeV. The LHC serves as a robust test bench, providing a solid foundation for the FCC's design. In this context, we have improved luminosity determination at the LHC by proposing a parametric correction to the luminosity analysis from beam-beam effects. Additionally, a new surrogate model based on active learning, developed with the Swiss Data Science Center (SDSC), demonstrates collider parameter optimization and design improvement. This approach uses modern machine learning techniques to prepare for the second stage of the FCC study, focusing on parameter exploration and optimization sustainably by avoiding redundant simulations and reducing computation time.

Beam Dynamics Studies for a Muon Collider: Regarding muons, studies focus on modeling the muon cooling and acceleration systems, including collective effects. The objective is to increase muon density, which can trigger brightness-dependent effects. Therefore, the entire cooling chain should be designed to minimize such impacts. Finally, initial studies for a potential muon collider are also underway.

3.3 e^+e^- Injector

The project encompasses two critical deliverables. The first deliverable involves a comprehensive review of the CDR (Conceptual Design Report) that was published in 2019, along with a detailed cost estimate. This review reassesses the initial design and budget considerations, ensuring that the project remains viable and within financial constraints. The injector study is a collaboration between PSI and CERN with some external partners, such as CNRS-IJCLab (Orsay, France), INFN-LNF (Frascati, Italy) and

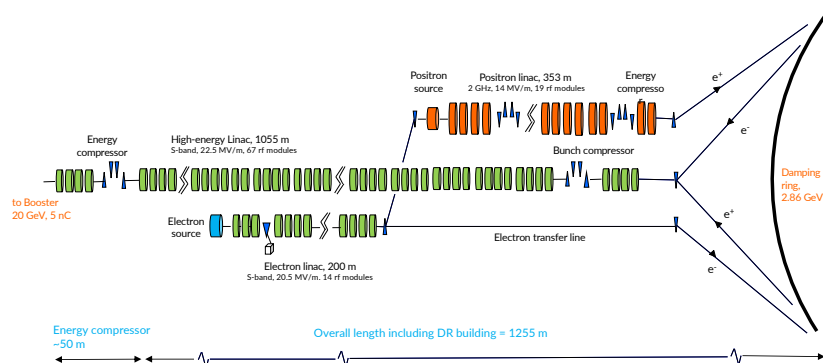


Figure 7: Latest baseline layout of the FCC-ee Injector complex.

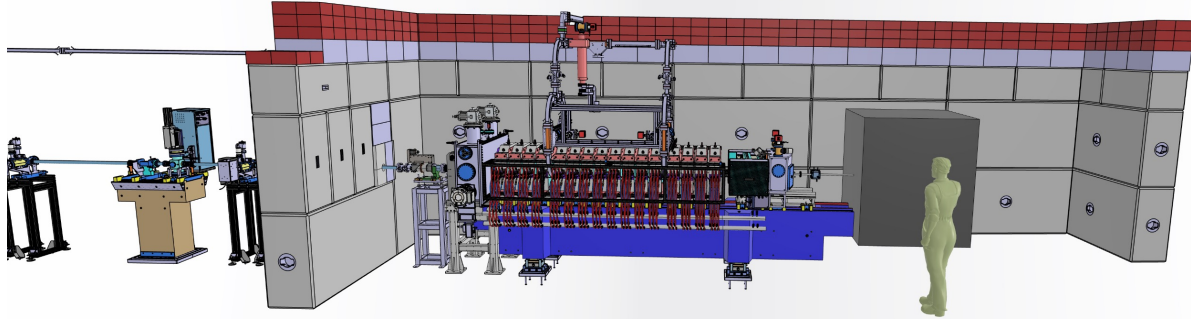


Figure 8: The PSI Positron Production (P^3) Experiment

SuperKEKB (Tsukuba, Japan) involving more than forty people. The second deliverable is the proof of principle positron source experiment, which is to be installed at the SwissFEL facility at PSI (Paul Scherrer Institute). This experiment aims to validate the feasibility and performance of the proposed positron source technology in a real-world setting, providing essential data and insights for further development and potential large-scale implementation.

FCC-ee Injector Design Study: The FCC-ee injector complex must provide the electron and positron bunch trains for alternating bootstrapping injection during, both, top-up and filling-from-scratch operations. Considering the charge per bucket and lifetime for this operational mode, an alternating injection of a train of positrons and electrons approximately every few tens of seconds is required to ensure the correct balance between positron and electron bunch charges during collider operation. Figure 7 schematically shows the latest basic layout of the injector complex.

It includes two separate linacs for electrons and positrons up to a beam energy of 2.86 GeV – the Electron Linac (e-Linac) and the Positron Linac (p-Linac), respectively. Following the positron and electron linac, both species are injected into the Damping Ring (DR) for emittance reduction. The layout also includes the high-energy (HE) linac, which boosts the beam energy from 2.86 GeV up to 20 GeV in order to inject beams directly into the Booster Ring (BR). The baseline for the positron source is based on a conventional scheme using electrons from the e-Linac impinging on a tungsten target. This approach allows all linacs to operate at 100 Hz with 4 bunches to meet the collider ring filling specification for the Z running mode. The linacs in the injector complex were optimised in terms of accelerating gradient and power consumption considering capital, building, infrastructure and operation costs. After the feasibility study, the technical design report will be written including the prototyping phase of the accelerator structures and the electron source.

P^3 Experiment: The PSI Positron Production (P^3) ex-

periment is a demonstrator for the positron source and the goal is to design and install such a demonstrator in the SwissFEL facility, and validate through an experiment a range of novel techniques that, according to simulations, have proven potential to increase the e^+ yield by one order of magnitude with respect to the state of the art. The remarkable e^+ capture capabilities of P^3 are enabled to great extent by the usage of high temperature superconducting (HTS) solenoid around the target region, as well as a novel standing-wave solution for the RF cavities that provides a large iris aperture. The P^3 project is driven by the luminosity requirements of the FCC-ee, and its results will constitute one of the main deliverables of the FCC-ee injector feasibility study. The SwissFEL facility is an ideal host for the P^3 experiment since it can provide an up to 6 GeV electron beam, corresponding to a maximum drive beam energy of the FCC- ee positron source. Two beam lines (Aramis and Athos) are currently operating at SwissFEL, while the accelerator tunnel already foresees space for a future, third beam line (Porthos) leaving enough room for the (temporary) installation of the P^3 bunker and switchyard. Figure 8 shows the current, and almost final, design version of the P^3 experiment. According to the preliminary timeline, the currently ongoing works are expected to conclude by the end of 2025, as operation with e^+ production is envisaged for 2026.

3.4 Geodesy and Geology

One of the objectives of the FCC Feasibility Study is the optimisation of the placement and layout of the ring and related infrastructure, and the demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and the surface areas. CHART is supporting the study with the two following projects.

