Report of 2023 Activities in MagDev1, FCCee HTS4, and MagMu

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1. LTS Program

1.1 The BOX Program

Over the past two years, the BOX (BOnding eXperiment) program of MagDev1 has established a low-cost fast-turnaround test bed for technology development, in close collaboration with the University of Twente. The experiment allows to test material solutions to the training problem in Canted Cosine Theta magnets. 18 standard BOXes have been tested to date. Figure 1 shows a schematic layout of the typical sample, which is placed into the background field of a Solenoid at the University of Twente. All seven types of resin impregnation showed long training behavior. Filled resins performed considerably better, with the widely used Stycast 2850FT with 23LV hardener leading to only 2 training quenches to short sample, compared to 40+ quenches in most other systems. Another clear outlier was paraffin wax, which reproducibly suppressed all training; see Fig. 2. In 2023, alumina-filled wax has been identified to be another interesting candidate material, combining the no-training property of wax in the BOX setting with enhanced resilience to transverse pressure on par with epoxy impregnation in the compression-BOX setting; see Fig 3. Also, in 2023, several demonstrators have confirmed the ability of wax to eliminate training: a 5-T Nb3Sn subscale CCT magnet was built and tested at LBNL, a Nb-Ti outsert magnet for the SuShi (Superconducting Shield for an FCC Septum) was built at the Wigner Institute, and a prototype final-focus Nb-Ti CCT quadrupole magnet was tested. All three magnets ramped to nominal and short sample performance without training.

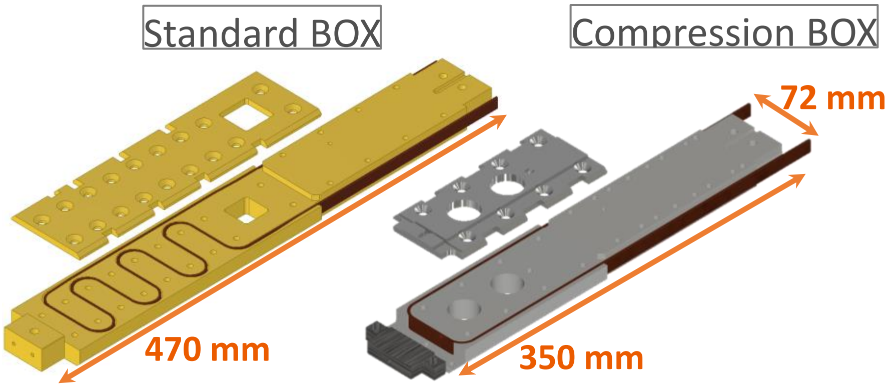


Figure 1 Lleft: standard BOX sample; right: compression BOX sample (courtesy M. Daly)

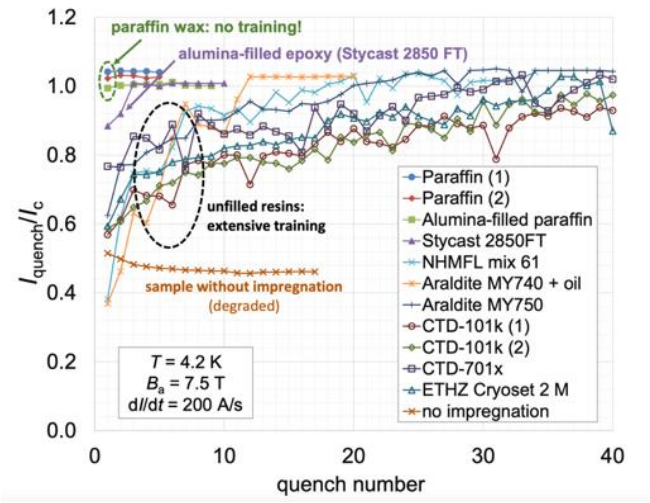


Figure 2 Comparative plot of training performance in different BOX samples. Alumina-filled paraffin wax (light green) is the latest no-training system. Data provided by Simon Otten, University of Twente.

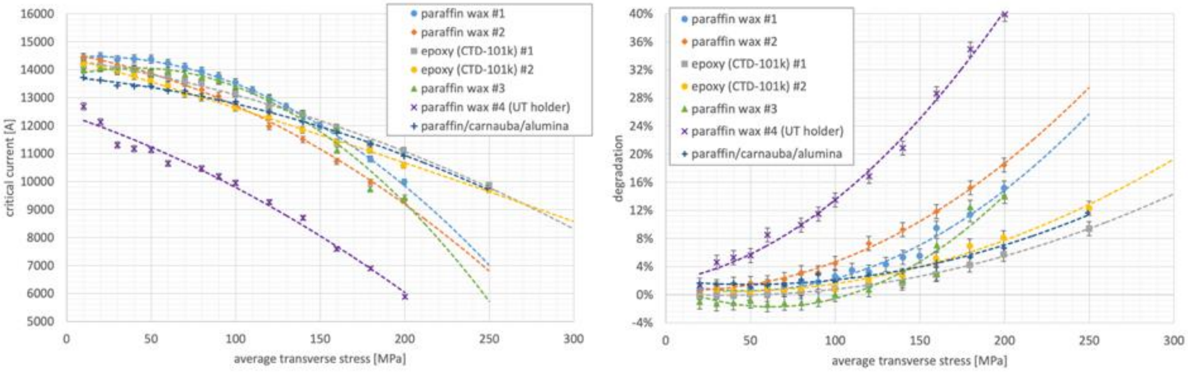


Figure 3 Left: Reduction in Ic under transverse load of two epoxy impregnated samples and three wax-impregnated samples. Right: Permanent degradation after unloading in the same samples. Data provided by Simon Otten, University of Twente.

1.2 The 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. Differently from these samples, BigBOX is a multi-turn coil in stress-management configuration.

