

CCA (Coated Conductor for Applications) 2025 workshop

Monday 10 March 2025 - Thursday 13 March 2025

CERN

Book of Abstracts

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Registration

2

Conductor Material Research

Cables for Magnets / 3

The status of HTS CICC magnet development for the next fusion reactor in China

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High magnetic field is one of the important parameters required for lots of scientific researches. High temperature superconducting (HTS) materials have the potential to generate a magnetic field beyond 15 T. According to the commercial production technology development of the high temperature superconducting materials, the REBCO tapes are the promising candidate for high field magnet application. The maximum operation magnetic field of the Central Solenoid coil required for the next generation fusion device in China is around 20T. In order to achieve this magnetic field, the hybrid magnet design concept was proposed, and the inner high field part is planned to use the REBCO tapes, thus the REBCO CICC magnet technology is being developed at ASIPP. To meet the space confinement conditions, six stacked REBCO modules with an inner diameter of around 475.5 mm shall be connected through joints. Each module has 150 turns which shall be wound from about 560 m long CICC. Based on the design, critical manufacturing technologies such as HTS CICC forming, coil winding, insulation manufacturing, CICC joints and so on are under developing. Here, activities related to the magnet design, analysis and critical components manufacturing technology development were summarized and reported.

Session:

Cables for magnets

Electromagnetic and Mechanical Properties 1 / 4

Lessons learned from ultra high-field, high-stress REBCO coil tests

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The ‘Little Big Coil (LBC)’ experiments investigate key coated conductor characteristics in a high field and high stress environment by testing a REBCO coil in the bore of the NHMFL 31.1 T Bitter magnet. Indeed, LBC3 first demonstrated excessive screening current stress (SCS) resulting in wavy plastic conductor damage, while obtaining the record-high DC magnetic field of 45.5 T by generating 14.4 T in a 31.1 T background field. The important result of LBC 3 was that single slit tapes with slit edges pointing to the coil center barely damaged while those with opposite orientation showed large damage. To explore this apparent paradox, LBC4 was wound completely from single-slit tapes whose slit edges were all pointed towards the coil center. Indeed, almost no damage was seen on LBC4 attaining 44.0 T. Our *post mortem* showed that the key reason was a specific peculiarity of the MOCVD tapes used in our LBC coils. The edges of the tapes have markedly higher density of blocking CuO and *a*-axis grains that markedly lower the edge J_c below that of the more central slit edge even with its cracked edge. Measurement of the transverse J_c variability and implementation of the local edge J_c into the SCS model yielded stresses consistent with the transition from large SCS-initiated damage in LBC2 (42.5 T) and 3 (45.5 T) to much lower SCS damage in LBC4. We are now aiming to investigate key characteristics of recent laser-slit, thicker REBCO, and PLD conductors for compact superconducting fusion magnets through the LBC framework and compare them with mechanical slitting, thin REBCO, and MOCVD conductors that we have mainly used until now.

Session:

EM & Mechanical Properties

5

Thermal Quench Modeling of a REBCO Superconducting Coil for Aircraft Propulsion Motors for Conduction Cooling at 30 K

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Proposed area of relevance: Power and Mobility Applications

High-temperature superconducting (HTS) racetrack coils are ideal for high-power, lightweight motors but face thermal quenching risks from self-heating caused by AC currents or DC faults. Electrothermal modeling is essential for safe motor design. We developed a computational model combining the Minimum Electro-Magnetic Entropy Production method with the Finite Difference Method. This study uses temperature-dependent thermal parameters, like thermal conductivity and heat capacity. We found that screening currents from high-frequency AC voltages during normal motor operation can trigger electrothermal. We also analyze the short-circuit DC voltages (1–1000 V) under two conditions: fully adiabatic and conduction cooling from one side at 30 K. We compute the current and temperature evolution assuming one or several damaged turns, where the critical current density can range from 5% to 90% of its original value. We have found that high DC voltages trigger thermal quench in damaged turns, while lower DC voltages cause oscillations in time. These insights will guide the design of stable, efficient HTS motors for greener electric aircraft.

Session:

Power and Mobility applications

6

The progresses of the REBCO magnets with pancake coils for high field applications exceeding 20 T**Author:** Fang Liu^{None}**Co-author:** Huajun Liu¹¹ *Chinese Academy of Sciences***Corresponding Authors:** fangliu@ipp.ac.cn, liuhj@ipp.ac.cn

In recent years, the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) has been committed on the research of ultra-high field magnets with pancake coils for high field applications. On the basis of 19.8 T and 24 T all superconducting hybrid magnets, ASIPP launched a new project to design and manufacture of 35 T all superconducting hybrid magnet, which consists of a 15 T low-temperature-superconducting (LTS) background magnet and a 20 T high-temperature-superconducting (HTS) REBCO insert magnet. In the first test under the LTS background magnet, the highest central magnetic field reached 32.4 T, in which the magnetic field contribution of the insert coil was 20 T, and more tests are underway. For the all HTS magnet, a 20 T class all-REBCO conduction-cooled magnet was developed and successfully tested at 4.2 K, and the maximum central magnetic field reached 26.86 T, which is the highest magnetic field achieved by the HTS magnet. In addition, no obvious degradation was found in the performance of the magnet after quench at 26.86 T of 295.5 A. These test results demonstrate the great potential of REBCO magnets in high field applications.

Session:

High Field Applications

7

Estimation of ReBCO superconductor stability under variable conditions using the overcurrent multi-pulse transport method**Author:** Marek Búran^{None}**Corresponding Author:** elekburm@savba.sk

The electro-thermal stability of high-temperature superconducting (HTS) tapes was investigated under various cooling conditions across a wide range of temperatures and magnetic fields. A non-standard multi-pulse technique, employing a 1-second current pulse with a complex waveform, was utilized for this study. Stability tests were conducted in liquid nitrogen (LN₂) at 77 K under self-field conditions. For in-field testing, at temperatures below 77 K, a cryocooler combined with subcooled water (H₂O) ice as the coolant was utilized. Tape stability was evaluated using the stability indicators incorporating the ratio between the overcurrent pulse amplitude (I_o) and the critical current value (I_c). Additionally, the energy of the individual pulses was calculated and compared across varying measurement conditions. The results demonstrate that tapes cooled with subcooled H₂O ice exhibit superior stability, particularly under dynamic and rapid operational scenarios.

Session:

Cables for magnets

8

Impact of magnetic field-dependent superconducting behaviour on HTS dynamo performance

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Abstract:

The high-temperature superconducting flux pump provides a possibility to energize the superconducting coils without current leads and allows the magnets to be in a quasi-persistent current mode due to the second-generation high-temperature superconducting wires having a strong magnetic field. It is smaller and has a more powerful magnetic field than traditional power supplies. So, the common applications include MRI, fusion, particle accelerators, superconducting electric machines, etc. In the last decade, people have been involved in improving the structure of the flux pump itself to draw a conclusion on which parameters or indexes can affect the output performance of the flux pump. In this paper, we used the fitting method to get the parameters about parallel dependence of the magnetic field and magnetic field dependence for each 6 commercial HTS tapes. Then, I put those parameters into the modified benchmark model (in the published paper, which can verify my results well) to see if the tendency is the same as the published paper. Besides, according to the current parameters, we further updated the 2D flux pump model, which can get a more ideal output voltage performance.

Session:

Power and Mobility applications

9

Reinforced HTS Wire for High-Field Magnet and Cable Applications

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HTS coated conductors consist of very thin metal foils slit into narrow strips after coating. Their unfavorable aspect ratio and exposed slitting edges constitute weak points of the conductors. Abrasion can easily occur at the edges during handling and rewinding. When used in magnet coils, high magnetic fields and screening currents can result in very high local Lorentz- and shear forces, which are concentrating at the edges and can lead to delamination and mechanical failure.

The surround copper coating, which is usually required for electrical stabilization, adheres very poorly to the cut Hastelloy edges and may not provide sufficient mechanical protection. We have therefore developed a new method of stabilization by wrapping. On the one hand, this ensures very

robust edge protection and, on the other, it allows the design of multi-ply assembled HTS conductor structures. They open new freedom to modularly adapt the properties of HTS tape to customer needs. One such embodiment is the mirrored combination of two anisotropic, individual HTS tapes to form a so-called JANUS wire™, exhibiting a symmetric, stable and broad angular dependence of the critical current in magnetic field. Such HTS conductors have wide angular tolerances and can be used preferably in the edge areas of solenoid or stellarator coils where the magnetic field is naturally tilted with respect to the tape surface.

Acknowledgment: Part of this work is supported by the German Federal Ministry of Education and Research under grant No. 13F1014A (HTS4Fusion).

Session:

Conductor Manufacturing

10

Advances and perspectives in HTS wire production at THEVA

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THEVA is the only established HTS wire manufacturer in Europe. Our wire manufacturing technology has been developed in-house over many years and differs significantly from the mainstream. THEVA's coated conductors belong to the top group in terms of performance, but exhibit also some peculiarities. The main advantage of our approach is its industrial suitability and scalability, as this is the only way to achieve a significant reduction in unit costs when producing large volumes.

In recent years, THEVA has enabled a number of unique and world's first application projects, from the first HTS wind turbine (3.6 MW) to high power HTS cables (500 MW), 200 kA busbars, and currently the most powerful MRI body scanner (14T).

THEVA focuses on sustainable markets with high growth potential. In the field of magnetic field generation, these are medical technology and nuclear fusion, and in the field of power technology, high-performance HTS cables for urban distribution and the transformation of the energy system.

We report on current developments in the area of product development, where our focus is on wire robustness for processing by the customer and mechanical strength. For fusion applications, we are investigating and optimizing the neutron resilience of HTS conductors as well as the widest possible tolerance range for processing in high-field magnets with complex structures.

In the area of production technology, we are looking at scaling concepts that go far beyond the current cloning of established equipment and we will discuss the challenges we face with the mass production of HTS conductors.

Session:

Conductor Manufacturing

11

Stable mass-production by Hot-Wall PLD approach for uniform REBCO wires and magnet applications

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REBCO wire is now a vital component of high-field magnets as NMR facilities over 1 GHz operation, and also radically demanded from compact fusion programs that have brought worldwide mass production, both mainly formed by vapor phase approach of IBAD/PLD. PLD is characterized to be much supersaturated high-rate growth, resulting from fine and rapid evaporation by UV pulsed laser, creating blast wave that can reach far beyond mean free path in high enough oxygen pressure suitable for REBCO growth. It allows good growth controllability, high in-field J_c , high production throughput, good homogeneity attained by Hot-Wall architecture, and resulting excellent production yield. Those features could shrink the equipment cost of UV lasers per production length effectively and a significant scale-up investment has been on-going to increase production capacity. We have REBCO wire line-ups with or without APC, with varied width, thickness, and protection layers. Both longitudinal and lot-to-lot uniformity of in-field J_c are quite good that should also be important to explore reliable quench protection, even in large-scale magnets using NI technology, assembled or striated conductors, etc.

