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Superconducting Magnets for a Future Circular Hadron Collider

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Abstract

The European Strategy for Particle Physics is a long-term roadmap guiding Europe's particle physics research priorities. It coordinates major projects like the LHC and future collider studies through CERN and aims to maximize scientific impact via international collaboration and technological innovation. This article summarizes the status, challenges, and plans for superconducting magnet R&D towards a future circular hadron collider at CERN. The special Swiss contribution through CHART, the Swiss Accelerator Research and Technology program is highlighted, as well as the concrete synergies and expected societal impact of R&D in the field of superconducting magnets for high-energy physics.

Introduction

Collider physics over the last decades has led to some of humanities most impressive science facilities, most recently – and notably – the Large Hadron Collider (LHC). Around the world national and transnational science programs have invested significantly in magnet technology to enable ever more sophisticated colliders. The Future Circular Collider (FCC) in its hadron-collider variant FCC-hh will be an experiment that pushes the frontiers of superconducting magnet technology, at a scale that requires involvement of the full international community's expertise.

The multi-decade time scale for FCC-hh allows to aim for the highest possible performance of the hadron collider. At the same time, recent years have brought an increased focus on energy effciency and the minimization of helium inventory. Both requirements have strong implications for magnet design and increase the accelerator-wide systems engineering challenge. At the high end of magnet performance, high-temperature superconducting (HTS) technology may enable lower power consumption for the same field, and/or open the way to fields up to 20 T. The baseline today is defined as 14 T low-temperature superconducting (LTS) dipoles, which are closer to the state of the art of High-Luminosity LHC technology, with relatively low technical risk, and potential for fast industrialization [1].

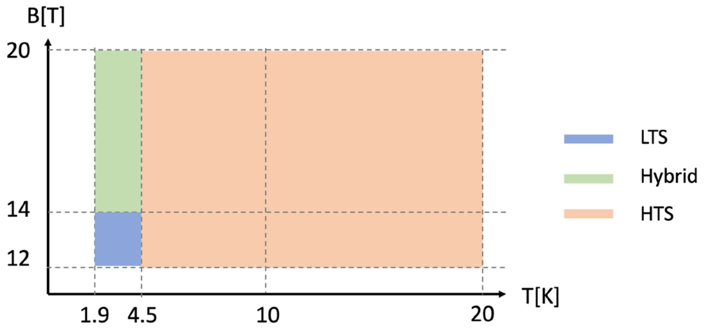


Figure 1: Parameter space for accelerator magnets (T, operating temperature, and B, nominal field) and magnet technologies that may cover some or all the parameters space. Dashed lines indicate parameter values of particular interest, e.g. 12 T Nb_3Sn lower bound, 14 T Nb_3Sn baseline, etc.

FCC-hh magnet R&D must canvass the full range of magnetic fields for a variety of conductor and magnet technologies as well as for a range of operating temperatures and cryogenic concepts. We may draw a diagram with operating temperature (1.9 - 20 K) and nominal field (12 - 20 T) on the axes; see Figure 1. LTS conductors (Nb_3Sn and Nb_3Sn/Nb-Ti hybrids for cost efficiency) follow the lower vertical axis, HTS REBCO conductors can cover the entire parameter range, and hybrid LTS / HTS magnets (typically Nb_3Sn and Bi-2212 or a future iron-based superconductor) cover the upper vertical range at low temperatures.

In this article, we discuss the inherent technological challenges of different options, introduce the global research programs towards next-generation High-Energy Physics (HEP) accelerator magnets, and place outcomes of the Swiss Accelerator Research and Technology (CHART) initiative in the wider context.

Research directions and state of the art in LTS accelerator magnets

LHC dipole magnets, with a nominal field of 8.3 T [2], represent the maximum performance achievable with Nb-Ti alloyed superconductor that is also used in the largest commercial application of superconductivity that is Magnetic Resonance Imaging (MRI) magnets. Dipole fields are shaped by so-called cos-theta coils, i.e., up to 15-m-long coils that, in their cross-section, feature a turn distribution that approximates in azimuthal direction a cosine-theta modulated current density; see Figure 2.

