CHART2 Final Scientific Report on Magnet Projects

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Introduction

Key Results

The CHART R&I program on superconducting magnet technology for particle accelerators is one of the pillars of the mission-oriented CHART program. The MagDev laboratory at PSI is the integrating facility for superconducting magnet technologies developed at UniGE, ETHZ, and PSI. Collaboration and exchange with EPFL SPC are also steadily increasing – for the time being in an informal capacity.

Over the past years, the CHART research network has produced several highlights. Among the standout magnets and magnet technologies we name: the test of the Canted Dipole 1, the first Nb_3Sn magnet designed and built at PSI which achieved 100% of the theoretical maximal performance at 4.5 K and over 10 T central field at 1.9 K; the 18-T no-insulation solder-impregnated HTS solenoid with an aperture of 5 cm with follow-up projects lined up for use in PSI facilities (SLS2.0, SwissFEL, and SINQ); the identification of combination of stress management and paraffin-wax impregnation for the complete elimination of the fastidious training problem in Nb_3Sn magnets; novel insulation, powering, and cryogenic solutions for minimal power-consumption high-temperature superconducting magnets; and the invention of the stress-managed asymmetric common-coil for FCC-hh magnets with a first validation in a subscale magnet that reached 100% of maximum performance without training.

The combination of stress management and paraffin-wax impregnation has now been applied by PSI, BNL, CERN, LBNL, and the Wigner Institute. A total of five LTS magnets (Nb-Ti and Nb_3Sn) have reached maximum performance without training. We believe that this recent series of successes raises the bar and nurtures an expectation that accelerator magnets should 'just work'.

Research and Innovation Methodology

We ascribe the success of the past years to several factors, listed below in arbitrary order:

- **Successful hiring** from within and outside the high-energy physics community. Over the years, attracting and hiring top talent has been facilitated by the lab's rising reputation for meaningful innovation and for an open and positive workplace atmosphere.
- The flexible structure of CHART facilitates **networked research**, enabling a quick and unbureaucratic genesis of multi-disciplinary and multi-institute research projects. In particular, the close collaboration between PSI and various ETHZ institutes has been highly impactful and inspiring.
- A **flexible laboratory space** at PSI that fosters a fast turnaround of ideas (see below) and provides **modern infrastructure** for cutting-edge research.
- A research methodology based on the concept of the **innovation funnel with fast-turnaround testing of minimum viable products** to feed-forward new and sometimes unorthodox ideas.
- An idiosyncratic implementation of **new-work principles** that include the creation of ad-hoc empowered research teams and radical openness about everything from technical difficulties and failures to budgets, schedules, and relationships.
- A strive for a broad **systems understanding** in every area of our research, which helps to focus on the most important problems and devise roadmaps accordingly.
- The colleagues forming teams in the CHART magnet-technology R&D have been able to keep their undivided **mission focus** almost 100% (except for best-effort synergetic projects described below).
- Finally, we mention the recent conversion of some time-limited contracts to indefinite contracts for key engineers of the MagDev Laboratory. While we advocate and prepare for additional permanent positions, this decision is strong sign of support for the **long-term sustainability** of our efforts that underpins any future progress by CHART in this field.

Infrastructure

MagDev Laboratory

In August of 2020, the construction of the MagDev Laboratory, a 400 m^2 extension to the WLHA hall at PSI West, was completed. Major infrastructure items such as winding machines, furnaces, and an autoclave are installed, commissioned, and in regular use. All other laboratory infrastructure is designed for flexibility and the continuous evolution of workplaces and methodologies. Moreover, with local mobile workstations for all mechanics, technicians, engineers, and PhDs on the shop floor, there are no barriers to communication, and new ideas flow quickly and unhindered.

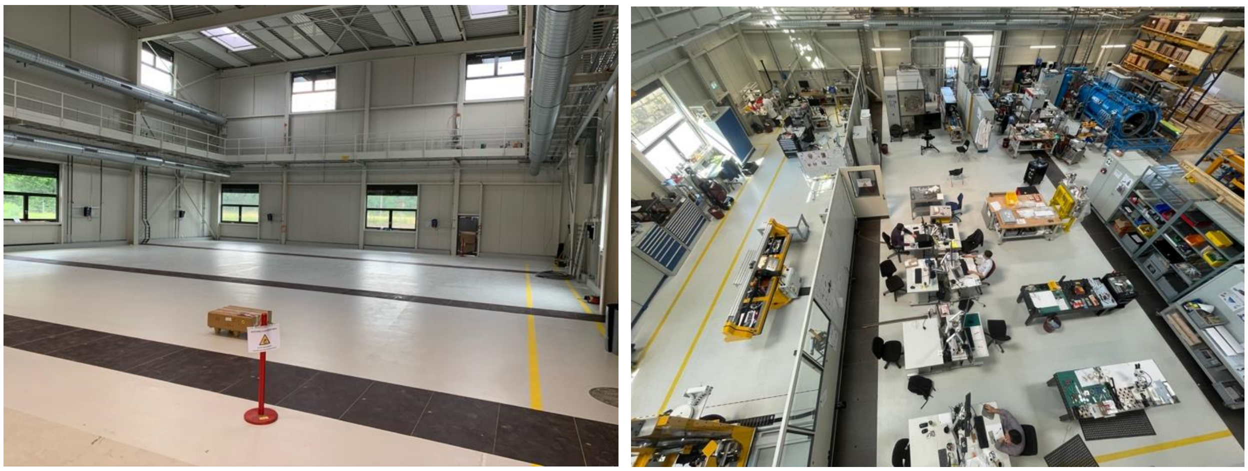

Figure 1 MagDev Laboratory at handover (left) and in May 2024.