Session:

Conductor Manufacturing

12

Thermo-electric numerical model of 10 kA superconducting cable in dynamic conditions

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We have developed a detailed numerical model of DC superconducting power cable designed to transport nominal current of 10 kA. The model is implemented in Comsol Multiphysics in a 2D approximation. In order to realistically assess the thermo-electrical behavior of the cable for different time-profiles of transport current, in each time instant the transport current is imposed on the cable by the means of self-consistently calculated static electric field. This allows to study the heating and temperature distribution in different parts of the cable in dynamic conditions, like during the energization and fault in the grid operation. Detailed geometry of 62 superconducting REBCO tapes, the inner metallic core, outer metallic sheath and intermediate insulating layers is incorporated in the model. Electric properties of the superconductor are described with a modified power law and the dependence of local critical current density on magnetic field and temperature is included. Results calculated for the transport current profiles obtained from the circuit model analysis indicate a safe maximum temperature increase of approx. 0.4 K at the superconducting parts during the fault.

Session:

Cables for magnets

13

HTS dipole magnets for the muon collider

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As part of the International Muon Collider Collaboration (IMCC), a feasibility study for a 10 km-long collider capable of reaching 10 TeV center-of-mass energy is currently underway, supported by the EU grant 101094300. Within this framework, Work Package WP7 focuses on the development of collider superconducting magnets, which face significant challenges due to the requirements for high magnetic fields, large apertures, and their ability to endure substantial radiation and heat loads. High-temperature superconducting (HTS) materials are promising candidates for these magnets, thanks to their exceptional critical current density and thermal stability. However, several technical challenges remain to be addressed, including winding feasibility, mechanical structure design, current redistribution in the no-insulation configuration, AC loss management, and quench protection. In this contribution, we present a preliminary study aimed at assessing the performance limits of these magnets: such study is based on an analytic evaluations and includes the constraints of the margin on the load line, the stress on the conductor, the feasibility of the protection system and the cost. The status of the conceptual design for the arc dipoles will also be reported.

Session:

Accelerator Applications

14

Current sharing and AC losses in filamented high-temperature superconducting tapes and cables.

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The division of the superconducting layer in narrow filaments is a well-established technique for reducing hysteresis AC losses in coated conductor (CC) tapes. However, the ReBCO superconductor must be covered by a metallic layer to prevent the atmosphere's destructive effects and enhance the wire's thermal and electrical stability. Unfortunately, the structure of filamented CC tape gives rise to an additional source of AC losses, namely coupling losses, which are caused by transverse currents between the superconducting filaments through metallic stabilization. The selection of optimal parameters for the stabilizing layer represents a compromise between the objective of achieving

good electro-thermal stability and good current sharing between the filament on the one side and avoiding excessive coupling losses on the other side. In the case of superconducting cables, the estimation of losses may be further complicated by their complex geometry. Our work demonstrates a finite element (FEM) numerical model that can be used to estimate the AC losses in cables made of CC filamented tapes, considering current distribution in superconducting and metallic parts of the tapes.

Session:

Cables for magnets

15

Progress and Opportunities of the Transient Liquid Assisted Growth (TLAG) method

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The remarkable potential of REBa₂Cu₃O₇-coated conductors (REBCO CCs) has finally become a tangible reality by unlocking new technological opportunities like compact fusion, hybrid electric aviation, DC transmission lines or complex magnets in accelerator physics. However, the market perspectives advices to invest in high throughput manufacturing processes of reduced cost-to-performance ratio to compile with the large demands and foster initiatives to improve performance ensuring robustness. To address these challenges, in ICMAB we are developing a scalable, high-throughput growth process known as Transient Liquid Assisted Growth (TLAG) [1]. This method achieves ultra-high growth rates exceeding 1000 nm/s while maintaining high critical current densities [2] by using nanocrystalline precursor films that can be prepared from chemical solution deposition (CSD) [3,4] or low temperature physical deposition (like Pulsed Laser Deposition) [5]. In the CSD case, the use of multifunctional colloidal inks enables the fabrication of nanocomposites CC for high-magnetic field applications.

TLAG is a highly non-equilibrium liquid-solid growth process in which nucleation and growth are kinetically controlled. For that reason, we have developed advanced in situ techniques to elucidate the underlying growth mechanisms and establish correlations between process parameters, epitaxy, growth rate and performance. This includes, an in-situ growth installation at ALBA synchrotron with fast acquisition XRD and XAS coupled with mass spectrometry and in-situ electrical resistance. Results show that TLAG can operate at a very wide PO₂-Temperature window, where nucleation density and growth rate can be tuned by liquid composition, RE ion and process parameters. Moreover, the CSD approach enables us to employ high-throughput experimentation by developing inkjet-printed combinatorial compositional gradient films for fast process screening and data driving science.

Besides, in order to improve performance in a robust manner, we are investigating the modification of the electronic structure by increasing the charge carrier density up to the overdoped state, where the vortex pinning centres improve their effectiveness by the increase of the condensation

energy [6,7]. The combination of advanced transmission electron microscopy and high field angular transport measurements permits the understanding of the vortex physics of these complex materials grown at these high rates [8].

In this presentation, I will report on the progress of the above mentioned challenges with the aim of designing a robust, high throughput and flexible growth method for the manufacturing of CC at competitive cost-performance ratio.

We acknowledge funding from EU ERC-AdG-2014-669504 ULTRASUPERTAPE, EU-ERC-PoC-2020-IMPACT, EU-ERC-PoC-2022-SMS-INKS, CSIC-TRANSENER-PTI+, MICIN-SUPERENERTECH and SEVERO OCHOA MATTRANS42 (CEX2023-001263-S)

- [1] L. Soler et al, Nature Communications (2020)
- [2] S. Rasi et al, Advance Science (2022)
- [3] L. Saltarelli et al, ACS Appl Materials and Interfaces (2022)
- [4] L. Saltarelli et al, ACS Appl Materials and Interfaces (2024)
- [5] A. Queralto et al, SUST (2023)
- [6] A. Stangl et al, Sci. Rep (2021)
- [7] X. Obradors et al, Nat Mat N&V (2024)
- [8] T. Puig et al, Nat Phys Rev. (2024)

Session:

Conductor Material Research

16

Development of a Coated Conductor with Superconducting Joint Capability

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Advancing High-Temperature Superconducting applications, such as superconducting magnets, requires minimizing joint resistance to improve performance. Developing a reliable superconducting joining method remains a major technical challenge. In previous work¹, we demonstrated bridge-type joints using a REBCO intermediate layer for coated conductors (CCs). In this study, we have fabricated lap-type joints using joinable coated conductors, which enable scalable conductor extension.

The REBCO CCs used in this study exhibit a characteristic surface structure consisting of REBCO microcrystals, similar to the joint strap configuration reported in previous work. The joining process involves aligning the surfaces in direct contact, applying mechanical pressure, and heating at 800°C, resulting in atomic-level bonding of the REBCO layers.

Two CCs, each 50 mm long, were joined with a 20 mm joint length. As a result, the joint sample demonstrated a critical current (I_c) exceeding 200 A. The joining process required 1 hour for every 10 mm of joint length, totaling 2 hours for the 20 mm joint. Additionally, the oxygenation process required 6 hours per batch.

Although increasing the joint length enhances the I_c , it also extends the processing time. This trade-off introduces a scalability challenge that future work must address to fully realize the potential of coated conductors with superconducting joint capability.

- [1] Ohki K et al. 2017 Supercond. Sci. Technol. 30 115017.

Session:

Cables for magnets

17

The compressive and tensile limits of coated conductors at 77K

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The influence of mechanical loading on the electrical properties was measured for several commercial coated conductors. The measurements were conducted on an internally developed measurement setup utilizing an in-situ bending of samples at liquid nitrogen temperatures (77K). Due to the asymmetry of the geometry of coated conductors, we are able to measure both tensile and compressive loading of samples at different angles. A nearly identical compressive limit was established for samples from two producers. A variance between the two samples and another one are explained by the difference in the structure of the coated conductors, which is shown by scanning electron microscope (SEM) studies. As verification of the measurement setup, the tensile limits of the coated conductors were measured, consistent with published results. A compressive angular dependence of the samples was measured by applying compressive loading at 30, 45, 60 and 90 degrees with respect to the coated conductor length. The experimental results are supplemented by numerical and analytical calculations.

Session:

EM & Mechanical Properties

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Influence of process parameters on the growth rate and superconducting properties of REBCO films grown by TLAG

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Reducing the costs of REBCO CC can be achieved by increasing the growth rate while maintaining high critical current density [1]. In the high-throughput growth technique Transient Liquid Assisted Growth (TLAG) [2,3], a Ba-Cu-O transient liquid dissolves the rare earth element, enabling ultrafast

REBCO growth, of up to 1000 nm/s. This study examines the effect of growth rate on the formation of microstructural defects and its implication on the superconducting properties of REBCO films (RE=Y, Gd) grown by TLAG, under varying key parameters such as temperature, partial oxygen pressure and rare earth choice. Using in situ resistivity and in situ XRD measurements at synchrotron facilities, we analyzed nucleation and growth mechanisms to determine the growth rate dependence on process parameters. We observed a clear correlation between higher growth rates and higher temperatures and pressures. Post-growth magnetic granularity studies [4] suggest that samples grown under these conditions have smaller grain sizes and higher critical currents. TEM analysis further showed that microstructure strongly depends on process parameters, ranging from defect-rich to clean regimes.

[1] T. Puig et al, Nat. Rev. Phys. (2023)

[2] L. Soler et al, Nat. Commun. (2020)

[3] L. Saltarelli et al, ACS Appl. Mater. Interfaces (2022).

[4] A. Palau et al, Phys. Rev. B (2007)

Session:

Conductor Manufacturing

19

Design, manufacture and performance evaluation for the REBCO CICC joint for fusion magnet

Author: Chao Zhou^{None}

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Institute of Plasma Physics is developing the REBCO cable in conduit conductor (CICC) technology for the next generation of fusion device. Because joints are unavoidable for connecting different conductor unit length in large scale superconducting magnets manufacturing, and their ohmic dissipation may cause an uneven distribution of transport current within the conductor cross section, especially for the REBCO tapes having the stainless steel substrate, design and manufacturing a REBCO CICC joint with low resistance is important for its high field fusion magnets application. In this manuscript, the design and technology developing for REBCO CICC joint for our next generation fusion device is introduced. The design is based on the concepts of trimming the sub-cable into a staircase-like geometry. To demonstrate its feasibility, samples were manufactured and tested at 77 K self-field and 4.2 K different magnetic field conditions. The results are reported here.

Session:

Cables for magnets

20

Highly effective secondary phase doping in pulsed laser deposited YBCO thin films

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Proposed area of relevance: Conductor Material Research

The potential for utilizing REBCO-based coated conductors in numerous applications has been significantly advanced through the incorporation of Artificial Pinning Centers (APCs), which have elevated their performance to meet the necessary standards. Among the proposed APC structures, the Ba₂Y(Nb/Ta)O₆ (BYNTO) double perovskite stands out for its extraordinary stability, demonstrating exceptional characteristics across various operational regimes, including low-to-medium temperatures and medium-to-high magnetic fields for nuclear fusion [1], as well as high temperatures and low fields for electrical machines and power distribution cables [2].

