

CHART Scientific Report

Superconducting Accelerator Magnet R&D at PSI (MagDev)

PSI

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1. Introduction

This report presents the main achievements, results, and outcomes of the superconducting accelerator magnet R&D carried out at PSI in 2025 and early 2026, as well as the milestones reached. The projects covered in this report include the two workpackage of the MagDev2 and MagDev3 projects: High-Field Magnet Low-Temperature Superconductor (HFM-LTS) and High-Field Magnet High-Temperature Superconductor (HFM-HTS).

2. Realisation, Results, Publications and Outreach

2.1 High-Field Magnet Low-Temperature Superconductor (HFM-LTS) roadmap

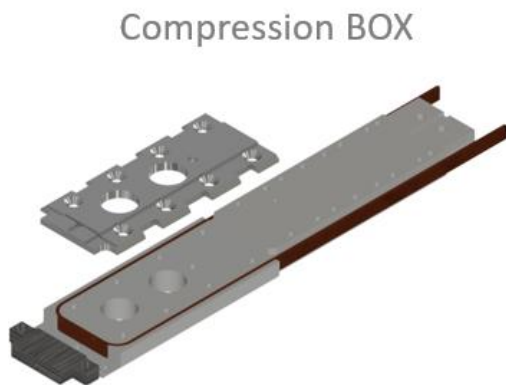
In 2025, several important milestones were achieved. These include progress in the technology programme, with the preparation of coil-composite samples (so-called 10-stack samples) and their mechanical characterization at ETH Zurich (D-MAT), as well as the Compression BOX experiment carried out at the University of Twente. The subscale magnet subSMCC2a was also successfully completed and tested.

In addition, the conceptual design review of SMACC1, the 12 T demonstrator magnet, took place. This was followed by the completion of its engineering design, the procurement of components, and the start of coil manufacturing. The feasibility study of the second demonstrator, SMACC2 (14 T hybrid Nb₃Sn/Nb-Ti), was also completed. This study enabled the start of R&D on the Nb-Ti cable in collaboration with CERN and industrial partners.

BOX, Compression BOX, and BigBOX (MagDev2)

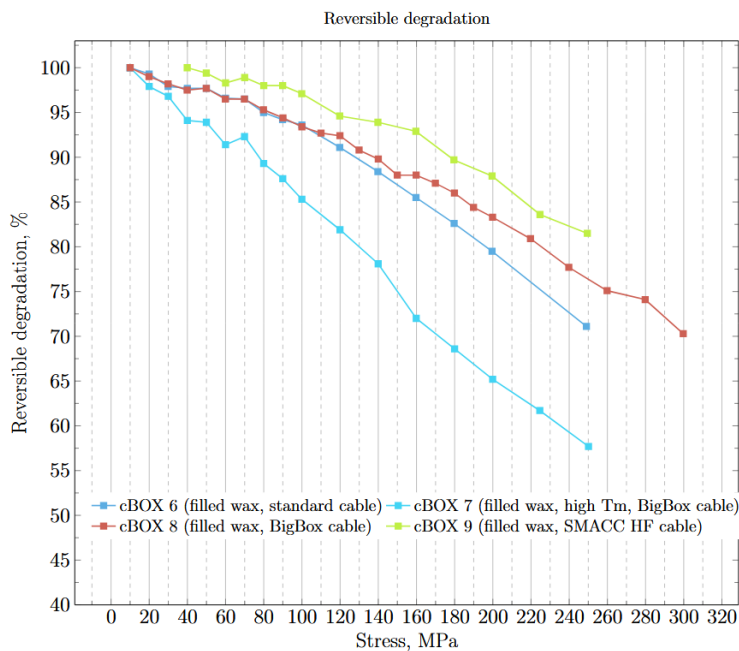
The BOX (Bonding eXperiment) program¹ is an established fast-turnaround R&D platform for technology development related to high-field magnets. The samples are prepared at PSI and tested at the University of Twente, enabling the development, testing, and validation of new insulation, impregnation, and instrumentation technologies, as well as the evaluation of cable performance.

¹A. Brem *et al.*, "From Hot to Cold: Advanced Materials and Processes for NbSn Based Magnets," *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1–5, Aug. 2024, doi: [10.1109/TASC.2023.3338588](https://doi.org/10.1109/TASC.2023.3338588).