Infrastructure items such as the programmable semi-automatic winding setup, 3D scanning metrology, experimental furnaces with Lab4.0 recording and control of process values and exhaust gas diagnostics, and a highly flexible custom-built autoclave all enable a wider range of materials and processes, inviting researchers to experiment with new ideas and materials.

Cryogen-free test station upgrade

The cryogen-free test station at PSI was upgraded with CHART funds from 600 A operating current to 2000 A, and a recent redesign of the cryostat header enables the testing of larger and heavier magnets. The cryogen-free test station was instrumental in the fast-turnaround research on no-insulation coils and the study of novel materials at cryogenic temperatures.

Outlook

Looking ahead, we notice that the 400 m^2 of the MagDev laboratory are starting to become a limiting factor. Discussions are underway to unite the lab space with the PSI Magnet Section's normal-conducting magnet workshop. At some point soon, it may become necessary to move workplaces for engineers and students to a first-floor level above the winding tables. Such a move would be somewhat detrimental to the short paths of communication but could enable magnet projects that require a larger footprint than what is available today. Moreover, we stress the long-term strategic need of a test station for larger magnets with higher operating currents and stored energies.

Nb_3Sn High Field Magnets for FCC-hh

Figure 2 provides an overview of the CHART MagDev innovation funnel for Nb_3Sn high-field magnets. At each successive level, the number of samples to be tested per year decreases. Novel ideas can be tested with fast-turnaround vehicles before feeding them forward into larger magnet demonstrators.

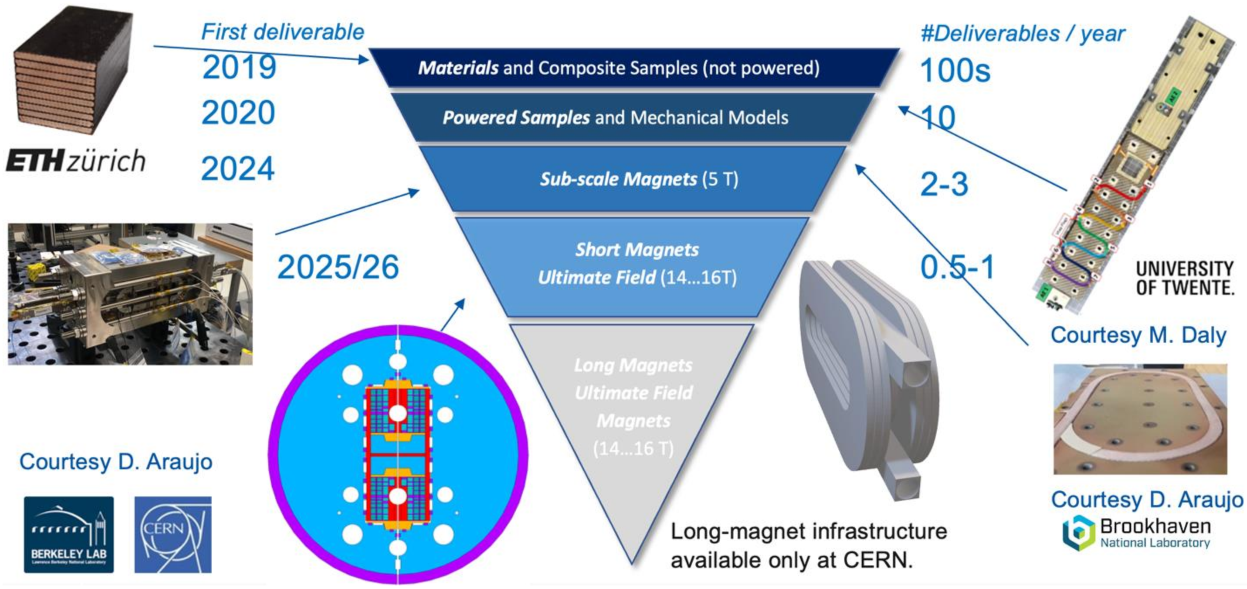

Figure 2 Innovation funnel with fast-turnaround minimum viable products for the CHART Nb_3Sn high-field magnet R&D.

BOX and Compression BOX

Over the past years, the BOX (BOnding eXperiment) program has established a low-cost, fast-turnaround test bed for technology development. In close collaboration with the University of Twente, the experiment allows for testing solutions to the training problem in stress-managed magnets. Figure 3 shows a schematic layout of the typical sample, which is placed into the background field of a 10-T solenoid and powered up to its critical current limit at the University of Twente. Twenty-two standard BOXes have been tested to date, with three more currently under preparation (see Figure 4).

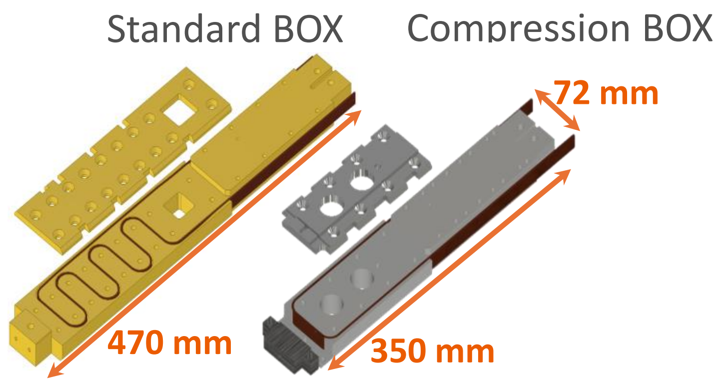

Figure 3 Left: standard BOX sample; right: compression BOX sample.

