Swiss Accelerator Research and Technology

CHART Collaboration

Phase 2 Scientific Report

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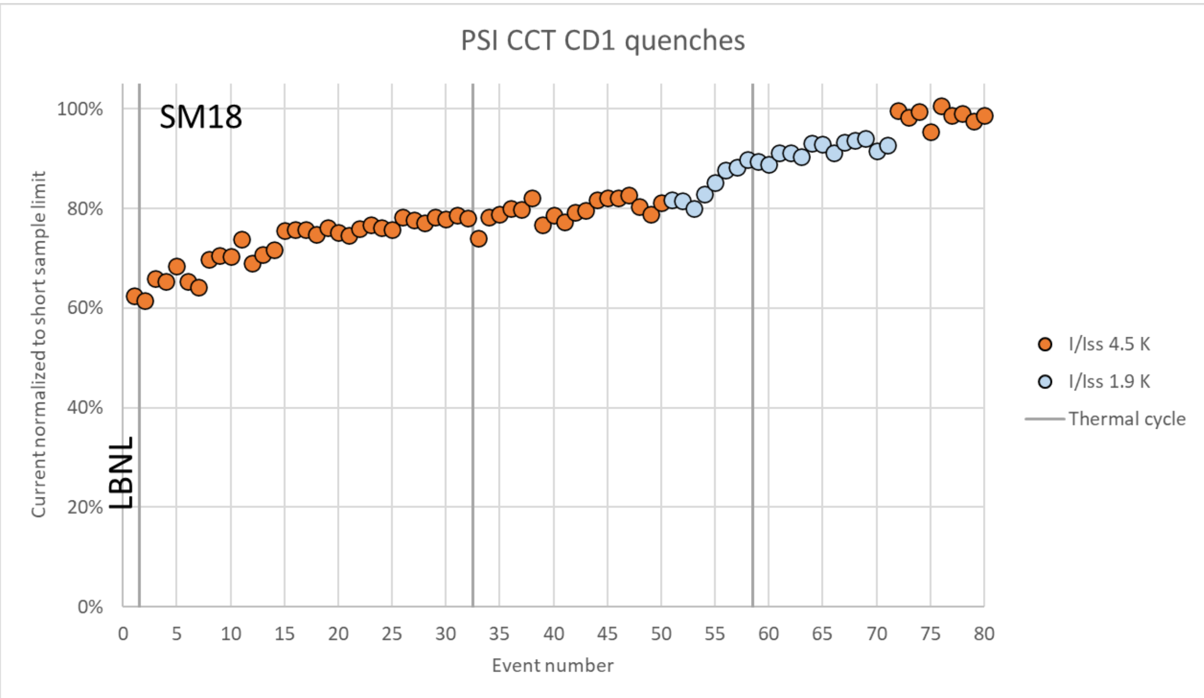


MagDev1 Canted Dipole (CD1) magnet normalized training plot, showing performance relative to the estimated maximum performance or short-sample limit. Credit: Franco Mangiarotti (CERN)

Executive summary

This is the scientific report of CHART Phase-2 activities until the end of December 2022. It gives a summary of the goals and achievements of CHART over the 2019 – 2022 period. The projects were concentrated around the superconducting high-field magnets developments and beam-dynamics studies related to the FCC study at CERN. Some of them develop accelerator physics and technology in synergy with interests of other accelerator-driven scientific fields of research.

The European Strategy for Particle Physics (ESPP) 2020 update has set a new target for the feasibility study of the FCC project within the time frame of the next ESPP update. The key-phrase of the strategy document states 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*".

The first period of CHART Phase-2 saw a significant growth in the number of projects carried out at the partner institutions. The majority of these aim at the FCC feasibility studies, for both the electron - positron collider FCC-ee and the hadron collider FCC-hh.

CHART can reach its full potential only as an active, distributed research network, embedded in an international web of partners. The CHART Phase-2 projects individual scientific reports detail significant progress achieved towards this goal. Nevertheless, as can be seen in the summary of the CHART projects timelines at the end of this summary, some delays accumulated due to the slowdown in hiring under the restrictions due to the COVID-19 pandemic.