The introduction of APCs into YBa₂Cu₃O_{7-x} (YBCO) thin films represents a promising approach to enhance critical current density (J_c), particularly in high magnetic fields. In this work, we investigate the integration of Ba₂Y(Nb/Ta)O₆ (BYNTO) as a secondary phase into YBCO thin films at different concentrations to form columnar nanostructures that act as effective pinning centers.

The research on YBCO-BYNTO films has shown excellent performance on single-crystal substrates such as SrTiO₃ (STO). The deposition parameters, particularly the laser settings in the PLD process, play a crucial role in determining the microstructure of the nano-defects. This microstructural control has direct impact on the critical current density (J_c) as a function of magnetic field intensity, J_c (B).

[1] L. Opherden et al., Scientific Reports 6,21188 (2016).

[2] F.Rizzo et al., APL MATERIALS 4, 061101 (2016).

Session:

Conductor Material Research

21

Design and manufacture of a 20 T HTS solenoid coil wound with REBCO cables

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Advances in the performance of high-temperature superconducting (HTS) enable the development of high field magnets for a range of applications, including tokamaks for fusion energy, high scientific instruments and so on. To develop the technology of HTS high field magnets with large central bore, one insert coil with ~400 mm inner diameter which can carry a current of 10 kA was designed and wounded from long length REBCO CORC-like cables. The aim is to provide a magnetic field of 10 T under a background magnetic field of 10 T. Due to the limitation of lengths from commercial REBCO tapes, the coil was assembled from five parts, and connected through demountable joints. Each was wounded with 2 pieces of REBCO cables having a length of over 100 m. Now, it has been assembled and tested at 77 K, the results show a predicted critical current of around 1.8 kA at 1.45T, and the calculated n-value is around 22, which shall be tested at 4.2 K next year.

Session:

High Field Applications

22

Multifilamentization of HTS tapes via photolithography for superconducting cable fabrication

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Reducing AC losses in superconducting tapes is crucial for their use in applications involving alternating or varying magnetic fields. This study aims on developing multifilamentary superconducting tapes with reduced AC losses by manufacturing striations using photolithography process. Tapes with varying numbers of striations were produced and tested to understand how these modifications affect their critical currents and AC loss performance. To protect the exposed superconducting layer due to groove creation, a thin protective coating was applied on the tape surface, and its influence on AC losses was also assessed. One of the modified tapes, demonstrating the best results, was wound onto a non-conducting core to evaluate its behavior in a cable-like configuration, providing insights into its suitability for building superconducting cable applications. The quality of produced grooves and filaments were analyzed using scanning electron microscopy, from top view and in cross-sectional samples. DC and AC measurements were conducted to comprehensively evaluate the performance of the tapes. By exploring how striations impact AC losses and the performance of the tapes in a wound state, this research seeks to provide valuable insights into designing superconducting tapes and cables with enhanced efficiency.

Session:

Conductor Manufacturing

23

Smart REBCO coated conductors' development through combinatorial chemistry using inkjet printing

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REBCO superconductors can transport electrical current with minimal losses making them a key element for a sustainable and efficient electrical industry. The main drawback of mass production for these materials is the cost/performance ratio. To overcome this issue, we have developed a novel methodology for REBCO growth that combines the versatility of the low-cost chemical solution deposition with an ultrafast (>1000 nm/sec) epitaxial crystallization from a Ba-Cu-O transient liquid called Transient Assisted Liquid Growth (CSD-TLAG), which is easily scalable. We will demonstrate the scale-up from laboratory scale to 1L of the multifunctional colloidal ink (patented) needed for the production of 1km of coated conductor with a thickness of the REBCO nanocomposite layer of 1µm.

The HTS industry is in a continuous development for continually improvement of the CC performances. By using high throughput experimentation together with inkjet printing assisted combinatorial chemistry, we can acquire a high amount of data in a record time that allows us to quickly optimize the performances of the REBCO CC. We will report on the study of compositional gradients of (Y,Gd,Er)BCO and REBCO nanocomposites.

Acknowledgments. The funding by ERC-2014-ADG-669504 ULTRASUPERTAPE, H2020-ERC-2019-POC-LS IMPACT, HORIZON ERC Proof of Concept, SMS-INKS, GA n.101081998 and FUNFUTURE-FIP-2020 DATOPTICON is acknowledged.

Session:

Conductor Manufacturing

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Improving the cost-effectiveness of Coated Conductors through Transient Liquid Assisted Growth (TLAG)

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The high cost-to-performance ratio of traditional methods for producing coated conductors, essential for superconductivity applications, presents challenges for their large-scale development. To overcome this, we present an innovative technique called Transient Liquid Assisted Growth (TLAG), which enables the rapid growth of high temperature superconducting Coated Conductors (CC) with various rare earth elements (RE). TLAG operates on a unique non-equilibrium principle, combining transient liquid growth with Chemical Solution Deposition (CSD) [1,2,3]. By adjusting process parameters and liquid composition, as well as selecting specific RE elements (such as Y, Gd, or Yb), TLAG allows for better control of growth temperature, a critical factor in preventing undesired interactions between the liquid and buffer layers. We explore the corresponding kinetic phase diagram and link it to superconducting properties and surface morphologies. TLAG significantly accelerates epitaxial growth, achieving rates exceeding 1000 nm/s, with further improvements in pinning properties (3-5 MA/cm² at 77 K) by incorporating oxide pre-formed nanoparticles. The evolution of TLAG from single crystals to metallic substrates will be discussed. Various characterization techniques—such as XRD, SEM, TEM, optical microscopy, Tc, Jc, and Hall microscopy—have been used to identify and address key parameters impacting performance. In-situ XRD analyses at synchrotron have provided valuable insights into the growth mechanisms, helping refine the process. At the laboratory scale, both spin coating and slot-die coating methods have been employed to produce tapes up to 15 cm long. Additionally, ex-situ integration of customized nanoparticles (e.g., BaZrO₃, BaHfO₃) into precursor solutions has been carried out to improve superconducting performance under high magnetic field conditions.

[1] Nature Communications 11, 344 (2020)

[2] ACS Applied Materials and Interfaces 14, 48582 (2022)

[3] Advanced Science 2022, 2203834, doi.org/10.1002/advs.202203834

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Session:

Conductor Material Research

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Towards large area growth of superconducting REBCO coated conductors by Transient Liquid Assisted Growth (TLAG)

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Despite the exceptional properties of REBCO High Temperature Superconductors (HTS) commercial devices have been limited, though recent prospective from compact fusion has changed this tendency. The thin film growth fabrication processes required in REBCO long-length tapes lead to high production costs. This work represents a significant step towards the large-area growth of superconducting REBCO coated conductors, employing a disruptive technology with promising implications for the field.

The Transient Liquid Assisted Growth –Chemical Solution Deposition (TLAG-CSD) technology for the fabrication of REBa₂Cu₃O_{7-x} (RE=rare earth, REBCO) layers offers growth rates 1-2 orders of magnitude faster than most currently employed methods without the need of extensive vacuum installations. It is based on a non-equilibrium process where a transient liquid growth is combined with Chemical Solution Deposition (CSD) [1,2,3]. Through the choice of process parameters and different REs different substrates can be accommodated. The TLAG-CSD-method has been intensively studied by our group on small (5x5mm) single crystalline substrates as model systems achieving Jcs of up to 5 MA/cm² [1].

To transfer this process to substrates and deposition methods more suitable for coated conductors many adaptations have to be made. To this end we are depositing our propionate based REBCO precursor solution through slot-die coating on different commercially available substrates which are characterized with various techniques (XRD, SEM, optical microscopy, Tc and Jc). Printhead widths of up to 40 mm have been tested and optimal pyrolyzed films have been obtained. The viability of different process parameters has been studied and grown films have been evaluated by XRD, SEM and Jc.

[1] Nature Communications 11, 344 (2020)

[2] ACS Applied Materials and Interfaces 14, 48582 (2022)

[3] Advanced Science 2022, 2203834, doi.org/10.1002/advs.202203834

Session:

Conductor Manufacturing

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Striation for the reduction of AC loss and magnetization of CC tapes and cables

Authors: Fedor Gömöry^{None}; Ján Šouc¹; Martin Kucharovič¹; Mykola Solovyov¹; Tomáš Kujovič¹; Sara Landvogt²; Marcela Pekarčíková³; Christian R. H. Bahl⁴; Anders C. Wulff⁴

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The use of coated conductor tapes is a possible way to achieve better energy efficiency in particle accelerators, fusion reactors, or electrical motors. In an AC regime with a time-varying magnetic field, the energy dissipation caused by magnetic hysteresis in hard superconductors is directly proportional to its width. An effective remedy for reducing this hysteresis AC loss is a striation of the superconductor layer, forming parallel filaments as narrow as possible. In order to allow the redistribution of current flow to avoid local imperfections, a metallic connection between filaments is desirable. However, this introduces another loss mechanism: coupling AC loss.

Based on extensive experiments with filamentized tapes produced by SUBRA, using large-scale low-cost technology, where the buffer and the superconductor layer are deposited via standard industrial procedures at THEVA on a 3D-patterned Hastelloy substrate, we have developed an analytical model to predict AC losses in filamentized tapes and round cables. We demonstrate how it could help in optimizing the tape architectures, as well as in understanding the potential and limitations of the striation approach for various applications.

Session:

Cables for magnets

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Wet Chemical Etching for Striating of REBCO Coated Conductors

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Striation of superconducting coated conductors (CC) has been a well established method for reduction of alternating current (AC) losses already for several decades. Among the different striation methods developed so far, the main advantage of the wet chemical etching (WCE) is a low processing temperature, as it poses a negligible risk of thermal degradation of the superconductor. Despite this benefit, systematic studies on the parameters of the WCE method are very scarce and/or incomplete. We investigated REBCO-based CC from various producers, with different layer thicknesses and compositions, to assess the etchability of their metallic overlayers and the REBCO itself, with different agents and at various etching conditions. We paid a special attention to the effect of overetching, as its influence on the final width of filaments could not be neglected. The criterion

upon which the optimal etching conditions were selected was the effectivity of AC losses reduction measured on short samples (in the order of 0.1 m), but with the intention to upscale the WCE method for production of superconducting striated CC cables.

Session:

EM & Mechanical Properties

Conductor Material Research / 28

Pinning Mechanisms, Lengthwise Fluctuations, and Flux Jumps in REBCO Coated Conductors: A Torque Magnetometry Study up to $B = 45$ T

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This study explores the angular (θ) dependence of the critical current $I_c(B, T, \theta)$ in REBCO coated conductors using a torque magnetometer (US Patent) optimized for high magnetic fields (B) and low temperatures (T)—a critical regime for magnet development and pinning mechanism studies, where high I_c complicates transport measurements.

Data from over 200 samples reveal significant I_c variations, even among samples fabricated to the same specifications. When B is near the ab-plane,

strong pinning dominates and I_c exhibits exponential and stretched exponential decays ($I_c \propto \exp(-B) \exp[-(T)^s]$, $s \approx 2$). When B is away from the ab plane, I_c shows power-law and simple exponential decays ($I_c \propto B^{-\alpha} \exp(-T)$, α

lessim1) This enables clear assessment of different pinning contributions into $I_c(B, T, \theta)$.