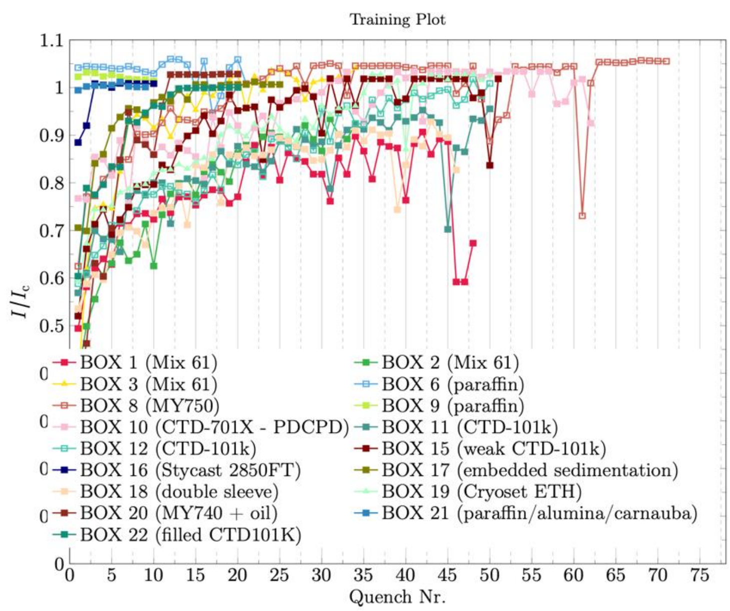

Figure 4 Comparative plot of training performance in different BOX samples. BOX 21 with alumina-filled paraffin wax is the latest no-training system. Data provided by Simon Otten, University of Twente.

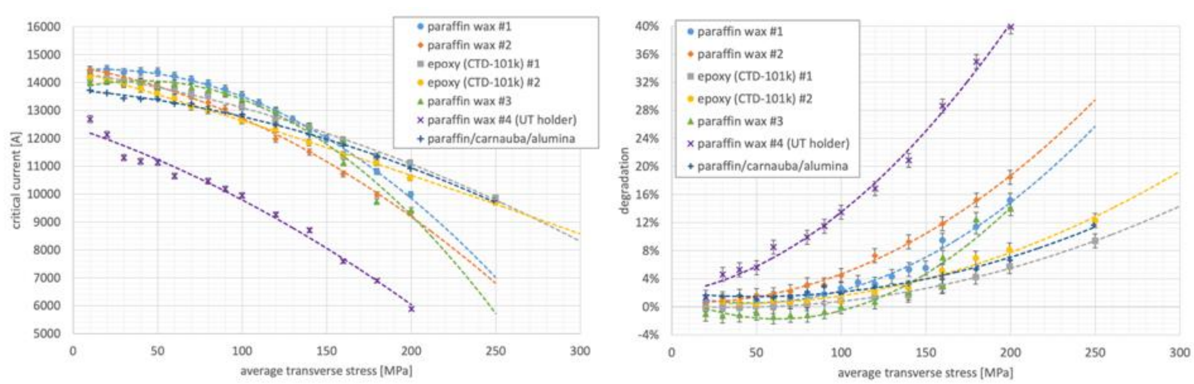

Figure 5 Left: Reduction in Ic under transverse load of two epoxy impregnated samples and three wax-impregnated samples. Right: Permanent degradation after unloading in the same samples. Data provided by Simon Otten, University of Twente.

BigBOX

The BigBOX (Big BOnding eXperiment) platform serves as an R&D vehicle, focusing on testing enabling technologies emerging from the BOX and Compression BOX programs in even higher fields. Unlike these samples, BigBOX is a *multi-turn* coil in a stress-management configuration (see Figure 6). The BigBOX is conceived for testing inside the DCC17 magnet at Brookhaven National Laboratory. During the most severe test run, the coil experienced a computed magnetic peak field of 12.3 T and 169 MPa without a measured sign of degradation (note that the locations of peak field and peak stress, respectively, are found on opposite sides of the stack).

A BigBOX2 sample is currently being finalized at PSI with alumina-filled wax impregnation. This sample will be tested at BNL with alternating current to observe degradation – if any – on both sides of the stack.

SMCC Subscale

Following an in-depth analysis of the Canted Cosine Theta concept as a candidate technology for the main dipole of the FCC-hh, the team decided to explore alternative stress-management ideas instead. After first considering a stress-managed cosine theta magnet, the final choice fell on the stress-managed common coil (SMCC) concept. In the SMCC, flat racetrack coils are wound from one aperture towards the other with relatively big bending radii. Following the innovation-funnel paradigm, a subscale SMCC was designed and built (see Figure 7) for the purpose of developing and testing a slew of new manufacturing methods required to make SMCC a reality. SubSMCC1 was tested at CERN in June 2024 and achieved 100% of theoretical maximum performance at 4.5 K. At 1.9 K there was a small amount of training starting at 93% of maximum performance before reaching 100%.

