CHART/RM/02

CHART

Swiss Accelerator Research and Technology

CHART Roadmap

ACCELERATOR SCIENCE AND TECHNOLOGY RESEARCH AND DEVELOPMENT

February 7, 2022

Contents

Purpose and Scope of this document

This first Roadmap for Swiss Accelerator Research and Technology 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, photonics, neutron scattering and life sciences including medicine. The Roadmap addresses the research and technology infrastructure needs of these accelerator driven research fields and of potential energy production (Accelerator Driven Systems, ADS) 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.

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 2040 and it is attracting the best scientists in this and related fields of research and engineering from all over the world. To maintain and further strengthen Europe's prime position beyond the present LHC Physics Program, the development of a new world-class high-energy physics research infrastructure must be put on track starting now. The European Strategy for Particle Physics (CERN-ESU/13) underlies this, stating *inter alia* that:

Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.

Such a feasibility study of the colliders and related infrastructure should be established as a global endeavor and be completed on the timescale of the next Strategy update.

Defending CERN's unique role at the high-energy physics frontier is of utmost importance for Europe as a whole and in particular 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 worldwide.

CHART, the Swiss Center for Accelerator Research and Technology, was founded to support the future oriented, ambitious post-LHC accelerator project, the Future Circular Collider (FCC) at CERN and the development of advanced accelerator concepts in Switzerland beyond existing technology. The CHART program is of strategic importance not only for CERN but also for Switzerland.

CERN and its partners have to remain the world leader in the field of high-energy physics. 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 state-of-the-art for the future CERN facility, research and development of accelerator science and technology needs to be built up now.

The roadmap at hand was established under the auspices of CHART and covers specifically the period of 2025 to 2028. In view of the long-term nature of these activities it is foreseen to periodically update this Roadmap beyond 2028.

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), A. Fasoli (EPFL), G. Dissertori (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.

The CHART Roadmap Editorial Board

B. Auchmann, M. Calvi, T. Pieloni, L. Rivkin (Chair) and M. Seidel

Executive summary and Recommendations

The CHART Collaboration supports future accelerator based projects in Switzerland. The Future Circular Collider 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, published last year. CHART is actively contributing to the Accelerator R&D Roadmap that is in preparation 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. It is also highly relevant to possible energy production using Accelerator Driven Systems as well as such medical applications as isotope production.

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. Accelerator technology can also contribute to the sustainable production of energy involving the Accelerator Driven Systems.

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Accelerator Development in Switzerland and the ongoing CHART program

Switzerland hosts two world-leading laboratories, CERN and PSI, that develop and operate accelerator based research infrastructures. 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. PSI large-scale accelerator-based facilities support a broad range of fundamental and applied research, supporting a large national and international user community from particle physics, material and life sciences, as well as medical applications. Energy production utilizing accelerators (ADS) is another example of R&D activity relying on expertise available in Switzerland.

Research at CERN's and PSI's facilities 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.

Today CERN has to dedicate major part of its resources to the very next project HL-LHC. It is the mission of CHART to support CERN for the phase beyond HL-LHC, the realization of FCC. CHART has contributed to the FCC Conceptual Design Report (CDR), published at the end of 2019. The majority of the present CHART projects contribute to the FCC Feasibility Study presently under way. The results should come in time for the next update of the European Strategy for Particle Physics in 2026.

Superconducting high field magnets are the key enabling technology for the future hadron colliders. Switzerland has a particularly compact but also diverse "Applied Super-Conductivity Landscape (ASC)". CERN and its accelerator complex with the flagship LHC and the Future Circular Collider (FCC) project are located on the Franco-Swiss border. The Paul Scherrer Institute operates technology-frontier light sources, advanced neutron tomography, and proton therapy, which are making forays into superconductivity. The University of Geneva is home to a cutting-edge superconductor R&D group. The Swiss Plasma Center is the European technology hub for applied superconductivity in nuclear fusion. ETHZ is an active partner in enabling-technology R&D such as material sciences, additive manufacturing, and numerical simulations. The Bruker BioSpin company is dominating the important market of superconducting NMR devices. With von Roll and Brugg Cables, two of the suppliers for cables and insulation for the LHC who have expressed interest in collaboration towards an FCC are equally located within the borders of the geographically small nation; see Figure 1.

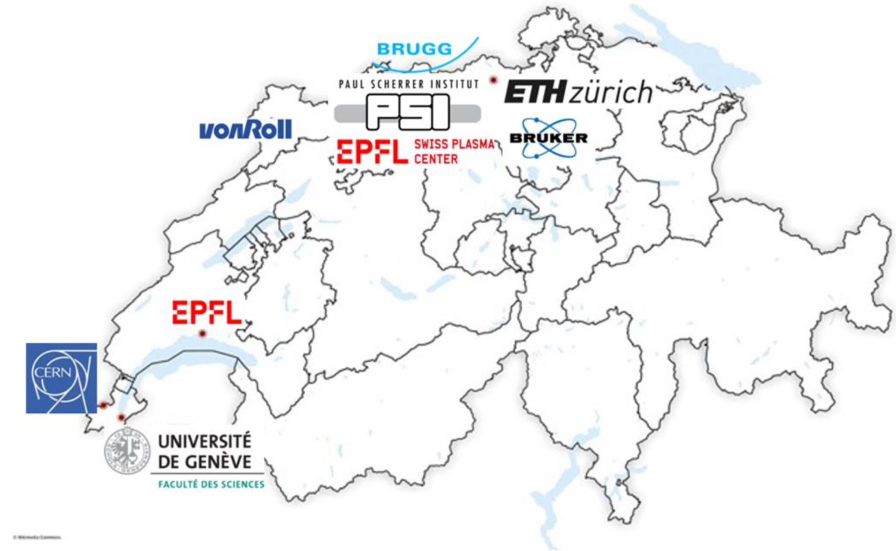


Figure 1 Swiss Applied Superconductivity landscape.