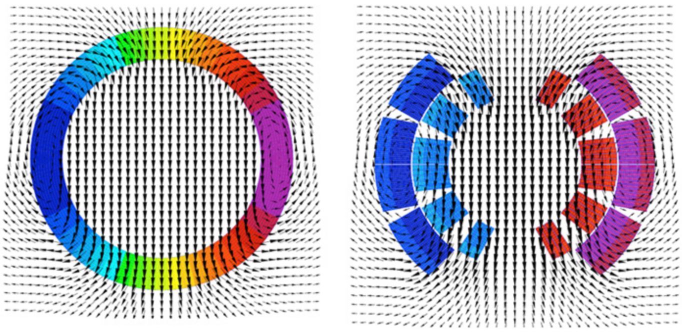


Figure 2: Idealized (left) and approximate (right) cos-theta current distribution producing a homogeneous dipole field. The right picture represents the coil cross-section of the main bending dipole in the in the LHC (Courtesy: Stephan Russenschuck)

To reach higher fields, the community turns to Nb_3Sn, a brittle intermetallic compound. With Nb_3Sn 21 T for Nuclear Magnetic Resonance (NMR) solenoids have been commercialized, but accelerator dipoles pose a few specific challenges; most notably, dipole forces push the two long straight sections of a coil apart, with a force that is equivalent to 1200 t/m of weight pulling on the two legs of the coil. A sturdy mechanical structure surrounding the coils is required to keep coil movement on the order 100 μm to maintain the high field quality requirements. Moreover, the coil's heat capacity at liquid-helium temperatures is extremely small, so that tiny sudden magneto-mechanical disturbances (e.g., stick-slip motion) can lead to a local temperature increase that triggers a transition to the normal-conducting state - a quench. For this reason, the coils need to be clamped. The applied pre-stress must ensure that the coil remains in compression up to the maximum current. Given the strain sensitivity of the critical current in Nb_3Sn wires and its brittleness, the combination of pre-stress and Lorentz forces requires careful mechanical design and tight tolerances in assembly in order not to overstress the cable at any point of manufacturing, cool-down, or operation.

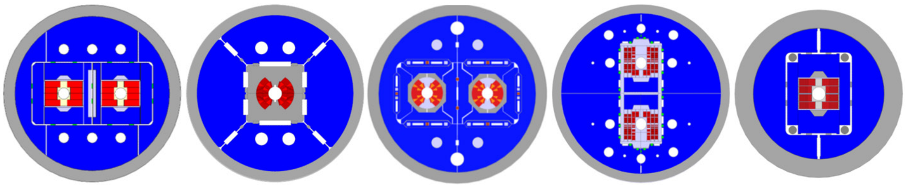


Figure 4: Five cross-sections of R&D magnets proposed by (from left to right: CERN, INFN/CERN 2x, PSI, CEA), on a roadmap towards a design pre-selection in 2028/29. The designs feature different coil topologies (from left to right: block coil double aperture, cos-theta single- and double aperture, common coil, and block coil single aperture). The final FCC-hh dipole must feature two apertures.

In the coil ends, the two straight sections of the coil join in a saddle shape to leave an aperture for the beam pipe. The end region requires careful attention to the transition from a transverse force distribution in the straight section to the longitudinal forces acting on the coil end. Axial pre-stress is applied to respect strain limits in the conductor. This task is rendered more complex due to the overall thermal shrinkage of a 15-m-long magnet by several centimeters. Small differentials in thermal contraction among materials such as Nb_3Sn wires, steel structures, or aluminum shrink cylinders, if not controlled well, can degrade the conductor over multiple powering and thermal cycles.

The High-Luminosity LHC (HL-LHC) project [3], underpinned by the US-LARP (US LHC Accelerator Research Program, 2004 - 2017 [4]) development program for Nb_3Sn magnet technology, has tackled each of the above problems and more systematically and successfully. The series manufacturing of 30 quadrupole magnets of 4 and 7 m length in three manufacturing locations (FNAL for 4-m-long coils, BNL for 4-m-long coils and magnet assembly, and CERN for 7-m-long coils and assemblies) shows a mature and reliable manufacturing process that could be scaled up to industrial production [5]; compare Figure 3.

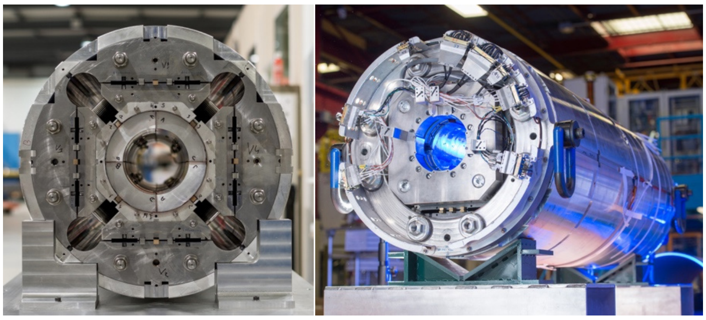


Figure 3: HL-LHC inner triplet quadrupole magnet with Nb_3Sn technology. Cross-section of the mechanical structure on the left, and triplet magnet produced in by US-AUP (US Accelerator Upgrade Program) on the right.

The European High-Field Magnet (HFM) program [6,7], hosted at CERN and including 13 institutes and universities (among them major national research institutes CEA, Ciemat, INFN, KIT, and PSI) tackles, among others, the development of 14-T dipole magnets for the FCC-hh. The collaborative effort explores novel coil geometries and mechanical concepts towards cost-effective magnets that can reliably be produced at industrial scale. Design variants include conventional cos-theta, as well as rectangular block coils, common coils, and canted cosine theta designs; see Figure 4.

