Report of Activities at CHART2/MagDev1

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Introduction

Over the reporting period, the build-up of the MagDev project team has been completed, with the last member arriving in Januyary of 2022. Over the year, critical and significant progress has been achieved in all key areas, to be: technology R&D for stress-managed Nb_3Sn magnets, Materials R&D, R&D on HTS non-insulated coil and their applications, and design studies for the FCC-hh main dipole.

BOX Program (M. Daly)

The Bonding eXperiment (BOX) samples (shown in Figure 1) were introduced and commissioned last year. The goal of the program was to study critical failure mechanisms (cracking, debonding, sliding) present in Nb_3Sn Canted Cosine Theta (CCT) magnets, to come to a final appreciation of the suitability of CCT technology for an FCC-hh main dipole magnet. At the same time, the failure mechanisms under study are present also in other magnet types, leading to long magnet training, limited performance, and degradation over time (cyclic fatigue).

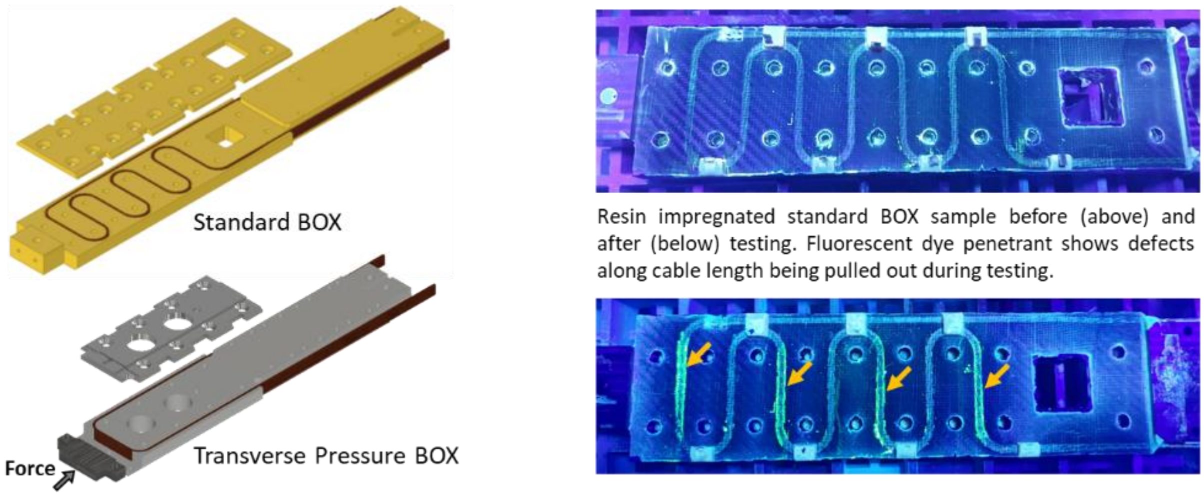

Figure 1 Left Top: 3D representation of standard BOX sample and, left bottom: transverse pressure BOX sample. Right: Example of non-destructive analysis of a resin (CTD-101K) impregnated sample using a fluorescent dye penetrant.

This calendar year brought the full exploitation of the new sample type, proving convincingly that BOX is a fast-turnaround and relatively low-cost R&D vehicle for technology development under approximately operational conditions. Over the past year, 12 samples (10 standard/shear samples and 2 transverse compression samples) have been produced at PSI and 11 samples were tested at 4.2 K within high magnetic fields (7.5 - 11 T) and high currents (14-25 kA) at the University of Twente in Netherlands. The samples used existing magnet fabrication technologies and materials such as vacuum impregnation and various resins (CTD-101K, CTD-701X, Mix 61, MY750 and Paraffin Wax). The aim of this phase of testing was to screen existing technologies, establish a baseline for comparing samples, ensure reproducibility and assess BOX samples' performance in realistic operating conditions. Furthermore, improvements in the fabrication processes of samples were trialled resulting in samples with better performance.