The main scientific highlights with links to the individual project reports published on the CHART website are grouped below by the main activities.

Superconducting magnets developments

The CHART research roadmap for high-field magnets was designed in view of the R&D Roadmap for High-Field Magnets, published in January of 2022 by the Laboratory Director's Group in response to the 2020 Update of the European Strategy for Particle Physics. The goal is to demonstrate the maturity and robustness of Nb_3Sn magnet technology towards 16 T field dipoles, and to explore the potential of high temperature superconducting (HTS) technology to usher in a paradigm shift for future circular colliders by reaching higher fields, operating at higher temperatures, or both.

The **WireDev** project at UniGE has made progress towards reaching and surpassing the performance goals of Nb_3Sn wire, set out by the FCC conductor R&D program. A first billet of the industrial Rod-Restack Process has been produced that uses internal wire oxidation for improved flux pinning and increased performance which can be used to either reduce cost or increase engineering margins. With this billet, WireDev sets out to demonstrate the breakthrough performance of internal-oxidation mono-filamentary wires at an industrial scale and in wires with hundreds of sub-elements. The **WireChar** project has provided convincing evidence that stress-induced permanent performance reduction of Nb_3Sn, is mainly due to plastic deformation and lattice distortion. This experimental observation, accompanied by predictive numerical models, forms the basis for improved engineering on the one hand, and an optimization of wire technology towards higher stress-resilience on the other hand. Both goals are instrumental for a robust Nb_3Sn magnet technology.

The **MagDev1** project has opted for stress-managed coil technology, i.e., a technology where the magnet coil is wound into a metallic former. A convincing demonstration of the promise of stress-management was given by the cold test of the CD1 magnet (Canted Dipole 1) that was built in 2017-2019 as a deliverable of the first CHART research period. The magnet reached 10.1 T in the aperture of 6.5 cm diameter at 1.9 K and 94% of the estimated maximum performance (called short-sample limit), and 9.9 T at 4.5 K at an exceptional 100% of the short-sample limit, proving that the conductor performance was fully preserved. The magnet performance has withstood three thermal cycles and provided a wealth of data for future research.

Like its "twin" magnet CCT5, built and tested at LBNL, CD1 exhibited a long training curve, that is, it required a prohibitively large number of ramps to gradually reach its full performance. In anticipation of this problem about 20 BOX samples (BOnding eXperiment) have been tested at Twente University and two potential solutions have been identified so far: impregnation with paraffin wax, and the addition of particulate fillers to epoxy resin. MagDev's BOX's success with wax impregnation has been shared with the community and LBNL in the USA has recently tested their first wax-impregnated CCT layer, confirming the elimination of all training in that layer. The Wigner Institute in Hungary is next to test a Nb-Ti CCT magnet with wax impregnation. MagDev1 will move on along our R&D roadmap stress-managed common coil magnets, starting out with sub-scale magnets, followed by a demonstration of ultimate-field in time for the next European Strategy for Particle Physics update period 2025-2027.

MagDev1 research on high-temperature superconductor (HTS) magnet technology led to a non-insulated solenoid that produced 18.2 T in the aperture of 5 cm diameter and 20.3 T on the conductor in a custom-designed cryogen-free test facility. The performance of the coil and the test facility exceeded expectations and demonstrates the level of expertise that has been established at PSI in just under two years of research and collaboration with Tokamak Energy Ltd (UK). The non-insulated coil technology is now applied for a scaled-up solenoid to be installed around a tungsten target in the positron source of the FCCee injector test stand at SwissFEL. The recently approved project **FCCee HTS4** aims to demonstrate that highly optimized HTS magnet systems can replace the normal-conducting short straight section magnets in FCCee by more power-efficient HTS magnet systems. The project is as challenging as it is promising due to the direct applicability of the research to a variety of magnet systems of high societal impact (research, medical applications, energy conversion etc.). Last but not least, **MagDev1** has initiated R&D on HTS magnet technology for the main dipole magnet systems of a future circular hadron collider as an alternative to Nb_3Sn. The technology is in its infancy, but the program is structured such that early versions of HTS coils can be mixed with Nb_3Sn LTS coils in a stress-managed common-coil configuration, thus, achieving full synergy between the program's LTS and HTS activities.

