Report of 2022 Activities in MagDev1 and FCCee HTS4

Douglas Martins ARAUJO, Bernhard AUCHMANN, André BREM, Michael DALY, Michal DUDA, Oliver KIRBY, Jaap KOSSE, Thomas MICHLMAYR, Henrique Garcia RODRIGUES, Paul Scherrer Institut, Villigen, Switzerland

1. LTS Program

1.1 Canted-Dipole 1 (CD1) Test and Take-Aways

The CD1 magnet, produced at PSI in 2017-2019, was fully tested at CERN in November 2022 and January 2023 after a 3-year delay, caused by COVID and other adverse circumstances. The magnet exhibited extensive training at 4.5 K, illustrated by the training plot in Fig. 1. This behavior was expected, not least since the test of LBNL's CCT 5 magnet, which used similar technology, performed analogously. The training slope accelerated at 1.9 K. At this temperature, the magnet produced 10.1 T in the aperture, a record for a CCT magnet, reaching 94% of the estimated maximum performance (the so-called short-sample limit). Returning to 4.5 K, the magnet retained memory and performed at an exceptional 100% of the short-sample limit; see Fig. 2.

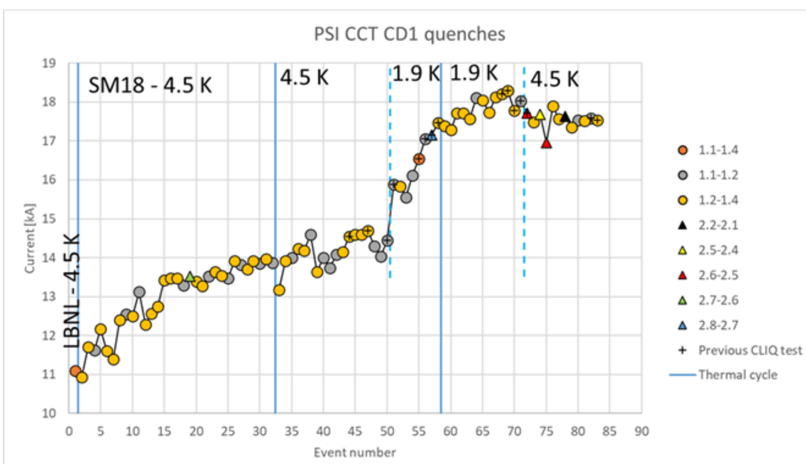


Figure 1 CD1 training plot, provided by Franco Mangiarotti (CERN). The markers indicate different sections of the coils, with 1.x being in the inner high-field layer, and 2.y in the outer low-field layer.

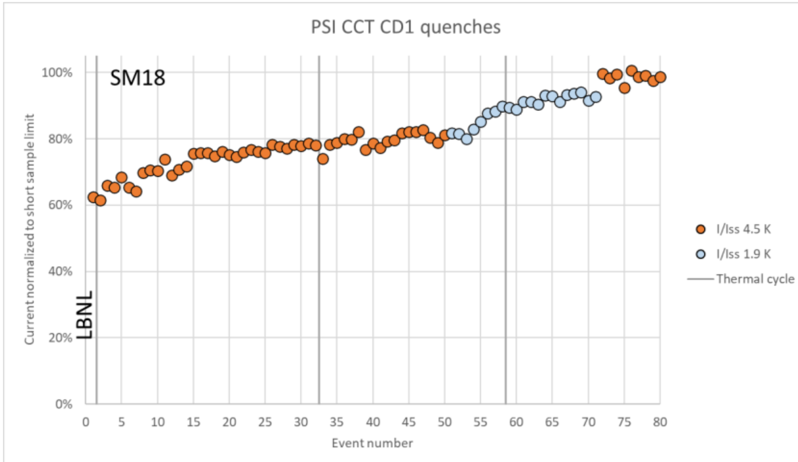


Figure 2 CD1 normalized training plot, Franco Mangiarotti (CERN), showing performance relative to the estimated maximum performance or short-sample limit.

The test confirms the strategy of the MagDev1 project at PSI, which aims to solve the issues of stress-managed magnets by tackling de-bonding and cracking that are thought to cause the excessive training. It also shows that stress-management upholds its promise of robustness, adequately protecting the fragile Nb3Sn conductor from degradation due to mishandling or extreme Lorentz forces. These insights are fully reflected in the ongoing MagDev1 LTS program.