The 13-turns Nb_3Sn racetrack coil was conceived to allow high Lorentz forces acting on the wide face of the cable and to let the outsert (DCC17) enhance those forces. To achieve this purpose, the MagDev laboratory HFM team succeed in winding the coil on the so-called hard way bend direction. During the most severe test run, the coil experienced a computed magnetic peak field of 12.3 T and 169 MPa, on opposite directions of the coil winding, respectively, without a measured sign of degradation.

The results obtained with this experiment marked an important milestone and motivate us to move forward with a subscale stress-managed common coil magnet; see below. BigBOX also contributed to the superconducting magnet community, along other programs, and several projects are testing some of the features implements on this very device.

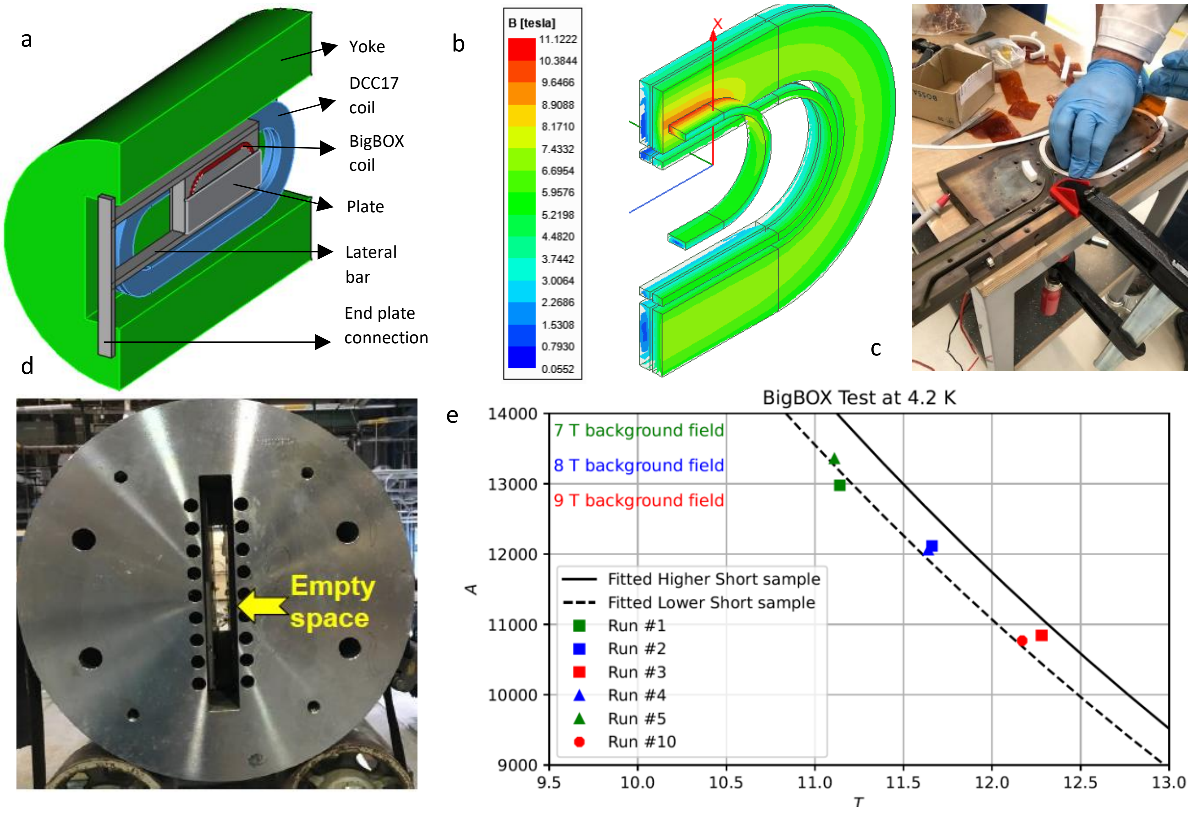


Figure 4 BigBOX powered coil integrated with BNL Dipole DCC17: a) conceptual design model. b) 3D magnetic analysis. c) Stress-managed coil winding. d) DCC17 magnet. e) test results with measured applied coil current and computed coil peak-field for 7, 8 and 9 T background fields.

Figure 4 illustrates one half of the conceptual design, featuring Nb_3Sn DCC17 and BigBOX coils, iron yoke and the mechanical components of this integration. The figure also showcases the initial 3D magnetic model, the Nb_3Sn coil under production at PSI, the BNL DCC17 magnet, before the integration with BigBOX and the test results. The test results plot six different runs performed with the setup. The measured applied coil current and computed peak magnetic field match the maximum expected conductor performance.

We would like to thank the Brookhaven National Laboratory for donating the cable and the Magnet Development Program of the US for funding the tests and contributing to the project. We also would like to thank the Lawrence Berkeley National Laboratory cabling team for providing the necessary information for the coil reaction. Our gratitude also goes to the PSI Magnet Section, in particular to M. Duda, for his contributions during cold measurements.

1.3 Subscale

The subscale stress-managed common-coils (Sub-SM-CC) platform serves to test all manufacturing steps for a high-field stress-managed common coil magnet (see SMACC below). In the subscale, we can focus on testing with relatively fast turnaround various enabling technologies, innovative design concepts, LTS, and Hybrid LTS/HTS coils for high-field magnets, etc.

Key enabling technologies applied to the Sub-SM-CC include spin coating with heat-resistant insulation on the winding former, and coil impregnation systems with wax, filled-wax, or filled epoxy. These technologies have proven to be effective when tested in powered samples and coils. BOX, Compression BOX and BigBOX were powered to the conductor limit without an intermediate quench.