The most striking results of this stage of the program was the great performance of paraffin wax impregnated samples. The two wax samples did not train (see Figure 2), reached a higher current than the estimated critical current, exhibited excellent memory when warmed up and cooled down again and performed very well through extended cycling (up to 200 cycles). For the standard BOX sample configuration, the wax samples outperformed all resin impregnated samples by a large margin. The resin samples suffered from typical extensive training and in some cases were limited in maximum current, all of which are effects observed in actual magnets. More complex transverse pressure tests on wax samples i.e. where compression is applied unto the samples in-situ and in a background field, showed good results albeit with some noticeable permanent degradation beyond 80-100 MPa. These encouraging wax results have formed the baseline for the design of PSI's stress managed cosine theta (SM-CT) magnet (see below) and initial BOX sample results have already been published in SuST [1] and presented at the MT27 conference [2] with further publications planned in 2022 [3].

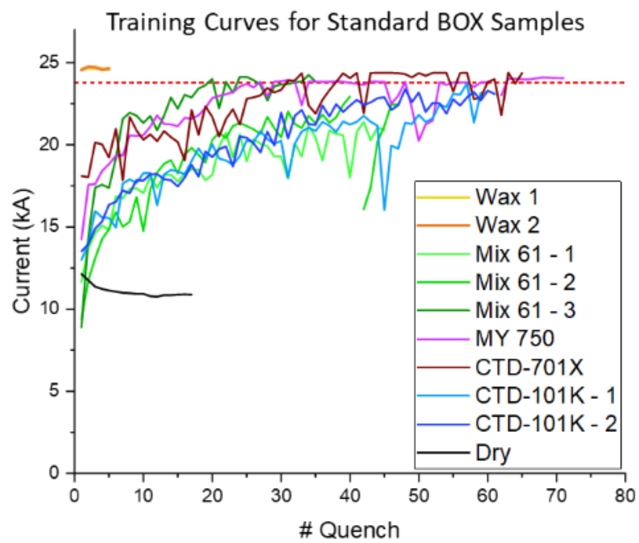

Figure 2 Plot of training curves for resin impregnated samples, wax impregnated samples and a sample with no impregnation. Note how wax-impregnated samples (yellow and orange, top left) did not exhibit any training, while all resin impregnated samples exhibited substantial training, akin to that observed in accelerator magnets.

The next stage of the BOX program aims to improve sample processing such as efficiently cleaning away fibreglass sizing to improve sample cleanliness and to further improve performance. More innovative fabrication techniques will also be trialled such as ceramic coatings to improve dielectric properties. In addition, new wax compositions with improved mechanical performance will be tested and tailored resins will also be trialled that aim to reproduce certain properties of paraffin wax such as low fracture toughness and low friction sliding. Finally, the performance of wax under transverse pressure will be further validated by comparing with samples fabricated using more conventional resins.

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Progress in Materials R&D for Superconducting Magnets (A. Brem)

Materials R&D activities started at PSI at the beginning of 2021. Over the year, we performed literature research, commissioning of laboratory infrastructure, initial screening studies, as well as material development and characterization. We mainly focused on impregnation systems, insulating coatings and ways to achieve cleaner magnets after reaction.

Impregnation Systems

The paraffin wax used in the BOX program was characterized in terms of elastic modulus and fracture toughness at room temperature and 77 K. The wax has an extremely low fracture toughness of 0.18 $MPa \cdot m^{1/2}$ and a modulus of 4.2 GPa at 77 K. Further, the wax shows very poor bonding. An epoxy with very low fracture toughness was developed to mimic the behavior of wax. The system is based on CTD101K and has a fracture toughness of 0.25 $MPa \cdot m^{1/2}$ at 77 K; see Figure 5 (right). Filled systems, like Stycast 2850FT, were also investigated. In general, fillers cannot be used in combination with glass fiber insulation. The filler particles are filtered by the glass braid; compare Figure 5 (center top). Nano-fillers are also not an option, due to the strong increase in viscosity with volume fraction, high loadings, which are needed for CTE matching or a significant increase in modulus, are not possible; compare Figure 5 (center top). Nevertheless, the impregnation of a BOX sample with Stycast 2850FT was achieved by removing the glass fiber braid. In this case, the electrical insulation is provided by a ceramic coating (Aremco SGC4000-HT) on the channel walls.