In 2025, three compression BOX tests took place. cBOX7 and cBOX8 are samples with the BigBOX/BigBOX2² cable (RRP OST 54/61 strand) and filled wax as impregnation media. cBOX7 had a high-melting-point wax (Deurex T19G, $T_m \approx 80^\circ\text{C}$) as matrix. The tests provided a complementary measurement to the BigBox2 coil test that uses the same cable and impregnation system to test a 13-turn coil in a 10-T background field. The BigBox2 experiment is going to be carried out in summer 2026 in collaboration with the US Magnet Development Program (MDP) at Brookhaven National Laboratory (BNL).

²D. 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.*, vol. 34, no. 5, pp. 1–8, Aug. 2024, doi: [10.1109/TASC.2024.3368995](https://doi.org/10.1109/TASC.2024.3368995).



The cBOX9 sample was prepared with SMACC cable (RRP 162/169 strand) and filled wax as impregnation system. Results of this experiment went directly into the design of SMACC1³ and confirmed the expected cable performance, with a reversible reduction of the order of 10% with a load of 150 MPa.

³D. Araujo, B. Auchmann, A. Brem, T. Michlmayr, and A. Haziot, "Electromechanical Design of Nb₃Sn 13-T Stress-Managed Asymmetric Common-Coils (SMACC): a 2-in-1 Dipole Magnet," *submitted to IEEE Transactions on Applied Superconductivity*, 2024.

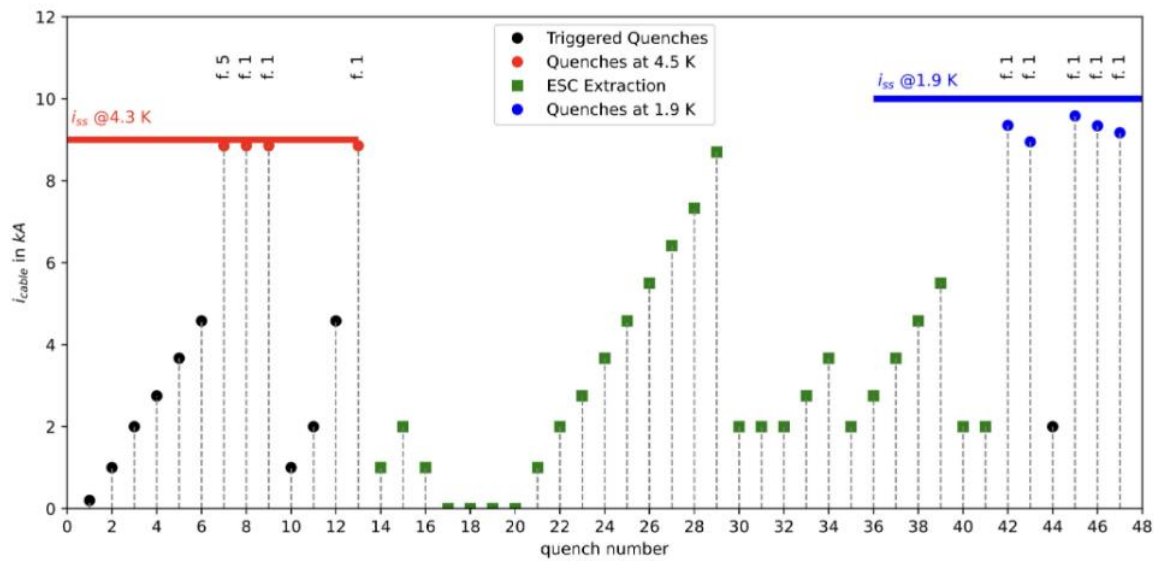
subSMCC2a (MagDev2)

The test of the subscale Stress-Managed Common Coil (SMCC) model magnet was also carried out in 2025. In this version, two out of four Nb₃Sn coils were reused from the previous magnet, subSMCC1, while two new coils were manufactured at PSI. The magnet was also delivered to CERN for tests with four copper coils, to evaluate the performance of the Energy Shift with Coupling (ESC⁵) protection method.

As highlighted in the plot (red dots), the reused coils showed no training, and the new ones also operated without training, all performing very close to the expected limit.