Block coils retain the record for highest operational field in an accelerator-relevant design. Over the past years, CERN has built and tested RMM1 (see Figure 5), a block-type magnet, albeit with flat coilends, which has achieved stable operational field close to 16 T [8].

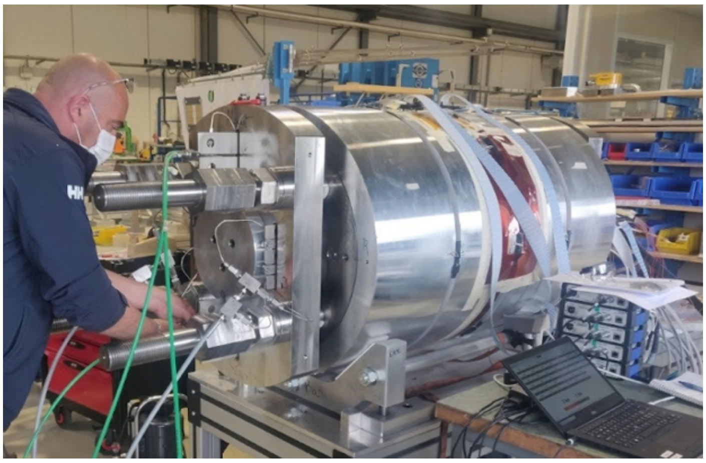


Figure 5: The RMM1 single-aperture dipole, designed and built at CERN, in the final steps of magnet assembly. The magnet reached ~17 T maximum field and 16 T stable operational field.

Common coils promise simplified coil manufacturing, especially the asymmetric common-coil variant, where the coil-pack is made up of only wide-bending-radius flat racetrack shapes. The CCT is a stress-managed coil variant, i.e., a coil wound into a metallic winding mandrel that acts as an endoskeleton to protects the coil from high stresses. The CCT variant has since been abandoned in favor of a stress-managed common coil.

14 T versions of block coils and common coils are being built at CERN and in the European labs, in view of a down-selection milestone at the end of 2028. At the same time, the HFM Programme pursues alternative research directions, such as a hybrid Nb_3Sn/Nb-Ti coil layout, operated at 1.9 K that saves up to 50% of the more costly Nb_3Sn conductor, a 4.5 K all-Nb_3Sn design that could save up to 33% of cryogenic power consumption and up to 50% of helium inventory, a 12 T cos-theta variant that would save about 30% of cost wrt. a 14 T magnet system, as well as other supporting technologies (quench protection, numerical multi-scale modeling, robust insulation materials, etc.).

As for Nb_3Sn conductor, we note that today the European and US partners use a single supplier for high-performance wire. The lack of a functioning market creates risk and is detrimental to the conductor cost in a large-scale project such as the FCC. A thriving market is, however, not a prerequisite for an efficient and affordable large-scale manufacturing effort. The Tevatron was the first large-scale application of superconductivity. At the time, the US labs and institutes owned the IP and trade secrets of wire making, controlled the supply-chains, and worked closely with industrial suppliers to produce quality wires on their manufacturing lines. The HFM Programme is considering a similar scenario with the HL-LHC-type Nb_3Sn high-performance wire. Further improvements of this wire appear to be within reach, based on first multi-filamentary wire samples with artificial pinning. In addition, HFM partners with Korean and Japanese manufacturers to boost their Nb_3Sn wire technology towards FCC-hh specifications [9]; see Figure 6.

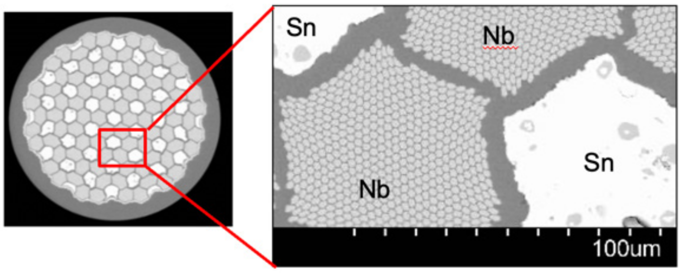


Figure 6: Microscopic picture of a high-performance conductor developed by the Japanese JASTEC company in collaboration with CERN and the HFM Programme [9,10]. The conductor performance approaches that of HL-LHC specifications.

With the above efforts and results, the community is confident that 14-T magnets for FCC-hh can be developed and produced in an adequate timeline (first beam in 2050 - 2055) and meeting the cost targets within the FCC program.