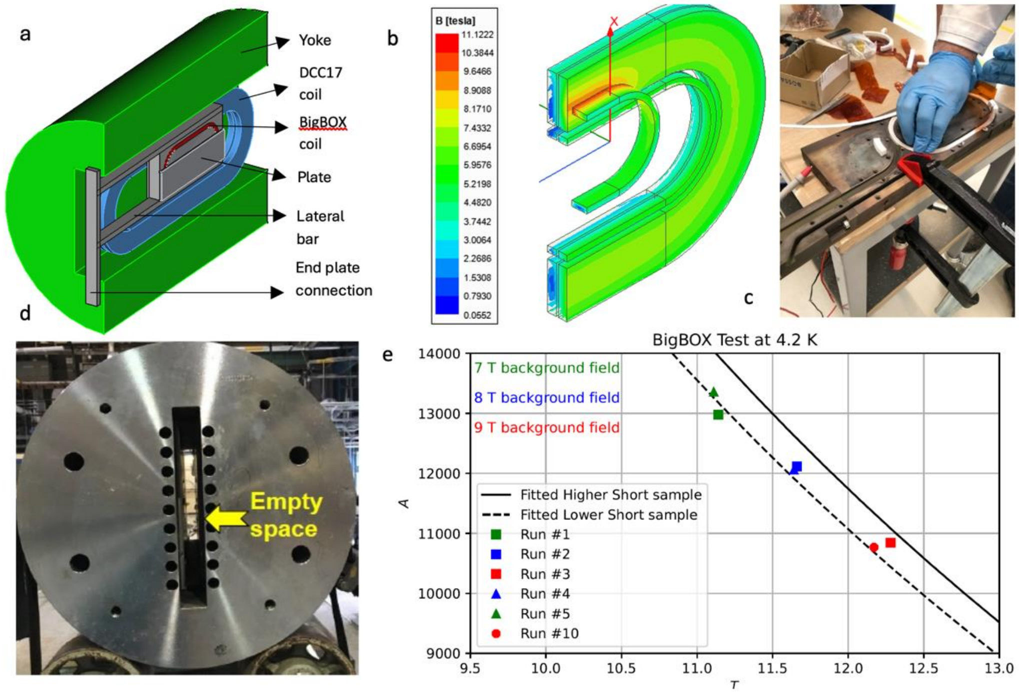

Figure 6 BigBOX powered coil integrated with BNL Dipole DCC17: a) conceptual design model. b) 3D magnetic analysis. c) Stress-managed coil winding. d) DCC17 magnet. e) test results with measured applied coil current and computed coil peak-field for 7, 8 and 9 T background fields.

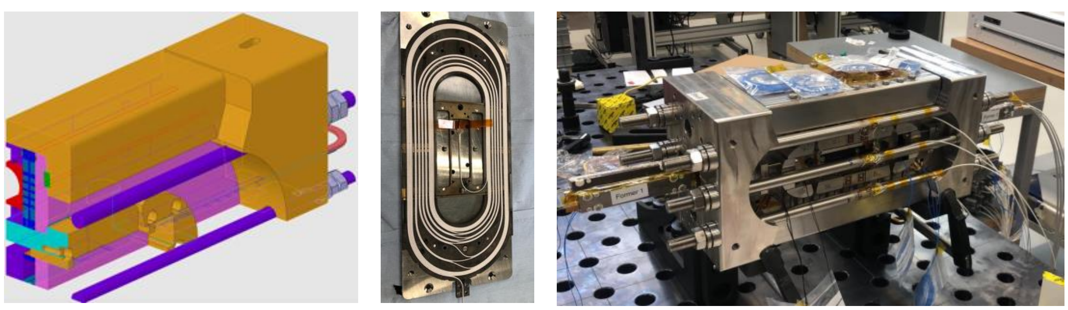

Figure 7 Subscale SMCC, Left: technical design; Middle: Coil winding inside stress-management winding former; Right: Assembled subSMCC1 magnet.

SMACC Concept

For the 14 T target of Nb3Sn high-field magnets for FCC-hh, the team in the MagDev Laboratory has invented a novel variant of the common coil (CC) – the asymmetric common coil. While standard CCs require pole coils on top and bottom of each beam pipe, the asymmetric common coil achieves homogeneous fields with only big-bending-radius common coils – a critical advantage in terms of manufacturing methods and mechanical design; compare Figure 8. The Stress Managed Common Coil (SMACC) design with filled-wax impregnation is now the baseline of the MagDev LTS roadmap. The concept lends itself in a unique way to a drastic reduction of touch-labor in an industrial setting, promising to lower manufacturing cost and increased reliability.