The ESC system could be validated with two out of the four coils; due to a short circuit, only two coils could be used. The ESC system was nevertheless tested up to 8.5 kA even with only two coils. A new

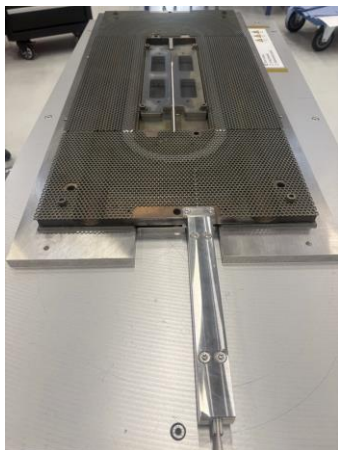
version of the magnet, subSMCC2b⁴, equipped with four new copper coils, was assembled and delivered to CERN in early 2026.



⁴D. Araujo *et al.*, “Manufacturing and Testing of the Nb3Sn Subscale Stress-Managed Common Coil Dipole Magnet 2 With Energy Shift With Coupling Quench Protection Method,” *IEEE Transactions on Applied Superconductivity*, vol. 36, no. 3, pp. 1–5, May 2026, doi: [10.1109/TASC.2025.3630129](https://doi.org/10.1109/TASC.2025.3630129).

⁵E. Ravaioli *et al.*, “ESC Enables Protection of an Accelerator Superconducting Magnet with > 5 kA/mm² Copper Current Density,” submitted to *IEEE Transactions on Applied Superconductivity* in 2025.

SMACC1 (MagDev2/3)



The design review of the Stress-Managed Asymmetric Common Coil³ magnet 1 (SMACC1) took place in early 2025, and the related documents are available on the following Indico page: <https://indico.psi.ch/event/16981/>.

This short-model magnet, which can reach 12 T with a 23% margin at 1.9 K, represents the first step towards the 14 T short model (SMACC2). Following the completion of the design review, the engineering design was finalized and the procurement of the magnet structural components was carried out in early 2026.

As of March 2026, all eight layers have been wound, six out of eight have been reacted, and the instrumentation and impregnation of the coils have started. The blank assembly of the mechanical structure is scheduled for April. The magnet is expected to be delivered to CERN in summer 2026 for testing.

The pictures show one of the coils just before reaction, as well as the machined half-yoke and an end plate.



subSMACC (MagDev3)

The subscale Stress-Managed Asymmetric Common Coil (SMACC) magnet, developed within the MagDev3 project, explores an integrated concept for cooling and protection of high-field superconducting magnets. Increasing the current density of superconducting cables reduces conductor volume but also makes magnet protection more challenging. To address this, the above-mentioned ESC system is deployed.

At the same time, improving cryogenic efficiency is essential, both for steady-state cooling and for managing transient losses. Operating magnets at 4.5 K instead of 1.9 K, and reducing the helium inventory of a Nb₃Sn accelerator are important research directions that address the sustainability of FCC-hh. Instead of relying on helium-bath systems, a conduction-cooling approach using forced-flow super-critical helium in pipes embedded between coil layers is being studied. A two-in-one concept is proposed: a hollow electrical conductor that serves simultaneously as the protection circuit and the cooling channel.

The conceptual design⁶ and protection studies⁷ have been completed, and the prototype is now entering the engineering phase.

⁶I. S. P. Peixoto, D. Araujo, and B. Auchmann, "Subscale Stress-Managed Asymmetric Common Coil Design," *IEEE Transactions on Applied Superconductivity*, vol. 36, no. 5, pp. 1–5, Aug. 2026, doi: [10.1109/TASC.2026.3666514](https://doi.org/10.1109/TASC.2026.3666514).

⁷D. Araujo, I. S. P. Peixoto, B. Auchmann, and E. Ravaoli, "Combined System for Cryogenics and Protection of High-Field Superconducting Magnets," *IEEE Transactions on Applied Superconductivity*, vol. 36, no. 5, pp. 1–5, Aug. 2026, doi: [10.1109/TASC.2026.3658047](https://doi.org/10.1109/TASC.2026.3658047).