Clean magnets

The high temperature and inert atmosphere during the reaction cycle of Nb3Sn conductor causes any organic substances to pyrolyze. The pyrolytic products contaminate surfaces and are partially conductive. The introduction of oxygen during the reaction cycle could solve this problem. A reaction furnace was equipped with an O_2 and CO_2 sensor at the exhaust to monitor the combustion of organic substances as well as the oxidation of copper. Initial experiments showed promising results if the right amount of oxygen was introduced; compare Figure 5 (left). Further evaluation of the process is in progress starting with RRR and contact resistance measurements of the Nb_3Sn strands' copper matrix in early 2022.

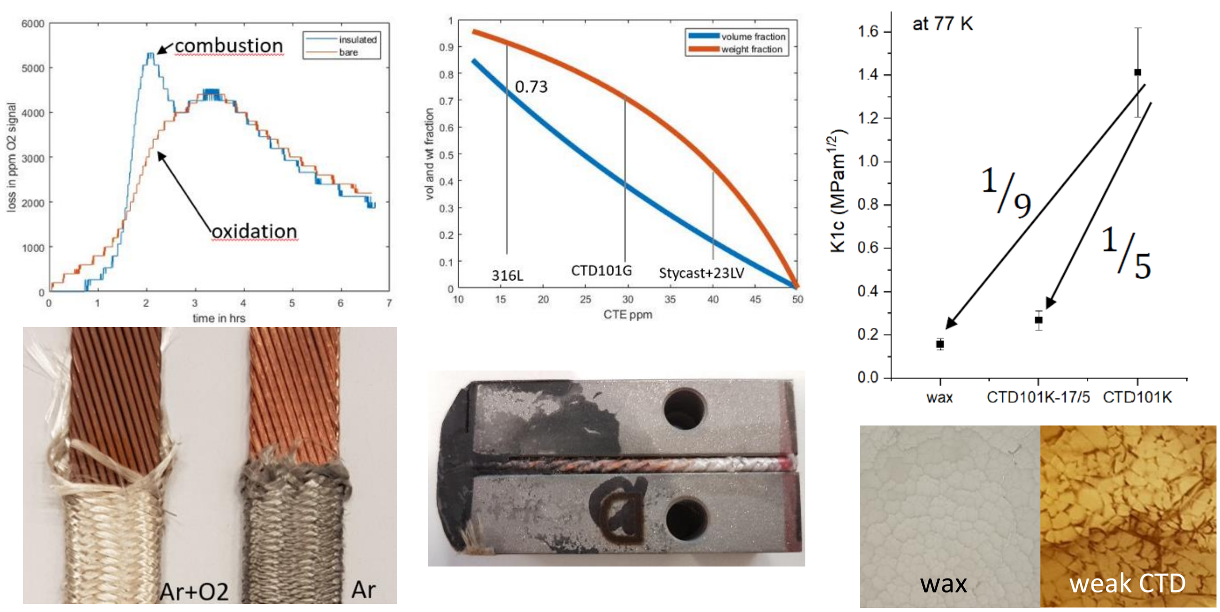

Figure 3 Left top: oxygen signal of the exhaust gas with and without combustable organic substances, clear distinction between oxygen consumed by oxidation vs. combustion. Left bottom: picture of the Rutherford cable after heat treatment with and without oxygen. Middle top: theoretical calculation of filler content needed to match the CTE of 316L stainless steel. Middle bottom: filtering effect of the glass fiber braid when filled systems are used. Right top: fracture toughness of CTD101K, weak CTD and wax in comparison. Right bottom: fracture pattern after thermal shock in LN_2 of wax and weak CTD.