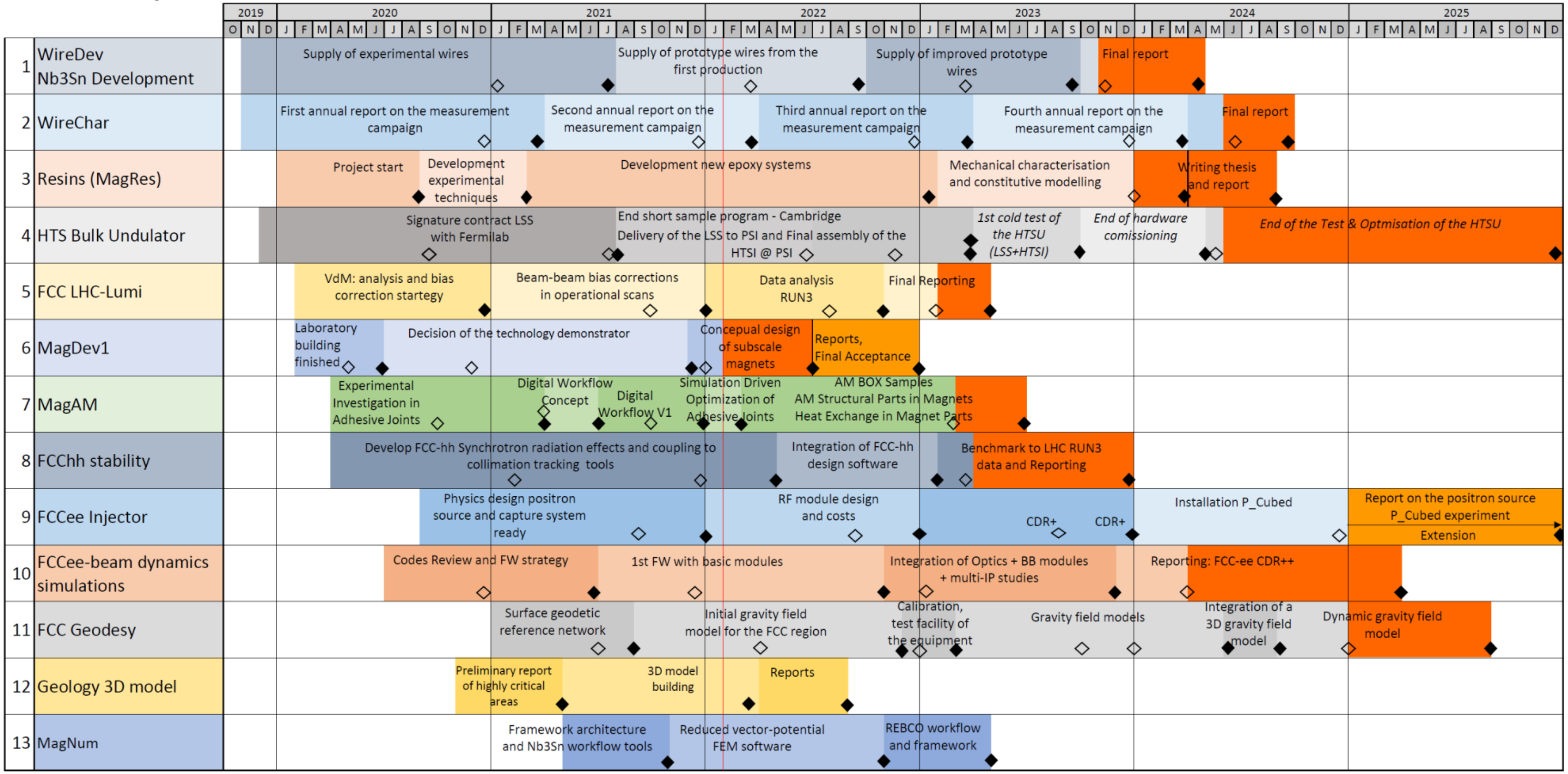
The high field magnet R&D has strong synergies with PSI projects as superconducting magnets are of great interest for production of bright hard X-rays (SLS-2, compact sources for lithography, security and personalized medicine applications) and for future proton therapy gantry designs as they have the promise of making possible lighter and cheaper gantries. The latter may open the possibility to outsource such infrastructure to hospitals that are capable to host dedicated installations for patient treatment in a clinical environment.

Securing the future of CERN beyond LHC apart from keeping the center for cutting-edge academic research will also benefit the training of both electrical as well as mechanical engineers and technicians in Switzerland. By offering such opportunities, CHART motivates younger generations to choose an academic or professional education in these domains. Teams composed of highly qualified apprentices, technicians, engineers, and scientists are key for ambitious technical developments. CHART partners direct their efforts towards excellence in education at all levels.

The synoptic table on the next page summarises the CHART projects presently under way. More details are available at the CHART web site (www.chart.ch).

CHART 2 Projects

Updated on: 02.02.2022



◇ Originally planned milestones
◆ Currently planned milestones
Project delay (mainly because of COVID)
Extension

High Field Magnet Development Strategy

In this context, it becomes clear why a push to support a Future Circular Collider through a Swiss research program on accelerator technology has for its largest component an R&D program on applied superconductivity and high-field accelerator magnets.

In CHART Applied Superconductivity, activities can be grouped into two categories: ***Technology pillars***, i.e., activities with substantial, dedicated infrastructure, where competences must be maintained over long enough time scales; and ***Enabling technology R&D***, i.e., focused R&D projects at competent laboratories and industrial partners, which re-use existing infrastructure, and employ short-term contracts such as PhD and post doc positions. The relationships between technology poles and enabling-technology laboratories must grow over long enough time scales to develop mutual understanding and intrinsic motivation.

Technology pillars are given by strand- and tape R&D, cable manufacturing and characterization, magnet design, coil manufacturing, mechanical assembly, and magnet testing (cf. Figure 2). CHART has pre-existing infrastructure such as the 21-T Nb_3Sn solenoid with variable-temperature insert as well as manufacturing equipment for superconducting wires and tapes at UniGE, and the SULTAN cable-test facility of EPFL-SPC situated at PSI. Infrastructure investment under CHART included the creation of a superconducting-magnet laboratory at PSI and the upgrade of a cryogen-free test station for HTS magnet R&D. Future infrastructure investment is foreseen in the areas of multi-filamentary wire manufacturing of up to 100 m unit length, in a test station for the qualification of HTS wires and tapes in external fields exceeding 25 T, as well as in a test cryostat for on-site magnet tests. The cable-manufacturing pillar is, for the time being, covered by partner laboratories such as CERN, LBNL, or FNAL, and investment in a cabling machine is not foreseen until a pre-series manufacturing stage of an approved future collider project.