Research directions and state of the art in HTS accelerator magnets

Two types of HTS are available from industrial processes: Bi-2212 multi-filamentary wires and REBCO tapes. The market for REBCO production has seen a rapid growth over the past decade with multiple suppliers worldwide, driven by the demand from commercial fusion companies. At the same time, REBCO is produced as a flat tape of 4 – 12 mm width; see Figure 7. Screening currents, which are induced in all types of conductors during a magnet ramp, increase with the major dimension of the superconductor. Keeping ramp losses low and achieving good, stable, and reproducible field quality during injection, ramp, and physics is considerably more challenging with REBCO tapes than other conductors with smaller filament sizes (e.g., Nb-Ti: ~5 µm, Nb_3Sn and Bi-2212: ~50 µm). Iron Based Superconductor (IBS) samples, produced in China on the scale of a meter length, perform a factor 3 – 4 lower at 4.2 K than industrially produced REBCO samples of several 100 m length at 20 K.

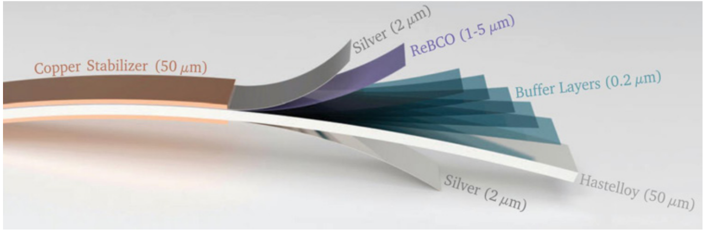


Figure 7: Schematic representation of a REBCO conductor (Courtesy of J. v. Nugteren).

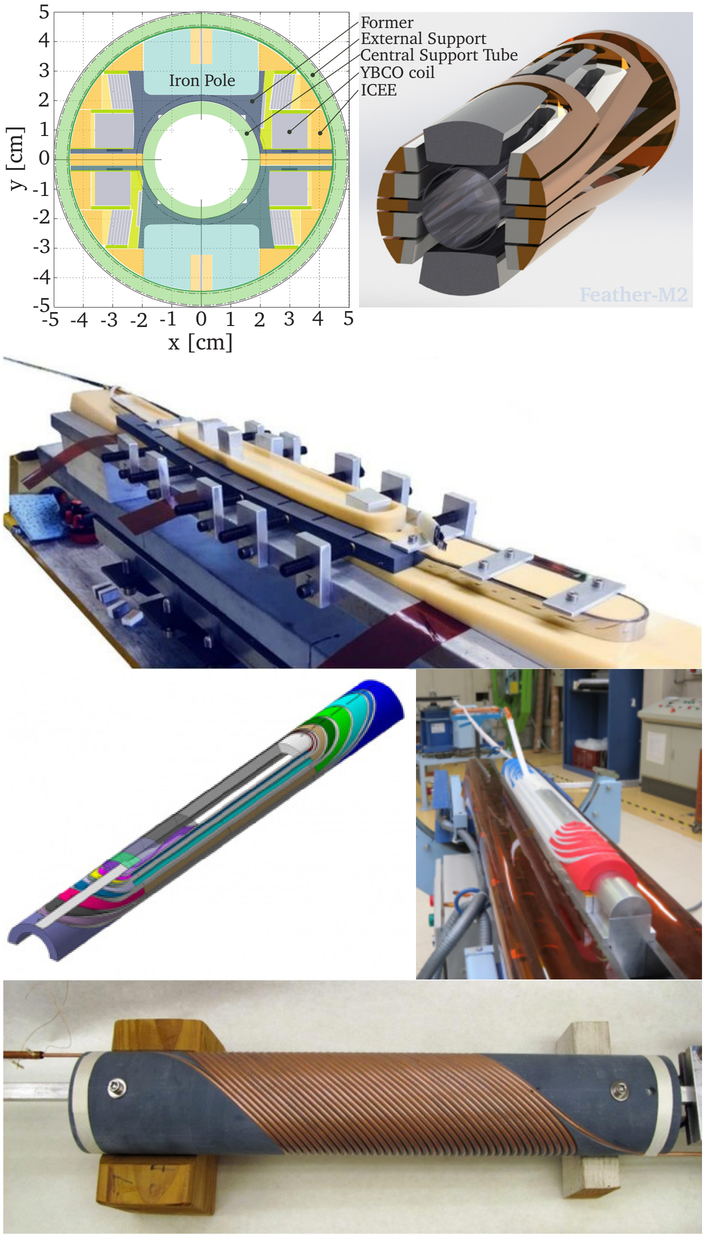


Figure 8: Top: Schematic of the CERN Feather M2 coil [12]. Middle: Schematic and trial winding of the CEA EUCARD2 cos-theta coil [13]. Bottom: Layer of the LBNL C3 canted-cosine-theta coil with CORC™ cable [14].