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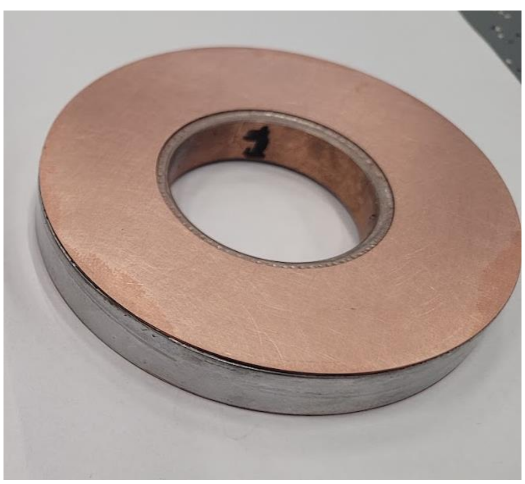
R&D on HTS Non-Insulated Coils and their Applications (J. Kosse)

Non-insulated (NI), solder impregnated HTS coil technology advancement at PSI during 2021 can be divided in roughly three parts. The first part consists of development and commissioning of winding, soldering, and testing infrastructure. The second and third concern applications. These are an HTS capture solenoid for positron sources, to be installed at the FCC-ee injector test stand at SwissFEL, and a high-field Superbend demonstrator for the Swiss Light Source, respectively. A summary of the activities was presented in [1].

To quickly advance the capabilities to manufacture, test and model NI coils, technology transfer between Tokamak Energy Ltd (UK) and PSI commenced at the start of 2021 as part of a license agreement to make full use of the extensive knowledge gained by Tokamak Energy in the past years [2].

Winding facilities, developed in collaboration with CERN, as well as dedicated soldering equipment have been commissioned by starting a test coil program. The goal of the test coil program is to reach 14 T in the new PSI conduction-cooled 2 kA test station at 10-20 K. These test coils use Tokamak Energy's modular coil approach, in which coils can be axially stacked using their patented joint technology [3]. So far, a stack of two coils has been successfully tested in a liquid nitrogen bath, reaching 1.3 T. As the conduction-cooled set-up is ready to go, and everything is in place to produce more coils, higher field strengths are expected early in 2022, up to the mentioned 14 T using a 4-coil stack.



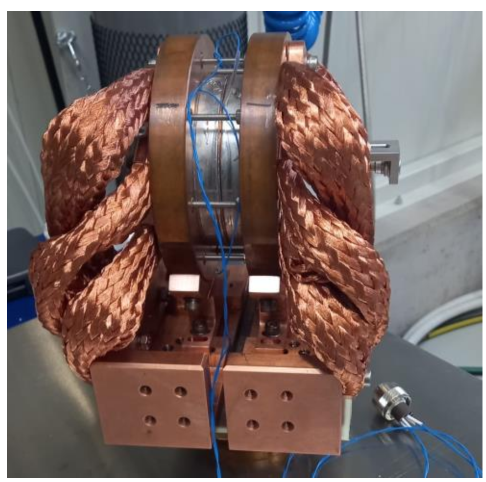


Figure 4 Left: soldered HTS coil with current lead plates attached. Right: Magnet consisting of two coils during mounting for testing in the conduction-cooled 2 kA set-up at 10-20 K.

To understand the behavior of NI coils, which can be very different from traditional insulated coils, a dedicated time-dependent coupled electromagnetic-thermal model has been developed. This model, which will be benchmarked against our test coil's experimental data, is also used in the design of a high-field NI HTS solenoid for use in a positron source. The role of the solenoid is to focus positrons created by impacting electrons at a tungsten-based target. State-of-the-art sources use pulsed normal-conducting magnets [4], limiting the beam repetition rate due to significant resistive heating, and operate using high voltages. As part of FCC-ee injector studies, high-field NI HTS solenoids are being considered as an upgrade to these pulsed magnets, providing higher yield and a continuous uptime.