Additionally, lengthwise I_c variations are prominent in tapes cut from the sides of 12 mm-wide production tapes, especially when the magnetic field aligns with the ab-plane. In contrast, tapes cut from the center exhibit stable I_c . Flux jumps are observed in samples with thick REBCO layers and thin Cu stabilizers, suggesting potential thermal instabilities. These findings provide crucial insights into the performance of CC tapes in high-field magnet and nuclear fusion applications. A. Francis, G. Bradford, A. Xu, R. Ries, D. Larbalestier contributed. NHMFL is funded by NSF DMR2128556 and the State of Florida.

Session:

Conductor Material Research

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Migration of current among superconducting filaments in REBCO coated conductors

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Filamentized superconducting tapes promise a reduction of AC losses, because a limited transverse conductivity reduces migration of current between filaments. Then, unlike non-filamented tapes, where the current can easily bypass a local defect, current redistribution in filamentized tapes is more

complex. Of particular concern is a local overheating of the filament containing less or lower quality superconducting material. To address this issue, the “bridges”, i.e. non-filamentized segments, can be incorporated into the tapes. These segments are intended to redirect current into filaments that had been defective in a previous section.

At 77 K, we conducted experiments on two kinds of samples. The first approach focused on analyzing the homogeneity of current distribution in a regular filamentized segment. We soldered voltage contacts onto each filament, which allowed us to measure local voltages, identify weak filaments, and observe inhomogeneities in current distribution. Then we investigated the behavior of current in the presence of bridges and their ability to redistribute current without introducing additional constraints. We complemented these experimental findings with numerical simulations.

Session:

Cables for magnets

Conductor Manufacturing / 31

Demonstration of high critical current on REBCO tapes fabricated by FF-MOD method

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Abstract body

High field magnets for MRI, NMR, and especially for fusion reactors have a strong demand for low-cost REBCO tape. Sumitomo Electric Industries, Ltd. has been developing REBCO tape fabrication by Fluorine-free MOD (FF-MOD) method, which is an environment-friendly process for REBCO fabrication. Additionally, FF-MOD is a cost-effective process since inexpensive and easily prepared solutions can be used, there is nearly 100% material yield, and no special energy source is required except for a conventional tube furnace. It used to be hard to include artificial pinning centers (APCs) in the process needed for high field applications. However, we recently reported successful fabrication of FF-MOD films with BaHfO₃ (BHO) nanoparticles as APCs by applying a poly-crystallization sintering process[1]. We developed BHO nanoparticles with a minimum diameter of 2 nm by utilizing the solvothermal method with some modifications[2]. By adopting those techniques, we have succeeded in fabricating epitaxial REBCO films with BHO on IBAD-MgO-based Ni-alloy tape by

FF-MOD method. When the film thickness is thinner than 350 nm, the in-plane texture of REBCO improves with film thickness and converges to 2-3 degrees [3]. The critical current of the thin films is dependent on the texture of the buffer layer. On the other hand, as the film thickness increases, the in-plane texture of thick film becomes constant regardless of the film thickness. Therefore, the contribution of the buffer layer texture to thick film becomes much less, resulting in a high I_c . As results, the I_c increases linearly with increasing REBCO thickness and 164 A/4mm-width at 20 K, 20 T (B||c) was achieved with the film of 3.1 μ m thickness. Furthermore, REBCO films grown by the FF-MOD method show very high I_c even at 77 K and self field, which exceeds 460 A/4mm-width. Furthermore, REBCO tapes longer than 300 m without defects related to the FF-MOD process were successfully fabricated recently.

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Session:

Conductor Manufacturing

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Characterization of electromechanical properties of striated REBCO tapes with different geometries

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REBCO CCs (rare-earth barium copper oxide coated conductors) are the best candidate materials for superconducting TORT (tapes on round tubes) cables due to their excellent mechanical strength, high current-carrying capacity, and magnetic strength. It is commonly known that AC losses can be decreased when TORT cables are constructed using REBCO multi-filamentary tapes. However, the mechanical strength of these geometrically adjusted tapes is just as important when winding them into cables. The objective of this study was to understand the effects of the mechanical loading on the I_c (critical current) of the striated tapes and, therefore, determine the safe stress limits. This work involved the preparation of various types of REBCO striated tapes through chemo-mechanical striating, as well as the deposition of stabilization multilayers. Subsequently, the striated tapes were bent at a lay angle of 45° over bending diameters from 13 mm to 1 mm, and current-carrying performance under self-field conditions at 77 K was measured. We observed that striated tapes remained without I_c reduction to a bending diameter of 2 mm, while for non-striated tape there was a more significant decrease at 3 mm. Finally, the effect of groove geometrical irregularities on the mechanical performance of striated REBCO tapes were supported by FE (finite element) analysis and correlated with experimental results.

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EM & Mechanical Properties

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Protection of High-Field, High Energy Density Metal-Insulated / Non-Insulated HTS Magnets

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The metal-insulated (MI) or non-insulated (NI) design of High-Temperature Superconducting (HTS) magnets is often used to improve thermo-electrical stability and as a passive way to protect the magnet in case of a quench. Low-resistance paths between turns allow current to bypass a quenched or resistive region within the coil. While a smaller turn-to-turn resistance allows for easier redistribution of current during such events, it also introduces drawbacks. Specifically, it can lead to the formation of loops with large induced currents, which locally increase the stored energy and Lorentz forces on the conductor. Moreover, a large magnet characteristic time negatively impacts the magnet's ramp time and ramp loss. For magnets with significant stored energy and current density, relying solely on minimal inter-turn resistance may not guarantee adequate protection during a quench. High local energy dissipation can push coil temperatures beyond acceptable limits, while induced currents may double or triple local Lorentz forces, leading to permanent degradation through delamination or cracking of the ceramic HTS layer.

Simulation tools have been developed to evaluate the quench behavior of various magnet types. These tools provide valuable insight into the influence of magnet design parameters on operational performance, quench survivability, and protection strategies. This contribution discusses the quench mechanisms and propagation, failure modes, potential protection solutions, and conductor requirements for high-field, high-stored-energy MI/NI HTS magnets.

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Accelerator Applications

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Current transfer length and interface resistance of KC4 REBCO tapes

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In recent years, high temperature superconductors (HTS) have been developed intensively for different applications. REBCO (rare-earth barium copper oxide) HTS tapes used for these applications are multilayered materials where the superconductor is thin layer within so-called Coated Conductor (CC) structure, and usually has a metal sheath, e.g. silver, copper, or stainless steel. The interface resistance between the superconducting layer and the surrounding layers is an important characteristic of an HTS tape, along with current density and critical temperature, as it strongly influences

the current transfer length (CTL) and the Normal Zone Propagation (NPZ) velocity.

There exists a well-known method for the evaluation of the interface resistance between the HTS layer and the surrounding metal layer [1, 2], or metal contact embedded in HTS material [3].

The interface resistance often differs by orders of magnitude in commercially available HTS tapes [4]. The values of the interface resistance and CTL together with critical current can be affected by conditions of storage and application environment. Often the tapes are stored in atmospheric conditions with certain humidity before Ag depositing step. Nowadays, with growing interest to hydrogen applications, HTS tapes are often considered for usage in hydrogen environment. However, it is unclear how the hydrogen atmosphere or humidity are influencing tape's performance.

For the tapes produced by KC4 - the KIT-CERN Coated Conductor laboratory - the influence of air humidity on non-stabilized tapes and H₂ exposure on silver stabilized tapes was investigated.

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Session:

EM & Mechanical Properties

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Production of multifilamented REBCO tapes by large-scale low-cost methods

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REBCO coated conductors are increasingly being used to build strong magnets. Conventionally high production prices and AC losses have limited the exploitation of the technology. We will show how large-scale low-cost production of tapes with numerous narrow filaments solves both these challenges.

The key to the multifilamented CCs is SUBRAs nano-polished 3D profile Hastelloy substrates, on which the superconductor stack (buffer and REBCO layers) is directly deposited at THEVA. This ensures optimum conditions for the growth of the superconductor stack and avoids any risk of damage to the CC which is present during conventional striation. The 3D profile is produced using large-scale reel-to-reel processes and can thus be done very cost effectively.

Recently, commercial production of 450 m long multifilamentary CCs has been established at SUBRA. The tapes can be specified according to requirements, with filament widths down to 250 μm and a separation of 25 μm . The thickness of the subsequent metallisation, typically plated Cu, can be tailored according to the application in which the CC is to be used. This tailoring is supported by an advanced modelling tool, predicting the AC losses in operation.

The optimisation of the structure of the multifilamented tapes will be presented, demonstrating a consistently high quality and performance of the filaments, in addition to excellent bending properties.

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Low surface impedance REBCO coatings for high-energy physics applications under high magnetic fields

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Emerging high-energy physics technologies require excellent RF response under high-magnetic fields or under high-electric field gradients; like CERN's FCC-hh next generation high-energy accelerator, which operates at 16T and at 50K; Dark Matter axion detection haloscope cavities, where the detection sensitivity scales as the square of the external magnetic field; or high-power linear colliders with an accelerating gradient above 100 MV/m. Therefore, at the operating conditions of these technologies, penetration of magnetic field lines into the superconductor is unavoidable and thus, its RF response is governed by vortex pinning. Under those conditions, NbTi and NbSn₃ superconductors offer a very poor, lower-than Cu, RF response and the high-energy physics community turned its attention back to Cu. However, we demonstrated that under the conditions required for such applications, REBa₂Cu₃O_{7-x} (RE = Y, Gd, Eu) (REBCO) offers outstanding, better-than-Cu RF response [1, 2]. The reason for this is its higher critical temperature $T_c > 90\text{K}$, larger upper critical field $H_{c2}(4\text{K}) > 100\text{T}$ and larger pinning forces $F_p(4\text{K}) = 1000\text{GN/m}^3$. Unfortunately, its usage in RF applications is impeded by complicated material growth that requires meticulous stoichiometry control and biaxially textured templates, making it virtually impossible to grow REBCO directly on the geometrically complex surfaces required for many applications.

In this talk, we present our recent studies, where we have worked towards understanding the high-field microwave response of REBCO coated conductors (CCs) up to 16T, in a wide cryogenic temperature range, at several RF-frequencies and under different RF-power levels. We will also present our developments on a coating technique using CCs to cover flat and curved surfaces (such as those needed for cavities). Our findings have placed CC's technology as a solid candidate to replace Cu as the low surface-impedance coating in high-energy physics applications, such as accelerators and dark matter detectors.

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Electromechanical properties characterisation of REBCO superconducting tapes using finite element method**Author:** Luca Benedetti^{None}**Co-authors:** Guilherme Telles ; Joffre Gutierrez Royo ¹; TERESA Puig Molina ; Xavier Granados ²¹ ICMAB - CSIC² ICMAB-CSIC**Corresponding Authors:** gtelles@icmab.es, granados@icmab.es, jgutierrez@icmab.es, lbenedetti@icmab.es, teresa.puig@icmab.es

Coated conductors (CCs) are promising for high-energy and high-field superconducting applications. However, practical applications subject CCs to various stresses and strains, from thermal mismatch and tensile stresses from Lorentz forces. These factors can reduce load-carrying capacity and risk degradation of electromechanical properties.