Figure 5 illustrates one-quarter of the magnet conceptual design, featuring rods for distributed axial pre-load, pads for high Lorentz forces, Nb_3Sn, and HTS ReBCO coils surrounded by stress-management formers and additional spacers. This flexibility allows testing of innovative magnet protection concepts. The figure also showcases the finalized engineering magnet design, magnetic analysis, and the first Nb_3Sn coil under production at PSI.

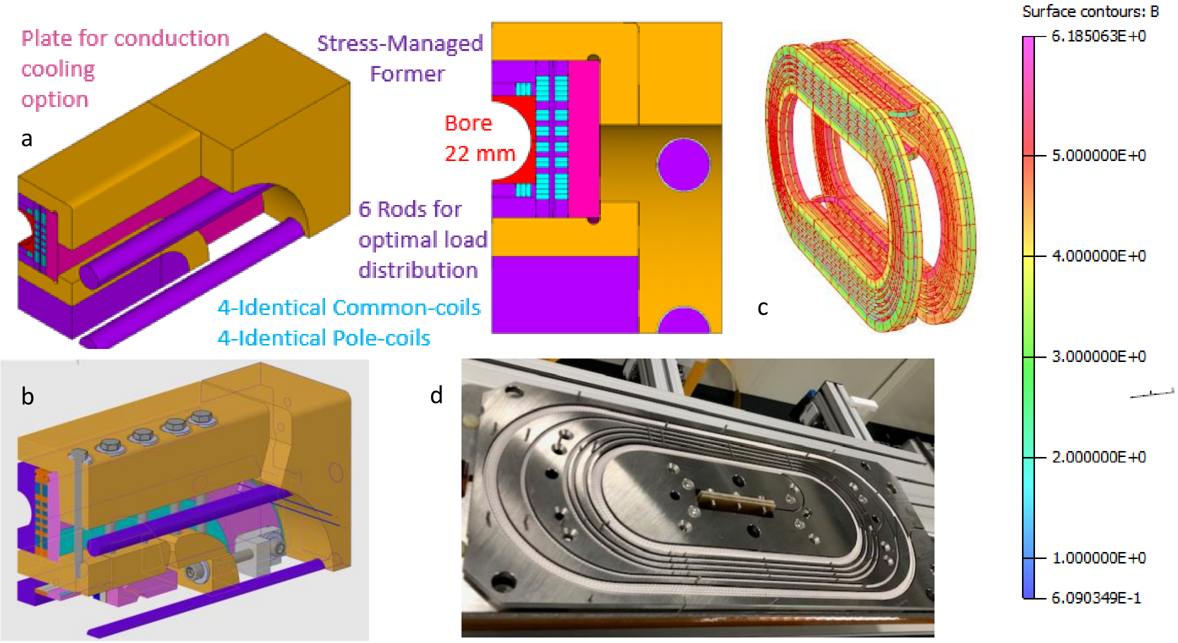


Figure 5 Subscale stress-managed common-coils platform: a) conceptual design model. b) finalized engineering design. c) 3D magnetic analysis. d) ongoing first coil winding.

Following the first magnet test, scheduled for Q2’2024, the following additional tests are foreseen:

- LTS coils with different impregnation systems.
- ESC (Energy Shift with Coupling) protection in collaboration with CERN/TE-MPE group.
- Hybrid LTS/HTS variant to study HTS AC losses and field quality.
- Conduction cooling reduced cryogen inventory in FCC-hh.
- React & winding coils.

The protection studies were performed in collaboration with the CERN/TE-MPE section. The integration into the cryostat and tests are taking place thanks to the help of the CERN/TE-MSC group. We extend our gratitude to the Lawrence Berkeley National Laboratory (LBNL) for their contribution in providing the superconducting cable. Our gratitude also goes to the PSI Magnet Section, in particular R. Felder, for his contributions during the splice trials. Additionally, we would like to acknowledge CIEMAT and Brookhaven National Laboratory for their constructive discussions on common-coils magnets, which have greatly enriched our understanding in this field.

1.4 SMACC

The MagDev laboratory, at PSI, is developing the stress-managed asymmetric common-coils (SMACC) two-in-one dipole, a Nb_3Sn-based 14 T short model, as a CHART contribution to the CERN HFM program.

Stress-management of Nb3Sn coils has been seen as an interesting path towards high-field magnets, thanks to the possibility of reducing the conductor stress, as demonstrated by the CD1 test results, and hence limiting the risk of performance reduction. This concept may also contribute to simplifying some manufacturing steps, as the coil former can be used as part of reaction and impregnation tooling.

The common-coils architecture is an attractive solution for two-in-one dipole high-field magnets. The simple racetrack-based geometry could allow a much easier implementation of an automated coil manufacturing process. Besides, this architecture may allow to exploit the react-and-wind technique, which would be a more cost-effective approach to produce long magnets at large quantities.

A common-coils drawback is the need for pole coils, not shared by the apertures, to achieve field quality compatible with high-energy physics. This drawback has recently been overcome with the introduction of an asymmetric architecture, in which only common-coils are used.