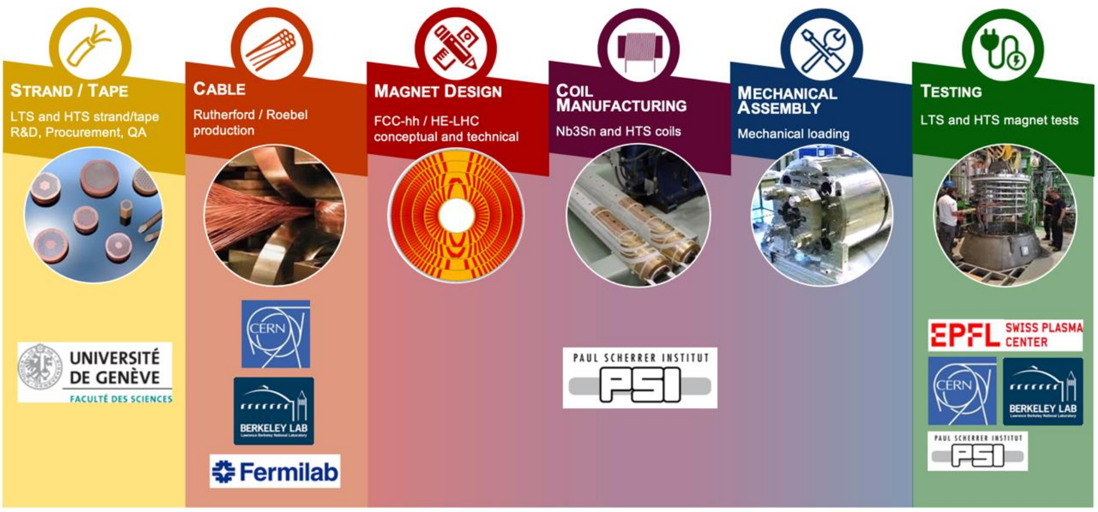


Figure 2 Graphical representation of CHART ASC technology pillars with logos of key laboratories providing the related services.

Enabling technology R&D includes topics such as soft materials (e.g., epoxy resins), composite materials, bonded and sliding interfaces, instrumentation, signal analysis, magnet protection, and numerical simulations, as well as the digitization and automation of manufacturing processes. These topics are tackled with partners at universities and technical high schools (Fachhochschulen) EPFL, ETHZ, FHNW and Fachhochschule in Freiburg im Breisgau, and industrial partners.

The CHART Council has set strategic goals, which apply equally to ASC and other projects and revolve around innovation, excellence, and focus on deliverables. For ASC activities, these goals translate into the following guidelines:

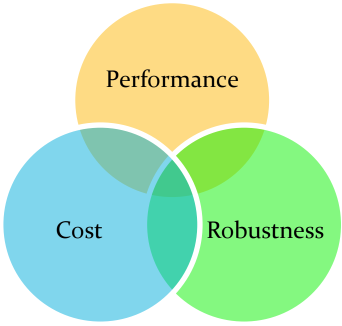
- Aim for innovative solutions to pressing problems.
- Fast-track key technology R&D with academia and industry.
- Use fast-turnaround subscale samples and coils as innovation funnel.
- Stick to fast-turnaround paradigm when stepping up in coil length and size.
- Benefit from existing infrastructure
- Where required, invest in new infrastructure early to maximize its impact.
- Strive to keep competencies and people on board across financing periods.
- Increase the cross-linking among CHART members to reach our full potential as a vibrant, distributed research network.
- Ensure optimal coordination with CERN and the international HFM effort.

Low Temperature Superconductors (LTS) based FCC magnets

Nb_3Sn-based wires and cables constitute a well-researched technology for high-field accelerator magnets. The push for highest achievable fields on a massive industrial scale, however, still poses important challenges. Below, we pose driving questions from which to derive R&D priorities:

- How to increase the overall robustness and performance of Nb_3Sn magnets in terms of
  - increased field,
  - increased yield of conforming coils,
  - reduced magnet training to ultimate field,
  - scalability to 15-m-long magnets, and
  - resilience to operational and thermal cycles?
- To which level can the magnetic field be pushed in an affordable way?
- How to improve processes for manufacturing at an industrial scale?

A graphical representation is given in Figure 3 (left) below.



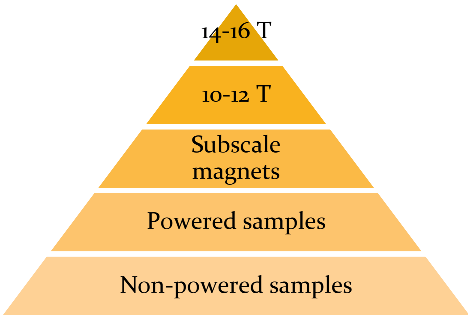


Figure 3 Left: Venn diagram of R&D priorities for Nb_3Sn accelerator magnets as specified in the 2020 ESPP update. Right: Schematic representation of an innovation funnel by means of scaled demonstrators.

Figure 4 below gives a time-line representation of the CHART LTS HFM research plans. It illustrates the goal to commission infrastructure for R&D conductor fabrication and for the manufacturing of magnets up to 2 m in length by 2024. The magnetic field reach of Nb_3Sn accelerator magnets is mainly driven by the conductor performance. Work in this focus area has two main goals: 1) to advance the properties of Nb_3Sn wire beyond the state of the art in terms of in-field current transport capability and mechanical robustness; 2) to ensure the development of fabrication processes scalable for industrial wire production. Magnet R&D includes technology R&D in the areas of insulation materials, mechanical interfaces, reproducible manufacturing processes, and advanced design techniques. To qualify new technologies, the magnet development program employs a variety of R&D platforms that vary in scale from individual material samples to small-scale powered samples, subscale magnets (5-T range, 0.5-m-long accelerator-type magnets for technology development) and 2-m-long accelerator magnets (compare Figure 3 right). In this way, new technologies can be tested under approximately realistic *in operando* conditions at the earliest possible stage and the smallest permissible scale and cost. The fast-turnaround R&D paradigm requires available magnet testing capacity in liquid helium. On the longer term, such testing capacity should become operational on-site on the PSI campus.