Understanding the mechanical behaviour of CCs under tension is critical for assessing stress-strain distribution within their complex, layered structure. However, the brittle nature of the REBCO layer, its sensitivity to environmental conditions, and its layered structure pose challenges in isolating mechanical properties of individual components. In this work we will present how, the combination of Finite Element Method (FEM) simulations with mechanical tests, can be applied to reconstruct the mechanical behaviour of each layer. This approach integrated with Hall scan analysis enables a detailed evaluation of electromechanical properties such as current and magnetisation distribution across the tape, offering insight into how mechanical deformation affects superconducting performance, leading to a comprehensive framework for optimizing HTS materials for demanding applications.

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Low impedance REBCO coating for the Future Circular Collider beam screen**Author:** Guilherme Telles^{None}**Co-authors:** Joffre Gutierrez Royo ¹; Luca Benedetti ; Neil Lamas ²; Sergio Calatroni ³; TERESA Puig Molina ; Xavier Granados ²; irfan ahmed¹ ICMAB - CSIC² ICMAB-CSIC³ CERN**Corresponding Authors:** jgutierrez@icmab.es, gtelles@icmab.es, sergio.calatroni@cern.ch, teresa.puig@icmab.es, nlamas@icmab.es, granados@icmab.es, lbenedetti@icmab.es, iahmed@icmab.es

The Future Circular hadron Collider (FCC-hh), CERN's next generation particle accelerator, aims to reach a sevenfold increase in the center-of-mass collision energies when compared to those currently

achieved in the most powerful collider in the world, the Large Hadron Collider (LHC). In these machines, the synchrotron radiation emitted by the orbiting particles is absorbed by the beam screen, protecting the superconducting magnets from excessive heat. However, in the operating conditions of the FCC, i.e. temperatures between 40 and 60 K and magnetic fields of up to 14 T, the copper coating usually employed does not present a low enough surface impedance to avoid collective instabilities of the charged beams. Therefore, an alternative High Temperature Superconductor (HTS) coating is proposed.

In this work we make use of a REBCO coated conductor-based coating methodology to achieve the required beam coupling impedance for the FCC beam screen. The impact in the surrounding magnetic field quality of the screening currents induced in the HTS coating by the superconducting magnets is evaluated through finite elements numerical analysis, as well as the Lorentz forces and high thermal loads generated in the demanding conditions of the accelerator. Finally, we present a prototype of the HTS-coated beam screen for photon-stimulated desorption measurements produced by soldering and delaminating coated conductors, exposing the internal REBCO layer.

We acknowledge collaborations with M. Pont and O. Traver from ALBA synchrotron, Spain, and Y. Tanimoto from KEK, Japan.

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Accelerator Applications

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A comprehensive characterization of commercial pulsed laser deposited coated conductors

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Comprehensive understanding is needed in order for the commercial pulsed laser deposited REBCO coated conductors to be effectively used in the magnet and cable design. Here we demonstrate the superconducting property characterization and microstructural analysis to show how different or similar the 3 commercial REBCO coated conductors are at present. Our work shows that the ab-plane of REBCO tilts from the coated conductor tape plane, leading to the offset of critical current density peak from the tape plane. In particular, the offset angle varies from less than 0.5° for one coated conductor to close to 5° for another. RE₂O₃ nanoparticles are dominant pins at 20 K and 15 T. The weak pinning introduced by RE₂O₃ particles and cation disorders contribute to critical current density at 20 K as well.

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Cables for Magnets / 40

Measurement and FE modelling critical transverse loading limits of REBCO CORC®-like cables for fusion

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High magnetic fields of up to 20 T in tokamak-type fusion devices, such as in Central Solenoids of the European DEMO and the Chinese BEST fusion reactors, require High-Temperature Superconductors (HTS). Among the potential candidates, REBCO tape has emerged as a promising candidate. However, the substantial Lorentz forces in these environments can lead to localized mechanical stress concentration, which can irreversibly degrade the critical current of the superconductor.

In addressing this challenge, the Conductor On Round Core (CORC®) –like configuration appears as a viable solution to withstand these demanding operating conditions. The design of such cables requires comprehensive electromechanical characterization of REBCO tapes, CORC® cables, and finite element analysis (FEA). This presentation outlines the work conducted at the University of Twente to investigate these three aspects.

For the mechanical characterization of ReBCO tapes, two experiments were performed to examine the strain sensitivity of the critical current under tensile and compressive strains. Tapes from three different manufacturers were tested, and the results are presented.

The transverse load response of four CORC®-like cables was studied using the hydraulic Twente Cable Press. Sample holders was designed to resemble the loading conditions in the actual CORC®-CICCs. Measurements of the critical currents of individual tapes and contact resistances between tapes as functions of applied load and load cycling are shown together with their respective compression versus applied force behaviour.

Finally, results from a 3D FEM model are discussed. After validation against experimental data, the model is used to predict the performance of CORC®-like CICC samples in SULTAN and Twente Press. The model predictions are in good agreement with the experimental results, allowing for further conductor optimizations.

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Electromagnetic and Mechanical Properties 1 / 41

Recent topics on ac loss characteristics of Spiral Copper-plated Striated Coated-conductor cables (SCSC cables)

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The Spiral Copper-plated Striated Coated-conductor cable (SCSC cable) is our novel concept of high current cable with low ac loss, in which copper-plated multifilament (striated) coated conductors are wound spirally on a metal core in multiple layers. Whereas copper-plating allows current sharing among filaments against local defects in filaments, the spiral geometry of filaments decouples them against transverse ac magnetic field to reduce ac loss effectively. The structure of an SCSC cable, in which copper-plated filaments are spiraled, is like the structure of a conventional LTS wire, in which

filaments embedded in copper matrix are twisted. In this presentation, we report two recent topics on ac loss characteristics of SCSC cables.

The first topic is the estimation of ac losses under magnetic fields with various amplitudes and at various temperatures. We measured coupling losses of SCSC cables in a wide range of frequency up to 20 kHz at various temperatures. We can determine a coupling time constant from the peak of a coupling loss –frequency curve. Using determined coupling time constants, we can calculate coupling loss under the magnetic field with an arbitrary amplitude and at an arbitrary temperature. Meanwhile we found that the hysteresis loss of an SCSC cable can be calculated reasonably by using the formula by Brant and Indenbom for a filament with a correction factor for field orientation. Combining these methods for calculating coupling loss and hysteresis loss, we can estimate ac losses in various coils such as CS coils of tokamaks and beam bending magnets for synchrotron at various operating conditions.

The second topic is the enhancement of robustness against local defects in filaments. Multifilament coated conductors used in SCSC cables are with copper-plating, which allow current sharing among filaments so that a current can bypass a local defect in a filament. However, this current sharing through copper generates a finite voltage. We propose the use of multifilament coated conductors with inter-filament superconducting bridges, which allow current sharing without any resistance. The magnetization loss characteristic of this new type of SCSC cable is studied numerically and will be studied experimentally.

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Progress in Development of Electric Propulsion System for Aircraft by REBCO Superconducting Devices

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The superconducting technologies can be a solution for realization of electric propulsion system for aircraft with light weight, since the coated conductors have a high potential for the extremely high current density. In our previous works, we have key technologies to establish the superconducting propulsion system. Based on the background, we have been proposing the electric propulsion system including fully superconducting generator and motors which are connected by the superconducting cable. Additionally, the system will be operated in the liquid nitrogen temperature to obtain the thermal stability. A five-year project was started at FY2019 after the feasibility study. In this project, we have successfully fabricated a 400kW-class fully superconducting rotating machine. Through the evaluation as a motor mode, an actual rotation of 460rpm was confirmed. On the other hand, an actual power generation ability of 250kW was made sure. Additionally, an operation under the simulated aerial flight environment was taken place and it revealed no change of the performances on all stages.

Following on the above results, a new project was started. It will be ahead to scaling-up of the rotating machine, and verifying a system integration of fully superconducting generator, motor and

cable connecting these devices.

This work is based on results obtained from a project commissioned by NEDO and METI.

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Progress in Development of Coated Conductors for Electric Propulsion System of Aircraft

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The REBCO superconducting devices are expected to realize a lightweight & high-power electric propulsion system for aircraft. In our group, the propulsion system including generators, motors and cable by REBCO coated conductors is being developed. One of the features of the system is operation in the liquid nitrogen temperature. In order to realize the system, the high I_c performance even under the magnetic field in the liquid nitrogen are strongly required. Additionally, the low ac loss conductor is also necessary for the armature coils in a fully superconducting rotating machine. In the last national project, the development of the coated conductors for high $I_c(B)$ and low ac performances is included as one of the themes for the development for fundamental technologies of elemental functions.

The PLD and TFA-MOD process are being employed for the fabrication of the superconducting layers on the IBAD templates. By both approaches, the intermediate goal of the project (500A/cm@70K, 2.5T) was satisfied. Additionally, the laser-scribing technology was applied for filament structure in coated conductors to reduce AC loss. Actually, a 100m long scribed tape with 10-filaments was fabricated by using a pico-sec pulse laser to suppress the dross and it revealed 1/10 loss reduction and high $I_c(B)$ property.

This work is based on results obtained from a project commissioned by NEDO and METI.

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Progress in Development of Superconducting Cable for Electric Propulsion System of Aircraft

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The superconducting technologies can be a solution for realization of electric propulsion system for aircraft with light weight, since the coated conductors have a high potential for the extremely high current density. We have been proposing the electric propulsion system including fully superconducting generator and motors which are connected by the superconducting cable. In this presentation, a progress in development of the superconducting cable for the propulsion system will be shown. In the development of cable, a light-weight cable with prescribed current-carrying characteristics is aimed. According to an analysis for weight proportion in the cable for an electric power application, it was found that the proportion of the corrugated tubes are dominant. As a one approach to realize the lightweight in the cable, the stacked structures were selected as conductors by reducing the radius of the cable. It was confirmed that it is possible to fabricate 20 m-class cables using the stacked C.C. Reasonable current-carrying properties for both DC and AC were confirmed. Additionally, a new plastic material was applied to the corrugated cable as the other approach to reduce the cable weight. The cable revealed drastic weight reduction of 1/10 comparing those for electric power applications.

This work is based on results obtained from a project commissioned by NEDO and METI.

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Mechanical Characterization of REBCO CC layer materials at the microscale

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REBCO CCs, the leading candidate conductor for ultra-high field (UHF) magnets, have a laminar structure with thin layers of different materials. From a mechanical perspective, a single tape acts as a complex structure, as external loads distribute unevenly among material layers leading to intricate internal mechanics. Knowledge of the mechanical behavior of each material is of crucial importance for UHF magnet design, as it allows for the understanding of both the coils' behavior under loads and the nature of the degradation mechanisms, which lead to the conductor's limits. In this contribution, we present the mechanical characterization campaign we carried out on individual layer materials of a commercial REBCO CC, by exploiting established micromechanical measurement methods. The work is based on nanoindentation, micropillar compression, and micropillar splitting techniques, and it allowed for the measurement of the elastic, plastic, and fracture toughness properties of material

layers at the scale of the REBCO tape's constituents. The study, by linking the properties measured to the materials' microstructure, provides an overview of the internal mechanics of REBCO CC.