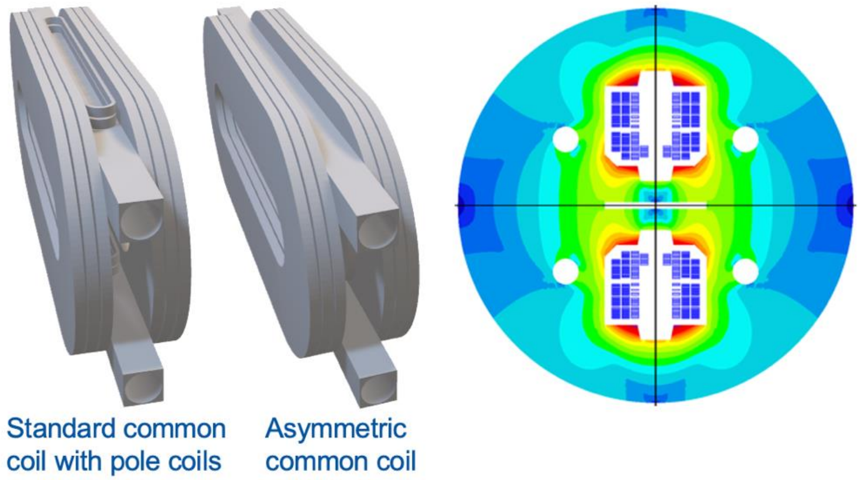

Figure 8 Standard (left) and asymmetric (right) variants of the common coil (CC) layout. Standard CCs require pole-coils on top and bottom of each beam pipe for field shaping. The Asymmetric coil has only a field-shaping common coil in between beam pipes, and main coils that compensate for field errors due to the asymmetric layout. A cross-section through a 14-T stress-managed asymmetric common coil (SMACC) design is shown on the right.

Modeling Complexity

Due to the steady increase in compactness and performance, modeling of accelerator magnets increasingly relies on multi-scale analysis, where detailed models of conductors, cables, or cable stacks provide information for models of entire coils and magnets. At the same time, while the different physical domains (electromagnetic, thermal, mechanical) become ever strongly coupled, the modeling and development efforts become more networked and might span several teams and continents over a prolonged (multiple decades if the accelerator is built and operated) period. To tackle the difficult task of remaining tightly coupled, consistent, traceable, and repeatable, the 'MagNum' project at ETHZ D-ITET developed a Model-Based Systems Engineering (MBSE) methodology that is now in use in the CHART LTS magnet R&D for accelerators, and in the 'MagNum2' project with ETHZ D-ITET that focuses on multi-scale modeling in LTS and HTS magnets. Efforts have been undertaken in collaboration with the FHNW institute for automation to implement MBSE methodologies also in the manufacturing and testing processes. More work is needed to increase the technical maturity in a way that allows other institutes and projects to buy into this strategically important development.

Outlook

In the coming 2-3 years, the LTS team in the MagDev laboratory plans to demonstrate the SMACC concept in 2-3 short magnets (2 m) and will push for an early validation of the length scale-up in collaboration with CERN. The team is planning for a major push to provide a fist high-field magnet test during the relevant phase of the upcoming European Strategy for Particle Physics update.

HTS No-Insulation Coils and Magnets

The HTS no-insulation program in CHART had been foreseen as a first step towards HTS high-field magnets for FCC-hh. In the meantime, the technology's success has led to three follow-up projects which are being implemented on a best-efforts basis due to their strategic importance for FCC-ee and PSI.

18-T Solenoid

The R&D on non-insulation solenoids, in collaboration with Tokamak Energy Ltd, reached a milestone with the test of a four-stack of round pancakes that achieved 18.2 T in the free bore and 20.3 T on the conductor at the maximum power-supply current of 2 kA at a coil operating temperature of 12 K; see Figure 9. The coil was tested in the newly refurbished cryogen-free test station. The thermal performance of the test setup was subject to several optimization cycles to provide optimum thermal contacts throughout the setup. The result exceeds the initial expectations. Extensive development has meanwhile been invested in the optimization of the solder-impregnation process. The result had a strong resonance, ultimately leading to a consequential collaboration of PSI with a compact-fusion startup company from Germany (see below).

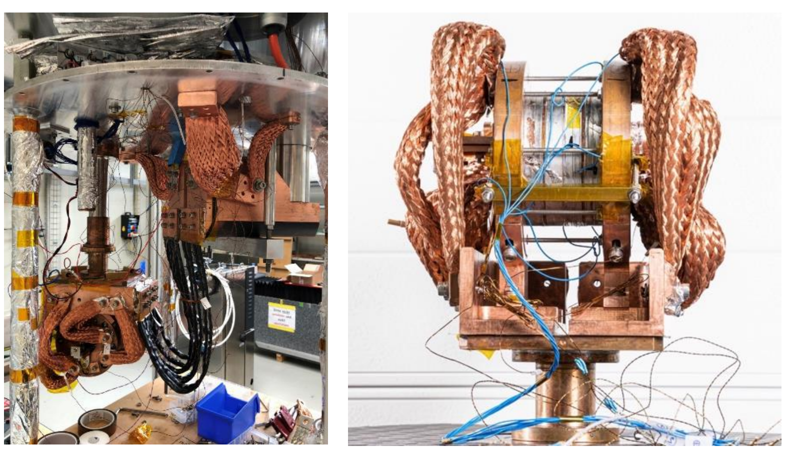

Figure 9 Left: 4-stack mounted on the header of the cryogen-free test station. Right: 4-stack of round pancakes of NI coils.

P3 Positron Capture Solenoid

For the P[3] (PSI Positron Production) experiment, a part of CHART FCC-ee Injector project, the technical design of the HTS capture solenoid was designed and is being built at PS; see Figure 10l. The positron capture solenoid is a standalone system with coils, cryostat, innovative protection features, two cryo-coolers and a power supply. It features five no-insulation coils of the type used above, with an inner diameter of 110 mm. The field reaches 15 T in the aperture and above 20 T on the coil. Assembly is well under way, coil manufacturing will be completed in September 2024, instrumentation by December 2024, and Commissioning will be completed in March 2025.