FCC Geological Modeling: The Department of Earth Sciences of the University of Geneva is investigating the subsurface geology that is crossed by both the tunnel and the access shafts of the FCC. This project focuses on two

major activities:

I) establishing a Geographic Information System (GIS)-based subsurface data set and data base architecture in support of the feasibility and execution of the FCC tunnelling work by defining a standard data set framework for new data. The main outcome of this work U-SOLSTISS, is a reference tool for the FCC subsurface segment, which will be continuously maintained and populated with new data acquired during the overall project from initial site investigation, feasibility, design and execution. This tool provides the necessary and required critical information on a large variety of data encompassing geological data (rock formation, rock type and properties), natural seismicity, hydrological and hydrogeological data, that are essential for the feasibility and implementation phases of the FCC project's subsurface segment.

II) establishing a consistent high-resolution 3D geological model, supported by quantitative geological analytical investigations along the FCC trace aimed at predicting geological features and possible risks in support of tunneling design, planning and execution. The data is used to produce a reference 3D geological model in the project's perimeter, incorporating all available data from various data providers through the usage and integration into a 3D environment of the data collected into the GIS project. The 3D geological and hydrogeological model is a key tool to predict subsurface rock properties and guide the feasibility and detailed design of the FCC tunnels and access facilities. This product also serves to capture the baseline information regarding the water ground distribution and quality and serves as tool for predicting possible short and long-term environmental impacts (impact on geometry and physical property of ground water, contamination, etc.) of the civil-engineering work.

FCC Geodesy Studies: The FCC Geodesy project aims at a collaboration of the Institute of Geodesy and Photogrammetry at ETH Zurich, the Federal Office of Topography (swisstopo), and the Institute of Territorial Engineering (HEIG-VD).

For the FCC, an evolution of the geodetic reference systems and geodetic infrastructure already established for the current CERN site is required in order to cope with the demanding challenges of this large new infrastructure. This does not only include a significant improvement of the gravity field models but also a revision of the geodetic reference systems, frames and datum definitions, along with the selection of an appropriate cartographic map projection and a reconsideration of the various geodetic facilities and infrastructure components at CERN that support the realization of these reference frames.

The project has two major objectives: the determination of a high-precision gravity field model for the FCC region, and an improvement of the Geodetic Reference

Frames and the Geodetic Infrastructure. In view of the size of the FCC and the region it covers, it is clear that new static and dynamic gravity field models are needed over a site with a surface area around ten times larger than the current CERN site. The concepts for the determination of these models (for the different phases of the construction and installation of the accelerators), and the designs for their implementation and validation have to be carefully studied and checked for their feasibility. Extensive field work has been designed and carried out for the gravity field study. In particular, experimental research was carried out within the study with the Differential Geodetic Interferometric Deflectometer, specially developed for this purpose in an earlier collaboration between CERN and ETH Zürich. The results indicate that the repeatability of the measurements with this instrument is not good enough. Future research needs to look into alternatives.

In addition to the gravity field activities, the reference frame in the region of the FCC and its realization on the surface as well as in the tunnels require a new foundation and detailed considerations based on the most up-to-date knowledge and instrumentation. This part includes the choice of a suitable horizontal datum and cartographic map projection for the civil engineering work, the establishment of a geodetic reference network at the surface, the design and configuration of control baselines, and the preparation of methods to transfer position and orientation from the surface into the tunnels using sufficiently accurate instrumentation and methods. Finally, conceptual designs for a new instrument control and calibration facility and for the types and locations of monitoring sensors required around the shafts have to be developed.

The conclusion of the studies so far is that it is best to create a specific and proprietary static CERN Terrestrial Reference Frame (CTRF) as a backbone of all future CERN infrastructure and as a central hub for transformation between legacy data and future data. For planning and carrying out the construction works with distinction between horizontal and vertical situation, a CERN projected reference frame (CPF) and a (gravity-based) CERN Vertical Frame (CVF) uniquely linked to the CTRF have been proposed. Also proposed are transformations to link the existing and new reference frames.

The concept of a multi-purpose surface geodetic network (SGN) as a backbone for implementing the above reference frames, for all civil engineering and surveying works as well as for monitoring the FCC area, has been developed, resulting in a conceptual proposal of a geometric configuration that has in the meantime been picked up by CERN and is currently being implemented.

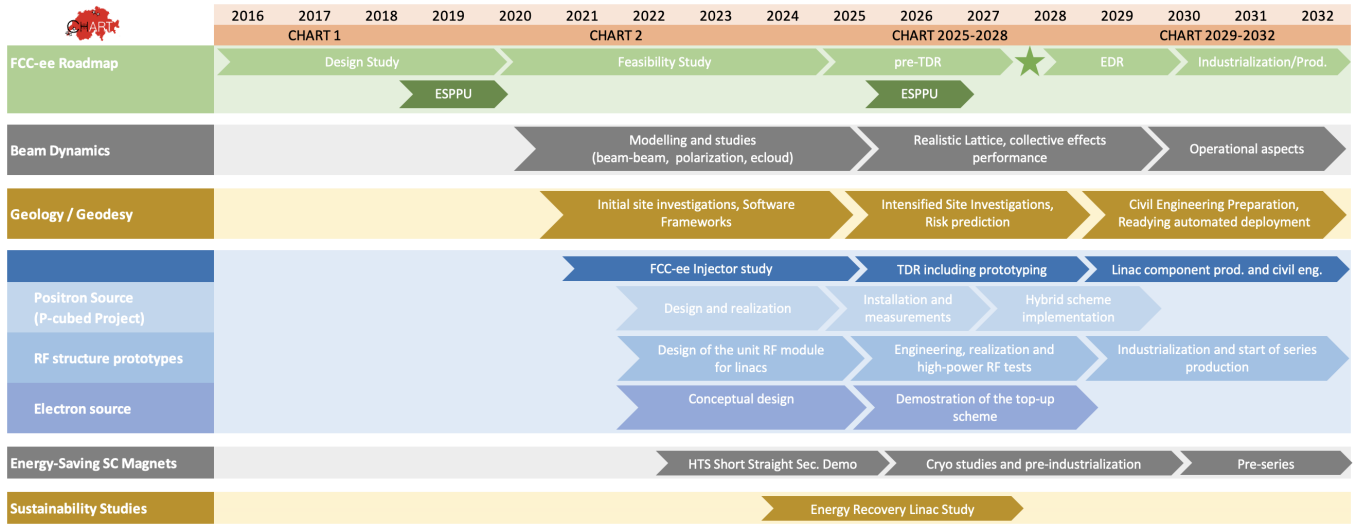


Figure 9: Timeline of CHART research for FCCee in the context of the FCC development phases and CHART research periods.