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Introduction / 51**Cryogenic and Superconducting Powertrain for Electric Aircraft Propulsion**

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Power and Mobility Applications / 52**Development, fabrication and test of the round, multi-layer RE-BCO cables of the Cold Powering Systems of the HL-LHC**

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The magnets of the High Luminosity Upgrade of the Large Hadron collider (HL-LHC) will be electrically connected through Cold Powering Systems incorporating superconducting, 100 kA class, power transmission lines to direct current (DC) power converters in service galleries. These transmission lines or 'Superconducting Links' are based on multi-circuit magnesium di-boride (MgB₂) cables in 74.5 m to 120 m long flexible, vacuum-insulated, cryostats. In the HL-LHC tunnel, the Superconducting Links are electrically connected to niobium-titanium cables in dedicated feedbox cryostats (DFX and DFM), operating at 4.5 K, that provide the cryogenic supply and the electrical connection to the HL-LHC magnets. In the service galleries, the MgB₂ cables of the Superconducting Links connect in the DFHX and DFHM feedbox cryostats through flexible, round, rare-earth-barium-copper-oxide (REBCO) cables to current leads. These REBCO cables with current ratings ranging from 0.6 to 18 kA bridge the 20 K to 60 K temperature gap and are essential for the cryogenic efficiency of the entire system.

We have established at CERN the cabling and quality control capabilities required to produce the REBCO cables of the HL-LHC Cold Powering Systems. In 2024, we have successfully completed the assembly and the electrical and cryogenic cold testing of the 1st full, 74.5 m long, system transporting combined currents of |94 kA| while cooled with a helium gas flow rate flow of ≤ 5 g/s.

We report on the cabling of the REBCO cables, the quality control process and results as well as on the cable performance during the cold test of the Cold Powering System.

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Understanding the Magnetisation of Striated REBCO Strands and the Implications for Assembled Cables

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While reduction of magnetisation losses is widely expected for striated REBCO strands, we show that the magnetic coupling among the filaments due to the high demagnetisation effect leads to a behaviour markedly different from the the proven strategy of lower losses by fine filaments. By establishing the concept of magnetic coupling using qualitative arguments, 1D analytical results and 2D numerical modelling are used to obtain the magnetisation quantitatively in agreement with experimental results and highlight that the ‘filaments’ in a striated strand are not a set of isolated filaments of Norris’ strips. We then explain that small random misalignments among the striated strands when assembled into a Roebel cable would alter significantly magnetic coupling within the stacks of strands and result in the ac loss behaviour observed experimentally.

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Advances and perspectives at Faraday Factory Japan

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Stable mass-production by Hot-Wall PLD approach for uniform REBCO wires and magnet applications

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Mass Production and Performance of SST REBCO Tape

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Advances and perspectives in HTS wire production at THEVA

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Advances and perspectives at SuperPower/Furukawa

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Improvement of in-field properties with PLD and progress in production scale-up at SuNAM

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ICMAB activities in the TLAG fast growth process

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HTS R&D at Ampeers - Houston University

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Recent topics on ac loss characteristics of Spiral Copper-plated Striated Coated-conductor cables (SCSC cables)

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HTS Magnet technology at Tokamak Energy

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Advances in HTS magnets for fusion at CFS

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Experience from the startup of SuperLink

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From 32 T to 40 T

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The progresses of the REBCO magnets with pancake coils for high field applications exceeding 20 T

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Cryogenic irradiation reduces radiation resistance of REBCO tapes

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UHF HTS properties measurements at LANL

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Analytical activities on HTS at CFS

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Progress and Opportunities of the Transient Liquid Assisted Growth (TLAG) method

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CONTRIBUTED - HTS materials and magnets R&D at Renaissance Fusion

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Advanced REBCO Conductor Development for Large-scale Deployment

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An overview of HTS high-current conductors tested in SULTAN

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Overview of EU efforts towards HTS accelerator magnets

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Construction Technology for the 10 T HTS Energy Saving Dipole Magnet of the Italian Facility IRIS

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HTS for high-power RF applications

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Studies, concepts and simulation tools for the protection of HTS magnets

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HTS dipole magnets for the muon collider

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Solenoids for the muon collider

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Winding of accelerator dipoles and quadropole magnets

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Development of 100kW superconducting propulsion unit for Zero Emission Sustainable Transportation

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The aviation industry has committed to a long-term global goal of net-zero carbon emissions by 2050. Zero Emission Sustainable Transportation 1 (ZEST1), which was funded by UK's Aerospace Technology Institute and consorted by 10 partners led by Airbus, aims to accelerate technology breakthroughs to enable zero emission commercial aircraft by 2030. Within the consortium, the University of Strathclyde is responsible for the delivery of a high-temperature superconducting (HTS) machine and its motor drive (two identical 100kW inverters in parallel connection). The motor, comprising two HTS stators and one HTS rotor, is designed to achieve a power density target of 15 kW/kg.

The HTS stator utilizes double-stacked HTS windings to increase current loading while maintaining relatively low AC losses. The HTS rotor incorporates a novel charging system that enables persistent-current operation with low-resistance soldered joints. Complementing the motor, the cryogenic drive system features three-phase IGBT switches with customized cryogenic gate drives.

The presentation will detail the latest advancements in motor and drive design, along with testing results for the customized cooling system, HTS stators, HTS rotor, and the cryogenic motor drive.

These developments represent significant progress toward achieving sustainable propulsion systems for future aviation.

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Power and Mobility applications

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SuperEMFL and latest developments at LNCMI

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The European Magnetic Field Laboratory (EMFL) gathers several infrastructures providing access to static resistive magnets (up to 38 T), pulsed non-destructive (up to 100 T) and semi-destructive (up to 200 T) magnets for all qualified European researchers.

The SuperEMFL project is a design study aiming at adding an entirely new dimension to the EMFL through the development of novel SC magnets, using high temperature superconductor (HTS) coated conductors. This is meant to be achieved by combining high temperature superconductor (HTS) insert magnets, a still emerging technology that can work in field above 25 T, with low temperature superconductor (LTS) outsert magnets, a more developed and commercial technology but limited in field below 25 T.

The project has two design magnetic field targets, 32+T and 40+T. The first design target proposed to combined a single stack of HTS pancakes in combination with a 19 T / 150 mm LTS magnet; the second can be reached with a similar arrangement at the sake of a narrower central space or by a design with two nested HTS coils combined with a 15 T/ 250 mm LTS magnet to maximise the central space for experiment and reduce mechanical constrains.

The particular choice of the project is to use no insulation but a metallic tape co-wound with the bare HTS tape. This so-called Metal as Insulation (MI) technology enables a self-protection feature of the HTS coil by allowing the electrical bypass of defects as well as better mechanical performances in a very compact winding.

The results of this project (HTS CC selection, insert design, HTS/LTS coupling model) are being used to implement such a magnet at LNCMI.

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High Field Applications

Conductor Manufacturing / 101**Progress in 2G-HTS Tape Development at High Temperature Superconductors, Inc. (HTSI)**

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The global demand for second generation high temperature superconducting (2G-HTS) tapes has significantly increased over the past few years, largely driven by applications such as fusion or rotating machines requiring moderate to strong magnetic fields. As the only 2G-HTS tape manufacturer in the U.S. employing Pulsed Laser Deposition (PLD) for the HTS layer, High Temperature Superconductors, Inc. is uniquely positioned to become the leading HTS tape supplier in the United States. Over the last three years, we have qualified a fully functioning buffer line utilizing IBAD (Ion Beam Assisted Deposition) for long-length tapes (up to 600 m), and made significant progress on shorter length, high quality superconducting tapes. Our superconductor performance meets typical industry requirements for power transmission (150 A for 4 mm wide tape at 77 K, self-field), and at high magnetic fields suitable for fusion magnets (20 K, 20 Tesla). At CCA, we will share the most recent status of our development and journey to long-length, large scale production.

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Advances and perspectives at SuperPower/Furukawa Electric

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SuperPower is now in the transition from small scale production to large scale production for REBCO HTS wires. This transition is driven by the increasing demand from a variety of applications such as HTS based compact fusion, high-field magnets, and electric machines. Over the last several years, we were focusing on advancing our manufacturing technologies and upgrading the processing systems. We completed our Phase I plan in 2023 for the first step production capacity expansion. At this time, we are working on further increase of our production capacity by increasing throughput and yield. Great efforts are also being made to continuously improve the performance and quality. The production of long-length REBCO wires with high performance and quality such as consistent critical current and uniform geometric dimension relies highly on the processing stability. We are making progresses in implementing more effective monitoring and control measures to stabilize the processing.

Continuous R&D efforts are being made at SuperPower on the further development of REBCO coated conductors, aiming at improved performance and specifically required functionalities. Following the widely adopted HM tapes, we are working on the development of a new REBCO formula that will have a further increase in in-field performance at high fields around 20K. Seeing an increasing demand, we will establish the manufacturing capability in-house for making filamentized tapes which is based on laser striation. We are also establishing the capability in-house for making insulated

tapes with polyimide coating. We are developing an alternative slitting technique for the improvement of the slit edge quality. In this talk, we will present an overview on the current status, our progresses, and our perspectives.

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Advanced REBCO Conductor Development for Large-scale Deployment

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Large-scale deployment of REBCO conductors requires overcoming several grand challenges: cost, throughput, critical current (I_c) uniformity, quench stability, mechanical robustness, neutron irradiation tolerance, and geometry. We have been developing advanced REBCO conductors and manufacturing processes to address these grand challenges. Using an Advanced MOCVD process, 50-meter-long tapes have been produced with a I_c over 1,270 A/4mm at 4.2 K, 20 T. In-line quality control methods such as 2D X-ray Diffraction, Raman Spectroscopy, and Machine Vision, coupled with Machine Learning techniques are being developed to assure consistency in REBCO film quality to maintain a high I_c over long tapes. Defect-tolerant REBCO tape architectures have been shown to enhance current sharing between tapes and result in better quench stability. Round REBCO STAR® wires made with unique tape architectures exhibit excellent bend performance; these wires are being used to construct compact, high-field insert coils for future accelerator magnets. Our progress and outlook in the development of advanced REBCO conductors will be discussed in this presentation.

This work was supported by awards from the U.S. Department of Energy and the U.S. Navy.

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Conductor Material Research

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Coated Conductors and their Applications for Compact Fusion

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Next-step US spherical tokamak test facilities and/or compact stellarators configured as fusion pilot plants (FPP) to support fusion commercialization are recommended options by multiple recent consensus studies. The goal for a FPP is to make 50-100 MW net electricity power plants with either extended long pulses or steady state options. Significant HTS conductor and coil technology efforts are underway by privately funded startups with the goal to demonstrate mature REBCO magnet

technology. Test results, however, indicate critical issues remained to meet performance goals, and demonstrate coil operation repeatability and reliability. Maturing affordable and reliable HTS cables is critical for enabling next generation fusion magnets beyond ITER with advances in conductor materials, HTS coil manufacturing, and diagnostic sensors. To integrate HTS characterization into the design, fabrication, testing of high current cables to validate coil technologies, low loss, simpler ohmic heating coil module is investigated and developed for next step compact tokamak devices. High current density cables are required for the design of FPP magnets to allow space for interior plasma components. High current cables are also critical for next generation accelerators in HEP and high field magnets for fundamental sciences such as Muon colliders, Axion search in cosmic frontiers & commercial MRI/NMR applications.