Nevertheless, the HFM Programme develops IBS technology in collaboration with CNR-SPIN [11] and will evaluate the conductor's potential to meet the required critical-current performance and industrial-scale manufacturing.

As of today, accelerator-readiness with REBCO magnets has not been demonstrated. The closest to an accelerator-relevant layout were the Feather M2 magnet [12] and the REBCO cosine-theta coil [13] built in the EuCARD2 project and CERN and CEA, respectively, both using a fully transposed Roebel cable. More recently, LBNL has successfully tested the C3 CCT magnet [14] with a round REBCO cable (CORC™), producing ~5 T central field; compare Figure 8.

A high-priority research direction of the HFM Programme is the continued exploration of different cable architectures, and their test in sub-scale magnets for an initial qualification. Several racetrack-shaped magnets with 5 T in the magnet centre have been tested; see Figure 9.

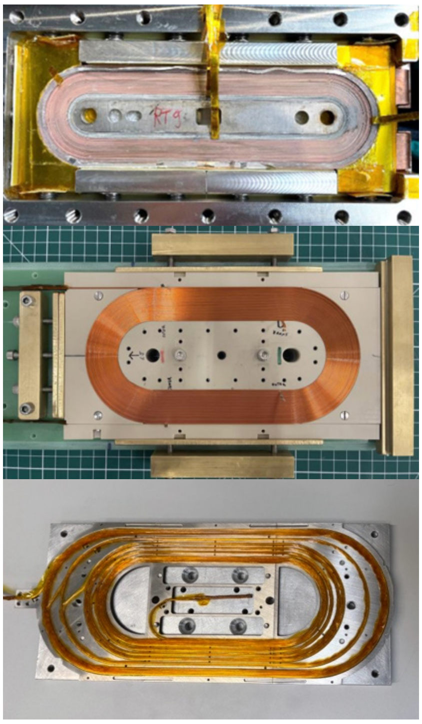


Figure 9: R&D REBCO racetrack coils produced at (from top to bottom) CEA, CERN, and PSI.

First tests of magnets with apertures for field-quality measurements are planned for 2026. Fast-turnaround R&D with subscale magnets will allow to develop and validate numerical models and use them to extrapolate parameters such as field quality and ramp losses to an HTS magnet for FCC-hh. These predictions are necessary to include beam dynamics, cryogenics, powering, magnet protection, and vacuum considerations and define appropriate magnet specifications (field, operating temperature, operational margin, field quality, etc.) that balance the competing criteria of physics reach, power consumption, and magnet cost. The main field in an HTS FCC-hh dipole may range between 14 and 20 T, with a factor 4 larger synchrotron-radiation heat load and increased ramp losses for the 20 T/120 TeV case. For the highest fields, US Magnet Development Program (US-MDP, comprising, among others, BNL, FNAL, LBNL, and NHMFL) is developing single-aperture hybrid Bi-2212/Nb_3Sn and REBCO/Nb_3Sn options [15].

A key milestone in the timeline or HTS magnet development for FCC-hh is the successful demonstration of a short-model dipole with accelerator quality by 2035 [1]. This is essential for a decision between LTS and HTS technology for FCC-hh. We note that, due to the low technological readiness level of HTS technology for accelerator magnets, the 2035 demonstrator milestone and all subsequent target dates are affected by uncertainties on the scale of +5 to +15 years, with the highest risk associated with the highest fields (given the quadratic scaling of forces and stored energy). First beam in an HTS FCC-hh could arrive on a timescale of 2060 (+10/-5 years). A 2070 date would coincide with the planned startup date for FCC-hh in an FCC integrated program with FCC-ee starting operation in 2045, followed by FCC-hh in the same tunnel [16].

CHART and the HFM Programme

CHART, the Swiss Accelerator Research and Technology initiative is a mission-oriented R&D effort [17], supported by four institutes (EPFL, ETHZ, PSI, and UniGE), as well as CERN, SERI, and the ETH Council. The mission of CHART is to develop innovative solutions for a higher-performance, more sustainable, and cost-effective future circular collider in the Geneva basin. Accelerator research in a Swiss network is expected to create synergies with other Swiss science priorities, not least the PSI accelerator and experimental facilities.