4 Prioritized Research towards Particle Physics Needs

The mission of CHART is to provide the high-energy particle physics community with technology that will maximize the physics reach of a future collider facility at CERN and enable its sustainable operation. Below we lay out the CHART technology roadmap in the context of the FCC Integrated Program (FCC-ee before FCC-hh) and discuss synergies with the Muon Collider roadmap.

4.1 FCC-ee

Work on the FCC integrated programme, with a lepton collider FCC-ee first and a hadron collider FCC-hh second, is structured into several phases, from the FCC Design Study, starting in 2015 and culminating in the CDR of January 2019, to the ongoing FCC feasibility study 2020-2024 that provides input into the next update of the European Strategy for Particle Physics 2025-2026, and which will lead into an FCC pre-TDR phase up until 2028, i.e., the date of a prospective project approval by the CERN council. CHART projects contribute in several ways to a sustainable FCC-ee in terms of physics performance, energy consumption, cost, and societal benefits. A graphical overview of the FCC-ee timeline is given in Fig. 9.

4.1.1 Beam dynamics

The next steps in designing a future collider and advancing the beam dynamics aspects of accelerator physics can be divided into three main areas:

Parameter Optimization and Exploration: With the developed tools, we can now conduct extensive parameter scans to define tolerances and explore optimal operational settings robustly. This includes developing tuning knobs and correction schemes to refine the collider's performance. Pushing modeling to higher parameter dimensions and complexities is essential.

Experimental Benchmark of Tools: To enhance the robustness of our numerical tools, intensive benchmarking with existing accelerators is essential. Although no current accelerators exactly replicate the FCC, facilities like SuperKEKB in Tsukuba, Japan, and the LHC at CERN can serve as valuable test benches for beam dynamics models. SuperKEKB, the closest machine we have today to the FCC-ee, demonstrates the complexity and often poorly understood dynamics of colliding leptons. Several effects interleave, creating unstable dynamics and complex situations to model. Benchmarking tools developed for FCC against operational facilities will be crucial. Additionally, understanding and experimentally pushing the intensity limitations of such colliders will help build a solid foundation for the FCC program.

Modeling Multiple Effects: Continuing numerical studies that incorporate interleaved effects in collider models is vital, as real-world operation demonstrates that problems typically arise from multiple interacting factors. For instance, modeling the combined effects of electron clouds on colliding beams and machine impedance is essential. Leveraging advanced technologies such as ML/AI and GPUs can enable more realistic simulations. Tools should continue to be developed in this direction. A multidisciplinary push towards innovative ideas and technologies, such as high-temperature superconductors (HTS),

will also be crucial for future advancements.

In summary, these steps will help define the feasibility of the project, identify and mitigate potential issues, and propose a robust operational scenario with precise technical tolerances and requirements to drive technological advancements and in preparation to a technical design study.

4.1.2 Energy-saving magnet systems

In the CDR of the FCC-ee machine, the (de)focusing quadrupole magnets and sextupole correctors in the arc sections of the machine constitute the main components of the so-called short straight sections (SSS). In order to minimize synchrotron radiation, the dipole filling factors of the arcs is maximized, and the space available for quadrupoles and sextupoles is limited. This requirement, in turn, increases the required magnet strength, which in turn increases the power consumption of the normal conducting magnets. In the CDR, the 2900 SSSs, with 80 MW peak power, consumed seven times more power than the entire dipole system.

To reduce magnet power consumption, increase beam-optics flexibility, and reduce RF power, the HTS4 project proposes a superconducting SSS design based on ReBCO high-temperature superconductor. The project aims for radially nested sextupole, quadrupole, and dipole magnets, thereby increasing the dipole filling factor and reducing synchrotron radiation around the ring. The HTS SSS (hence HTS4) system is engineered for minimum power consumption and optimizes operating temperature, cryogenic system layout, and coil geometry for minimal total cost of ownership, i.e., investment cost and operating cost combined. The project drives sustainability-enhancing and cost-saving innovation in multiple areas such as heat-activated partial insulation systems, cryogenic power-electronic systems, and cost-optimized distributed cryogenic systems. After a successful test of a 1-m-long prototype module in 2025, the project will work to include the latest developments in powering and cryogenics into the prototype, and lift the technological readiness of all components in view of near-term industrialization starting 2030.

4.1.3 Geology and Geodesy

CHART continues to support the FCC Feasibility Study, contributing to the preparation of the FCC site with geological modeling (UNIGE) and geodetic aspects (ETHZ).

FCC Geological Modeling: The 3D geological model built by UNIGE in support of the FCC trajectory design provides a solid knowledge framework based on all available data known to date, highlighting the different lithological and structural heterogeneities crossed by the planned

trace of the FCC tunnel. Specifically, the model allows the visualisation of the subsurface conditions known to date in the identified high-risk areas, thereby enabling informed decisions during the forthcoming geotechnical and seismic investigation campaign which will take place across the French and Swiss border. Further studies aiming at prediction of seismic hazard associated with critical fault reactivation and ground deformation will be preformed in a collaboration between UNIGE, SED, and ETHZ.

Following this investigation campaign, the geological 3D model will be updated with the new acquired data from France and Switzerland and will therefore provide more accurate view of the subsurface. This 3D model represents a practical working tool which will support the FCC project throughout the different phases of tunneling design, planning and execution. The forthcoming phase of geological investigation of areas of high geological uncertainties associated with the selected FCC trajectory will produce a large amount of new knowledge of the subsurface and surface consisting in geological/stratigraphic and geophysical and geodetical data. Two goals will be pursued:

- Maintain and manage UNIGE's U-SOLSTISS database, an Arc-GIS-based subsurface database in support of the feasibility and execution of the FCC tunnelling.
- Maintain and ensure seamless updates of a consistent high-resolution 3D geological model focusing on incorporating and updating the fault geometry and location and the top Molasse/Base Quaternary and base Molasse/top Cretaceous surfaces.

FCC Geodesy Studies: The work on the high-precision gravity field model for the FCC region and on improving the geodetic reference frames and geodetic infrastructure will continue. Once the construction is completed and the installations start, the geodetic underground measurements and civil engineering monitoring will need to be connected, allowing for measurements with a high degree of automation. A preliminary study of available information about the FCC area revealed the presence of potentially significant surface and subsurface displacements exceeding 1 mm/yr. Continuous and interdisciplinary geomonitoring of the area should start well before the FCC tunnel construction and a dedicated study will be initiated.