The coated conductor options for ohmic heating (OH) magnets will be summarized to demonstrate its capability to achieve 100 A/mm² current density desired in a high field OH insert module for compact fusion. Recent studies show that a REBCO insert wound with coated conductors meet physics requirements for plasma startups of the spherical tokamak advanced reactor (STAR). Advanced Ic inspection methods for coated conductor characterization and detailed assessment of AC losses during coil current ramping, cooling capability during quench, and expected coil fatigue performance under cyclic loading will be presented.

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Fusion Applications

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Reduced-Order Models for Superconducting Accelerator Magnets: experimental evaluation

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Advanced automation tools offer promising solutions to a wide range of challenges still affecting High-Temperature Superconducting (HTS) magnets, including Non-Insulated (NI) ones. State-of-the-art techniques have the potential to enable online monitoring and control of these devices, significantly enhancing their operational robustness to the extent of entirely preventing quench events. However, the implementation of such tools requires reliable models capable of running in real-time. To address this, we recently proposed a technique for constructing reduced-order models derived from 3D physics-based models. This reduced model of the as-built device can replicate the behavior of the full model under operational conditions at a fraction of the computational cost.

We have now conducted an initial experimental campaign to validate the model, the methodology, and the selected measurement system. The test specimen is a small racetrack coil made of insulated REBCO tape, tested in a liquid nitrogen bath. This presentation highlights the initial outcomes of this campaign and provides insight into the upcoming developments in this research activity.

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Comparison of the angular dependence of the critical current in commercial REBCO tapes for high-field applications

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As part of an international collaboration between the University of Geneva (UNIGE) and Tohoku University, five commercial REBCO tapes produced by leading manufacturers were tested with the objective of extensively characterizing their critical current, I_c , dependence on field intensity, orientation and temperature. At UNIGE, full-width tapes were measured at 4.2K, 20K and 40K over 5 fixed angles (from 0° to 90°), and with magnetic field from 0T to 19T. The second part of the campaign, conducted at Tohoku University, involved patterned tapes with microbridges (30 μ m width, 1mm length). These samples were measured at the same temperatures, plus 10K, 55K and 77K at 20 angles (from -20° to 115°) and magnetic field from 1T to 24T, using an in-field rotating set-up. This study presents also an analysis of the anisotropy of I_c and the scaling behaviour of the pinning forces. Results highlight significant variations in these quantities between manufacturers, reflecting differences in processing methods, layer thicknesses and pinning centers. It may offer a valuable dataset for manufacturers and magnet designers aiming to optimize the next generation of high-field magnets.

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Mass Production and Performance of SST REBCO Tape

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With the beneficial characteristics of high irreversible field, high superconducting transition temperature and high critical current density, REBCO material has reached the stage of mass commercial production. Meanwhile a large number of superconducting power transmission projects and superconducting magnets have been developed using REBCO tapes. Recently, due to the significant demand for REBCO tapes by compact fusion industry, Shanghai Superconductor Technology Co., Ltd. (SST) has kicked off a new round of production expansion. Through independent design and manufacturing, SST has swiftly built a large number of vacuum coating equipment and post-processing equipment, including MS, IBAD, PLD, slitting, copper-plating, lamination and so on. This production expansion targets to further reduce the fabrication cost and improve the performance of REBCO tapes, providing a consistent supply of high performance tapes for downstream applications. By the end of 2023, the SST's annual REBCO supply has reached 2000 km/12 mm, and will be further expanded to 4000 km/12 mm in 2025. Along with the production expansion, SST also carries out researches extensively on tape customization and problem solving for specific application scenarios, covering laser slitting, stainless steel lamination, insulation coating, low resistance joints, continuous online thickness measurement techniques, and superconducting coil winding technologies, to

help customers meet their technical requirements and achieve a successful project using SST's REBCO products. This paper will focus on the industrialization and R&D progress that SST has recently achieved.

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Conductor Manufacturing

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Winding of accelerator magnets

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REBCO tapes have large stress resistance if loaded along certain directions but give poor results if stressed along other paths. Shear or traction can cause cracks in the superconducting material or a delamination of the tape layers. The mechanical structures to contain the coils during assembly at room temperature, cooling and powering are designed to prevent dangerous stresses in the tapes. But this is not enough, during the coil manufacturing unacceptable defects can be introduced by wrong handling.

This presentation will focus on the coil construction, the first step in the magnet fabrication sequence. A conform winding requires the mastering of specific manufacturing techniques and the control of important practical aspects. Some of the key parameters can be computed in advance, others, the majority, must be defined by tests and trials. The design of the coil components and of the manufacturing tools must be sound to avoid accidental loads that could impair the performances of the conductor.

Tapes are currently wound in flat, round or racetrack configurations. Then, these elements can be assembled in groups to obtain common coil dipoles, CCT dipoles, quadrupoles, or higher order correctors. For the time being, the freedom in the definition of the coil shapes is limited by the need of not over-stressing the tapes.

Session:

Accelerator Applications

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An overview of HTS high-current conductors tested in SULTAN

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In the past decade, a variety of HTS high-current fusion conductors, manufactured at SPC or provided by external partners, have been measured in SULTAN. Similar to LTS CICC, their cross-section is mostly occupied by copper and steel. However, the choice of cooling conditions, transposition

methods, and mechanical support is less straightforward due to the specific features of HTS materials, such as high thermal stability, large aspect ratio, and strong mechanical and electrical anisotropy. For example, faster quench propagation and simplified quench detection can be achieved by weak cooling, thus eliminating the need for forced-flow helium cooling in certain applications. In this regard, the design of HTS conductors is strongly affected by mechanical, electrical, magnetic, and thermal requirements, which often counter act one another. In this work, we will present the key results obtained on the HTS SULTAN samples, including performance degradation due to Lorentz forces, AC losses, and quench characteristics, and attempt to assess how well the samples meet their target applications. To better illustrate the importance of application requirements, we will particularly focus on a conductor layout based on indirectly cooled non-transposed soldered REBCO tapes, designed for in-situ wound TF coils of the VNS tokamak by EUROfusion and tested in SULTAN up to ~ 1200 kN/m as a 20-turn flat racetrack coil.

Session:

Cables for magnets

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Measurements of the Electromechanical Delamination Strength of REBCO CCs Under Lorentz Force: the Numerical Modeling

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The feeble adhesion strength between layers of REBCO Coated Conductors (CCs) represents a major concern for magnet design because of the low allowable tensile stress through the interfaces. At the University of Geneva, an experiment is ongoing to study the electromechanical delamination strength (EDS) of REBCO tapes under Lorentz forces, replicating closely the behavior of a conductor in an operating magnet configuration. In this study, we report on the numerical analyses that accompany the experimental campaign, both in the design evolution of the hardware and in the interpretation of the results. After introducing the experiment, we analyze the stress state inside the REBCO layer when subjected to Lorentz forces, evaluating the impact of modeling approximations and experimental uncertainties. We then highlight the limiting factors and considerations that led to a new sample holder, assessing the improvements in terms of stress state in the superconductor. Finally, we present the interpretation of the experimental results through the numerical models, linking the observables of the experiment, i.e. critical current and degradation current, to the measured EDS of the REBCO CCs.

Session:

EM & Mechanical Properties

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Change of performance of superconductors under radiation

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Predicting the change of performance of superconductors under radiation is indispensable for designing compact fusion devices. Various commercial coated conductors were exposed to thermal and/or fast neutrons, as well as 1.2 MeV protons. The favorable enhancement of the critical current caused by flux pinning on the introduced defects is separated from the adverse effect of increased scattering of charge carriers. The degradation of the critical current turned out to be universal if quantified by the decrease in transition temperature, since both have the same physical origin: pair breaking by scattering. It does not depend on the particular tape nor the particle radiation and is modelled quantitatively using the expected change of the superfluid density and the observed increase in flux creep. The derived relation between superfluid density and transition temperature reduces to Homes' law in the dirty limit.

The degradation function enables an analysis of changes in flux pinning corrected by the adverse enhancement of scattering that always occurs simultaneously with the introduction of defects not only by radiation but also intentionally for an optimization of the critical currents. A more reliable prediction of the performance change of coated conductors in fusion magnets based on proxies for the real radiation environment is anticipated.

Session:

EM & Mechanical Properties

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KC4 status and perspectives

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Coated conductors (CC) are becoming increasingly promising candidates for both power and magnet applications, but the cost remains an issue. CC production still has many open development areas that require improvement, including yield, mechanical issues, production of thin conductors, electromechanical properties of full conductors, and AC losses. Specific CC properties/architectures are often necessary for each application (such as magnetic field and temperature dependence of critical current, AC properties, stabilization, mechanical properties, insulation etc.). New scientific ideas frequently necessitate just a few hundred meters of highly specific CC, which are hard to obtain from commercial vendors, due to the industry's need to concentrate on just a few CC variants to enable economic production. In Europe, there is currently no independent public research institution that can bridge the gap between small-scale basic materials research on PLD-based CC and larger-scale

industrial synthesis, while also providing tailored, high-quality CC for 100 m+ classes that are designed specifically for the customer needs. KIT and CERN established a joint, open HTS CC synthesis lab, which will bridge the gap between small scale materials research on CC and larger scale component requirement of tailored, high quality CC architectures in sufficiently long length. KC4 will focus on R&D CC issues, not on low-cost CC production, and will address specific CC architectures required for CERN and KIT projects. Possible goals of production line are, for example, investigation of scaling laws to transfer small-scale PLD materials development results towards larger scale CC production systems, and development full CC architectures with better electro-mechanical, thermal, or internal properties like mechanical stability, interfacial electrical and thermal resistances. First successful depositions of longer and wider tapes with highly homogeneous critical current distribution, mechanical test results, first successful pinning experiments, and interfacial resistance measurements are presented.

Session:

Conductor Material Research

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Studies, concepts and simulation tools for the protection of HTS magnets

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Protection of LTS magnets has been studied for decades, and simulation models are now available that are used to assess protectability during the design phase and provide results in good agreement with experimental data. Most high-field LTS magnets rely on energy extraction, quench heaters, coupling-loss induced quench (CLIQ) units or a combination of these methods. Typically, 2D or 2D+1D network or finite element models, combined with appropriate conductor homogenisation, can be solved relatively fast.