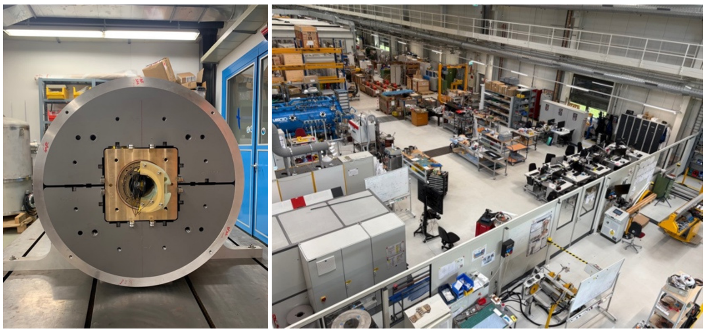
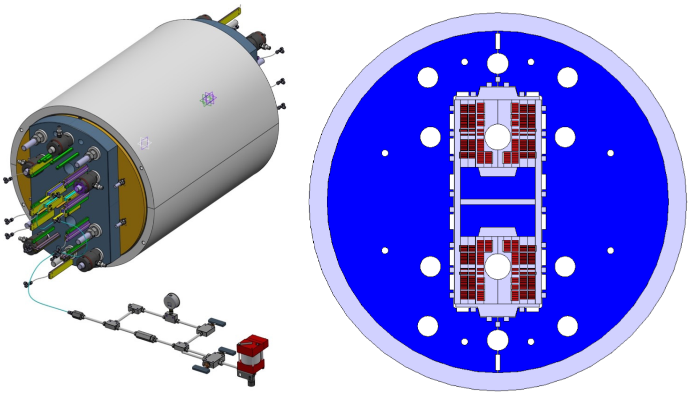


Figure 10: Left: CD1 canted cosine theta dipole, manufactured at PSI in 2018/19 in the former MagDev 90 m^2 laboratory. Right: View of the new 400 m^2 MagDev laboratory (2021 - today) at PSI.

Since its inception in 2015, CHART has pursued applied superconductivity for particle accelerators in collaboration with CERN as one of its main research directions, funded in equal parts by the CERN contribution to CHART through the HFM Programme, and other CHART. The Canted Dipole 1 (CD1 – see Figure 10 left) magnet was built in 2017 - 2019 in close collaboration with LBNL as a first Nb_3Sn accelerator magnet built at PSI and tested at CERN. This initial phase was followed by an increase in CHART funding for the 2020 - 2024 period, and the creation of the MagDev laboratory (see Figure 10 right) at PSI - a 400 m^2 lab with state-of-the-art infrastructure, which is today home to 17 researchers.

The construction of CD1 was followed up by an increased focus on stress-management technologies, involving the Soft Materials Group at ETHZ, the Institute of Information Technology and Electrical Engineering, and the Product Development Group. Novel impregnation materials for Nb_3Sn coils have eliminated the ‘training’ problem, i.e. premature powering aborts due to cracking and debonding of the impregnant from the metallic stress-management winding former. A new coil topology called SMACC (Stress Managed Asymmetric Common Coil) promises simplified coil manu-



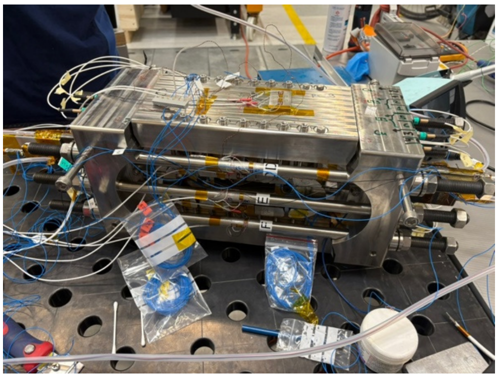


Figure 11: Top: Technical design (3D and cross-section) of the SMACC1 stress-managed asymmetric common coil magnet. Construction at PSI has started. Bottom: subscale stress-managed common coil magnet that reached maximum performance without quenches during tests at CERN.

facturing and assembly procedures. SMACC1, an all-Nb$_3$Sn double-aperture high-field magnet (see Figure 11 top), is being built and will be tested in 2026, following the successful tests of subSMCC1 and subSMCC2 (see Figure 11 bottom), two iterations of 5-T class subscale magnets that implement and test the above-mentioned innovative technologies in a cost-effective fast-turnaround device. The conceptual design of a hybrid Nb$_3$Sn/Nb-Ti SMACC2 magnet is under way. This magnet will be a contender at the HFM Programme's down-selection milestone at the end of 2028.

The Applied Superconductivity Group at UniGE, under a long-standing collaboration agreement with CERN, performs electromagnetic and mechanical performance characterization of Nb$_3$Sn wires, providing crucial insight into performance degradation mechanisms and engineering guidelines for Nb$_3$Sn magnet design. At the same time, the group develops high-performance wires with artificial pinning, suitable for implementation in industrial processes of high-performance wires. Based on results of early multi-filamentary wires, performance values well above the baseline specifications should be possible; compare Figure 12. If the enhanced wires can be produced at a competitive price, the technology promises to lead to lower cost and a reduction in ramp losses, with direct implications for the power consumption of cryogenic systems.