As the environment around the target is hostile towards low-temperature magnets, mainly due toa large power deposition and the risk of radiation-induced electrical insulation damage, this application is ideally suited for NI HTS coils operating at moderate temperatures (~20 K). Work performed in 2021 indicates that NI HTS solenoids can greatly increase the yield compared to traditional pulsed magnets [5] and can handle the power deposition and radiation dose [6]. Due to these promising results, it is planned to install an NI HTS solenoid in SwissFEL as part of a proof-of-concept positron source experiment in 2024 [7].

As part of a future upgrade to SLS2.0, an HTS variant of a Superbend, whose role is to generate hard X-rays, is being investigated. Exploration of the parameter space of operating temperature and magnetic field started in collaboration with Little Beast Engineering. LBE's modeling capabilities are second-to-none in performing detailed time-dependent analysis of 3D NI magnets and can accurately predict quench behavior [8].

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Stress-managed cosine theta and LTS roadmap (D. Araujo)

Answering to the European Strategy for Particle Physics (ESPP) update [1], CHART pursues Nb_3Sn accelerator magnet R&D with the goal of demonstrating through innovation an improved robustness and performance. By 2025 we aim to manufacture a first demonstrator producing fields of the order of 10-12 T and by 2027 of the order of 14 T and above.

Robustness and performance are defined by short magnet training, the absence of degradation during powering, electro-mechanical cycling, and thermal cycling, and by a high production yield. The training curve is strongly linked to crack-induced energy release in the coil's composite matrix, as well as debonding between the impregnated coil and the surrounding components. Recent BOX experiments showed fast training curves, or even absence of training curve, in single turn wax impregnated Nb_3Sn Rutherford cable in stress-managed situation [2]. At the same time, we note that the use of wax during the impregnation process makes room-temperature preload on the coil impossible.

Stress-management, i.e., mechanical structures internal to the coil, are studied as a means of decreasing the mechanical stresses to which the coil is subjected. CCT technology is an example of stress-management, [3]; other stress-management concepts have been presented before [4][5]. As consequence of the points discussed above and in continuity with the CCT magnet assembled in 2019 [6], we propose a fully stress-managed cosine theta (SM-CT) magnet, wax impregnated (or similar material to be developed), without room-temperature pre-load. The SM-CT concepts promises to combine key advantages of CCT magnets (stress management) with those of conventional cosine theta (CT) magnets (easier assembly, coil-manufacturing, and winding), providing higher efficiency and lower cost than CCT. Recently, the introduction of two stress-managed outer layers as an update of the MDPCT1 dipole magnet have been proposed [6].

To validate step by step the key innovating points of the proposed magnet a roadmap with a panoply of different designs and devices is proposed:

BigBOX

The BigBOX insertion coil, Figure 5 (left top), is a racetrack to be tested under background field. This project is being developed in collaboration with the Brookhaven National Laboratory (BNL) and co-funded by the U.S. Magnet Development Program (MDP).

The goal is to test a multi-turn wax impregnated Nb_3Sn coil in a stress-managed situation, which would allow us to assess mechanical limitations, training as well as validating some of the key manufacturing processes.

The coil in box is to be tested inside the common coil dipole DCC17 at BNL under a maximum background field of 10 T allowing to have mechanical stress of the order of 120 MPa in the test coil, representative of critical coil stresses in the 4-layer magnet below.

5-T Subscale

The subscale magnet, Figure 5 (left bottom), would be the first stress-managed cosine theta magnet of the LTS roadmap. With its tiny cable of 1.1 x 4.0 mm, a short sample field of 5 T could be reached with 10 kA on the 11 turns per coil. The coils are small (0.5 m in length) and can be handled manually, allowing for a fast and cost-effective turnaround. The magnet was optimized to have good field quality and would allow CHART to develop and optimize SM-CT manufacturing processes and assess critical performance aspects of a wax impregnated and stress-managed magnets without pre-load. The design will feature innovative LTS-HTS joints in the high-field zone and can evolve towards a 2-layer magnet configuration.