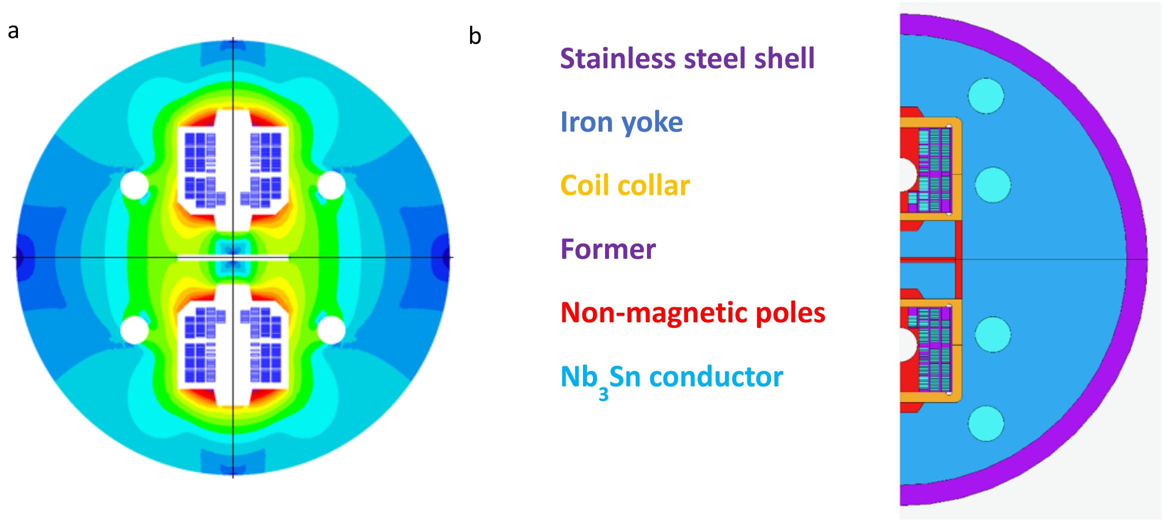


Figure 6 Stress-Managed Asymmetric Common-Coils (SMACC): a) 2D magnetic analysis. b) cross-section conceptual design.

Figure 6 shows the PSI baseline two-in-one dipole magnet, with eight stress-managed Nb_3Sn common-coils. The concept is based on bladders and keys technology and axial rods to pre-load the magnet structure at room-temperature. Thanks to the nature of stress-management, the loading step does not increase the stress on the conductor. The design, with a clear bore of 500 mm, total diameter of 730 mm and intra beam distance of 250 mm, respects the FCC-hh project constraints.

SMACC will be the first Nb_3Sn stress-managed asymmetric common-coils magnet. It will include two cable grades, which can be spliced on the low-field region of the common-coils. The magnet is designed and manufactured at PSI. Protection studies and testing are carried out at CERN.

Some of the goals and parameters of the most up-to-date cross-section are:

- B_0: 14 T

- T_{op}: 1.9 K
- Engineering margin on the loadline of 14%
- Field quality harmonics ax, bx < 15 units (r = 16.67 mm) from 1.5 T (injection) to 14 T
- I_{op}: 14.4 kA

2. HTS Program

2.1 No-Insulation Technology

Several topics involving no-insulation (NI) high temperature superconductor (HTS)-based magnets were elaborated in 2023. In doing so, we build upon the experience gained in 2021 and 2022, which resulted in an 18 T solenoid, tested successfully in PSI's cryogen-free test stand as part of the CHART project MagDev1. Several of the below topics constitute first examples strong synergistic benefits from the CHART MagDev1 and FCCee HTS4 projects for PSI research infrastructure.

P^3. For the P^3 experiment, a part of CHART FCC-ee injector project, the technical design of the HTS capture solenoid was finalized in 2023, and all major parts (cryostat, coolers, power supply, superconductor) were procured and received at PSI. The conceptual design, largely finished at the start of 2023, was refined and is written down in a draft paper, illustrating the major design choices. The CAD design and technical drawings of the cryostat were made in house.

The technical design work includes the mechanical support of the coils to handle the large Lorentz forces, both to prevent excessive stresses inside the windings and to prevent the cold mass from moving towards the downstream normal-conducting solenoids. For this, we performed mechanical tests on the warm-cold connections of the mechanical support structure. Also, two large blocks of lead (110 kg each) will be cast in 2024 to act as heat-capacity reserve. This will allow a safe ramp-down in case of a fault (e.g. a power cut). The feasibility of obtaining a decent connection between copper braids and casted lead was investigated by means of small-scale samples.

An assembly and test plan are now in place, and foresee an acceptance test of the complete magnet in late Summer 2024.

18 split solenoid. The feasibility of adapting the existing 18 T 4-coil NI stack towards an actual application at PSI was investigated. Working together with Marek Bartkowiak (Probenumgebung, NUM, PSI), a plan is was devised to incorporate an 18 T split solenoid (6 coils, 10 mm split) inside a cryostat for neutron scattering experiments at PSI's SINQ facility. Initial electromagnetic-thermal calculations show that the 18 T goal can be realized at an operating current of 1.8 kA, while maintaining safe stability margin.

The 10 mm spacer ring is being designed. It needs to balance requirements of low electrical resistivity, transparency to radiation, and mechanical strength (600 kN compressive force). We foresee to test the cold mass in 2024 in the cryogen-free test stand, and to work towards integration inside a new cryostat in collaboration with Marek and technicians in his group in late 2024.

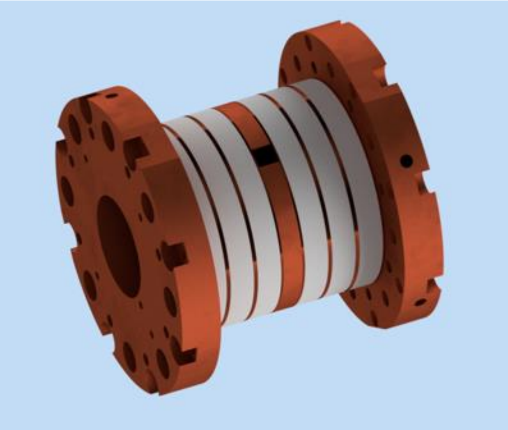


Figure 7. Sketch of 18 T split solenoid.