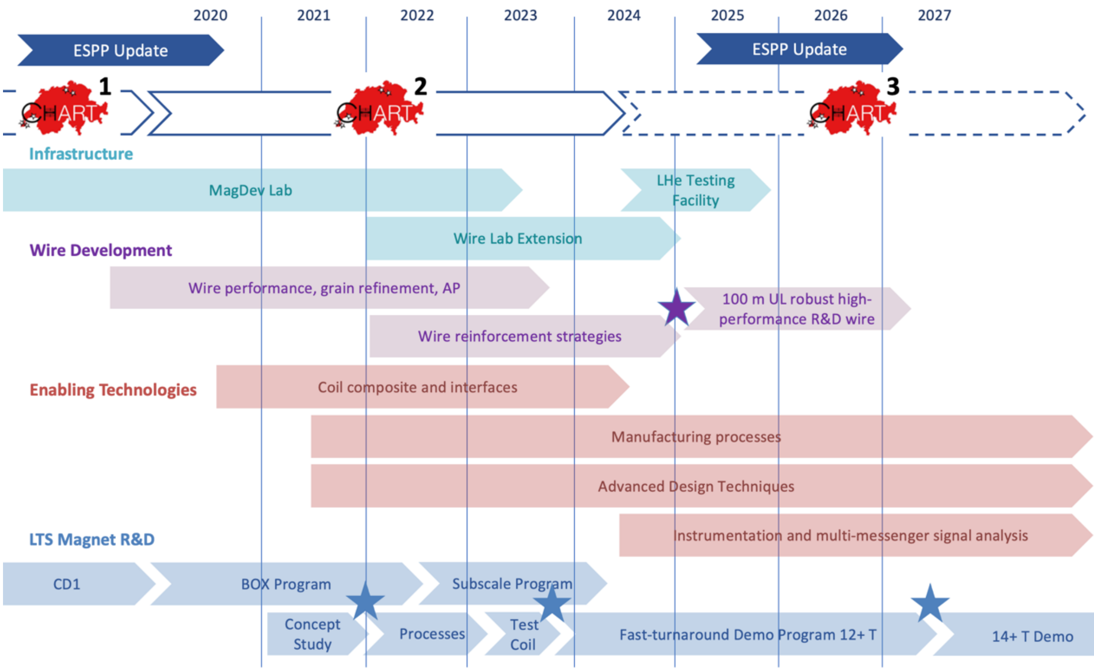


Figure 4 Simplified timeline of the CHART Low Temperature Superconductors High Field Magnet roadmap.

High Temperature Superconductors (HTS) roadmap

The driving questions for HTS accelerator-magnet R&D are, by necessity, more fundamental in nature. One could describe them casually as in “What would an HTS accelerator magnet even look like?”. Driving R&D questions are given below.

- Basic technology questions:
  - Which aspects of tape technology need improving?
  - What is the adequate cable type, coil configuration, insulation, and quench protection?
- Route to high fields:
  What are the relative advantages of roadmaps pursuing, respectively,
  - a hybrid HTS/LTS strategy, aiming for 20+T,
  - or an HTS-only path towards 16+T?
- Accelerator integration:
  - How to reach “accelerator quality” in terms of field quality (homogeneity) for a 20+T accelerator?
  - What is the optimal operating temperature of an HTS-only accelerator?

CHART HTS R&D is limiting itself to REBCO tapes due to their availability from multiple suppliers, relative robustness, low infrastructure requirements, and the proven track record. Cost is an issue, but not one that we expect to directly address in the coming years. Figure 5 provides a graphical representation of research focal points in the CHART HTS roadmap.

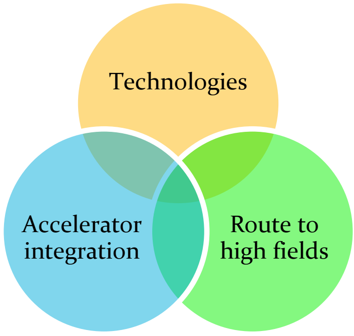


Figure 5 Venn diagram of R&D priorities for a qualification of HTS technology in accelerator magnets.

Figure 6 gives a time-line representation of the CHART HTS HFM research plans. In a first stage, CHART2 explores REBCO no-insulation coil technology with solder impregnation, and its applicability to two special magnets in the PSI accelerator complex. Beyond this initial phase that is getting the team acquainted with state-of-the-art HTS technology, the program will be devoted to the development of technologies required for HTS accelerator magnets at larger-scale, all-the-while preparing conceptual designs and a roadmap for an HTS accelerator-magnet demonstrator program. Conductor activities at the University of Geneva will focus on improved tape performance for accelerator magnets, specifically a reduction of tape anisotropy as well as the internal resistance of REBCO tape and robust joints made between tapes.

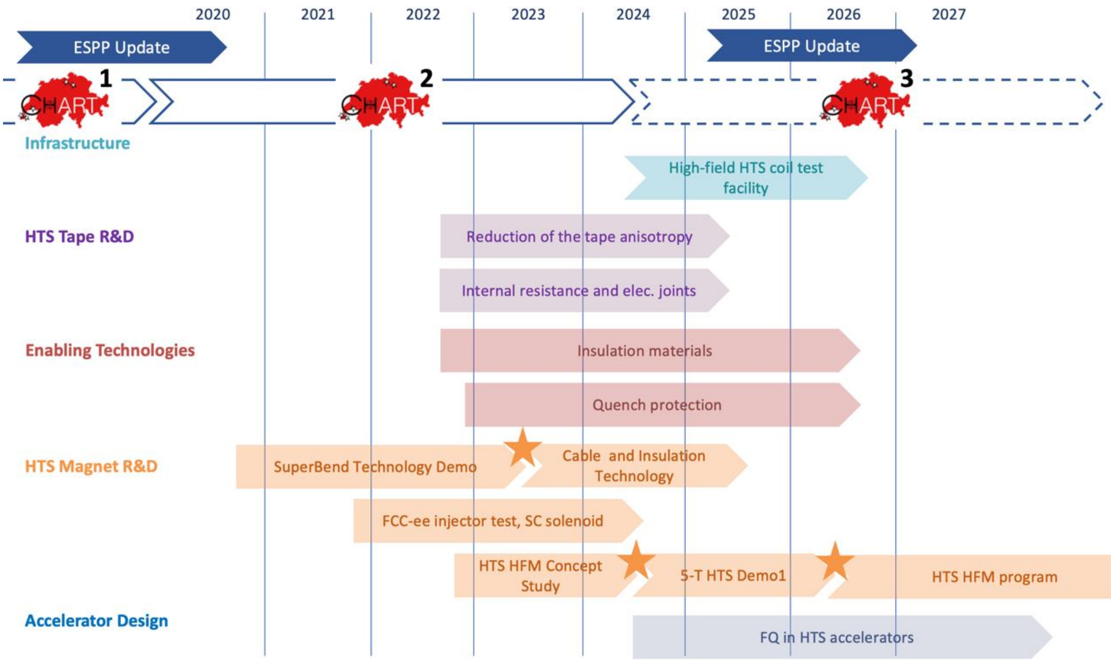


Figure 6 Simplified timeline of the CHART High Temperature Superconductors High Field Magnet roadmap.

SUMMARY OF THE MAGNET DEVELOPMENT ROADMAP

CHART as a distributed research network has the unique opportunity and mission to engage leading institutes in the ETH domain and Swiss Universities, as well as local industries. In this network, the magnet-development laboratory at PSI has a key role in that it formulates research needs and provides direct feedback to the partner institutes. At the same time, direct and decentralized collaboration between participating institutes is strongly encouraged, as it will benefit the present program and strengthen each partner's network for R&D outside the scope of CHART.