Several research projects on enabling technologies are under way at ETHZ: **MagNum** at D-ITET/IEF creates a platform for Model-Based Systems Engineering (MBSE) in magnet and accelerator design. The platform is currently in use in 3 independent pilot projects and has been transferred to a CERN repository for long-term support, maintenance, and development. **MagRes** and, very recently, **MagComp** are projects with ETHZ D-MAT/SMG characterizing, modeling, and improving the coil-insulation material of Nb_3Sn magnets. MagRes has had a breakthrough in 2022, providing a first-in-class fracture toughness in an epoxy resin that contains only off-the-shelf chemical components. MagComp has started in December 2022 to study the coil-composite material that includes the reacted Nb3Sn cable, glass insulation, and resin or wax filler. The project will provide constitutive modeling of the coil composite and link up with WireChar and other actors for a full multi-scale characterization and modeling of the Nb_3Sn coils, underpinned by MagNum's MBSE solution. **MagAM** at ETHZ D-MAVT/pd|z and inspire AG studies the potential of additive manufacturing with metal powder-bed fusion to build augmented functionality into structural components of Nb_3Sn coils. Proof-of-concept demonstrators include porous boundary layers for improved mechanical interlocking between epoxy filler and structural component, compliant spacer geometries that adjust to the actual coil-winding shape, and tunable E-modulus in support components, all serving the purpose of improving the performance and robustness of Nb_3Sn coils. The **FCCee CPES** project at ETHZ D-ITET/PES develops cryogenic DC power supplies for highest power-efficiency towards wall-plug superconducting magnet systems with HTS conductor. Specifically, CPES develops a cold power converter for the above mentioned FCCee HTS4 project.

Finally, the **HTS Bulk Undulator** project uses a 12-T background field solenoid to magnetize bulk REBCO samples that are configured to produce an undulating field on the beam. The project has solved several technological intricacies linked to mechanical constraints, assembly tolerances, and premature quenches. The project has demonstrated a record mean undulator field of 2.1 T with a period length of 10 mm and reached the specifications in terms of peak-to-peak variation after applying a novel sorting algorithm to the bulk samples. The manufacturing of a 1.2-m-long cryo-cooler-based background field magnet at Fermi National Accelerator Laboratory (FNAL) in the US, is well under way and will house the 100-period prototype magnet to be installed in the I-Tomcat beamline at SLS2.0. This development will result in a two orders of magnitude increase of hard X-Rays flux and stands to revolutionize the field of such synchrotron radiation sources world-wide.

FCC Beam Dynamics Studies

Beam stability aspects of the FCC collider design have been under study by the EPFL team. Simulations benchmarking utilized detailed analysis of the operational data from the LHC. Together with experiments performed on the running machine these studies resulted in significant contributions to the FCC Conceptual Design Report (CDR). In particular, the **Lumi-FCC-hh** project resulted in the study of the beam-beam interaction bias to the luminosity measurements and a proposed correction scheme to the analysis of the LHC physics data. The study has cancelled one of the main systematic errors in the luminosity measurement, the beam-beam bias, allowing ATLAS and CMS to reach unprecedented precision on the order of 1% or less.