4.1.4 Injector Complex

For the future development and construction phases of the injector, the involvement of the various international partners will also be crucial because after the completion of the Feasibility Study phase, a preliminary technical design report (TDR) will be produced by mid-2027. It

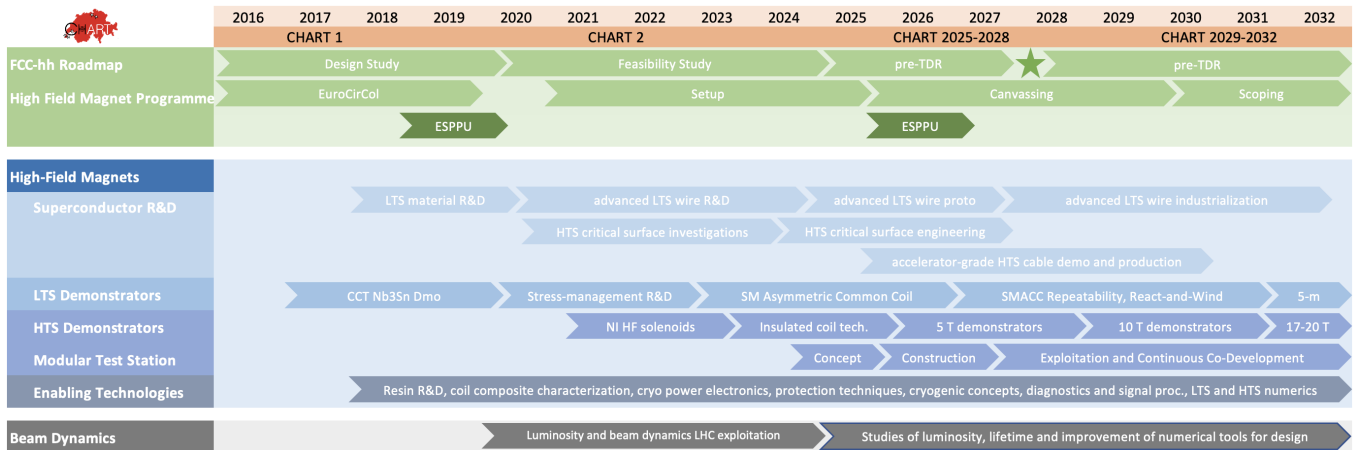


Figure 10: Timeline of CHART research for FCC-hh in the context of the FCC development phases, the High-Field Magnet (HFM) Programme roadmap, and CHART research periods.

will be fundamentally based on SwissFEL linac technology for RF accelerating structures and on related upgrade projects, but also on the experiences of international partners who operate or have operated light and positron sources. The objective of the preliminary TDR is to provide detailed specifications for the accelerator and technical infrastructure requirements necessary for the initial phase of the civil engineering design. This should ensure that the specifications are comprehensive and encompass all the requirements for the system and its sub-systems, thus enabling the initial construction phase and the subsequent series production of the components.

By the end of 2028, the Technical Design Report (TDR) for both the accelerator and the technical infrastructure will have been completed. The completion of the TDR will be crucial in enabling further engineering design efforts and will allow for the finalisation of all specifications necessary for the civil engineering design. This stage is of great importance, as it guarantees that all design elements are subjected to rigorous examination and incorporated into the overall scheme, thus paving the way for a smooth transition into the construction phase.

In this context, it will be essential to implement a prototyping phase. During this phase, the RF accelerator structures will be subjected to exhaustive testing in order to validate their performance and reliability. Moreover, it will be demonstrated that the electron source concept, which is based on a photo-cathode RF gun, can be relied upon to provide a reliable top-up operation for injection into the collider ring. It is essential that this demonstration will be carried out in order to guarantee that the proposed technology is able to meet all operational requirements and can be effectively integrated into the overall system.

Furthermore, the P^3 experiment at PSI for positron production will be completed, commissioned, and its further

development will be initiated. This development will include the use of the hybrid scheme, which is expected to enhance the efficiency and efficacy of positron production. Through this process, the specifications for the positron source will be verified, ensuring that all components meet the necessary criteria for successful operation within the broader system. This comprehensive approach will allow us to confirm the fundamental elements of the project, thereby enabling us to proceed with confidence in the technology and design choices made.

4.2 FCC-hh

Since the FCC CDR, published in January 2019, the main focus of the FCC program has been on the feasibility of FCC-ee as a first stage of an integrated program. Since then R&D activities for FCC-hh are mainly focused on the key technology of high-field magnets. At the same time, it is generally acknowledged that any future accelerator-magnet system will be strongly coupled to other accelerator subsystems such as cryogenics, beam optics, powering, etc. Novel conductors and cryogenic concepts will mean that this coupling is far more consequential and bi-directional than it was for past accelerators, HL-LHC included.

CHART contributions to FCC-hh focus on the development of high-field magnets with LTS and HTS technology with related cryogenic and powering concepts, and on beam dynamics where the LHC is used up to Long Shutdown 3 (2026-2028) for experimental validation of relevant concepts, and a suite of numerical tools is readied for a future design optimization of FCC-hh.

4.2.1 High-field magnets

LTS Technology - Nb₃Sn: In LTS high-field magnet R&D, we are building upon a technology stack for stress-managed Nb₃Sn magnets that was developed at PSI over the preceding CHART periods. Stainless-steel winding formers, high-temperature-resistant spin-coated secondary electrical insulation, and high-volume fraction alumina-filled paraffin wax impregnation are the key ingredients to robust, training-free performance of stress-managed coils. By 2026 we will demonstrate the application of the above technology stack in a novel coil geometry called the Stress-Managed Asymmetric Common Coil (SMACC). This magnet type needs only flat racetrack-shaped coils with relatively wide bending radii. This coil type lends itself to a high degree of automation of touch-labor and a significant cost reduction in industrial manufacturing of FCC-hh magnets. Combined with the training-free performance, SMACC technology is expected to be a very serious contender for the FCC-hh main dipole magnet system. After an initial technology demonstration, future iterations of the magnet will introduce further optimizations (higher-melting-point wax, react-and-wind manufacturing), a demonstration of the reproducibility, and eventually a demonstration of length scale-up to 5 m length in collaboration with CERN. The SMACC program will be accompanied by a continuation of the BOX (powered-sample) program, and of the subscale SMCC and hybrid-subscale SMCC programs to continuously infuse validated innovation into future iterations of SMACC.