Muon capture solenoid. PSI's muon facility will see large upgrades as part of the IMPACT project. In view of this, we were asked by division head Mike Seidel (GFA, PSI) to investigate the possibility of using two low-field, large bore HTS solenoids as capture devices around the muon production solenoid. This solution would drastically reduce the power consumption of the baseline normal-conducting solenoids (2x 100 kW). However, it was found, working with Andreas Knecht (Myonenphysik, NUM), that even with maximum shielding, the radiation from the target would limit the lifetime of the HTS magnet to ~3 months. Thus, an HTS system in this location is, according to today's knowledge, not feasible. The preliminary work will be used in 2024 to contribute to a design study on energy-saving HTS solenoids downstream of the muon target in the IMPACT HIMB project.

Compact solenoid for RIXS. Funding was obtained for a R'Equip proposal, *High magnetic field soft X-ray scattering manipulator*, headed by Thorsten Schmitt (Spectroscopy of Quantum Materials Group, PSI). As part of this proposal, we made a design concept for a very compact HTS solenoid that can generate 6 T on a sample placed inside a manipulator head; compare Fig. 8. This is a significant upgrade from the 0.6 T state-of-the-art manipulator based on a permanent magnet. Detailed design and manufacturing is foreseen in 2024/25.

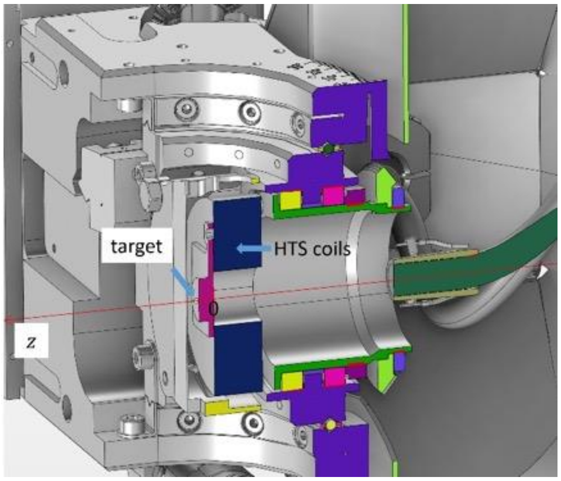


Figure 8. Concept of compact HTS magnet for manipulator head.

2.2 Towards HTS HFM Magnets

The HTS HFM activity in MagDev2 aims towards an HTS-based FCC-hh main dipole with a central field in the 17-20 T range (leading to an FCC-hh centre of mass energy >100 TeV). The technology stack leading to such performance (conductor, cable, insulation, coil shape, mechanical support, protection, cryogenic concept) has not yet been identified. Major questions persist, for example, on the topic of screening currents in HTS tapes, which will lead to field distortions, increased ramp losses, and potential mechanical limitations. The efforts in 2023 were concentrated on the modeling, production, and testing of HTS cables.

The simplest type of cable is a tape stack. Soldered tape stacks have intrinsic advantages in terms of controlled and possibly improved electrical, thermal, and mechanical properties, leading to a more stable building block of HTS coils. Tape-stack cables achieve a high engineering current density, in particular if aligned with the magnetic field. The down-side of cable stacks is the lack of transposition of individual tapes, potentially leading to increased coupling currents. Only a combined experimental and model-based analysis can provide guidelines for the applicability of the technology in a high-field dipole magnet.

COMSOL multi-physics FEM models have been developed with a high level of detail to allow for a quantification of numerical errors due to different strategies of model simplification and homogenization of materials. The refined model was implemented in a 2D representation of a 16-T single-aperture block-coil with good geometrical field quality. An initial estimate of screening- and coupling-current induced ramp losses indicated a ten-fold increase with respect to 16-T Nb3Sn magnets developed by the EuroCirCol program.

The experimental study got under way in the last weeks of 2023 and is in full swing since January 2024. Testing of small instrumented solenoid coils made from insulated soldered tape-stack cable will be performed at University of Twente. Initial manufacturing trials are converging and first tests in LN2 are under way.

The goal for 2024 is to make good progress on the cable-technology and design and build a racetrack coil to be assembled in the subscale stress-managed common coils mentioned above. This hybrid configuration in between tested LTS coils will allow to pin-point the effect of transient phenomena in the HTS cable on field quality and ramp losses. Moreover, in 2024 we will produce a roadmap based on the initial cable-tests towards standalone HTS high-field accelerator-magnet technology.

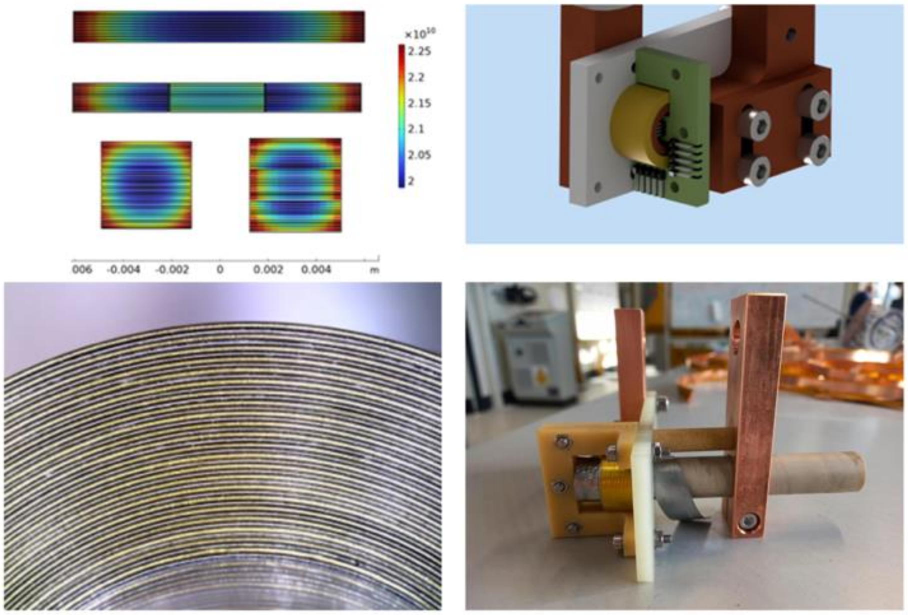


Figure 9 Towards a fast-turnaround HTS-cable manufacturing and analysis setup with (top right) numerical models, (top right) a test setup design, (bottom left) manufacturing trials and microscopic analysis, and (bottom right) experimental validation.