As of today, magnet-development-related activities take place at

- UniGE for LTS and HTS conductor development and multi-physics characterization of conductors
- PSI for LTS and HTS magnet R&D in the magnet-development laboratory, as well as cryogen-free testing of small-scale HTS magnets,
- EPFL-SPC for the operation of cryogenic test facilities with liquid helium, R&D on superconducting cables and splice technologies,
- ETHZ for R&D on impregnation systems (D-MATL, Soft Materials Group), additive manufacturing for structural coil parts (D-MAVT, Product Development Group), and advanced numerical tools for magnet design (DITET).
- FHNW for industry 4.0 concepts in QC/QA for magnet manufacturing.

CHART2/3 and the European High Field Magnet (HFM) Roadmap

First deliberations for a European HFM Roadmap, to be prepared by the Laboratory-Director's Group (LDG), point to an R&D schedule for FCC-hh magnet system lasting a total of three ESPP periods. The current period is devoted to the establishment of research infrastructure, innovation in key technologies, and technology demonstration. The key objective put forth in the wire development activity is the fabrication of novel Nb3Sn wires with improved performance beyond the state of the art in unit lengths up to 100 m, relevant for validation of the results in short Rutherford cables and model coils. The demonstrators would produce fields of the order of 12-T with adequate margins by 2025, with first 14-16 T demonstrators available by 2027. At the end of the period, key questions must be answered regarding the robustness and reach of the updated Nb_3Sn technology. The second ESPP period would be devoted to an ultimate field short-model program, where reproducibility and industrialization, as well as the preparation of infrastructure for long-magnet manufacturing and testing would be the main focus. Finally, the third ESPP period would focus on a long-magnet R&D and industrialization. Note that the above subdivision is indicative only, and that the individual R&D topics will almost certainly overlap.

In the light of the above, CHART2 covers the first part of the ongoing ESPP period. Its updated scope, therefore, includes an open yet focused canvassing study of novel of technologies and designs, proof-of-concept subscale experiments, as well as the commissioning of infrastructure for the construction of up to 2-m-long magnets, and the production of first demonstrator coils. The CHART3 period (2025 – 2028) must then focus on refined technology development and a fast-paced technology demonstration program, building and testing a series of accelerator magnets at the 12 T level and beyond.

International HFM Collaboration

Notwithstanding its status as a Swiss R&D network, CHART relies on strong international collaborations. First and foremost, CERN, in its double role as CHART member and main beneficiary of CHART R&D, is directly engaged in the follow-up of most R&D areas. Moreover, the US-MDP program continues to be a strategic partner for CHART MagDev, in particular for the exploration of stress-management strategies, and the sourcing of cables for demonstrator magnets; R&D agreements of different nature have been signed with both, LBNL and FNAL. For the testing of powered subscale samples, the partnership with university of Twente has proven highly productive. In the near future, the high-field magnet roadmap towards the next ESPP update will be finalized and endowed with a coordinating governance structure. Through this mechanism, CHART will coordinate its efforts with other European research laboratories.

Concluding Remarks

CHART is a Swiss research network, active in the field of superconducting accelerator magnets, contributing to the international HFM project. The HFM roadmap is based on strategic technology poles with substantial investment in infrastructure, and several strategic partners for focused and innovative enabling technology R&D. In this framework, we shall ***innovate***, through fast-turnaround experimental and modeling work at the smallest possible scale; ***focus*** on the most urgent R&D questions; ***invest*** in unique capabilities through infrastructure, relationships, ***people(!)***, and ***collaborations*** with other laboratories, fields through the HFM project.

From the above timelines, and from the experience of previous superconducting accelerators such as Tevatron, HERA, RHIC, or LHC, we must conclude that superconducting magnet R&D for accelerators is a challenging multidisciplinary activity that typically spans several decades. Continuity in terms of funding, facilities, human resources, network activities, and industrial involvement is of the essence in order for the related substantial investment to bear fruits. It is inconceivable to keep the momentum and build on previous achievements without planning security for highly qualified specialists.

BULK HTS TECHNOLOGY FOR LIGHT SOURCES

Within the framework of FCC and the roadmap of light sources in Switzerland, CHART2 started an R&D activity on HTS undulators (HTSU) to improve the quality of the existing accelerator based X-ray sources and to get a first hands-on experience with HTS technology. The research was focused on superconducting permanent magnets, both made of REBCO bulks and stacked tapes. The geometry chosen for this investigation, was the staggered array, first introduced in the '90s for compact FELs in the infrared spectrum. Several key partners have been identified in academia, national laboratories and industries and these collaborations will go beyond the present objectives and aim to a durable and constructive roadmap towards the implementation of the HTS technology in industries to serve, firstly, the scientific community and, on a longer time scale, a wider market.

> *The goal of CHART2 initiative on HTS undulator is to provide a prototype for the microscopy/tomography beamline of SLS 2.0 which is planned to be tested with the new beam in 2026. In parallel and beyond this important milestone, the following research program can be sketched today to follow the ambitious roadmap mentioned above.*

Superconducting Permanent Magnets

The use of REBCO bulks for superconducting permanent magnets in undulators, calls for a higher quality than available today on the market. This is true for the overall performance that should improve, but even more crucial for these applications is the reproducibility of their properties in a large-scale production process. This requires first a systematic measurement of the critical current in operational conditions: temperature, field and stress. Seeding activities have been initiated at PSI with the use both of muon beams for probing the vortex flux density and with neutron beams to measure the stress in operando conditions. Further efforts shall be made to correlate their performance with X-ray imaging, starting for instance with tomographic scanning of the samples which could lead to novel ad hoc devices for quality control to be implemented in the production chain.

The performance of HTS tapes does not deliver the same current density as the bulks available today. This could change in the future either by improving the Jc in the superconductor or reducing the thickness of the tape support, limited at 50μm for the thinnest available on the market. The higher degree of reproducibility of tapes production compared to bulks and the intrinsic randomisation of the stacking process, reduce substantially the spread in the properties of superconducting permanent magnets and associated with enhanced performance could substitute bulks in the applications. The HTS undulator can be one of the drivers of this process, thanks to its potential to be the leading device in future light sources and consequently a very successful product, such as in-vacuum permanent magnet undulators today available for instance at Hitachi.

Collaboration with Fermilab on the Large Solenoid

The backbone of the staggered array design is a long superconducting solenoid, produced and assembled today within a collaboration with Fermi National Accelerator Laboratory. The size together with the magnetic field level required for this application go beyond the capability of the available industrial partners. The technology transfer to a local company like AAT shall be on the long term a strategic choice to make this product available to the world market of analytical facilities based on synchrotron radiation sources. The implementation of Nb3Sn of the solenoid planned in CHART2 can be upgraded to HTS to make it more compact and reliable, thanks to the higher temperature safety margin.