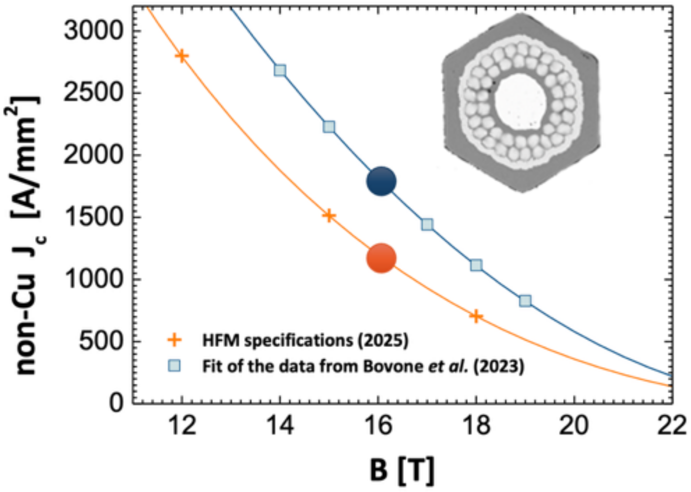


Figure 12: Test results of a subscale multi-filamentary wire developed at UniGE with internal-oxidation artificial pinning.

On HTS technology, the MagDev laboratory has built an 18-T REBCO no-insulation (NI) solenoid in a licensing and collaboration agreement with Tokamak Energy Ltd; compare Figure 13 top). The coil is being reassembled and upgraded into an 18-T split solenoid for neutron scattering at SINQ later this year. With the same technology, the lab has developed and built a wide-aperture positron-capture solenoid for the FCC-ee positron source. This DC-operated REBCO solenoid with 15 T central field and 21 T on-conductor field features a 70 mm warm aperture for the positron-production target and promises to increase the capture efficiency by a large factor; see Figure 13 (centre). The magnet is currently being commissioned and will be a part of the CHART P^3 (PSI Positron Production) experiment at SwissFEL. Equally for FCC-ee, PSI develops a nested REBCO sextupole and quadrupole assembly as an option for the FCC-ee short straight sections (SSS) in the arc sections of the collider. The purpose of this HTS4 (HTS SSS) project is to improve on the electrical consumption of normal conducting SSS magnets, increase the filling factor of the machine, and thereby reduce synchrotron radiation; see Figure 13 (bottom). The project is accompanied by studies on cryogenic concepts with FZ Jülich, and the development of cryogenic power supplies with the ETHZ Power-Electronic Systems laboratory.

Finally, the MagDev laboratory develops REBCO accelerator magnet technology for the FCC-hh. Here the focus is on coil configurations and cable geometries that would allow the magnet to generate low ramp losses and field distortions, while keeping a high engineering current density and optimal cost effectiveness. First racetrack coil assemblies have been manufactured and tested, with a subscale common coil magnet with two apertures for field quality measurements to be tested in early 2026; see Figure 9 (bottom).

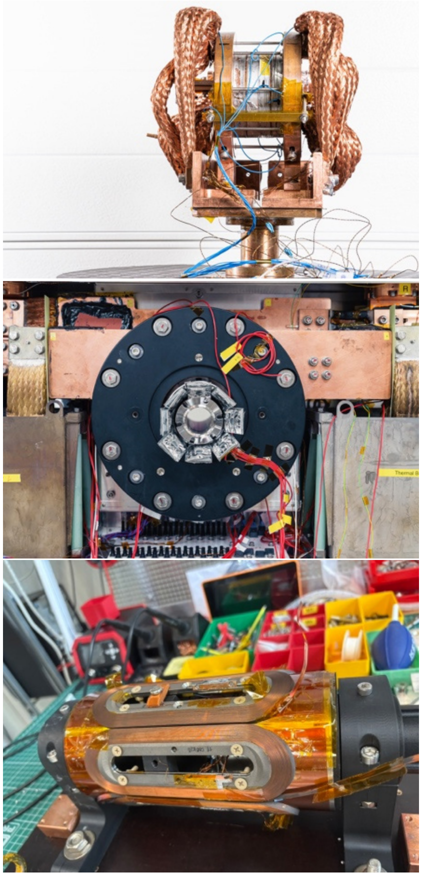


Figure 13: Top: 18-T no-insulation solenoid. Middle: 15-T warm-bore solenoid for positron capture in FCC-ee. Bottom: Subscale version of a REBCO sextupole coil proposed for the FCC-ee short straight sections.