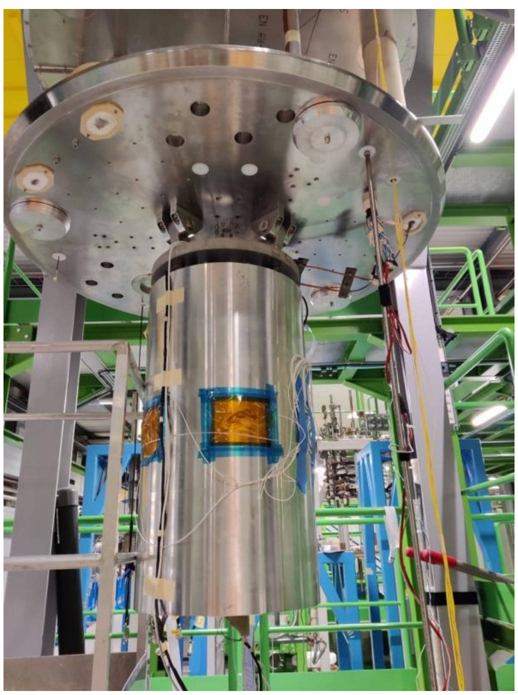


Figure 3 Left: CD1 magnet on the header of the test station at CERN. Right: Testing team in the control room of SM18 at CERN: Michael Daly (PSI), Daniel Molnar, Jean-Luc Guyon, and Franco Mangiarotti (CERN).

1.2 The BOX Program

Motivated by the test of CCT5, and confirmed by the CD1 result, the BOX program (Bonding eXperiment) continued at a high pace throughout 2022 to study solutions to de-bonding and racking. Particular points of interest were the excellent performane of filled epoxies, in particular the Stycast 2850 FT sample which achieved short-sample performance with only two quenches. While Stycast cannot be used for impregnating a full-scale magnet due to its high viscosity, additional research was started at the level of material samples (see below) in order to find particle sizes and process that will allow for the introduction of fillers in a resin-impregnated system. Two samples have demonstrated that the singular focus on the K1c property of resins, i.e., the propensity for crack propagation, is an insufficient criterion for improved performance. The research of the MagRes project at ETHZ has therefore been steered towards a combination of high K1c with low curing temperature.

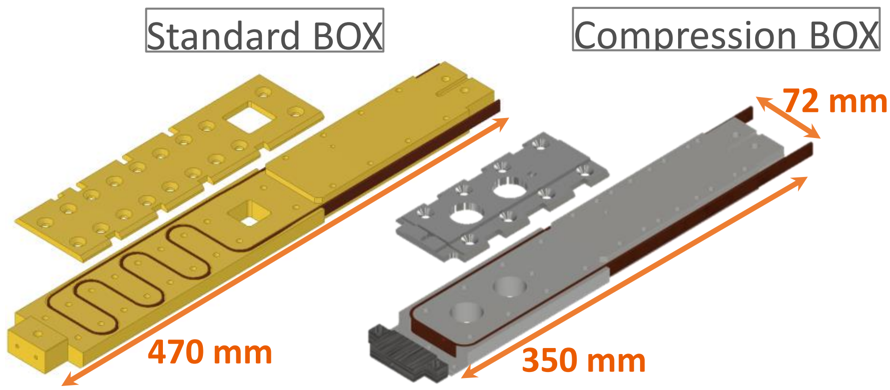


Figure 4 Lleft: standard BOX sample; right: compression BOX sample (courtesy M. Daly)

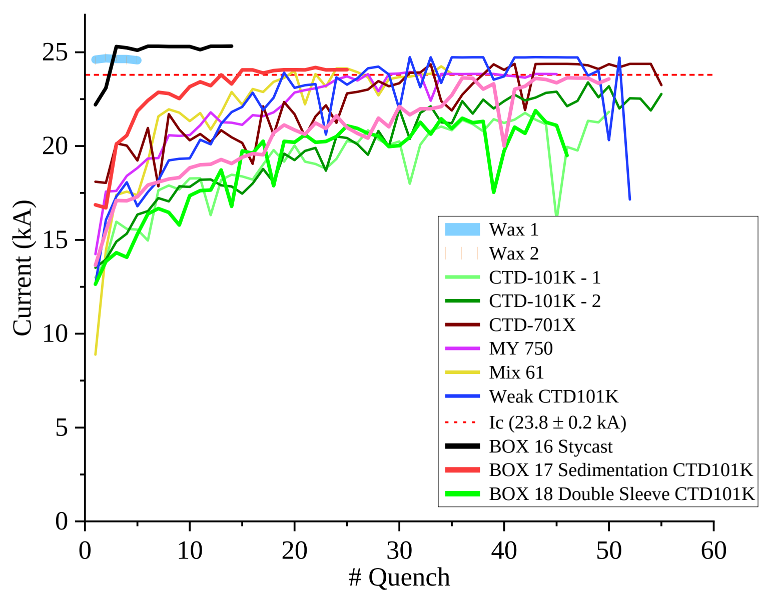


Figure 5 Comparative plot of training performance in different BOX samples. BOX 17 (red) constitutes a strong improvement over the curves called CTD-101K-1 and -2; the difference being additional filling of open spaces with Al2O3. The black BOX16 with Stycast 2850 FT joins wax as a potential solution to training. Data provided by Simon Otten, University of Twente.