The **FCC-ee-Dynamics** project aims to set-up a new software framework that can be extended in phases with existing and new functionalities. FCC-ee is used as the basis to evaluate the key requirements for such a framework and identify potential bottlenecks in the simulations. The framework serves as basis simulation tool for the FCC and the LHC, the project is developed in collaboration with the accelerator beam physics teams at CERN. The concept of the software framework is developed in a sustainable way, providing a modular structure and extendability in a collaborative approach. The ultimate goal is to create an open-source software to which a large number of developers can contribute in a systematic and efficient way. The framework allows easy utilization of modern computer science developments, in particular parallelization of numerical computations, advanced optimization techniques and scripting capabilities. The framework is aimed to be a tool for accelerator design work with a broad range of applications. The basic functionality that has been implemented includes beam-beam effects and 6D particle tracking simulations with radiation effects. These have been developed and benchmarked together with a transparent translation between existing optics codes used among the accelerators communities such as SAD, MADX, PyAT. The software is available and several collaborators are now users of this tool.

Another important development is a new FCC-ee magnet lattice that allows the use of energy efficient High Temperature Superconducting combined function magnets. This project will study the feasibility of designing a collider using such elements, propose a lattice solution and define preliminary tolerances in terms of field quality to feed back to the CHART **FCCee HTS4**.

In addition, the need for integrating spin dynamics and polarization studies has initiated a parallel development to have such tools available for energy calibration studies performed by the EPOL working group. The project **FCC-SPIN-POL** aims to model and study the feasibility of precise FCC-ee beam energy calibration via resonant depolarization. Unifying existing models with luminosity models and making it a robust and global tool for the community is an on-going effort. Preliminary studies of resonant polarization of FCC-ee beams have been presented with a simplified machine model. The development of a more realistic simulation scenario with machine errors is still under development.

Study cases of the beam dynamics of leptons and hadrons with multiple collisions and collective effects such as electron cloud is a major goal of the **FCC-hh-Stability** project**.** Numerical studies have been performed and benchmarked with theory where available and data of the LHC and the SuperKEKB facility in Japan. In this context, machine learning techniques applied to the LHC data analysis were subject of investigations in the framework of two projects (PACMAN and ML4FCC) performed in collaboration with the Swiss Data Science Centre (SDSC, located at EPFL and ETHZ). With the help of these techniques, the computational effort for studies on beam dynamics, such as maximising the dynamic aperture, can be reduced by orders of magnitude.

Muon colliders have a great potential for high-energy physics. They can offer collisions of point-like particles at very high energies, since muons can be accelerated in a ring without limitation from synchrotron radiation. In the context of the feasibility studies for such a collider the project **Muon Colliders Feasibility Studies** goal is to investigate and explore possible solutions for the major challenges in the production and acceleration of muons which are the control of collective effects induced instabilities during the ionization cooling process in the acceleration chain.

FCC site feasibility related studies

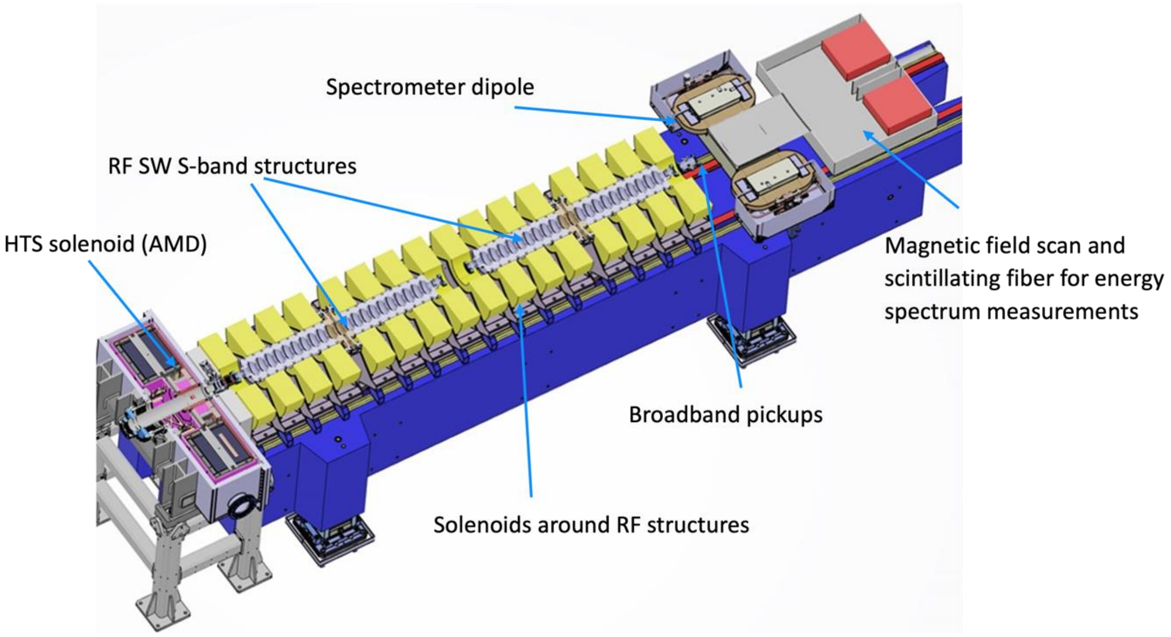
Two CHART projects that were approved by the CHART Council in the Fall of 2020 address geology and geodesy aspects of the FCC tunnel. Development of a high-resolution 3D geological model and associated GIS-based subsurface data set for the FCC tunneling work are subject of the work performed at the University of Geneva (**FCC geological modeling** project).