HTS Technology - ReBCO: ReBCO coated conductor in tape-form is the only HTS conductor that is available today at an industrial scale. Given the continued growth in demand from magnetically-confined fusion, and the prospect of an opening market for power-distribution lines, ReBCO offers a path to reach the ambitious cost targets of an FCC-hh magnet system. Critical field and current performance of today's ReBCO is sufficient to achieve even the most ambitious performance goal of 20 T field in the aperture. Nevertheless, coated conductor in tape form comes with a number of intrinsic challenges, each of which needs to be addressed by vigorous R&D over the coming years to provide empirical evidence that ReBCO technology is ready for use in accelerator magnets in a synchrotron. CHART projects must substantially improve numerical modeling of transient effects in ReBCO tape in order to reliably and efficiently predict screening-current induced ramp losses and field distortions in accelerator magnets. These parasitic effects can be orders of magnitude larger than in today's LTS magnets, endangering the sustainable operation of an HTS accelerator, even at 20 K operating temperature. Extrapolation via numerical models from small-scale experimental results to 20-T

accelerator magnets is fundamental to guide the magnet-technology R&D. Following initial simple-to-manufacture solenoid and racetrack coils, we plan to build a series of 5-T-range accelerator magnets, employing the successful fast-turnaround innovation funnel methodology that has propelled our LTS program over the past years. When accelerator-quality can be achieved, the field strength must be increased to address additional problems related to Lorentz forces and the large stored energy. Early on we must decide whether to build an LTS outsert magnet that could host an HTS insert for fast-turnaround high-field R&D, or whether to build all-HTS high-field magnets operating at 20 K. A new testing platform for HTS high-field magnets at PSI is of strategic importance. The test station shall allow for the simultaneous fast-turnaround R&D on magnet technology, cryogenic concepts, and protection methods. A feasibility study for a sustainable modular test station without a helium liquefaction plant is currently being finalized.

Enabling Technologies: Enabling technologies encapsulate a wealth of engineering challenges, ranging from insulating materials to structural materials, power-electronic systems, electronics and sensor development, machine-learning for diagnostics and preventive maintenance, protection concepts, cryogenics concepts, numerical models and tools, etc. The meaning of the term 'accelerator quality' needs to be re-evaluated for HTS accelerator magnets. They need not, and perhaps cannot meet the specifications in terms of magnet protection, field quality, powering, or cryogenics that have been validated in the LHC. We are confident that the boundaries in energy density (magnetic energy per coil volume, proportional to magnet cost) can be pushed and novel solutions to detection, protection, and cooling can be developed. HTS accelerator magnets are expected to increase the degree of mutual coupling between previously independent accelerator subsystems. Therefore, cryogenics, powering, protection, vacuum, beam operation, and other subsystems must be co-developed from the earliest design stages. CHART aims to provide a decisive push in this direction, building upon and extending a network of experts across the CHART institutions. A key element of this strategy is a novel and modular test station that allows for coordinated research in cryogenics, protection, powering, and magnet design. This multi-domain research is to be underpinned by a suite of improved and stream-lined model-based systems engineering tools to efficiently address the complex co-development task.

4.2.2 Conductors for high-field magnets

LTS Conductors: The latest concept for the FCC proposes a tunnel with a circumference of 91 km. By

employing Nb₃Sn-based dipole magnets operating in the 14–16 T range, the FCC-hh could achieve collision energies between 85 and 95 TeV, contingent on lattice optimization. These high-field accelerator magnets utilize high-current Rutherford cables, composed of several Nb₃Sn wires, to form low inductance coils, this design being crucial for effective quench protection and rapid energy dumping. Advancements from the CHART WireDev project have demonstrated significant enhancements in the critical current density (J_c) of Nb₃Sn wires through the internal oxidation method, reaching the required J_c levels for 16 T dipoles. The next milestone is to implement this result, obtained on simplified wire architectures, in application-ready wires as those produced industrially. Among the various industrial techniques for Nb₃Sn wire fabrication, the internal Sn rod-type method stands out. This method is favored for its ability to produce wires with high in-field current density and robust mechanical properties, particularly maintaining performance integrity during Rutherford cabling. The planned development of Nb₃Sn conductors involves also extensive R&D to integrate mechanical reinforcement into the wire architecture. Enhancing mechanical load tolerance without compromising current-carrying capacity is a significant challenge but indispensable for use in high-field accelerator magnets, due to the huge electromagnetic forces. This requires advancements in metallurgy, the use of innovative material composites, and finite element method (FEM) analyses to predict the mechanical behavior of the new wire designs. To achieve these goals, it is crucial to upgrade the capacity of the CHART laboratory for the production of Nb₃Sn wires. The ultimate objective is to produce these wires in sufficient lengths to test their performance in Rutherford cables and under conditions relevant to accelerator magnets. The aim is to establish a robust and cost-effective wire technology and collaborate with industrial wire manufacturers to transfer these methods, thereby scaling up production for future applications in the FCC.

HTS Conductors: High Temperature Superconductors (HTS) hold the potential to generate magnetic fields beyond the reach of Nb₃Sn and operate at temperatures above 4.2 K. However, the suitability of HTS for FCC-hh needs to be demonstrated by providing a proof-of-principle for HTS dipole magnet technology with a target field in the 20 T range, corresponding to proton-proton collisions at approximately 120 TeV in the FCC-hh. The surge in start-ups focusing on magnetically-confined fusion has led to a significant increase in the production capacity of REBCO (Rare Earth Barium Copper Oxide) coated conductors, resulting in a reduction in their cost. These conductors are typically in the form of tapes, which presents unique

challenges for high-field dipoles that require high-current cables. Currently, there is no established configuration to produce accelerator-grade cables from REBCO tapes. This aspect will be investigated within the framework of CHART, aiming to validate concepts, test properties, and facilitate the transfer to industrialization. These developments could also benefit other applications in the power sector.

While the cable layout is an essential issue, there are more fundamental challenges that must be addressed to make the use of REBCO feasible as a conductor for the FCC-hh. REBCO crystal has a highly anisotropic structure. In coated conductors, the superconductor is deposited on a buffered metallic substrate as a thin film, only a few micrometers thick, and must be nearly monocrystalline to avoid grain boundaries that impede the flow of superconducting current. As a consequence of this layered structure, REBCO tapes are prone to delamination, with stress components that can cause delamination (transverse tension, shear, peel, cleavage) having very low failure limits, around 10 MPa. Material science investigations will be carried out to understand the mechanisms underlying this interface fragility and to develop new tape architectures that mitigate this problem, which can cause magnet failure.

Another intrinsic challenge of the REBCO coated conductor architecture is the width of the superconducting layer, which typically ranges between 4 mm and 12 mm. This wide superconducting layer results in large magnetization losses, which must be considered especially in view of magnets operating at temperatures higher than 4.2 K and with simplified cryogenics. Additionally, the large width of the superconducting layer produces significant screening currents that can degrade magnetic field homogeneity and temporal stability. Within the CHART project, there is an intention to develop robust and cost-effective methods for filamentization of the REBCO layer to reduce these losses and mitigate the effects of screening currents.

4.2.3 Beam Dynamics

Continued research on the LHC is essential due to its similarities with the future collider projects. Emphasis should be placed on machine protection for a 50 TeV proton beam and addressing intensity limitations. Active involvement in the development programs of the LHC and its upgrades is critical. Possible solutions from optics, collective effects and protection for the FCC-hh should be developed and tested on the operating collider. Particularly the possible use of HTS technology and its implications to the dynamics and operation should be explored together with in deep studies of luminosity quality to fully exploit the collider physics potentials in view of the High Luminosity

era. Furthermore, CERN accelerators offer invaluable test facilities for implementing and optimizing novel technologies as ML/AI, driving forward advancements in operation and efficiency.