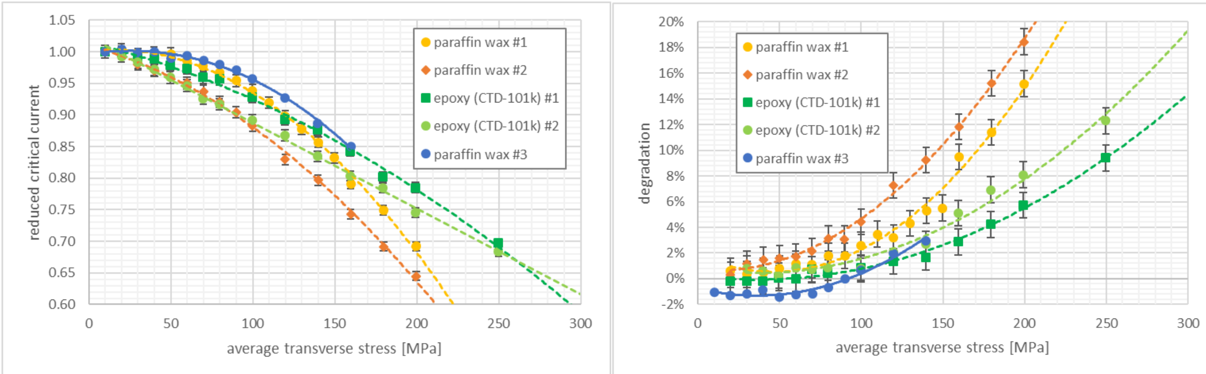


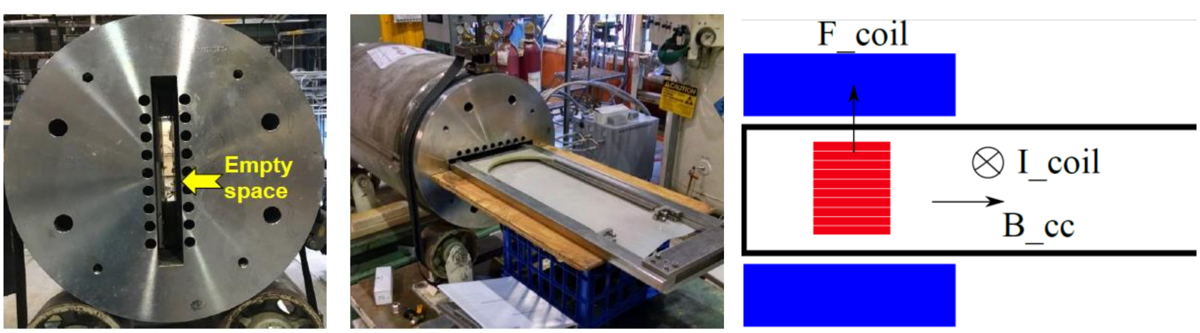
Figure 6 Left: Reduction in Ic under transverse load of two epoxy impregnated samples and three wax-impregnated samples. Right: Permanent degradation after unloading in the same samples. Data provided by Simon Otten, University of Twente.

In addition to standard BOX samples, the compression BOX has been exploited in 2022, with two epoxy-impregnated samples beeing tested under transverse load for reference (confirming previously published results in a new setup), and directly comparing three wax-impregnated samples. While wax is consistently weaker than epoxy under transverse stresses exceeding 120-150 MPa, for a working point below this range, wax-impregnated samples performed better than epoxy-impregnated ones. As a consequence, wax remains, for the time being, the baseline impregnation material for the MagDev research on stress-managed magnets.

1.3 The BigBOX

With wax-impregnation appearing as a viable candidate for stress-managed magnets with single winding turns enclosed in a metal winding former, the question remained whether wax would perform equally well in a block of multiple winding turns enclosed in a stress-management structure. Short of building a magnet, we devised a new sample type, the BigBOX, which is a racetrack shaped sample, wound into a ceramically coated stainless steel winding former. The sample is to be inserted into one of the two high-field apertures of the DCC17 10-T common coil magnet at Brookhaven National Laboratory (BNL), in collaboration with the US Magnet Development Program (US-MDP). The conductor size and number of turns in the racetrack are optimized to maximize the transverse pressure produced by Lorentz forces acting on the leg of the racetrack that is exposed to the 10 T background field.

Figure 7 Left: Superconducting common coils magnet DCC017 view from the end plate. Center: Structure for assembling samples



into DCC017. Right: Coil electric current I_coil, Background field B_cc and coil magnetic force F_coil direction. Photos courtesy of Ramesh Gupta, BNL.