14.5 T in 4-Layer Magnet and 10/12 T in 2-Layer Configuration

Finally, Figure 5 (center and right) show preliminary 4-layer and 2-layer SM-CT magnet designs. The magnets consist of the stress-managed coil layers, a stiff shell around the last layer, an iron yoke, and an aluminum shell. An alternative structure with welded shell is also being studied. The proposed mechanical structure could be re-used for both magnets: 14.5 T with four layers and up to 12 T with two layers. The magnet optimization was carried out such that the 4-layer magnet re-uses the 2-layer coils as inner layers.

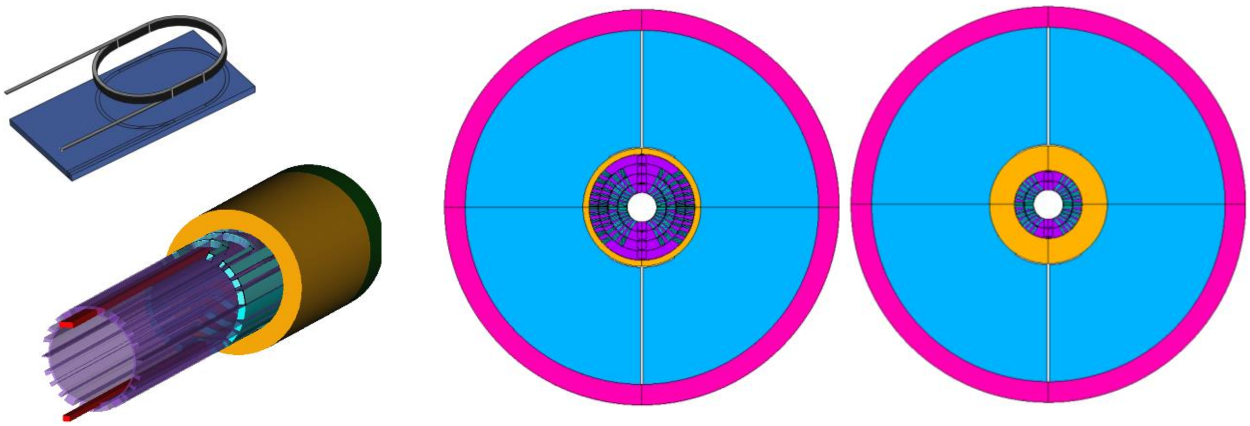

Figure 5 Left Top: BigBOX – a multi-turn stress-managed racetrack with Nb_3Sn Rutherford cable; Left Bottom: Subscale view – one-layered stress-managed cosine theta magnet without pre-load small Rutherford cable; Center: 4-layer magnet preliminary design: 14.5 T stress-managed cosine theta magnet structure with inner stiff shell, iron yoke and external Aluminum shell; Right: 2-layer magnet yielding up to 12 T.

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CCT and Low-Prestress Cosine Theta Variants

CCT Design Variant (B. Auchmann)

Despite the recent breakthrough performance of BOX samples with wax impregnation (see above) several fundamental obstacles remain for an application of CCT technology to the FCC-hh main dipole:

- No credible concept exists for the layer-in-layer assembly and alignment of 15-m-long coil layers with minimal assembly space.
- Windability, especially of the innermost layer, with big cables remains a major risk factor.
- Cable positioning radial and axial in CCT channels is poorly controlled.
- Former manufacturing remains costly and the assembly of long formers from segments has difficult-to-control alignment problems.

Nonetheless, we note and encourage continued interest in CCT in the areas of:

- Short (up to 2 m), no-heat-treatment accelerator magnets.
  - Nb-Ti magnets should be able to operate stably at much smaller margins than the HiLumi correctors (8-9 T target).
- Nb_3Sn background-field magnets.
  - Large bore, straight, limited in length, somewhat more flexible in field quality, reduced development time balances cost for reduced efficiency.
- Possibly curved magnets.