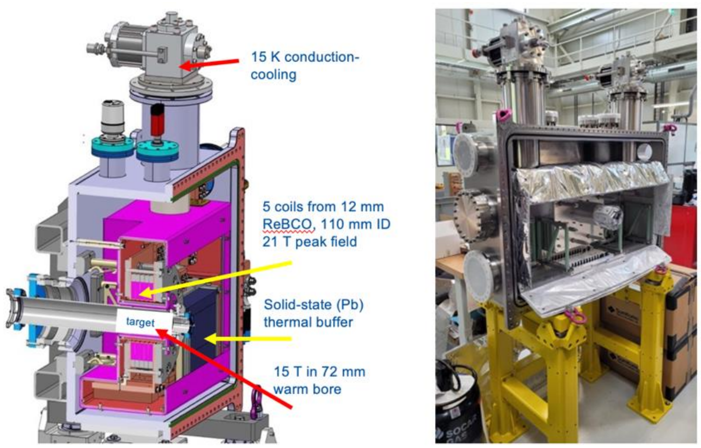

Figure 10 Design (left) and assembly in progress (right) of the P3 positron capture solenoid for the FCC-ee Injector project.

18-T Split Solenoid

The four coils of the above 18 T demonstrator, and two more coils that were built during the solder-impregnation R&D for P[3], are currently being re-assembled into a 6-coil split-solenoid configuration; see Figure 11 (left). The separation ring will be built from special-grade aluminum, directly coated in the MagDev with a copper layer for low-resistance electrical jointing towards the coil stacks. The Split solenoid will produce 18 T at around 5 K in a cryostat designed by the specialists of PSI's SINQ facility. The split coil will be the first CHART magnet that participates directly in PSI's physics program.

RIXS solenoid

Funding was obtained for a R'Equip proposal, *High magnetic field soft X-ray scattering manipulator*, headed by the Spectroscopy of Quantum Materials Group at PSI. As part of this proposal, we made a design concept (see Figure 11 right) for a very compact HTS solenoid that can generate 6 T on a sample placed inside a manipulator head. This is a significant upgrade from the 0.6 T state-of-the-art manipulator based on a permanent magnet. Detailed design and manufacturing are foreseen for 2025.

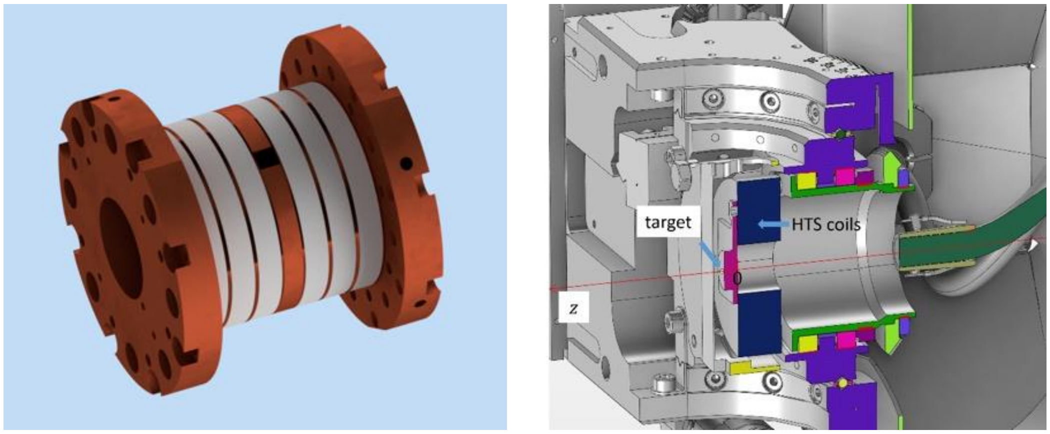

Figure 11. Left: Design of an 18 T split solenoid for neutron scattering. Right: Concept of a compact NI magnet integrated into the RIXS manipulator head.

Outlook

NI technology has distinctive strengths and weaknesses. Stability and efficiency are key enablers, while the lack of field-tracking with current, field quality, and the limitation in terms of maximum stored energy exclude a wide number of applications. Where the technology is applicable, though, it provides the most direct path towards a successful implementation of HTS technology and will continue to do so for years to come.

FCC-ee HTS4 – Energy-Saving Magnet Development

The FCCee HTS4 develops a highly energy efficient superconducting option for the FCCee short straight sections, i.e., the arc sections' (de)focusing quadrupoles, sextupoles, and corrector packages; see Figure 12. The goal is to demonstrate technical maturity and financial viability in terms of total expenditure (capital investment plus operating cost). We seek novel solutions in terms of cryogenics, coil winding, coil insulation, magnet protection, and magnet powering, striving for efficiency in every detail. coil shapes, cryo-cooler systems, powering concepts, insulation systems, etc. The project benefits from materials R&D, carried out in collaboration of PSI with ETHZ D-MAT SMG in the 'MagRes' project, and collaborates closely with the 'FCCee CPES' project for the development of power-efficient cryogenic power supplies. We aim for a full systems understanding, exchanging weekly with the team of the 'FCCee Beam Dynamics Studies and Development' project at EPFL. Relevant radiation studies are being carried out at CERN. Over the next two years, the 'FCCee HTS4' will build a demonstrator module and provide data to the FCCee Pre-TDR team on field quality, power consumption, investment cost, dependability (availability and repairability), and manufacturability. The technologies developed for 'FCCee HTS4' have direct applications in other projects that seek to use high-temperature superconductivity to reach stringent sustainability goals.