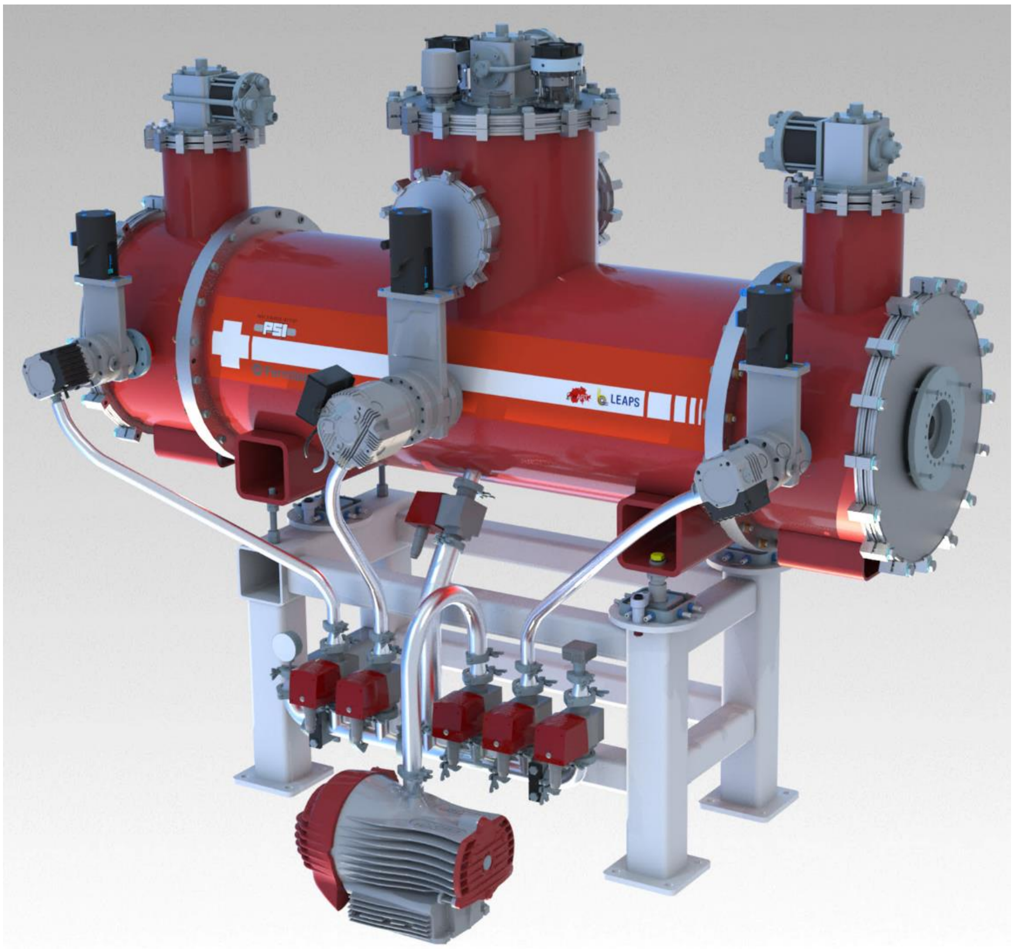


Figure 7 Computer Aided Design rendering of the HTS Bulk Undulator prototype

The Ultimate HTSU for Diffraction Limited Storage Rings (DLSR)

The present design of the HTSU is suitable for some techniques at the synchrotron light sources, like microscopy/tomography, but not for all. The lack of a mechanism to rapidly vary the deflection parameter does not allow for a smooth scan of the photon wavelength required for instance in X-ray absorption spectroscopy. The compensation of the solenoidal component of the magnetic field as it is implemented in particle colliders can profit from this application as well. Splitting the solenoid in two identical halves with inverse polarity would allow to continuously tune the photon energy without compromising the stability and the emittance of the stored electron beam. Beyond CHART2, the design and procurement of a second HTSU prototype with the above characteristics shall be initiated with the aim to be installed in the Material Science beamline of SLS 2.0 with the time horizon of 2025-2028.

Testing Facilities

During CHART2, a collaboration with the University of Cambridge has been established with the aim of working together with an expert group in manufacturing HTS bulk material and to share resources, in particular their test facility, to carry out an R&D program on short undulator samples (10 periods). This step was essential to increase PSI knowledge on this specific field of research and to foster the R&D program. This approach was successful but highlighted as well the limitations of a shared facility in term of availability of testing hours. The prototype phase of the meter long HTSU will temporary supply these limitations until its installation in SLS 2.0. A permanent test facility is required at the PSI site to continue the fast pace of the R&D. The baseline design of the facility should be a twin of the large solenoid developed with Fermilab, but with higher magnetic fields beyond 12T and a larger aperture could increase its potential for novel sample geometries and attract users from neighboring research fields.

FCC Feasibility Studies

CHART Collaboration projects address several feasibility aspects of the proposed Future Circular Collider. In addition to the beam dynamics and stability studies, they include geological, tunneling and geodetic aspects of the placement of the FCC.

CHART's goal is to contribute to the main deliverable: the Feasibility Study Report due at the end of 2025. This should enable the start of construction in early 2030.

FCC BEAM STABILITY STUDIES

CHART projects led by EPFL contribute to the FCC feasibility study with a new simulation and design framework that will contain and integrate relevant simulation tools to explore the dynamics of colliding beams in FCC.

In the case of FCC-ee, this will cover the modelling of multiple collision points effects, multi-turn effects and all relevant interactions as described below. This new model will allow for a self-consistent treatment of the important effects in the optics and dynamics of leptons leaving flexibility to extend to hadrons and muons in parallel. The availability of the tool set will make iterations of the design process and optimization of parameters more efficient. The modular design of the framework will allow future extensions of the functionality, like the treatment of polarized beams, and it will support collaborative work.

In particular, the following R&D areas will be covered.

The development of advanced **beam dynamics models and tools** must be pursued to address the beam dynamics challenges the FCC accelerators will pose. Simulations with a one flow model from source through the chain of injectors and into the collider ring are needed to establish realistic performance estimates. A full modelling of the start-to-end process will give reliable performance estimates and will allow operational studies of such facility, which have not yet been addressed. A newly developed software framework should utilize modern computer science tools including massive parallelization and machine learning techniques. Such developments are synergetic with the accelerator design needs for other fields, such as light sources. So far no tools of this type exist in spite of longstanding demand and CERN can become a focal point for such collaborative efforts being initiated in CHART.