For all applications, we recommend wax or a similar material for impregnation. CCT magnet tests with paraffin wax are currently under preparation at LBNL in their Nb_3Sn subscale program, and at CERN for a curved Nb-Ti CCT magnet. We are actively engaged in technology transfer with these teams.

A continuation of the testing of the CHART1 CD1 magnet is due to start in March 2022 at CERN. The move of the magnet from LBNL (Berkeley, USA) to Geneva was made necessary due to a pile-up of delays linked to the COVID crisis and a long repair of the cryogenic system at LBNL.

The legacy and importance of our R&D on CCT and the BOX program is three-fold: a) it allows the FCC-hh magnet R&D to set aside one of the four design variants based on solid R&D experience; b) it provides critical technology for CCT magnets in different areas of application; and c) the BOX samples with wax filler have demonstrated that stress-management, i.e., the use of a coil-internal mechanical structure to avoid conductor degradation, can be highly successful. Our design study of the stress-managed cosine theta variant was based on and, in fact, triggered by this astonishing result and opens an innovative pathway towards robust performance of Nb_3Sn accelerator magnets. Without the CCT program and the ensuing BOX program, this promising development would not have been possible.

Low-Prestress Cosine Theta (G. Vallone)

Prior to the exciting BOX results with wax, a potentially interesting alternative design concept was considered to be the low-prestress cosine theta. As the reader may know, pre-stress is applied to the coils of accelerator magnets to avoid abrupt coil movement under Lorentz forces, and in order not to lose contact between the mechanical structure and the coil during the cool-down process of the magnet because of differential thermal contraction.

In the low-prestress concept, the mechanical structure uses new material combinations compensating for the differential thermal contraction of coils and structure. As for the avoidance of abrupt movement, the concept foresees newly engineered cryogenic sliding planes that would drastically reduce the energy release during relative movement as to avoid unwanted training quenches.

The concept was studied by means of FEA parametric analyses by G. Vallone in collaboration with LBNL (Berkeley, USA). It was found that in the straight-section cross-section, the distribution of structural wedges and winding turns needs to be optimized not only for field quality and efficiency goals, but also to provide mechanically advantageous configurations. To this end, new software developed by the CHART2/MagNum project at ETHZ was used to genetically optimize cross-section designs [1-3].

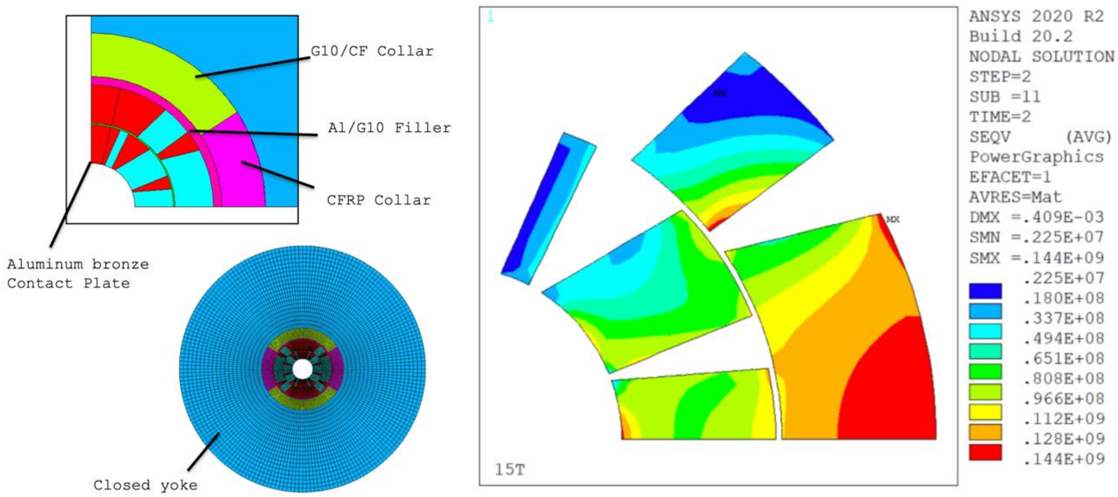

Figure 6 2D study of a 2-layer low-prestress cosine theta configuration with CFRP collars. Note the relatively low von-Mises stress at 15 T.