2.3 FCCee HTS4

The FCCee HTS4 project aims to build a 1-m-long single-aperture demonstrator magnet that has all features of a single module (out of six) of a superconducting short straight section for FCCee. This is the first time that an accelerator-quality HTS magnet system for a concrete purpose in a collider is being built and tested. The motivation for the project comes from the considerable power consumption of the baseline normal-conducting magnet systems, the reduced beam-optics flexibility, and the diluted dipole filling-factor. HTS4 shall demonstrate the feasibility of a significantly more power-efficient HTS magnet system.

In 2023 the efforts towards demonstrating the advantages of introducing HTS in the FCC-ee tunnel were focused on the following topics:

Identification of requirements and projected power savings
In collaboration with the group of Tatiana Pieloni (EPFL), CHART project FCC-ee Beam Dynamics Studies and developments.

It became clear in 2023 that nesting the dipole, sextupole and quadrupole has significant advantages. The energy savings relative to the normal conducting baseline can be as large as 20-30% of the total FCC-ee energy consumption. There is a need for individual control of the different harmonics, and their relative polarities are not the same in every operating mode (e.g., a focus quad in Z-mode has positive B2 and positive B1, but might turn into a defocussing quad (-B2, +B1) in tt-mode). This makes combined function magnets, and as an extension also superferric magnets, less attractive than independent nested solutions. Not including the dipole inside the quadrupole/sextupole would only result in half the savings.

Coil geometry
We looked at the cosine-theta (CT) geometry to identify how the required field quality can be achieved with a conductor-efficient layout. The ReBCO conductor, which dislikes hard-way bending, has to be wound in a stress-free way. For this, a 3D geometry was designed, which will be realized in 2024 in the

form of a short demonstrator, to be tested in PSI's cryogen-free test stand at 40 K. The superconductor for this demonstrator has been procured.

Development started on a coating line to coat bare (copper outer surface) tape with a self-bonding adhesive doped with graphite powder. In this way we hope to realize both, a bonding and a well-defined turn-to-turn resistance between turns.

Figure 10. Nested configuration consisting of, from outside-in, a dipole, quadrupole, and a sextupole.

Operating temperature

An algorithm was developed to estimate the ideal operating temperature of the HTS magnets. Here the amount of conductor ($\propto T$) is balanced with the cost of cooling ($\propto 1/T$).

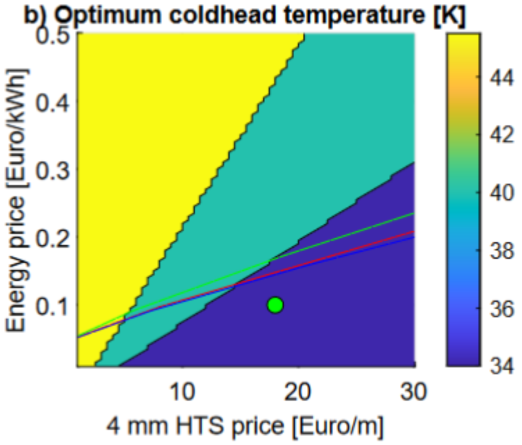


Figure 11. The optimum operating temperature can be identified based on the operational costs (via energy price) and HTS conductor price.

Cooling

The feasibility of cooling the 2900 magnets required for HTS-based FCC-ee operation has been investigated. This started with a cryocooler based approach, and will soon be augmented by centralized cooling options (via a collaboration with CERN TE-CRG group, T. Koettig).

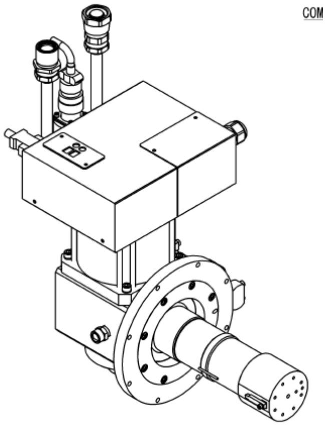
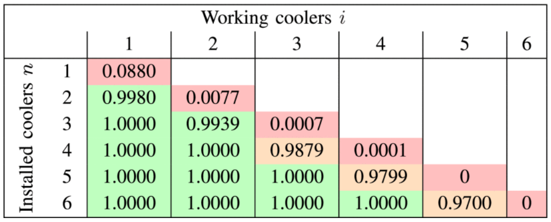


Figure 12. Drawing of high-reliability coldhead. We will be the first to adapt this device for the application of superconducting magnets.

Reliability

By basic reliability calculations, it was found that with the right choice of the type of cryocooler and with added redundancy it is possible to cool 2900 magnets with a high overall reliability. The required yearly preventive maintenance, estimated at 300 FTE-days, has not yet been gauged for acceptability. Neither has work on integration of, e.g., the compressors in the tunnel commenced.

A novel high-reliability compressor/cryocooler combination has been procured from Sumitomo Cryogenics. The unit will arrive in 2024, be tested (have the load map measured), and will serve as the cooling method for the 1 m prototype test at the end of the projet.



		Working coolers i					
		1	2	3	4	5	6
Installed coolers n	1	0.0880					
	2	0.9980	0.0077				
	3	1.0000	0.9939	0.0007			
	4	1.0000	1.0000	0.9879	0.0001		
	5	1.0000	1.0000	1.0000	0.9799	0	
	6	1.0000	1.0000	1.0000	1.0000	0.9700	0

Figure 13. Example of system reliability calculations, towards a credible cooling option for HTS.