SMACC2 (MagDev3)

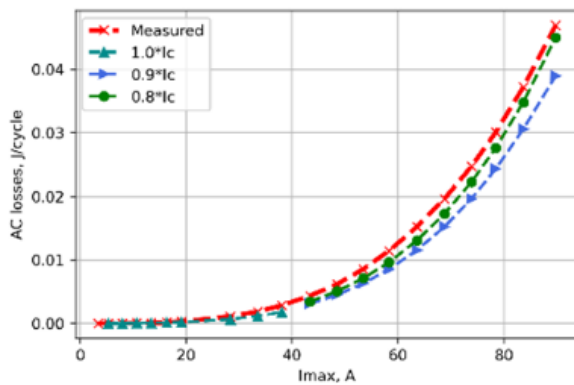
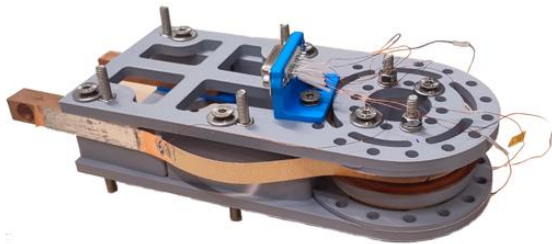
The Stress-Managed Asymmetric Common Coil 2 short-model magnet (SMACC2) is the final delivery of the MagDev3 project and represents a feature-complete 14 T LTS short model for the FCC-hh. The magnet will incorporate most of the technologies validated along the roadmap, including ceramic coating, stress management, the asymmetric common coil concept, conductor grading (where different cables are used within the same magnet to reduce conductor cost), protection strategies, and further conductor savings through the combined use of Nb₃Sn and Nb-Ti conductors. The feasibility study was presented at the HFM forum: <https://indico.cern.ch/event/1581999/>

Following the findings of the feasibility study, ongoing R&D is being carried out with Nb-Ti manufacturers and CERN to investigate I_c reduction due to cabling of low-copper-content Nb-Ti wires, as well as to optimize current density for high-field magnets.

2.2 High-Field Magnet High-Temperature Superconductor (HFM-HTS) roadmap

On the HTS roadmap, several important milestones were achieved in 2025. These included the testing of the babyHTS coils for the validation of numerical models, the completion of four dielectrically insulated REBCO soldered-tape-stack coils with tests in LN₂ for the REBCO Subscale Magnet 1 (RS1), as well as the feasibility study of the field-aligned REBCO Subscale Magnet 2 (RS2). In addition, the conceptual design of a compact cabling machine for prototyping short unit lengths of tape-around-core type REBCO cables was completed.

babyHTS



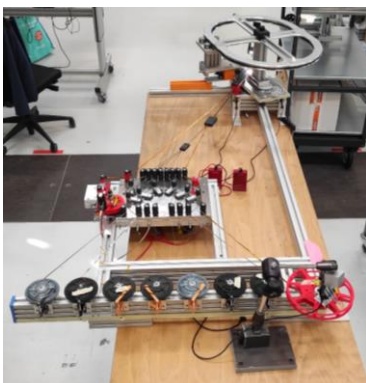
This work⁸ investigates the use of double-pancake coils (babyHTS) to validate electromagnetic numerical models of HTS REBCO cables for accelerator magnet applications. A design based on 3D-printed plastic formers was developed to produce test coils using face-to-face soldered REBCO tape stacks. These cables offer a high filling factor and are well suited for racetrack coil geometries used in block-type and common-coil magnet configurations.

AC loss measurements were performed at 77 K in self-field conditions over a frequency range from 0.1 Hz to 20 Hz, with current amplitudes up to 100 A. The results showed that AC losses per cycle remained nearly independent of frequency. Measured losses reached up to 25 mJ/cycle for the 4 mm soldered stack coil and up to 65 mJ/cycle for

the 12 mm single-tape coil. Finite element modelling using experimentally derived $J_c(B)$ data reproduced the measurements with discrepancies below 10%. These results demonstrate the suitability of the developed experimental and numerical methods, and provide a basis for further studies on REBCO stack cables for high-field accelerator magnets.

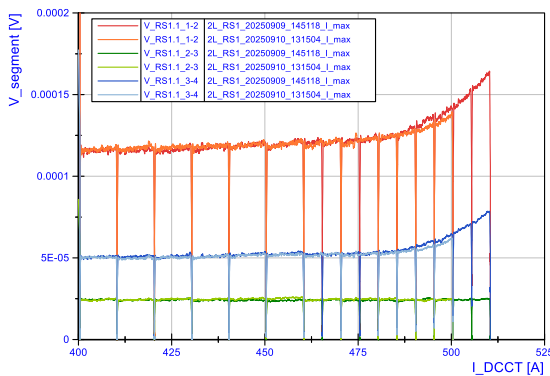
⁸M. Duda *et al.*, "AC Loss Measurement and Validation of an HTS Soldered Stack Cable for Accelerator Magnets," *IEEE Transactions on Applied Superconductivity*, pp. 1–5, 2026, doi: [10.1109/TASC.2026.3661477](https://doi.org/10.1109/TASC.2026.3661477).