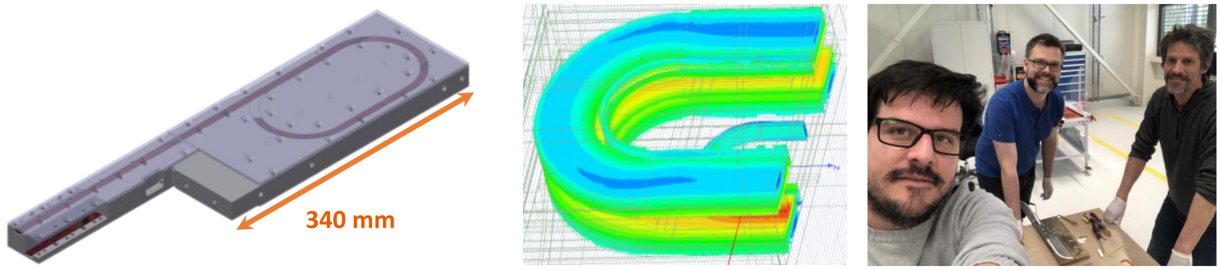


Figure 8 Left: BigBOX CAD design (T. Michlmayr). Centre magnetic field distribution in BigBOX sample and DCC17 coils (D. M. Araujo), and actual BigBOX sample, about to be closed, with (left to right) Douglas M. Araujo, Michael Daly, Thomas Michlmayr.

The sample was designed and built over four months in the first half of 2022. Unfortunately, access to the DCC17 magnet was since elusive, and the test is currently scheduled to occur in February of 2023. It will confirm or disprove the design space that was concluded from BOX and transverse-pressure BOX experiments and provide the basis for the magnet-development roadmap that is foreseen for MagDev2.

1.4 LTS HFM R&D Roadmap

LTS R&D in MagDev is following the multi-scale innovation funnel methodology depicted in Figure 9. The third stage "sub-scale magnet" is currently being prepared, with conceptual design under way for the consecutive iterations to make the sub-scale magnet representative in terms of manufacturing methodology and main mechanical concepts.

As for the type of magnet, MagDev is converging on a stress-managed common coil design. This design relies only on flat racetrack coils, wound into slots in a flat plate. The concept is chosen, among other reasons, for its compatibility with R&D on HTS high-field magnet technology. The common coil allows for a straight-forward integration of HTS coils in the high-field region to boost fields, and for a future re-calibration of the program as HTS technology matures and becomes more competitive in terms of cost and performance.

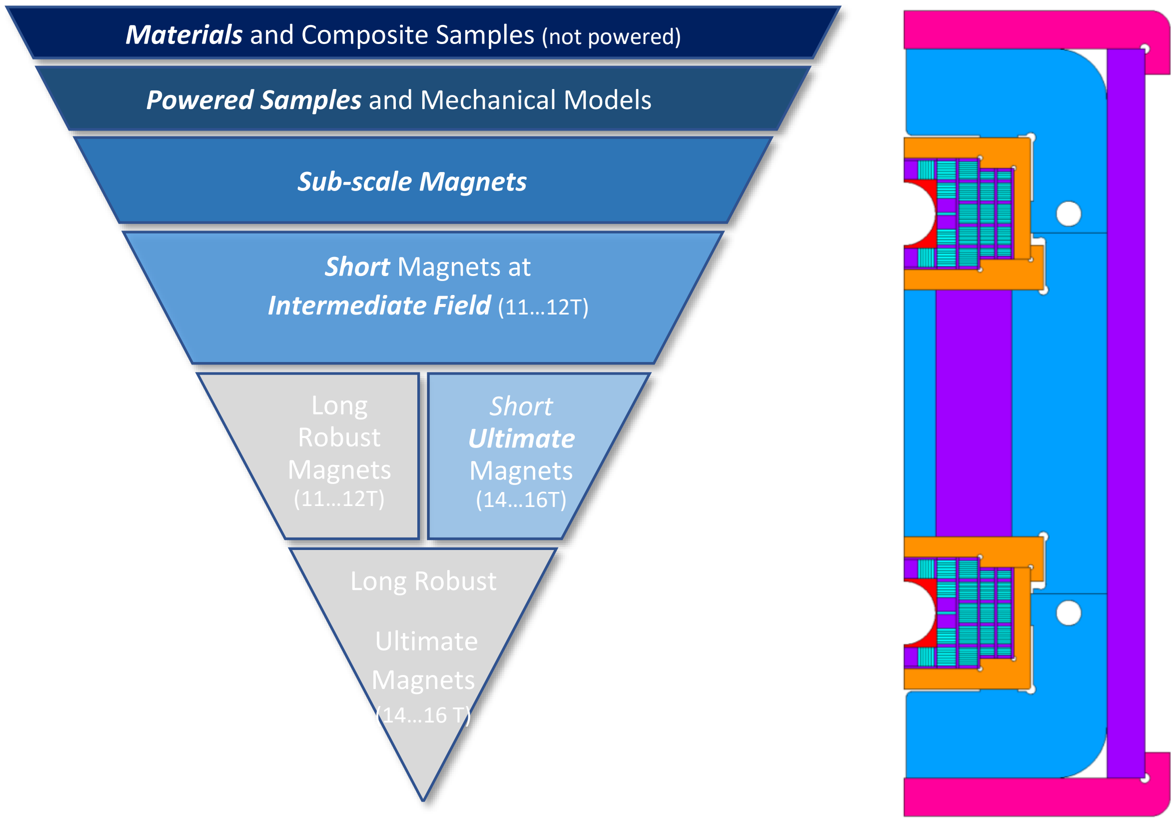


Figure 9 Left: Innovation funnel methodology with multi-scale minimal viable products for fast-turnaround R&D towards ultimate-field LTS magnets. Adapted from LDG Roadmap for High-Field Magnets. Right: ½ of a common-coil cross-section; snapshot of the conceptual design effort by Douglas M. Araujo.