Protection

The magnets in this project are expected to operate using a cryogenic DC/DC convertor (CHART project FCC-ee CPES at ETHZ D-ITET PES laboratory), to help avoid the heat load associated with traditional high-current leads. To be able to protect the coils in case of a quench, and at the same time limit the voltage seen by the convertor, we investigated the possibly of a fast HTS-based switch. An internship student built a switch which was tested support from M. Duda, PSI magnet section, and resulted in a 200 ms response time. A design now exists for a 50 ms switch, and the required materials have been procured.

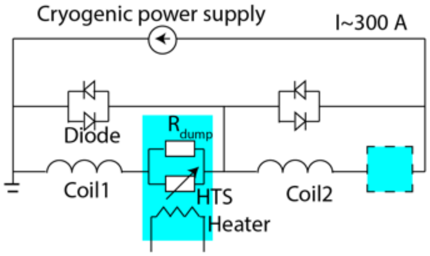


Figure 14. Simplified schematic of HTS4 circuit including protection.

3. Enabling Technology R&D

Materials R&D activities entered a new phase in 2023. After the intensive exploration phase in the past two years, the focus was shifted to fine-tune promising approaches. For the impregnation media (wax or epoxy), filled systems turned out to be superior, hence, processes for low-viscosity impregnation with filled systems were developed and tested. Regarding safer magnets, the processing of the heat-resistant insulating glass ceramic coating for the steel winding former was improved, this to a level where it can be consistently and reliably applied even in the case of narrow channels. Finally, the combustion of pyrolized organic material during the reaction cycle was refined, to enable clean magnets without a significant loss in RRR of the copper portion of the conductor.

Filled wax impregnation

Wax as impregnation medium for Nb_3Sn CCT magnets appears to mitigate the training issue [1-3]. Compared to epoxies, important properties like the coefficient of thermal expansion (CTE) and elastic modulus are too high, respectively low. By introducing filler, in the form of α-Al_2O_3, it was possible to decrease the CTE to the level of pure epoxy and increase the elastic modulus. The filler was chosen such that it is compatible with the glass fiber insulation on the Rutherford cable and can pass through the densely woven filaments. Figure 1A shows a so called 4-stack impregnated with the filled system in question. Transverse pressure experiments of a single cable impregnated with the above mentioned filled wax system showed comparable results to an epoxy impregnation, and a strong improvement over pure wax.

Clean magnets

The possibility to achieve a clean glass fiber insulation by means of introducing oxygen during the reaction heat treatment (RHT) wax explored extensively. This approach relies on the capability to introduce oxygen in a precisely controlled manner. The control of the process parameters, like gas flow and vacuum level, is key and it is essential to prevent excessive oxidation of the copper surface of the cable. Successful cleaning was achieved by injecting oxygen at 665 °C into the vacuum of the reaction chamber, the progress of combustion was monitored by measuring the resistance between cable and ground, see Figure 2B. This procedure showed a reduction in RRR of 16% which coincides with the area reduction in copper cross section due to the formation of a copper oxide layer.

Glass ceramic coating

The SGC-4000 HT glass ceramic coating turned out to be reliable and versatile regarding the application method, the viscosity and drying properties can be adjusted by adding the right solvents (ethanol and/or propanediol monomethyl ether acetate). The coating has a dielectric breakdown strength of 40 kV/mm and was used in the BOX and BigBOX tests. Narrow channels with a high aspect ratio can be evenly coated with spin coating, see Figure 1C.