RS1 (MagDev3)



The REBCO Subscale Magnet 1 (RS1)⁹ is based on the mechanical structure and coil shape of the subSMCC magnet. The conductor is an insulated cable based on a soldered stack of REBCO tapes. The cable and coils were manufactured using four face-to-face soldered REBCO tape pairs, with additional copper tapes acting as stabilizer. To improve quench detection performance, a co-wound insulated copper tape is used for noise cancellation. This conductor can also serve as a current discharge path to trigger quenches in the REBCO coils. A simple setup was built at PSI for the manufacturing of the cable and coils. After winding, all tapes are pre-tinned and the coil is heated with additional

solder paste and flux to complete the soldering of the tape stack. The coils are then impregnated with wax to fill the gaps between the coil and the stress-management formers.

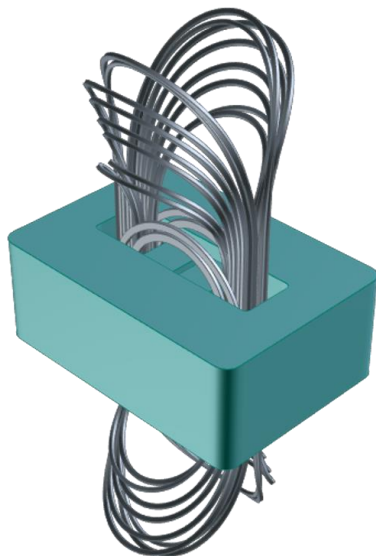


To date, six coils have been produced: a first trial using low-grade tapes, four coils tested in LN₂ (corresponding to the test results of layers one and two shown in the figure), and a fifth spare coil. Coils 3 and 4 tested in LN₂ showed about an 8% reduction in I_c between the first and second test campaigns, carried out four months apart. The reason for this I_c reduction is currently under investigation. The next steps include the assembly of the full magnet, testing in LN₂ at PSI, followed by tests at 4.5 K at CERN, scheduled for this summer.



⁹D. Sotnikov, D. Araujo, B. Auchmann, M. Duda, C. Lindner, and A. Stampfli, "Application of HTS Straight Soldered Stack Cable in Subscale Magnet Geometry," *IEEE Transactions on Applied Superconductivity*, pp. 1–5, 2026, doi: [10.1109/TASC.2026.3656860](https://doi.org/10.1109/TASC.2026.3656860).

RS2 (MagDev3)



Following the CHART/PSI roadmap toward insulated REBCO-based high-field magnets, and after the completion of the four coils for the first REBCO Subscale magnet (RS1), we aim to design a subscale demonstrator for a double-aperture high-field magnet, featuring alignment between the wide face of the cable and the magnetic field. The objective of this development is to enable high engineering-current-density insulated REBCO cables by optimizing both the cable design and its position with respect to the field orientation to minimize the tape's current degradation by angular dependence. This coil configuration would also be compatible with Roebel REBCO cables. The presentation of the concept was presented in the CHATS-AS workshop: <https://indico.cern.ch/event/1592716/>.