2. HTS Program

2.1 HTS Technology Solenoid R&D

The R&D on non-insulation solenoids, in collaboration with Tokamak Energy Ltd, reached a milestone in 2022 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. 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.

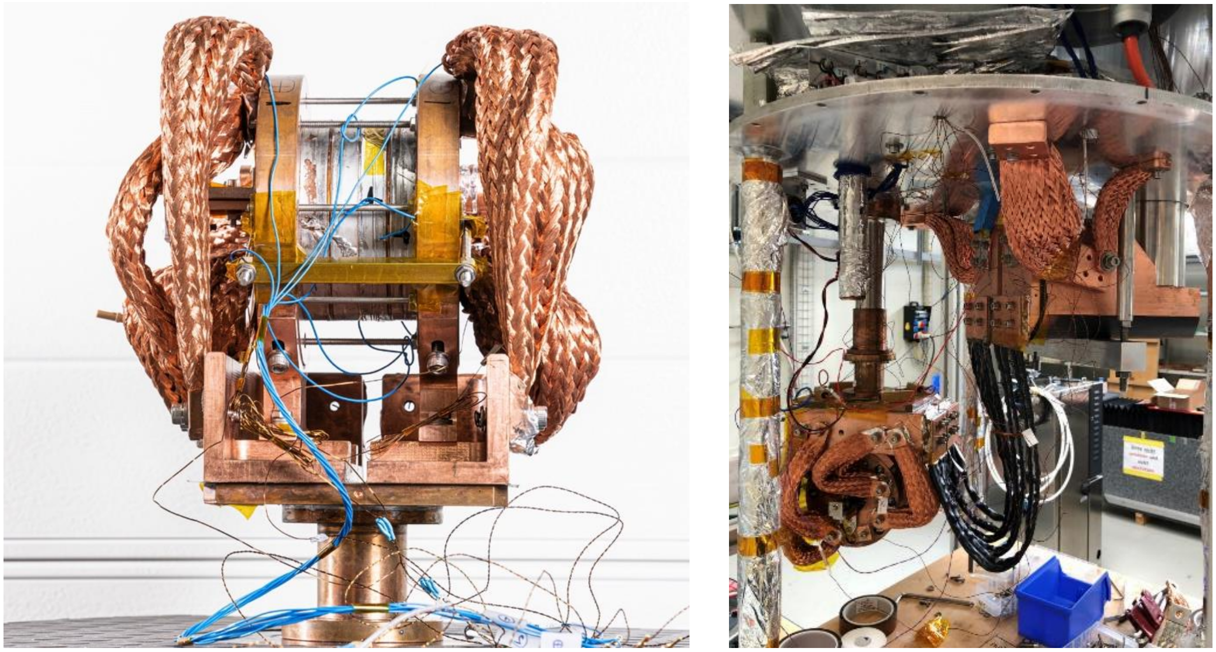


Figure 10 Left: 4-stack of round pancakes of NI coils. Right: 4-stack mounted on the header of the cryogen-free test station.

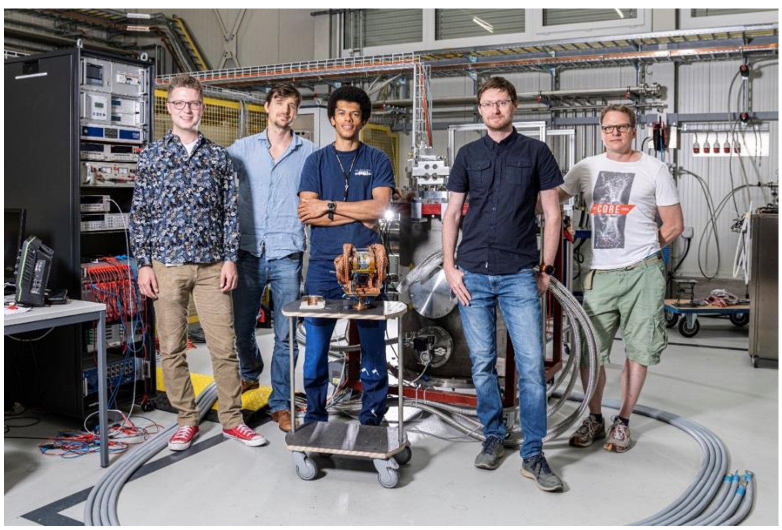


Figure 11 HTS Technology Solenoid project team, from left to right: Jaap Kosse, Bernhard Auchmann, Henrique G. Rodrigues, Michał Duda, Sebastian Hellmann.