A **fundamental study in support of the HTS high field magnets developments** of the previous section is the definition of the field quality requirements for such magnets. It is known that designing HTS magnets with low field errors is a particular challenge to meet the tight tolerances and constrains dictated by particle stability. Today tolerances are inherited by the superconducting magnets developments done for the LHC. Nevertheless the higher energies of future colliders make the beams more rigid and less influenced by field errors. New studies of the required tolerances on such magnets need to be addressed to feedback to the magnets R&D program in a concrete manner. This study should be done developing a realistic model of magnets errors and addressing the impact of such errors on the dynamic aperture of the particles tracked over a possible operational cycle. The outcome will be a realistic set of tolerances for the magnets R&D program.

After decommissioning of LEP to give way to LHC, the **lepton collider expertise** has been almost lost in Europe. For **FCC-ee** CHART is striving to create collaborations with experienced international partners (SUPERKEKB, Japan) and new project developments (EIC, USA) participating into those projects. Training of younger generation accelerator physicist is also a fundamental part of the effort. Particular studies for the CHART 3 era would include spin tracking and polarization studies, start-to-end simulations including top-up injection schemes and beam quality studies of the injector chain to provide realistic performance estimates of the global beam flow in such a complex. The study of collective beam stability for injectors and collider including the interplay between different effects will define the accelerators limitations and will initiate the studies to find possible mitigation techniques and schemes. In this frame seeing the enormous synergies between the operating SUPERKEKB machine and the FCC-ee studies benchmarking of models, personnel experimental experience and training activities should be established.

The preliminary design of the **FCC-hh hadron accelerator** described in the CDR is not complete and is a starting point for further studies which should aim at exploring different scenarios beyond an up scaling from the LHC design. An effort should be made to optimize and push new schemes for luminosity optimization with feedback to hardware, also in relation with energy efficiency studies. CHART projects have emphasized the experimental exploitation of the only existing hadron collider LHC and its upgrades. Concrete studies include synchrotron radiation effects with hadrons, modelling of beam losses in a real collimation system with energy deposition studies in one flow, and direct benchmarking on HL-LHC. Studies of new devices, as for example the bent crystals and electron lenses for halo and diffusion control, are needed. The application of Machine Learning (ML) and Artificial Intelligence (AI) for operation should be pursued, for example for controlling electron cloud and fast-ion instabilities.

Integration of **ML and AI for accelerator design** is still at a very explorative level. First studies and results seem to show significant potential in using these recent technologies for designing the collider and modelling the particle dynamics. In particular they can become a game changer in reducing the enormous numerical resources requirements of tracking simulations. Commissioning strategies for complex collider facilities and the required day-to-day tuning of the machine (e.g. aberrations tuning in collision) can be simulated in computer models, and be benchmarked and tested at the operating SUPERKEKB in Japan and the funded EIC project (2030) in the US. Today's modern sophisticated models are critically dependent on high performance computers and should foresee space for these innovative methods in the future technical designs.

Specialized diagnostics for colliders will provide the means to reach the ambitious performance goals. These include Beamstrahlung monitor signals for IP tuning and polarimeter (laser on beam measurements of polarization asymmetry and energy at t-ttbar production threshold) integration with optics and machine design.

GEOLOGY AND GEODESY OF THE FCC SITE

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 group of Prof. Moscariello at the Department of Earth Sciences of the University of Geneva is investigating the subsurface geology that 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 (e.g. GIS-based data base), will be 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 will provide the necessary and required critical information on a large variety of data encompassing geological (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. This will produce a reference 3D geological model in the project's perimeter using an industry standard software (e.g. Schlumberger Petrel) incorporating all available data from various data provider through the usage and integration in to a 3D environment of the data collected into the GIS project. The 3D geological and hydrogeological model will be a key tool to predict subsurface rock properties and guide the feasibility and detailed designed of the FCC tunnels and access facilities. This product will also serve to capture the base-line information regarding the water ground distribution and quality and serve as tool for predicting possible short and long-term environmental impacts (impact on geometry and physical property of ground water, contamination, etc.) of the engineering work.

FCC Geodesy Studies

The following project led by Prof. Dr. Markus Rothacher, at the Department of Civil, Environmental and Geomatic Engineering at ETH Zurich, will be carried out by 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 (or even a new design) of the geodetic reference systems and geodetic infrastructure already established for the current CERN site will be 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.

This R&D project has two major objectives:

- Determination of a high-precision gravity field model for the FCC region

- 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 will be 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 will have to be carefully studied and checked for their feasibility.

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.

FCC-EE INJECTOR DESIGN AND TEST STAND

This CHART project is a contribution towards the FCC-ee feasibility study and is led by the Paul Scherrer Institute. The collaboration that includes CERN and LAL (Orsay, France) will design and optimize the electron and positron linear accelerators of the injection chain, including the electron gun(s), the positron production and capture systems, and the positron damping ring. An evaluation and optimization of the accelerator costs and the preparation of an advanced CDR are an integral part of this study.

The FCC-ee Conceptual Design Report for an electron-positron collider with a centre of mass energy reach from 90 to 365 GeV, a circumference of 98 km and beam currents of up to 1.4 A per beam was published at the end of 2019.

The required beam intensities and emittances are imposing a true technological challenge in particular for the positron source design (target design, cooling systems, capture optics, power dissipated on the structures, remote handling/target removal engineering design, etc.).

Investigations, technological R&D and experimental tests are mandatory to ensure a performant and reliable injector for FCC-ee. Novel concepts for the production target and positron capture are investigated in theory and experiment with the goal to demonstrate production yield values and efficiencies well beyond present state-of-the-art.

For the positron production, a concept using superconducting magnet technology and high field RF capture cavities is under study. A demonstrator using the SwissFEL 6 GeV linac as target driver will validate the concept.

ENERGY EFFICIENT ACCELERATORS DEVELOPMENT

High-energy and high-luminosity collider facilities consume a significant amount of electrical energy that reaches the order of TWh/y. Besides the research capabilities and the significant investment cost, the aspect of energy consumption and sustainability of large research infrastructures is therefore an important aspect for public and political acceptance of new proposals.

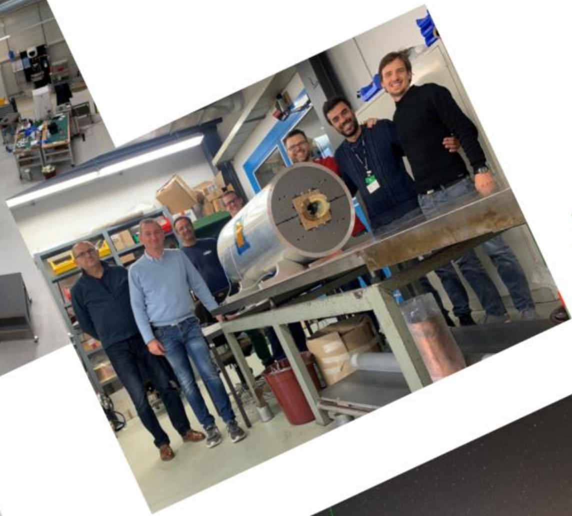
With the expertise at EPFL for advanced simulation and optimisation of the particle dynamics for future collider facilities it is a priority goal to maximise the luminosity of particle beam interactions per unit of power drawn from the grid. This can be achieved by implementing smart collider concepts and by optimising the complex parameter space of colliding beams. Modern scientific computing methods will be applied, including large-scale tracking simulations using parallelisation and machine learning methods.