4.3 Muon Collider

The Muon Collider Design Study, embedded in the International Muon Collider Collaboration, aims for a baseline design of a muon collider, based on successful technology demonstrators, by 2028. The design study is followed by the construction of a test facility and the prototyping of full-scale components.

4.3.1 Beam dynamics

The study of muon cooling and acceleration is a fundamental part of the process towards achieving collisions in muon collider studies and CHART supports this study. Investigating intensity limitations linked to collective beam behavior, such as space charge and the interference of wake fields in absorbing materials, will help define the muon beam characteristics. The next steps for CHART will be the design of the acceleration chain and the final collider, focusing on the particle dynamics and collective effects, such as beam-beam interactions and their impact on dynamics and machine protection. Technical requirements as magnets tolerances and the design of the entire infrastructure should be envisioned to support a realistic cost estimate and identify key technologies. One crucial area is the development of high-field magnets (HFM), potentially utilizing high-temperature superconductors (HTS).

4.3.2 Applied Superconductivity

Superconducting magnets are pivotal for the operation of a muon collider, with a significant accent on HTS. Two key high-field HTS magnets proposed for the muon collider are the target solenoid and the final cooling solenoid. The target solenoid is designed to maximize muon capture efficiency, necessitating a peak field of 20 T. To achieve this, the magnet will be wound using HTS cables composed of a copper slotted core with twisted REBCO tapes encased in a robust steel jacket. This design aims to operate effectively at 20 K. The final cooling solenoid plays a critical role in achieving the required final emittance of the muon beam, which is inversely proportional to the solenoid's field strength. To meet the final emittance requirements and enhance beam brightness, fields in the range of 40 T are being considered. For this magnet, a non-insulated (NI) REBCO winding solution operating at 4.2 K is under

development. The magnet design is constrained by a compact form factor, with a clear bore of 50 mm and a length of 500 mm.

Conductors: Both above magnet designs face challenges intrinsic to the REBCO tape architecture. As highlighted for the FCC-hh high-field dipoles, issues such as low delamination strength and significant screening currents need to be addressed in the conductor development phase. These aspects will be a focus of the CHART research activities on HTS conductors. Moreover, the textured nature of the REBCO layer in the tape presents additional design challenges. The anisotropic electrical transport properties of REBCO mean that the critical current density is sensitive to the orientation of the magnetic field relative to the REBCO crystallographic axis. This angular dependence varies with magnetic field intensity and temperature, and can differ between manufacturers. A strategic goal of CHART for optimizing magnet designs and ensuring their performance in the high-field environments is to develop a new high-field test station capable of mapping the critical current surface of REBCO tapes, accounting for temperature, magnetic field intensity, and orientation.

Magnet technology: CHART contributions to the Muon Collider magnets mainly focuses on topics with clear synergies to the FCC integrated program. The 'MagMu' is part of the Horizon 2020 Infra-Dev project MuCol and its R&D for the ultra-high-field solenoids in the final-cooling section of the muon collider with material research on so-called smart insulation. Smart insulation is provided by materials that change their behavior from insulating to (partially) conducting as a function of local temperature or local electric field. In this way, smart insulation can act as conventional insulation in nominal operating scenarios and as a current-sharing path in case of a local normal zone in the coil, enabling more compact coils and higher fields. Future developments include novel processes to apply smart-insulation materials to cables and/or winding formers, and to characterize and optimize mechanical properties of the materials in view of an application in extreme stress situations. Moreover, the NI-coil manufacturing experience at PSI is being shared with the 40-T development team for the muon collider, and future joint developments in this area are foreseen.

4.4 Sustainability of Particle Colliders

High-energy and high-luminosity collider facilities consume significant electrical energy, reaching the order of TWh/y. Energy consumption and sustainability are critical for public and political acceptance of new research infrastructures, given their research capabilities and significant investment costs.

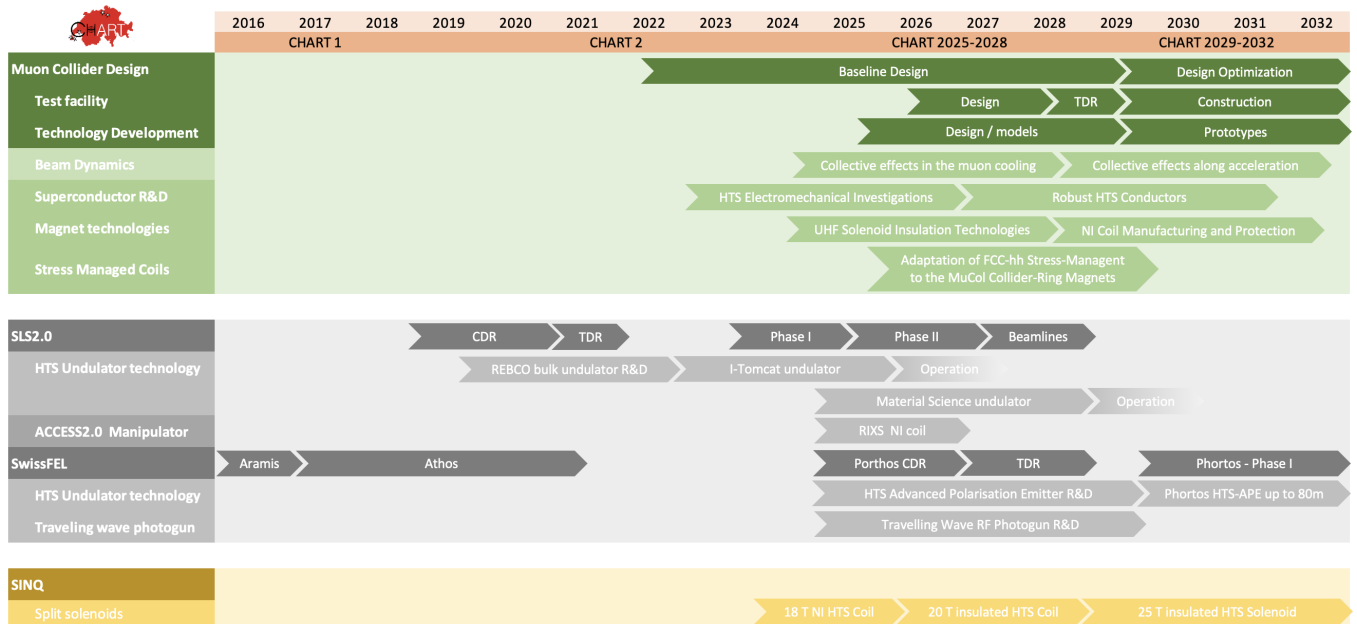


Figure 11: Timeline of CHART research for the Muon Collider study, PSI light sources SLS2.0 and SwissFEL, and for the SINQ neutron-scattering facility.