Extensive development has also been invested in the optimization of the solder-impregnation process. The technology will next be implemented in the positron-target solenoid at SwissFEL and a racetrack-shaped demonstrator for future SuperBend magnets in light sources.

2.2 HTS Solenoid for FCCee Injector Studies – P^3 Project

The FCCee injector test stand at SwissFEL will use a capture solenoid around the positron production target that is provided in collaboration with MagDev. The magnet coil is a scaled-up version of the 4-stack coil above, with a fifth pancake added and the free-bore diameter increasing from 48 mm to 110 mm. The peak field on the conductor is comparable to the 4-stack technology solenoid, and the field on the target reaches 14.6 T. With the increase in stored magnetic energy, the protection of the coil from thermos-mechanical shocks during a quench becomes a priority. The concept of a thermal buffer was adopted, whereby a volume of lead is cooled to operating temperature and adds heat capacity to the coil to increase margins and avoid fast transient thermal events.

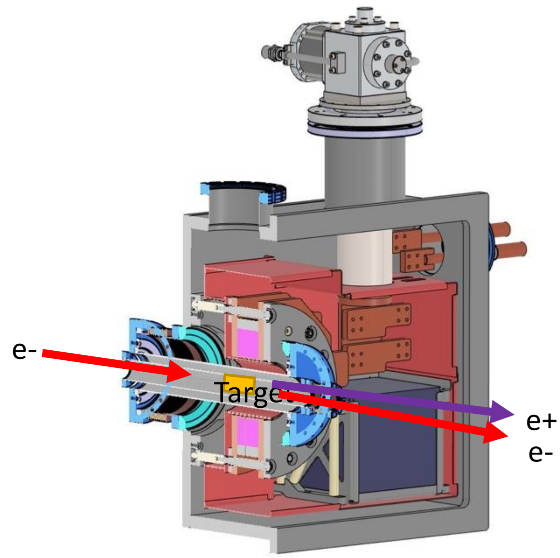


Figure 12 CAD visualization of the target solenoid in its cryostat. A cryo-cooler is shown on top, electrical connections to the side, a heat shield in red and the thermal lead battery in dark blue. The solenoid coil is depicted in pink. A visualization of the incoming and outcoming particles and the target is added.

The conductor for the coils has been ordered after a tendering process and the technical design is under way. It is foreseen to begin the actual construction in Q3/Q4 2023.

2.3 Towards HTS HFM Magnets

It is well-known that accelerator magnets lag solenoids in peak field. HTS magnet development is no exception. To build HTS HFM accelerator magnets, numerous technological challenges need to be mastered: a prospective cable needs to provide high current-carrying ability, accurate current tracking with the power supply, and screening-current induced losses that are compatible with the cryogenic-system specifications. The topic of field quality in the presence of sizeable screening currents is to be studied, and the magnet must be protectable from sudden quenches, e.g., induced by beam losses. Finally, the mechanical concept must provide adequate support to the coils under the extreme Lorentz forces of high-field magnets.

MagDev is setting up a Stage-Gate process, whereby material samples are being evaluated for their usefulness in HFM cables, a numerical model is set up to predict cable performance in long HFM magnets, short unit lengths of cables are being produced and tested in technology solenoids for model validation, and technology racetracks implement the cables and prepare the ground for their integration in a common-coil hybrid magnet. As of today, Stage 1 and Stage 2 have just begun. The Technology Racetrack platform shall be set up by the end of 2024, likely with an NI racetrack as the first test object, suited for a demonstration of NI HTS technology for SuperBend magnets in light sources. The individual stages will be used as an innovation funnel in the future.