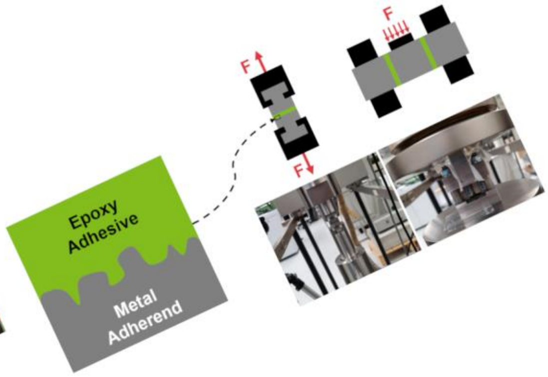
Today the two basic concepts of the ring collider and the linear collider are being developed for different parameters and particle species. While ring colliders are efficient in re-using the same beams in repeated collisions, their power consumption suffers from synchrotron radiation losses and the need to replace significant lost beam energy continuously. Even though protons radiate much less, the synchrotron radiation losses of the order of several MW in the hadron version of FCC are important since the radiation power must be removed from the magnets at cryogenic temperatures. Linear colliders have no radiation losses but use their beams rather inefficiently in a single collision. To achieve a reasonable luminosity the beams are strongly compressed in phase space, which is not possible to the same degree in circular colliders because of the long term dynamics in rings. A combination of both approaches seems possible through the concept of an energy recovery linac. Here beams with linear collider type parameters are collided only once as well, but the energy of the spent beam is recovered and recirculated. In this way the overall luminosity per grid power can be greatly enhanced. Of course, the described scheme represents just the basic idea for an efficient collider variant and many aspects need to be studied in more detail. These include for example the efficient deceleration of the spent beam with deteriorated quality through the strong fields and radiative effects during collision, the effect of synchrotron radiation by arc recirculation in several passes, the cost optimization of a machine with several arcs. Through concept studies EPFL can contribute together with collaborators to the development of an ERL scheme that can be realized.

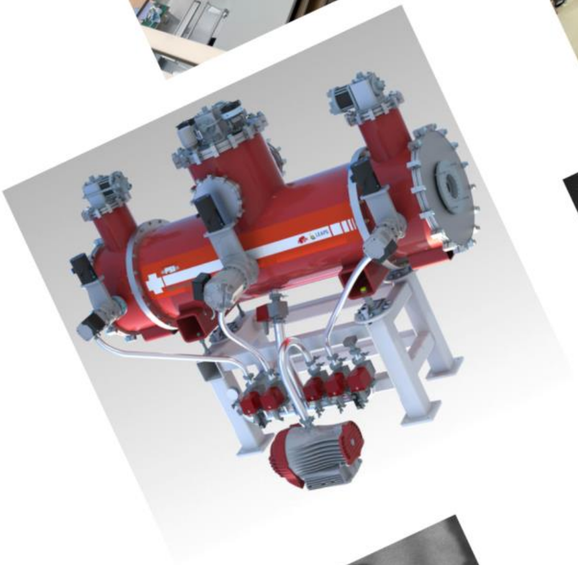
With an increasing fraction of sustainable energy sources in the future European energy mix, such as wind and solar power, the production of energy will fluctuate significantly. One way to mitigate the impact of HEP facilities on the electrical grid is to actively manage their energy consumption. High loads could be avoided during low supply conditions, and excess energy could instead be preferentially used. The possibility of managing energy usage by dynamically operating facilities and utilising energy storage systems are topics of interest to and investigated for industrial applications. It may be possible to identify synergies between such applications and HEP infrastructures. Colliders could implement smart standby modes from which an efficient and quick recovery of optimized luminosity operation is possible. Also developments in this field aimed at realising quick computer-aided startup and optimization schemes for colliders and aimed at advanced energy management in collaboration with partners in the Swiss science landscape are possible.

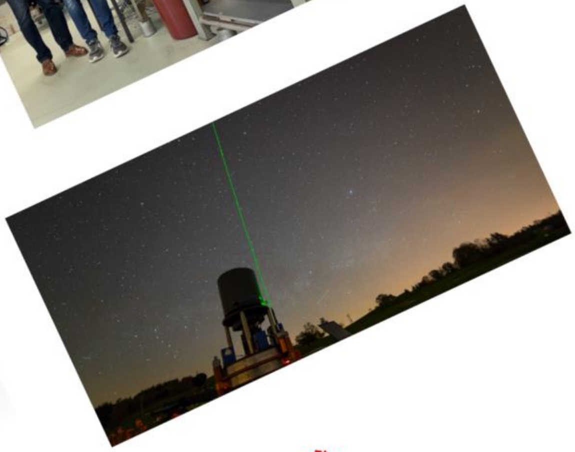
In addition to potential dynamic approaches, it is also necessary to invest R&D effort into improving the energy efficiency of HEP facilities through critical technologies. Possible options include efficient tube and solid state based RF sources, permanent magnet technology including R&D towards higher performance and tunability, high temperature superconductor magnets with a coil temperature allowing for vastly improved cryogenic efficiency.

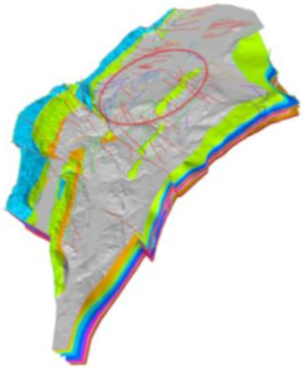
Accelerator technology can also contribute to the sustainable production of energy. Accelerator Driven Systems (ADS) are sub-critical reactors that can be used to reduce the storage time of radioactive waste (transmutation) of nuclear power stations by orders of magnitude. Such concepts address an important sustainability problem of nuclear power. The development of high intensity accelerators for ADS has synergies with applications for particle physics or neutron sources pursued at PSI.

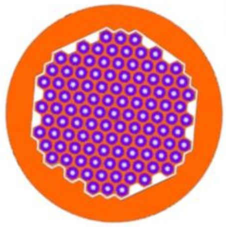


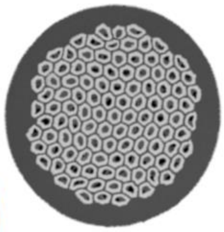












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