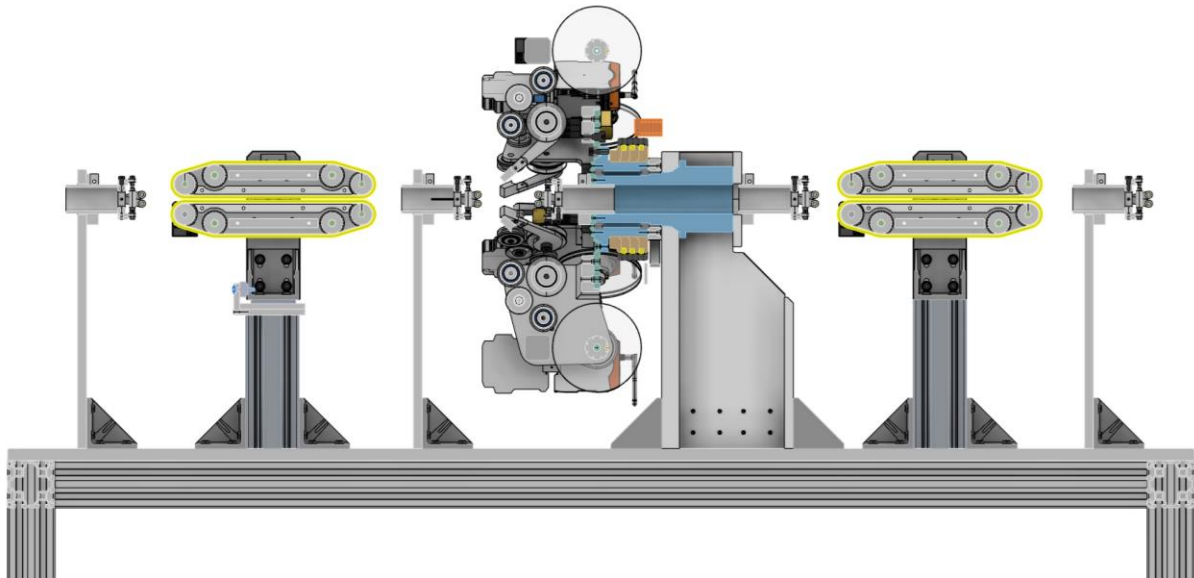
The next steps will include winding trials and the completion of the conceptual design of this magnet, REBCO Subscale magnet 2 (RS2) before moving to the engineering phase of the subscale magnet and starting coil manufacturing.

Short unit REBCO cable (MagDev3)



The field alignment of the RS2 magnet is expected to provide important insights for the HTS roadmap, particularly regarding improvements in AC losses, drift of the main field and multipoles, as well as the enhancement of the magnetic field resulting from the high I_c of REBCO when the field is aligned with the conductor. If these features are not sufficient to meet the FCC-hh HTS dipole targets, a different cable concept will be required.

In that case, we plan to adapt some existing concepts, such as spiral copper-plated striated coated-conductor (SCSC) cables, to make them compatible with the stress-managed asymmetric common-coil concept. This would require modifying the cable core to have an oblong cross-section rather than a circular one. To produce a short-unit cable prototype, we are developing a compact cabling machine. The next steps include completing the procurement of parts, commissioning the machine, and developing the cabling process.