At EPFL, the goal is to maximize the luminosity of particle beam interactions per unit of power drawn from the grid through advanced simulation and optimization of particle dynamics for future collider facilities. This can be achieved by implementing smart collider concepts and optimizing the complex parameter space of colliding beams using modern scientific computing methods, including large-scale tracking simulations, parallelization, and machine learning. In collaboration with the Swiss Data Science Center, efforts have been directed towards developing sustainable simulation strategies that reduce computational redundancy through the application of machine learning techniques with very promising results.

Currently, two basic concepts, the ring collider and the linear collider, are being developed for different parameters and particle species. Ring colliders efficiently reuse beams in repeated collisions but suffer from synchrotron radiation losses and the need to continuously replace lost beam energy. In the hadron version of the FCC, even though protons radiate less, synchrotron radiation losses of several MW are significant since the radiation power must be removed from cryogenic magnets. Linear colliders, on the other hand, have no radiation losses but use their beams inefficiently in a single collision. To achieve reasonable luminosity, beams are strongly compressed in phase space, which isn't feasible to the same degree in circular colliders due to long-term dynamics.

A combination of both approaches, through the concept of an energy recovery linac (ERL), seems possible. In an ERL, beams with linear collider-type parameters collide

once, but the energy of the spent beam is recovered and recirculated, enhancing overall luminosity per grid power. This scheme represents a basic idea for an efficient collider variant, requiring detailed studies on efficient deceleration of the spent beam, the effect of synchrotron radiation by arc recirculation in several passes, and cost optimization of a machine with several arcs. Through concept studies, EPFL has recently started contributing to the Innovative and Sustainable Accelerating Structures (ISAS) EU project, focusing on the development of sustainable accelerating structures, including a realizable Energy Recovery Linac (ERL) scheme for the FCC-ee.

With the future European energy mix increasingly relying on sustainable sources such as wind and solar power, energy production will fluctuate significantly. To mitigate the impact of HEP facilities on the electrical grid, actively managing their energy consumption is crucial. High loads could be avoided during low supply conditions, and excess energy could be utilized preferentially. Managing energy usage through dynamic operation and energy storage systems is being explored for industrial applications and could have synergies with HEP infrastructures. Colliders could implement smart standby modes for efficient and quick recovery of optimized luminosity operations. This includes quick computer-aided startup and optimization schemes for colliders, along with advanced energy management in collaboration with Swiss science partners.

Additionally, improving the energy efficiency of HEP facilities through R&D in critical technologies is essential. Potential options include efficient tube and solid-

state RF sources, advanced permanent magnet technology, high-temperature superconductor magnets with enhanced cryogenic efficiency, and improved tunability. A key starting point in this endeavor is advancing the development of new nested magnet optics for the FCC-ee that rely on HTS technology in parallel to the energy saving magnets projects described in Sec. 4.1.2. For FCC-hh, the key towards more sustainable physics production lies in the development of conductors, cables, and coil geometries that minimize the parasitic losses induced by the conductor while ramping up the current and field, as well as in the co-development of cryogenic concepts and magnet technology to minimize the amount of helium used in the accelerator's cryogenic system.

5 Synergetic CHART Research and Societal Impact

5.1 Research towards Photon Science Needs

Today's state-of-the-art photon sources rely on cryogenic permanent magnet in-vacuum undulators (CPMUs) and low-temperature superconductors, both commercially available. CPMUs utilise rare earth elements, which exhibit increased remanence and coercivity when cooled to near liquid nitrogen temperatures. Low-temperature superconductors, particularly Nb-Ti, operate around 4 K. However, superconducting undulators have not been as widely implemented in light sources as CPMUs. This is likely due to the challenges of operating at extremely low temperatures, higher RMS phase error (which is detrimental for medium energy storage rings requiring high harmonic operation to achieve Armstrong resolution), and their similar performance compared to CPMUs. To advance beyond current capabilities and significantly enhance performance, high-temperature superconductors should be implemented in the form of bulks or tapes. PSI has explored the use of bulks extensively during the CHART2 phase, and this technology is now ready for testing in an operational environment, as mentioned in Section 3.1.3. REBCO bulks currently hold the record in engineering current density, enabling extreme performance. However, their implementation in undulators has limitations in wavelength tunability, making them less optimal for certain applications. Therefore, efforts are underway to implement tapes to wind an undulator coil, allowing field strength adjustments by controlling the transport current. Various winding options exist, and PSI is developing a novel design in collaboration with Japanese partners. Several institutions, including CERN, KIT, EUXFEL, and ANL, have initiated small R&D projects to explore this op-

tion. PSI has recently joined a EU proposal to collaborate with EUXFEL, ESRF, and CERN on this topic, combining expertise from different fields such as accelerator magnets and solenoids to accelerate progress. The proposal's funding status will be determined in September 2024, and the outcome will significantly impact this technology.

The League of European Accelerator-based Light Sources (LEAPS) is developing its own roadmap and planning for a block grant agreement with the EC. LEAPS has highlighted the potential of high-temperature superconducting undulators for Free Electron Laser beamlines. The compact size of superconducting undulators allows for the integration of multipole coils in the same cryostat, which can serve different end stations. This approach would share experiment costs among multiple users, similar to current synchrotron facilities.

5.1.1 SLS2.0

Bulk Undulators: The Swiss Light Source is undergoing a significant upgrade to enhance the brightness of its beamlines by two orders of magnitude. This improvement will be achieved through a reduction in electron beam emittance and the implementation of new undulators, including a bulk superconducting undulator developed under CHART2. Following the first phase of the upgrade, individual beamlines will assess potential enhancements to their instruments. At least two beamlines are interested in utilising HTS (High-Temperature Superconductor) undulators to further extend their photon energy range and brightness. The first is the materials science beamline, which focuses on surface and powder diffraction. Higher photon energy and easy tunability of the radiation wavelength are crucial for maintaining a leading position in this competitive field. The second beamline is the cSAXS beamline, dedicated to small-angle X-ray scattering (SAXS) and coherent diffractive imaging, especially ptychography. This technique requires extremely high brightness, achievable only through advancements in HTS technology for undulators. In the long term, the success of this technology is expected to encourage beamline scientists working with hard X-rays to adopt these new insertion devices to ensure their instruments remain state-of-the-art.

Compact Solenoid for ACCESS2.0 Beamline: As part of a successful R'Equip application for an upgrade ACCESS2.0 of the ACCESS beamline at SLS2.0, CHART will provide a compact (2-3 cm in diameter, 1 cm in height) non-insulated REBCO magnet to enhance the field on sample in the RIXS manipulator head from the present 0.6 T to 6 T or more, thus significantly increasing the physics reach of the facility.