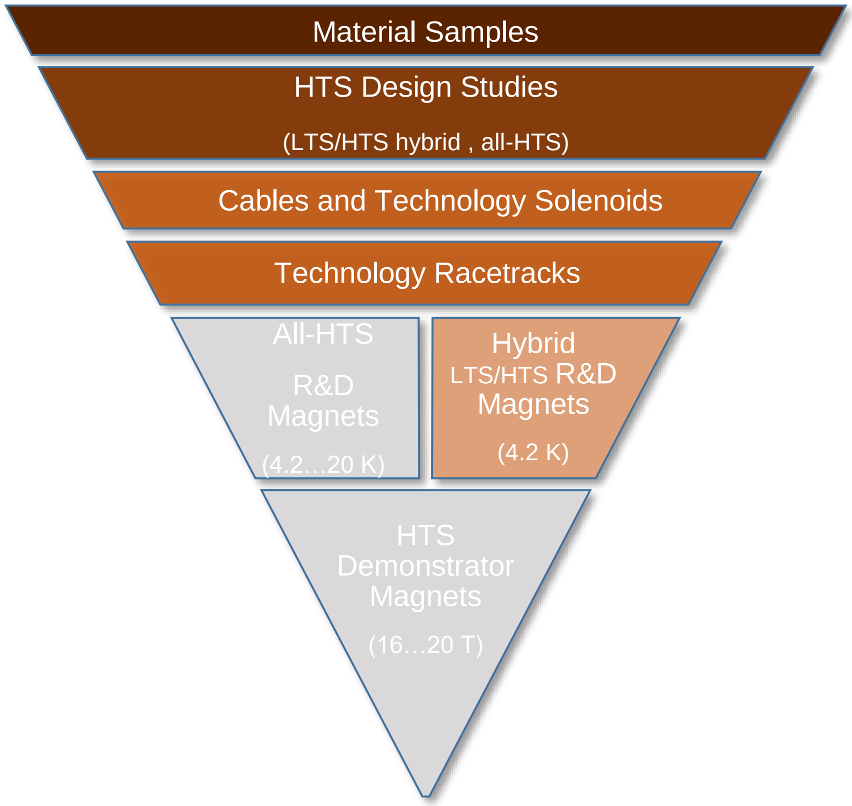


Figure 13 HTS HFM R&D innovation funnel for an initial Stage-Gate process.

2.4 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, operating at 40-50 K, with nested superconducting quadrupole and sextupole magnets. The project is in its initial canvassing phase for the most appropriate technologies in terms of coil shapes, cryo-cooler systems, powering concepts, insulation systems, etc. The impact of screening currents in the HTS tape conductor will be studied numerically and experimentally and provide valuable information to the wider community for the applicability of HTS tape in particle accelerators. To reduce plug power, the project collaborates with ETHZ's FCCee CPES project, which designs and builds a cryogenic power supply, thereby replacing high-current low-voltage leads that must enter the cryostat from a room-temperature environment with low-current high-voltage leads that produce considerably less Joule heating and thermal-conduction heat loads on the cold side.

3. Enabling Technology R&D

3.1 Burn-off of organic residues

Triggered by the manufacturing experience of the CD1 magnet, our R&D tackled the problem of residues from organic substances (e.g., sizing in glass braids, binder in mica sheets) that undergo pyrolysis during a heat treatment in inert atmosphere. These residues are conductive and render a reliable control of electrical integrity at room temperature near impossible. (Note that the carbon black particles become insulating below 20 K.) Moreover, the residues are deposited on all surfaces and result in very unreliable bonds between metal structures (endspacers, wedges, mandrels) and impregnated cables. It is, therefore, desirable to eliminate the reaction residues prior to impregnation.

Figure 14 From left – (2): Glass-fiber braid before and (2) after reaction cycle, the pyrolysis of the glass-fiber sizing leads to conductive residues on the braid and contaminates nearby surfaces (3 and 4).

After a screening phase, we selected as the most promising method the burning of residues with oxygen above 580ºC in vacuum. A long-standing open question in the community has been how the strand RRR is affected by the presence of oxygen at high temperatures. Initial measurements show an acceptable reduction. Additional RRR tests and a demonstration in a BOX sample shall follow.

3.2 Fillers

To increase mechanical stiffness and adjust the thermal contraction of epoxy towards values comparable with metal, filler particles are mixed into the epoxy. Since Nb3Sn cables are insulated by a glass braid, the braid must not act as a filter. Parametric experimental studies have pointed to a filler size around 1 µm with Al2O3 particles (30% vol%) allows for the penetration of the braid with fillers. The process will be further developed towards a full applicability for Nb3Sn coils in vacuum bags. For larger volumes (e.g., gaps resulting after winding and/or heat treatment) the sedimentation filling method has proven successful in achieving very high filler content (towards 70 vol%).

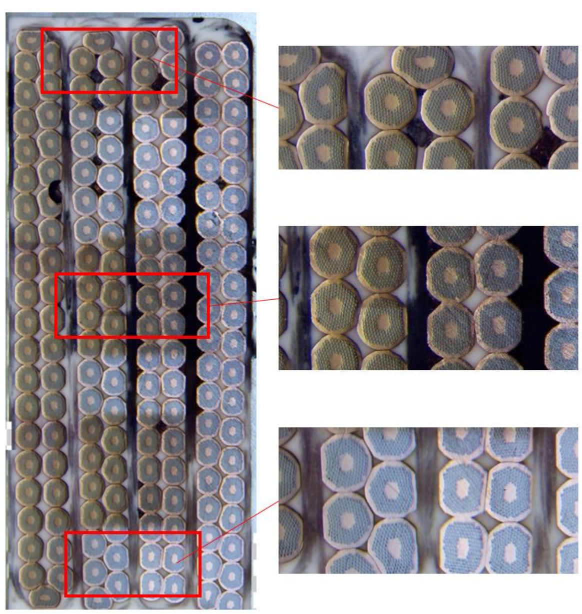


Figure 15 Post-processed plane showing (white) filler present in almost all cable interstices and in most of the glass braid.

3.3 Cryogenic sliding planes

A cryogenic characterization of sliding planes was carried out, with the goal of reducing stick-slip motion on interfaces that could cause magnet training. Wax was used as it was highly successful in BOX samples (see above), and the absence of stick-slip could explain in part the nature of this result.