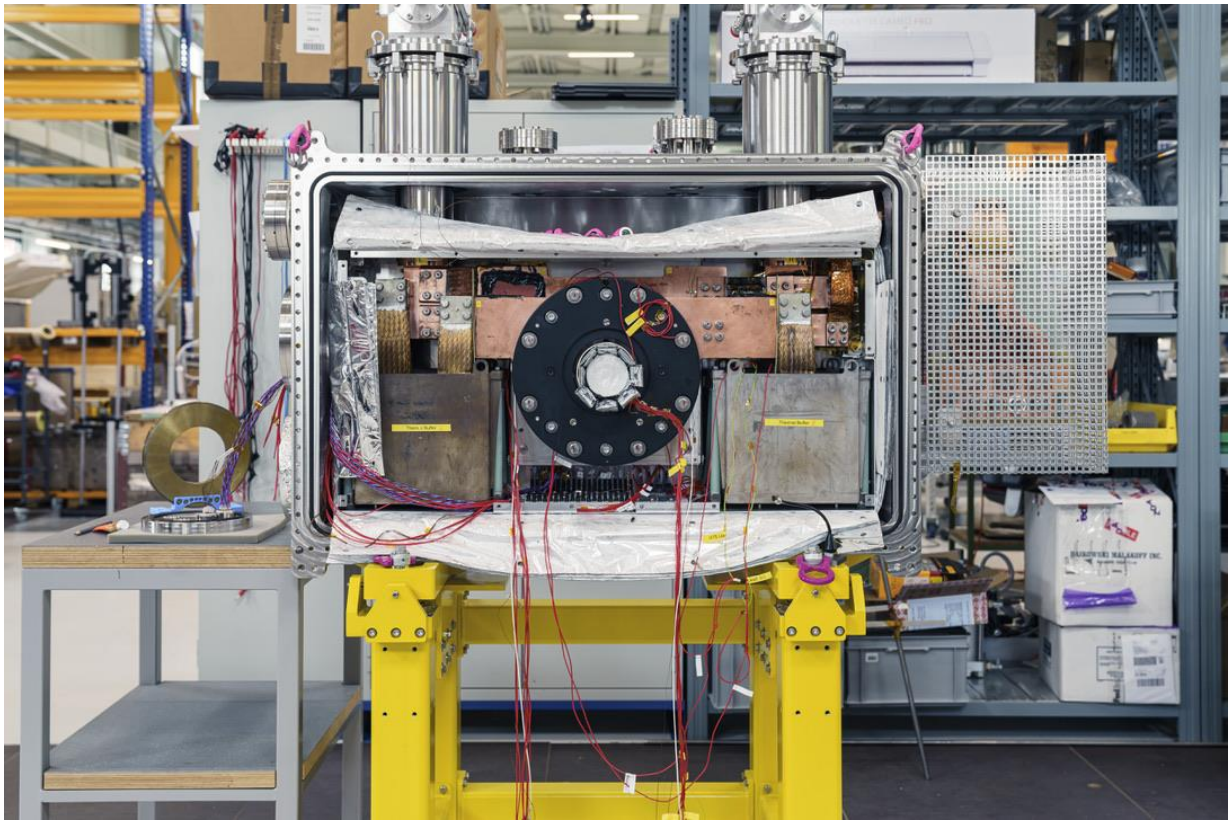
2.3 High-Field Non-Insulated Solenoids

Non-insulated, solder-impregnated coil technology was developed in the MagDev1 project 2020-2024. While the technology was not pursued for high-field accelerator dipoles, it was well adapted for the specifications of a positron-capture solenoid in the FCC-ee injector. Moreover, from the coils built in MagDev1, we have assembled a split-coil magnet for the Swiss Spallation Source (SINQ).

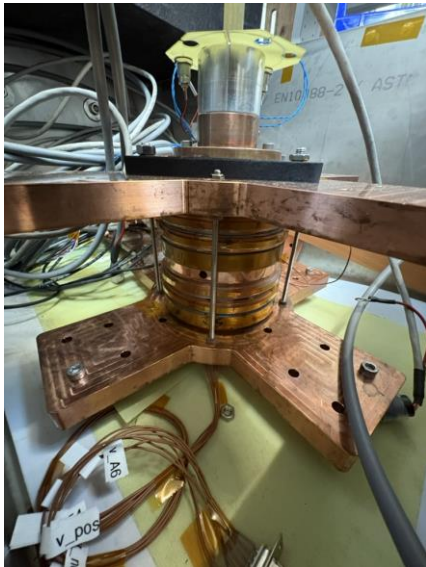
PSI's Positron Production (P³)

The capture solenoid was delivered in 2025 and installed in SwissFEL as part of the P³ (PSI Positron Production) experiment, which is part of the FCC-ee Injector project in CHART. The magnet, which features 110 mm cold bore diameter and 70 mm warm bore diameter, was commissioned up to 10 T central field, significantly short of the 15 T ultimate field that it is designed to deliver. The shortfall is due to several well-understood reasons: a low-grade coil that needs replacement, electrical intra-coil resistances that require an alternative assembly procedure, several electro-thermal contacts in the powering and cooling path that underperform, and possibly a stronger than anticipated shielding effect in the REBCO pancake coils.

The magnet will provide adequate field for the first run of the P3 experiment. It is then foreseen to return to the MagDev laboratory for refurbishment of the above issues, and to return to SwissFEL for a second run with ultimate or near-ultimate field.



Swiss Spallation Neutron Source (SINQ)



Four pancake coils with 5 cm inner diameter were assembled in MagDev1 and tested in the cryogen-free test station, reaching a maximum central field of 18 T. The effort was based on a cooperation and licensing agreement with Tokamak Fusion Ltd. Two additional coils were then produced as part of the process development for the P³ coil above. Following discussions with colleagues at SINQ, we found ways of low-contact-resistance copper coating of a neutron-transparent aluminum ring. The six coils were assembled around the aluminum ring in a split-solenoid configuration, which was tested successfully in liquid nitrogen. The magnet will be assembled in a SINQ cryostat later in 2026.