FCC geodesy studies project at ETHZ aims at the improvement of the geodetic reference systems and geodetic infrastructure already established for the current CERN site that will be required in order to cope with the demanding challenges of this large new infrastructure.

FCC-ee injector design

FCC-ee Injector Design and Test Stand at PSI is a multi-laboratory collaboration project, led by PSI and involving CERN, IJCLab (Orsay) and INFN-LNF (Frascati). As part of the FCC-ee pre-injector complex, consisting of the electron and positron linear accelerators of the injection chain and including the electron gun(s), the positron production and capture systems, and the positron damping ring are being designed and optimized. An evaluation and optimization of the accelerator costs and the preparation of an advanced CDR are an integral part of this study. This project is well integrated into the FCC Feasibility Study (FS). The mid-term review of this FS will be held in October 2023, where an initial assessment of the performance and costs of the entire pre-injector complex is to be provided. To this purpose, milestones and deliverables were defined in the different work packages in order to define the next steps leading up to the review meeting. Among the most important milestones are the definition of the specifications for the injector (for example the overall positron yield) and the baseline of the linacs and the damping ring. In this context, a comparison, in terms of complexity of operation and cost, between using the SPS or a high-energy linac will also have to be provided.

For the positron production, a concept using superconducting magnet technology and high field RF capture cavities is being studied. The goal is to design and install a demonstrator in the SwissFEL facility to experimentally validate a range of novel techniques that, according to simulations, will increase the positron yield by one order of magnitude with respect to the state of the art. In 2022, important progress has been made in the development of PSI Positron Production (P^3) experiment. Firstly, the highly advanced design phase made it possible to start procurement of the RF cavities, the parts that compose the Adiabatic Matching Device (AMD), and part of the diagnostics (cf. the figure below). As far as the AMD is concerned, reliable operation of the High Temperature Superconducting (HTS) solenoids at fields above the requirements of the P^3 on axis was demonstrated. According to the simulations of the positron target setup no long-term radiation damage problems are expected. Regarding the technology of the solenoids around the RF cavities, superconducting and normal conducting options were studied; the former is very promising because it guarantees exceptional positron capture efficiency, but conventional technology was chosen for the experiment because it can still guarantee adequate positron capture while keeping costs under control. For the beam diagnostic section, simulations have shown that the beam of positrons and electrons can be fully characterised using broadband pickups to evaluate the relative filling of the RF buckets, two Faraday cups to measure the total charge of electrons and positrons, and a charge detector combined with a spectometer dipole to measure the beam energy distribution. For all these reasons, we can conclude that the delivery of a complete technical project is feasible and on-schedule for the coming months. In the meantime, preparation for the installation of the experiment in the SwissFEL linac is ongoing.



PSI Positron Production (P3) beamline.