5.1.2 SwissFEL

Porthos Undulators: Today, SwissFEL consists of two beamlines, Aramis and Athos, which cover the entire range of soft and hard x-rays up to 14 keV photon energy with six instruments. A working group has been active for about two years, collecting ideas and specifications for a third beamline, Porthos. The proceedings of the last workshop indicate strong interest from the scientific community in a tender beamline with polarisation control and full temporal coherence. These specifications can be comfortably met only with superconducting undulators. With no final technical decisions expected before 2030, there is now a great opportunity to develop this technology using high-temperature superconductor (HTS) tapes. This design consists of four independent coils, all generating a sinusoidal field along the same path, allowing for polarisation variation by changing the relative current among them. Except for two pilot projects, one at the European XFEL and one at SLAC, where a low-temperature superconducting undulator afterburner is planned to extend the energy range, Switzerland, with Porthos, could be the first to assemble a full undulator beamline (up to 80 meters long) exclusively with high-temperature superconductors.

High-brightness photo-cathode RF sources: The first generation of S-band injectors for free-electron lasers has demonstrated high reliability and performance by driving the latest generation of high-brightness Free Electron Laser (FEL) machines. However, the ultimate electron beam brightness of these devices is limited by the electric field they can achieve at the cathode. The development of the travelling wave (TW) radio-frequency photogun will make it possible to work with a cathode gradient of up to 200 MV/m, which will be able to produce an electron beam with a 5D beam brightness up to five times higher than that of the current SwissFEL photogun. Furthermore, the low power dissipation within the photogun, resulting from the short RF pulse length and TW philosophy, opens up the opportunity for RF pulse repetition rates up to 1 kHz. This new approach to use a multicell RF photogun

together with a reduced phase velocity can also generate femtosecond-scale MeV electron bunches directly from the photogun. The electron bunches generated by this stand-alone device rival those generated by a FEL-style photogun with a magnetic or ballistic compression scheme allowing a significant reduction in the machine footprint and complexity of the beamline.

5.2 Research towards Neutron Science Needs

5.2.1 SINQ

In 2025, an 18-T no-insulation HTS split solenoid will become available in SINQ for neutron-scattering experiments, built through synergies with the CHART MagDev HTS technology development. Due to the no-insulation technology, the coil will be operated in DC mode and cannot provide fast field adjustments. Nevertheless, it will enable new experiments. As a next step, it is foreseen to launch a joint effort with other Neutron scattering facilities for the development of an insulated or partially-insulated 20-T split solenoid – a significant increase over the state-of-the-art 15-T systems available at SINQ. One possible route could be through the scientific membership of the Swiss Confederation at the ILL. The magnet could be shared between SINQ and ILL. Moreover, it can be explored whether a high field solenoid magnet could be installed at the new Quantum Matter and Materials Discovery Center at PSI to provide an extreme condition environment for experiments on quantum matter using lab techniques. The results of such experiments would be both complementary to the experiments at SINQ, as well as a stimulus to push for higher field magnets at SINQ. The complementary information will help to increase the success rate of SINQ experiments and their impact.

5.3 Societal Impact of CHART Research

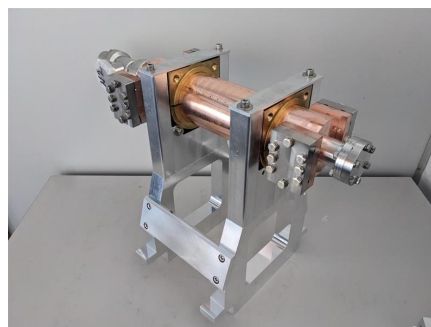
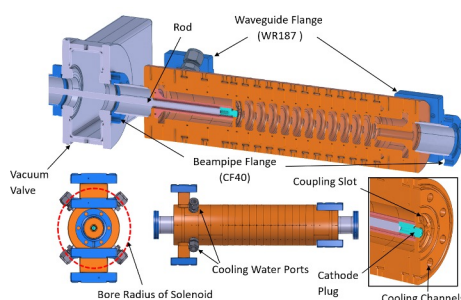


Figure 12: Mechanical drawings with some details (left) and first prototype of the TW gun realized at PSI (right).

5.3.1 Sustainability Upgrades for the PSI Proton Complex

Numerous normal conducting magnets in the PSI accelerator complex show a power consumption of the order of 100 kW each. As HTS conductor improves in price and performance, and as HTS magnet technology and advance cryogenics concepts become available, it is incumbent on the organization to consider their replacement by HTS magnet systems. Important problems remain to overcome, not least of which the high levels of radiation present in the PSI proton complex which could lead to conductor degradation and render local cooling and powering options impossible. At the same time, radiation studies for ReBCO tape have been undertaken in the HFM Programme, and the novel cryogenic concepts of the 'FCC-ee HTS4' project may provide a viable path for the cooling of multiple superconducting magnets in HIPA. The local competency and infrastructure at PSI, as well as the scientific global network that we can tap into, will enable a more sustainable operation.

5.3.2 Public-Private Partnership for Compact Magnetically Confined Fusion

Compact magnetically confined fusion is expected to be enabled by HTS magnet systems. Start-up companies have managed to secure substantial funding, sufficient to scale up the production of HTS tape to an industrial level and reduce costs. However, start-ups must assemble the wide range of competencies, experience, and infrastructure to launch a credible fast-tracked R&D effort on large-scale HTS magnet technology.

In recent years, a collaboration between MIT and Commonwealth Fusion Systems in the US has demonstrated how start-ups can benefit from the experience of established laboratories. More recently, the Munich-based start-up Proxima Fusion established an office at Park Innovaare in Villigen and initiated a collaboration with PSI. This partnership is underpinned by CHART's investment in magnet R&D and the rapid innovation funnel methodology that produced convincing results in CHART2. Over the coming years, the collaboration between PSI and Proxima Fusion is expected to intensify, contributing to the rapid learning curve that PSI has embarked on with CHART. The partnership will create meaningful and tangible synergies for both parties.

5.3.3 Accelerator Driven Systems

Accelerator technology can also contribute to sustainable energy production. Accelerator Driven Systems (ADS) are sub-critical reactors that can reduce the storage time of radioactive waste from nuclear power stations through

transmutation, addressing a key sustainability issue of nuclear power. Several technologies such as cyclotrons or high-field superconducting magnets could be enablers of ADS. Moreover, developing high-intensity accelerators for ADS has synergies with applications in particle physics and neutron sources, such as those pursued at PSI.

5.3.4 Advanced Acceleration Techniques

Research on alternative acceleration techniques has been performed with good results for the high gradient THz acceleration of relativistic electrons in close collaboration with the University of Bern and FAU Erlangen in the context of ACHIP project funded by the Gordon and Betty Moore Foundation. A structure for laser-based acceleration has been scaled to the needs of the THz acceleration. These efforts towards miniaturization of accelerator structures will continue to be highly relevant for a wide variety of societal applications.