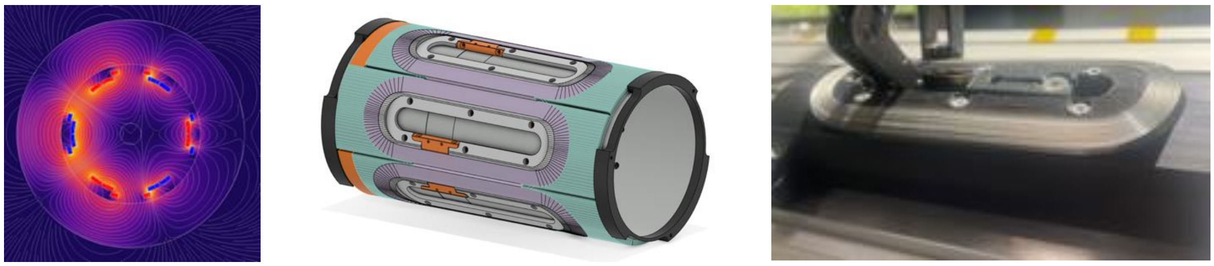

Figure 12 Left: cross-section of a nested sextupole, quadrupole, and dipole magnet for the FCC-ee short straight sections. Middle: technical design of a sextupole subscale demonstrator. The final magnet module will be 1 m in length. Right: winding tests for HTS sextupole coils with 4-mm ReBCO tape.

HTS High-Field Magnets for FCC-hh

Technical readiness and the ramp loss problem

The current consensus in the European high-field magnet community for FCC-hh is that HTS accelerator magnets will use the ReBCO conductor. Because of large investments by the compact-fusion community, ReBCO tapes have become an industrial product and the price gap between HTS and LTS conductors has shrunk rapidly. However, manifest technological challenges remain. The several-mm-wide tape structure restricts the permissible winding shapes and leads to a significant increase in parasitic screening currents during ramping with adverse consequences for field quality, ramp losses, and mechanical stress on the conductor. The proven LTS technology of Rutherford cables with micron-size superconducting filaments are not available, and an entirely new technology stack must be created for a ReBCO-based accelerator; see Figure 13. An additional HTS-specific problem is related to the protection of HTS magnets from quenches.

The above implies that the technological readiness level of HTS technology in general and ReBCO technology for accelerator magnets in particular is comparatively low. It will take a concerted effort over the coming five to ten years to close the TRL gap with LTS technology and allow for a well-informed decision about the FCC-hh magnet technology by 2040.

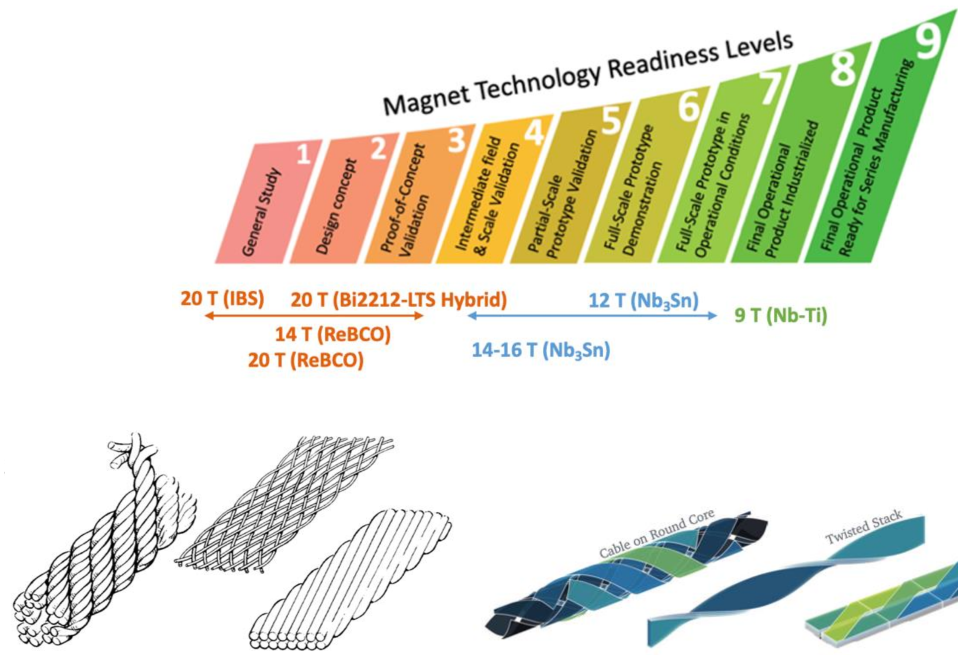

Figure 13 Top: Estimate of technology readiness levels for accelerator magnets. Bottom left: Alternative layouts for the cable of the first superconducting accelerator magnets that were developed for the Isabelle project in the 1970ies and early 1980ies. Bottom right: Some layouts of ReBCO-tape based cable layouts currently under discussion. The juxtaposition illustrates the very early stage in HTS magnet development for accelerators, comparable to LTS technology in the 1970ies.

A crucial technical issue for an HTS-based FCC-hh has been identified by the relevant CHART team in the MagDev laboratory: Ramp losses in ReBCO magnets may be so high as to make their use in a future collider prohibitive. This could be either due to an increased power consumption as compared to an LTS accelerator, or due to a size constraint, whereby a cryogenic system capable to deal with the losses along an arc has physical dimensions that make it incompatible with the proposed tunnel. Both issues are currently under study in a joint effort among the CER TE/CRG cryogenics group and the CHART magnet experts. The results will help shape the technical roadmap towards HTS accelerator magnets.