Societal Impact and Synergies

All the above research leads to substantial societal impact and synergies with other fields in the form of collaborative projects, technology transfer, accessible infrastructures, the education of dozens of experts every year, and the publication of over many tens of peer-reviewed articles per year. Areas of collaboration include other high-energy physics projects (FCC-ee, ILC), light sources and neutron spectros-

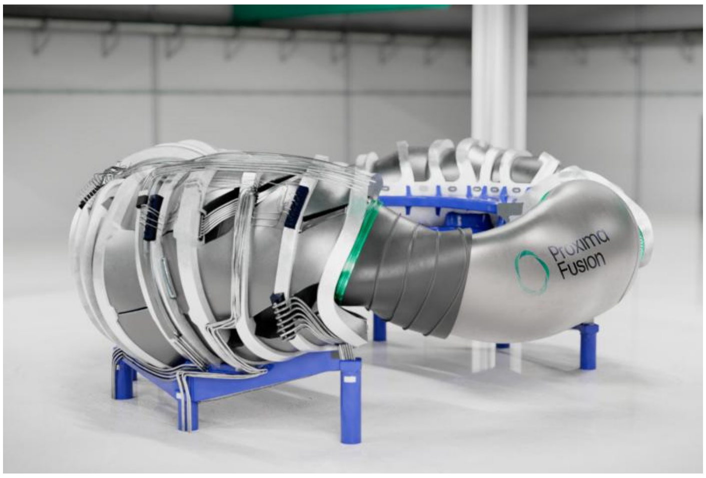


Figure 14: Illustration of a stellarator with REBCO coils. (Courtesy: Proxima Fusion GmbH).

copy, energy generation and transport (fusion, power distribution), medicine (hadron therapy), transportation (electric planes, maritime transport), etc.

As concrete examples of societal impact from CHART R&D we name UniGE's collaboration with Bruker Switzerland AG on conductor technologies, and the decision by the German-based fusion startup Proxima Fusion to re-locate their REBCO stellerator magnet (see Figure 14) technology development in Park innovAare, with laboratories located on the PSI Campus and a long-term collaboration with PSI. A large number of engineers in the Proxima Fusion magnet team have been trained at one stage at CERN and/or other national labs that pursue magnet R&D for high-energy physics.

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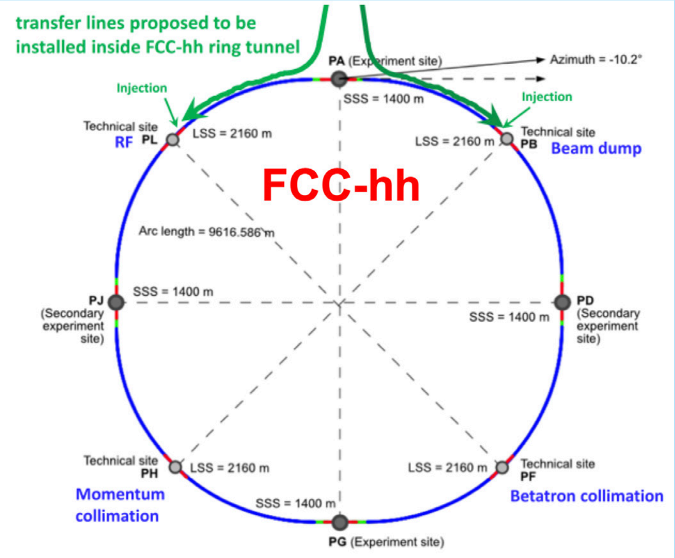
This report focuses on the state-of-the-art of magnet technology. It is also interesting to look at the number of magnet units that would be required to run the FCC compared to the LHC. The table also shows the actual design data compared to those of the Conceptual Design Review in 2019.

	FCC-hh: CDR 2019	FCC-hh: 2025 Nb$_3$Sn	LHC
Bore field B (T)	16.0	14.0	8.33
Aperture (mm)	50	50	56
Magnetic length (m)	14.3	14.3	
Operational temperature (K)	1.9	1.9	1.9
Tunnel length (km)	100	90.7	27
Arc length (km)	82.0	76.9	20
Arc filling factor	0.80	0.83	0.80
c.m. Energy E (TeV)	50 + 50	42.5 + 42.5	7 + 7
J_c at 16 T and 4.2 K (A/mm^2)	1500	1200	n/a
Number of dipoles	4587	4463	1232

Table 1: Parameters of the FCC-hh arc lattice and dipole magnets, Critical Design review 2019 and actual 2025 values [1].



Sketch of the proposed eight-point FCC-hh layout: The accelerator channel, consisting of 8 arc segments with an arc length of 9.6 km, interrupted by 4 short straight segments SSS of 1400 m length for experiments and 4 long straight segments LSS of 2160 m length for technical access.

In conclusion, one needs 4463 magnets of magnetic length 14.3 m resulting in an arc length of 76.9 km by using the arc filling factor of 0.83. According to the relationship $E = 2 \cdot e \cdot c \cdot B \cdot R = 0.6\ \text{TeV} \cdot B(\text{T}) \cdot R(\text{km})$ [2], a deflection magnetic bore field of B = 14.0 T is needed for a bending radius R = 10.12 km and E = 85 TeV.

BB

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[1] https://indico.cern.ch/event/1439855/contributions/6461640/

[2] https://link.springer.com/article/10.1140/epjst/e2019-900087-0