With exciting results in 2D, the study continued to investigate low-prestress end-region designs. This proved a lot more difficult than the 2D design. The status at the end of the year was that the low-prestress variant of the cosine-theta magnet remains an interesting variant with more studies required to come to final assessment of its feasibility in the 3D coilends.

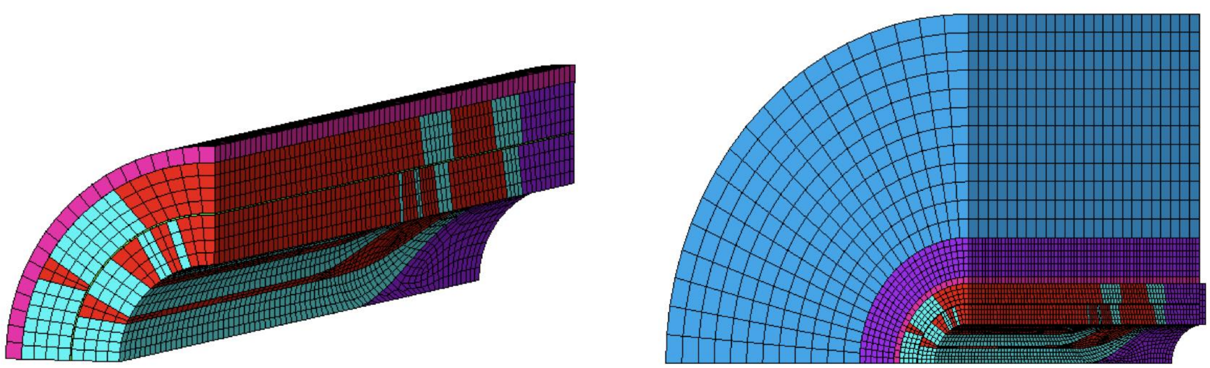

Figure 7 3D models of a 2-layer 11-T coil (HiLumi WP 11). The model was use to explore opportunities and difficulties of a 3D low-prestress design.

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Technical Review of the MagDev Results and Roadmap

All the presented results were discussed in depth at a technical review in December 2021 (http://indico.psi.ch/e/magdev1review). From the review committee's report to the CHART Council (full report available on the indico page), we cite the following general remarks: "The committee is impressed by the quality and the quantity of the work presented. … the computational and experimental work follows a rigorous development approach." "The committee appreciates the dynamism and motivation of the team and the complementary fields of expertise." "The team has shown to be well connected to other institutions through various collaborations - as foreseen by CHART2 - and open to analyze/implement existing technical solutions". Moreover, the committee endorsed our roadmap proposal to go ahead with the stress-managed cosine theta design concept: "the proposed LTS roadmap contributes to the HFM effort towards high field LTS magnets for particle accelerators, with particular emphasis on minimizing training, and reducing the risk of conductor degradation due to high stress". They asked for more in-depth 3D simulation of the SM-CT end regions and cautioned that the proposed schedule was aggressive.

In the light of the above results and the outcomes of the technical review, the MagDev team is keen to apply the lessons learned, explore new designs, and demonstrate how innovative approaches can tackle long-standing problems of next-generation superconducting accelerator magnets.

Publications and Presentations

[1] M. Daly, B. Auchmann, C. Hug, S. Sidorov, S. Otten, A. Kario, M. Dhallé, H. ten Kate, BOX: an efficient benchmark facility for the study and mitigation of interface-induced training in accelerator type high-field superconducting magnets, Superconductor Science and Technology , https://doi.org/10.1088/1361-6668/ac2002.

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