Tools development

As a part of the above drive for a better understanding of screening currents, the 'MagDev2' project is putting considerable efforts into the development of numerical tools capable to predict ramp losses in accelerator magnets. These efforts involve three commercial partners (Comsol, Quanscient, Little Beast Engineering) and one academic institution (TEMF institute, Technical University of Darmstadt). The goal of the effort is the establishment of a community-wide accepted, stable, and computationally efficient simulation workflow for the design of HTS accelerator magnets. First results from commercial partners are arriving, in time for a formulation of performance goals for magnets and cryogenic systems by October 2024, which will be reported in the FCC Feasibility Study's final report.

Mini-coil development for model validation

The efforts on numerical tools are accompanied by an experimental program (see Figure 14) which serves to produce data that allows for a validation of numerical models, and constitutes a technology development, focusing on winding, insulation techniques, jointing techniques and diagnostics.

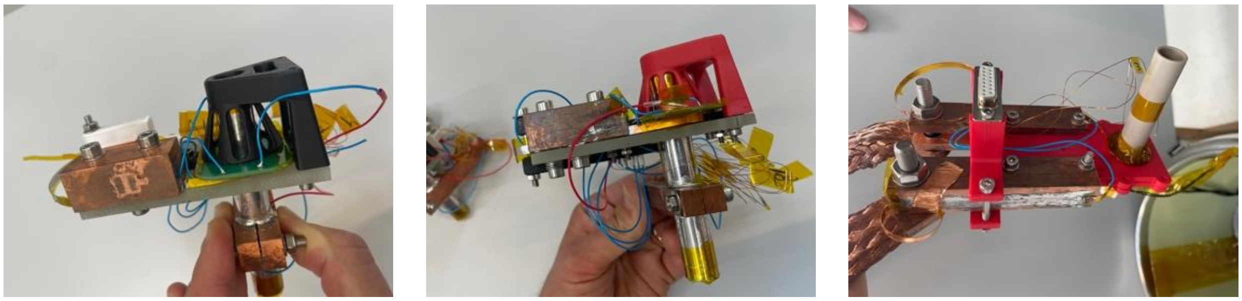

Figure 14 "miniHTS" Coils with 2-stack single-pancake (left and middle) and a 1-stack double-pancake (right) geometry.

Outlook and Synergies

Magnets for a future collider have very large stored magnetic energies, stringent field-quality-requirements, and a need for a precise tracking of the magnetic field with the operating current. Each of these criteria makes the above no-insulation technology unsuitable. The development of insulated HTS magnets that are protectable and provide good field quality, therefore, opens a path for many other applications where no-insulation coils are not an option.

Over the coming year, the 'MagDev2' project will build and test a first subscale HTS accelerator magnet, similar to the Nb_3Sn subscale SMCC (see above). With precise field-quality and ramp-loss measurements for model validation, this magnet will help shape our R&D roadmap for the coming years.

The developed technologies and competencies will, in the coming years, enable the use of ReBCO conductor for high-field solenoids for neutron scattering, compact fusion applications, and possibly compact superconducting cyclotrons. A collaboration on compact fusion (see above) has begun, and a roadmap for high-field solenoids for neutron scattering is being elaborated.

Materials for Superconducting Magnets

A strong focus on materials research has been a distinctive feature of the CHART R&D effort on superconducting accelerator magnets. After a collaborator from the CHART1 project on resin development at ETHZ D-MAT SMG could be hired for the MagDev Laboratory, providing an even stronger link among the two institutes. Outcomes from CHART materials studies in this setup include:

- **Bonding** studies for a variety of resins and surface conditions, involgin the 'MagRes' and 'MagAM' projects at ETHZ.
- The establishment of a process for **heat-resistant low-friction coating** for coil components in Nb3Sn magnets.
- A **cleaning process for electrically conductive pyrolysis residues** on the insulation of Nb_3Sn magnets introducing oxygen injections into the heat treatment.
- The development of a **coating line** for micrometer-thick functionalized coatings such as the **heat-activated partial insulation coating** for ReBCO tapes in the 'FCC-ee HTS4' project.
- The **manufacturing of 10-stack Nb_3Sn samples** with various matrix filler materials for the colleagues of the 'MagComp' project.
- Process development and characterization **of high-melting point technical waxes** for their use in stress-managed superconducting magnets.
- **Switching insulation materials**, also dubbed Smart Insulation (SI) is being developed and characterized in the 'MagMu' project, part of the HorizonEurope 'MuCol' project, with strong synergies towards the goals of HFM research for FCC-hh.
- And many others more.

Outlook

Materials R&D and the related development of manufacturing processes will remain a pillar of the CHART efforts in superconducting magnet R&D. A collaboration with the swiss-based Bruker BioSpin company is being prepared that will allow swiss industry to benefit from the CHART investment in FCC technologies.

Publications and Outreach

Reviewed Journal Publications

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P. Craievich, et al., The FCCee Pre-Injector Complex, Proceedings of IPAC 2022, WEPOPT063, 2022.

Y. Zhao, et al., Optimisation of the FCC-ee Positron Source using a HTS Solenoid Matching Device, Proceedings of IPAC 2022, WEPOPT062, 2022.

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