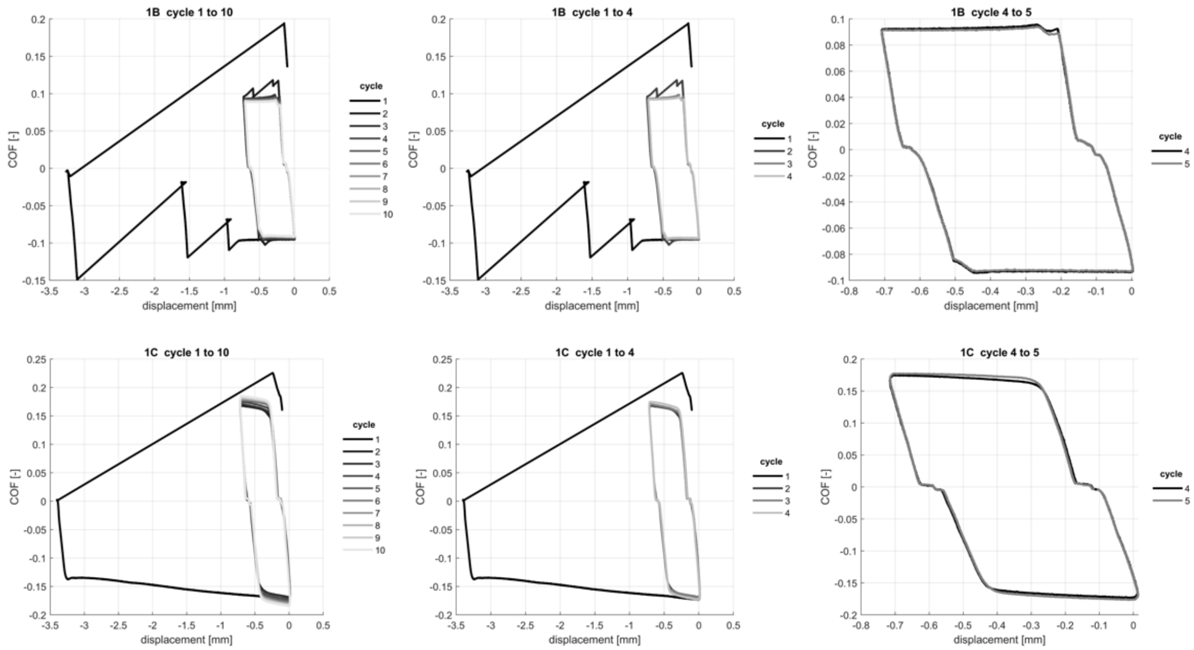


Figure 16 Tribological testing of steel/steel contact with (top) commonly used MoS2 spray-coating and (bottom) paraffin wax lubricant. None of the cycles following the initial displacement shows stick-slip motion in case of wax. Plots are courtesy of Tomas Gradt, BAM, Berlin.

4. MagDev Laboratory

4.1 Winder and Autoclave

The equipment of the MagDev laboratory continued throughout 2022. Important additions include a semi-automatic winding machine for up to 2-m-long magnets. An order for an autoclave was placed with delivery being delayed due to supply-line issues. For post-mortem analysis, the lab was equipped with a wire saw, polishing plate, and an optical microscope which are in daily use and provide valuable insights for quality control and defect analysis.

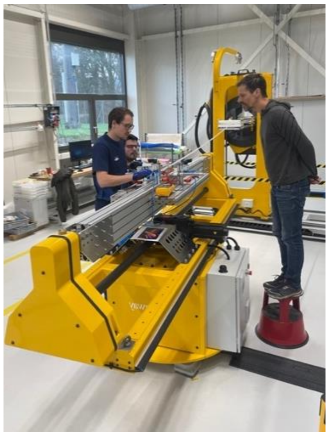


Figure 17 Semi-automatic winding machine with six degrees of freedom (5 movement + tension) and pneumatic clamping fixtures.

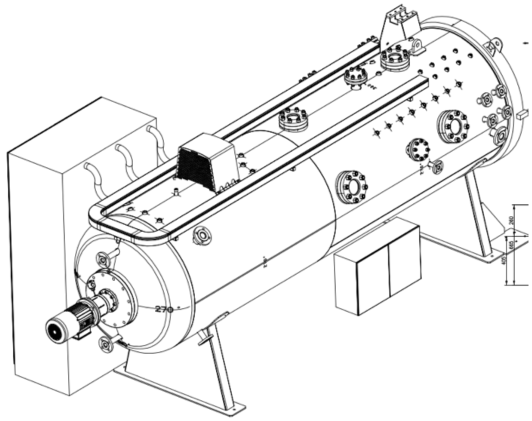


Figure 18 Drawing of the 10 bar, 250ºC autoclave for vacuum-pressure impregnation of up to 2-m-long accelerator magnets.

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.

Several collaborative efforts with **UniGE WireChar** are under discussion. A characterization of hall probes, carried out at UniGE at variable temperatures and fields up to 19 T was used in obtaining the 18.2 T HTS coil result.

Publications

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