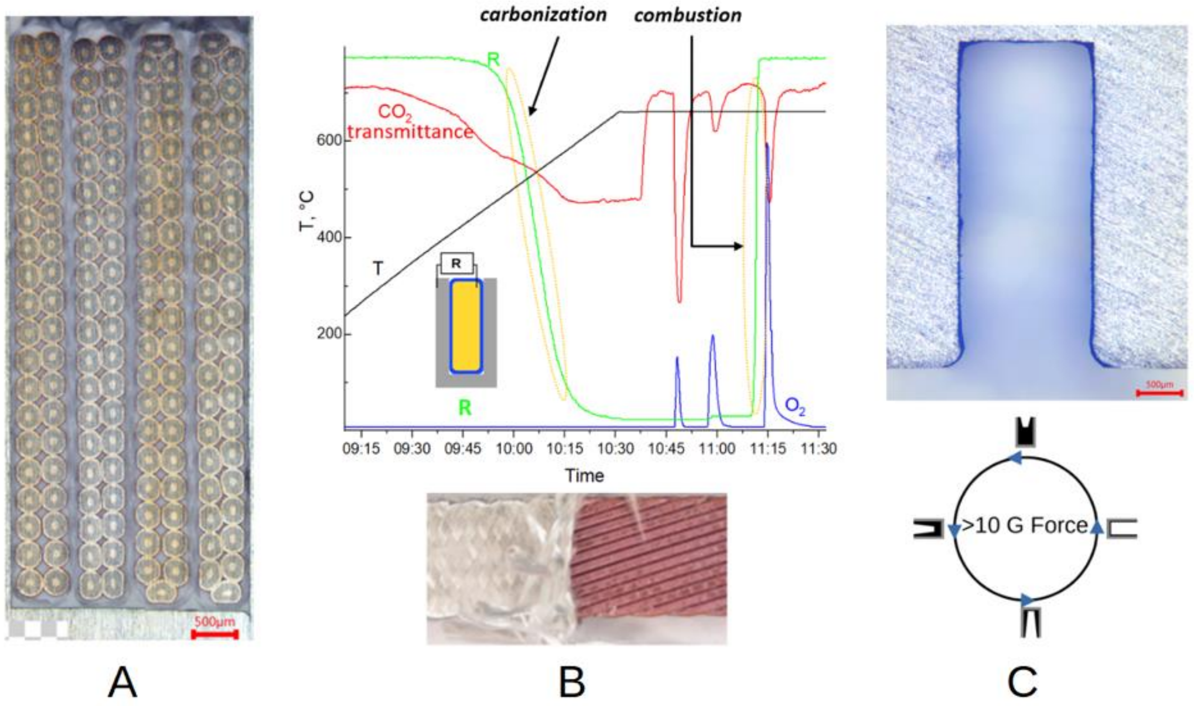


Figure 15, ***A)*** *4-stack of cables in a channel, cross-section after impregnation with filled wax* ***B)*** *Top: recorded relative gas concentrations and resistivity between cable and ground, note the decrease in resistivity due to the carbonization of the organic matter on the glass fiber insulation (sizing) in inert atmosphere. Bottom: cable after RHT with oxygen, clean white glass fiber and colorful cupper oxide on the cable.* ***C)*** *Top: channel coated with glass ceramic coating, Bottom: schematic of the spin-coating process.*

[1] P. Smith and B. Colyer, “A solution to the ‘training’ problem in superconducting magnets,” Cryogenics, vol. 15, no. 4, pp. 201–207, 1975.

[2] V. Edwards, C. Scott, and M. Wilson, “Training behavior of pressure impregnated superconducting racetrack magnets,” in Proc. 6th Int. Cryogenic Eng. Conf., 1976, pp. 477–478.

[3] L. Yan, D. Liu, F. Zhang, and H. Chang, “30 cm bore wax-filled superconducting solenoid: Design, construction and test results,” in Proc.MT-9, 1985, pp. 398–401.

4. MagMu

At the intersection of HTS technology and material science, the MagMu project explores switching insulation systems for the protection against and detection of quenches in ultra-high-field HTS solenoids for a muon collider. The project being only 3-months old, we are in the initial exploratory phase, creating first COMSOL multi-physics models, and devising a measurement procedure to qualify and develop novel materials with switching electrical properties from insulating to conductive based on temperature and/or electric field.

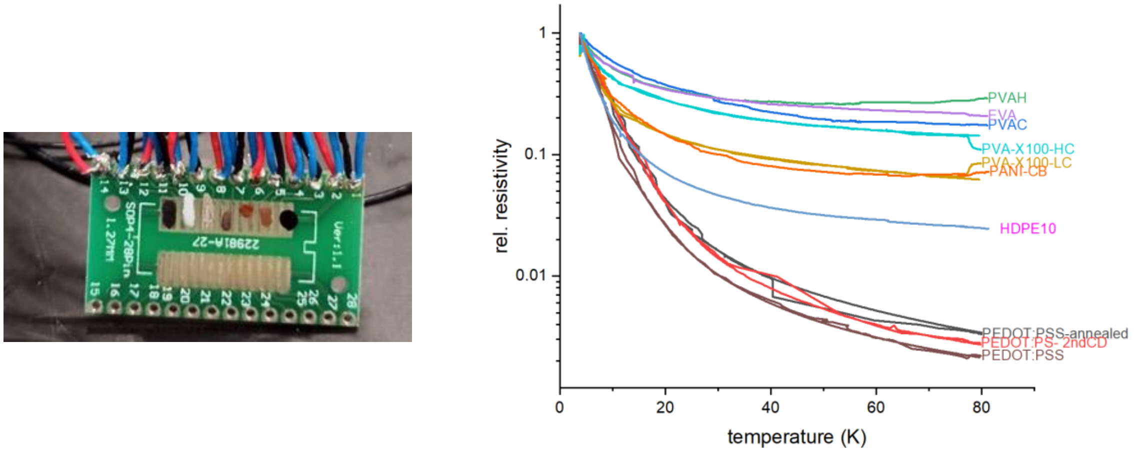


Figure 16 PCB for efficient testing of multiple candidate materials (left). Initial test results in collaboration with D. Uglietti (EPFL SPC) at the SULTAN facility.

5. MagDev Collaborations

MagDev is working closely with five projects at **ETHZ**:

MagNum provides IT solutions for the coupling of simulation software in the paradigm of Model-Based Systems Engineering.

MagRes develops a novel resin with high K1c fracture toughness and low curing temperature that are used in BOX samples at PSI.

MagComp has started at the end of the year and will test cube-shaped coil-composite samples, manufactured at PSI, and provide constitutive models for mechanical simulations.

MagAM studies the augmented functionality of magnet parts through additive-manufacturing, such as structured surfaces for improved adhesion (to be tested in a BOX), or compliant structures for an improved fit between coils and structural parts.

FCCee CPES, as mentioned above, develops cryogenic power supplies that shall reduce the overall thermal load to the cryogenic environment in the FCCee HTS4 demonstrator magnet.

In addition, **UniGE (WireChar, WireDev)** supports MagMu through the academic supervision of the PhD candidate and support in the experimental program.

Publications

D. M. Araujo et al., “Assessment of Training Performance, Degradation and Robustness of Paraffin-Wax Impregnated Nb3Sn Demonstrator under High Magnetic Field,” IEEE Trans. Appl. Supercond., 2024.

D. M. Araujo et al., “Subscale Stress-Managed Common Coil Design,” IEEE Trans. Appl. Supercond., 2024.

B. Auchmann et al., " Test Results from CD1 Short CCT Nb3Sn Dipole Demonstrator and Considerations about CCT Technology for the FCC-hh Main Dipole", IEEE Trans. Appl. Supercond., 2024.

A. Brem et al., "From hot to cold: advanced materials and processes for Nb3Sn based magnets", IEEE Trans. Appl. Supercond., 2024.

J. Kosse et al., "Reliability engineering of cryocooler-based HTS magnets for FCC-ee", IEEE Trans. Appl. Supercond., 2024.