Protection concepts and simulation tools for HTS magnets, especially when wound from (cabled) tapes, require a completely different approach. Novel quench detection and protection methods are envisaged to reduce the detection time and increase the normal zone propagation speed in case of a quench. The modelling of HTS tapes and magnets is also much more challenging. First, due to the slow quench propagation, 3D simulations are often required. Second, the highly anisotropic behaviour of the tape makes homogenisation difficult. Third, the optional metal-insulated (MI) or non-insulated (NI) coil design creates additional turn-to-turn current paths that must be modelled on a microscopic scale due to the anisotropic nature of the tape. Fourth, due to very large magnetisation effects and possible turn-to-turn currents, the local Lorentz force can increase significantly during a quench, requiring co-simulation between thermo-electro-magnetic and mechanical models.

This talk will give an overview of the studies, concepts and simulation tools that are being developed in the TE-MPE group at CERN, in view of the use of HTS magnets for possible future accelerators such as the FCC or a muon collider. Several simulation tools developed as part of the STEAM framework are presented, covering a variety of insulated and NI/MI magnet types. Methods to reduce

the computational cost, such as conductor homogenisation and thin-shell approximation, are highlighted. Finally, capacitive discharge and more efficient variants of CLIQ are being discussed as promising new protection methods.

Session:

Accelerator Applications

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HTS for Lepton Particle Collider Detectors: 3 T Solenoid Design for the IDEA project

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The high-energy particle physics community is exploring particle detector designs for electron-positron collisions at the Future Circular Collider (FCC-ee). Current proposals for the main experiments (CLD and IDEA detectors) include a 2 T solenoidal superconducting magnet based on aluminum-stabilized NbTi Rutherford cables, optimized for minimal material impact on particle trajectories and high energy resolution. A new design, Developed at INFN LASA, featuring a 3 T high-temperature superconductor (HTS) solenoid operating above 20 K to accommodate improved calorimeter configurations and drastically reduce the cryogenic power consumption enhancing the sustainability of the accelerator facility, is here presented and discussed. Based on aluminum-stabilized HTS conductors, the new design ensures excellent stability and safe quench performance. A preliminary mechanical analysis is discussed while the solenoid's transparency calculation is compared to LTS design showing high-temperature superconductors as a viable option for lepton particle detectors and future particle physics collider experiments.

Session:

Accelerator Applications

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HTS fusion in China

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Due to their higher critical current and lower cooling cost, HTS magnet are being increasingly adopted in fusion device. HTS magnets can realize 20 T level high magnetic field, a crucial factor for controlling the high temperature plasma and enhancing fusion power. Extensive researches on HTS fusion are underway at various institutions and companies, which are aiming for validating the performance of HTS magnet under fusion operating conditions.

Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) is now focusing on the large-scale

hybrid superconducting central solenoid coil for the new-generation compact fusion device, capable of achieving a 19.6 T magnetic field in the inner HTS magnet, which is wound with HTS CICC conductor with an operating current of 46.5kA. It can generate about 55 voltage-second to realize easier plasma discharge. To realize higher current capacity and improve preparation process of HTS conductor, ASIPP is currently developing the new TMMC conductor, which simplifies the preparation process by removing the need for soldering and twisting. TMMC conductor can realize better anisotropic properties and suppress the AC loss during fast current ramping rate, which is capable of achieving 50 kA@20T, 4.2 K. Based on TMMC conductor, ASIPP is working on the 21 T D-shape HTS fusion magnet, which is designed to be operated at 25 kA and total stored energy is about 94 MJ. It is aiming to be used on the next-generation high-field compact fusion reactors. Considering the critical performance degradation of HTS magnet under fusion D-T discharge irradiation conditions, ASIPP has carried out a series of pioneering research work on the damage formation mechanism and critical characteristics evolution process of HTS materials, and scaling-law of REBCO under stress and irradiation has been corrected. It has laid a theoretical foundation for the development and safe operation of large-scale HTS fusion magnets for fusion reactors.

In the research of small-scale HTS fusion devices, Energy Singularity Company in China has designed the world's first full HTS tokamak-HH70 (6.8 m height, 3.6m outer diameter, 1 T toroidal magnetic field @ R=0.7m). It has successfully achieved its plasma discharge in 2024. The Startorus Fusion, based in Xi'an, China, is cooperating with Tsinghua University on the development of a full-HTS Spherical tokamak device. They achieved first plasma based on the SUNIST-2. Currently, they are working on the world's first Negative Triangularity Spherical Tokamak (NTST), characterized by a 1 T magnetic field and a plasma center radius of 0.4 m radius at plasma center. Meanwhile, the R&D work on 3 T D-shaped TF magnets is also in progress.

Session:

Fusion Applications

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Nanostructure investigation of the integrity of buffer layers in commercially available coated conductors via transmission electron microscopy**Author:** Yan Xin¹**Co-authors:** Aixia Xu¹; Fumitake Kametani¹; David Larbalestier¹¹ FSU**Corresponding Authors:** yxin@fsu.edu, larbalestier@asc.magnet.fsu.edu, ax07@fsu.edu, kametani@asc.magnet.fsu.edu

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Presenter: Yan Xin
Proposed area of relevance: Conductor Materials Research

Due to the large demand for fusion applications, there has been great commercial interests and investments in REBCO coated conductors (CCs). For fusion magnet applications, the mechanical strength at the interfaces of constituent layers along the tape surface, so-called the delamination strength, is critically important. The delamination of REBCO's layered structure causes rapid crack propagation in the REBCO layer, resulting in sharp degradation of the critical currents that leads to failure of the magnets. There are several extensive investigations of delamination of CC tapes, all of which have shown the complexity and strong variability of this issue, mainly because we lack the fundamental understanding on the nanostructure features at the interfaces of the constituent layers in CCs. In this presentation, we will present the nanostructure investigation of the buffer layers and their interfaces to compare the variability of nanostructural integrity in the commercially available CC tapes. Our transmission electron microscope (TEM) analysis of the buffer layer nanostructures provides clear insights on the nanostructural cause of the delamination strength at the buffer layer interfaces. More details will be discussed at the presentation.

Acknowledgement

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Session:

EM & Mechanical Properties

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A Review of the Current State-of-the-Art REBCO Production and Performance

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Area: Conductor Manufacturing

The evolution of high-temperature superconductors (HTS) has been a cornerstone of applied superconductivity, with significant progress achieved since the introduction of rare-earth barium copper oxide (ReBCO) tapes in 1987. This paper explores advancements in HTS manufacturing techniques and performance enhancement strategies, as well as, the production process overview, current efficiency and growth of current density (Jc) performance.

The paper will analyze current production speed, bottlenecks, and quality hindrances, leading to a review of the current manufacturing market and future outlook. We list the current manufacturers, as well as, pricing trends.

The paper allows for a focused examination of ReBCO technologies' manufacturing and application challenges, in order to provide insights and a greater understanding of ReBCO development opportunities and outlook for HTS-based infrastructure projects.

Session:

Conductor Manufacturing

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Defect-Tolerant CORC® Cables and Coils Through Engineered Enhanced Current Sharing

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With the increasing interest in REBCO-coated conductors for various power, energy, and magnet applications, ensuring the reliability of superconducting devices based on these conductors has become a significant focus. The inherently fragile nature, high electrical resistance of the substrate, and low quench propagation velocities of REBCO-coated conductors make devices vulnerable to degradation under the electromagnetic and thermal stresses of high current and high-field operation when single tape conductors are employed.

Conductors can be bundled into cables and wires with engineered current sharing and improved mechanical strength or reinforcement to address these challenges and enhance device reliability. We utilized the Conductor On Round Core (CORC®) geometry to engineer improved current sharing among the REBCO conductors, creating robust conductors suitable for applications such as electrical motors, high-field magnets, power cables, and fusion power plant magnets.

We successfully demonstrated current sharing by fabricating long CORC® cables using both defective and defect-free coated conductors. These cables were used to construct magnet coils operating at 20 K to 76 K. The cables and coils with defective conductors performed well, with the additional heat loads from current sharing estimated from the measured voltages amounting to just a few milliwatts.

This paper will discuss the conductors used, the design of cables and coils, and the results of critical current tests. The engineered enhanced current sharing will bolster the reliability of these devices by addressing both manufacturing defects and those that may arise from operational fatigue due to electromagnetic and thermal stresses. The successfully engineered enhanced current sharing will improve the reliability of the devices by mitigating the defects at the conductor manufacturing stage and the defects that will inevitably be created due to the operational fatigue of electromagnetic and thermal stresses.

Contributor:

Session:

Cables for magnets

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Optimization of transport critical currents at 4.2K –20K at magnetic fields up to 31T for MOCVD REBCO conductors with variable Zr and growth conditions.

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Several companies have used ReBCO conductors to make plasma-confining magnets operating at 20K and up to 20 T. The transport properties of ReBCO conductors should be optimized for such conditions. We measured in-field I_c at a fixed orientation close to its lowest value and correlated it with the structure observed by SEM to find the origins of variability. We tested transport $I_c(4.2K, B)$ in LHe bath, $I_c(T, B)$ in He gas up to 15T with a superconducting magnet, and $I_c(T, B)$ in resistive magnet up to 31T for 4 mm wide short samples. We observed correlations of REBCO growth conditions with I_c , lift factor, and slopes of I_c vs. B (α -values) from a set of values of $I_c(4.2K, B)$ measured up to 31T. From these correlations, we detected optimum growth conditions for maximum I_c and J_c at 20T in tapes with 20% and 25% Zr doping. Pinning force density (F_p) in the range 1500-1750 GN/m³ was observed at 4.2K; 6-31T for tapes with 20%, 25% Zr. Experiments with variable temperature probe used up to 15T suggested that in-field $I_c(20K, 15T)$ values for 15% Zr doped tapes are comparable with I_c for higher doped tapes (20%, 25%). We found a growth condition yielding maximum $J_c(20K, 15T)$ for tapes with 25% Zr. Experiments with miniature variable temperature probes for 31T resistive magnet are the most direct way of getting $I_c(20K, 20T)$. As found from 10 tested samples, tapes with 20% and 25% Zr doping have higher $I_c(20K, 20T)$ than most tested 15% Zr-doped tapes with the same REBCO thicknesses. Ranges of $I_c(20K, 20T)$ are 236 A- 275 A for 20%-20% Zr doped tapes and 156 A -240 A for 7.5%-15% Zr doped. There is a good correlation between $I_c(20K, 14T)$ and $I_c(20K, 20T)$ for tested tapes. At 20K, tapes with 20% and 25% Zr show F_p between 400-900 GN/m³. We detected splitting in correlations between $J_c(20K, 20T)$ and slopes α between tapes with 7.5-15% Zr and 20-25% Zr. Ranges of $J_c(20K, 20T)$ are 2.2-4.02 MA/cm² for 7.5%-15% Zr and 3.54-4.27 MA/cm² for 20%-25% Zr. Tapes with 20%-25% Zr have higher average $J_c(20K, 20T)$; therefore, using 20% or 25% Zr doped tapes is more promising for applications at 20K, 20T.

Acknowledgments

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Session:

Conductor Material Research

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Improvement of in-field properties with PLD and progress in production scale-up at SuNAM

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With the proprietary high throughput capability of the Reactive Co-evaporation-Deposition and Reaction (RCE-DR) process, SuNAM has provided Coated Conductors(CC) for many applications, especially grid applications in a cost effective manner. As great demand arose from compact fusion application, we achieved improved in-field critical current by incorporating pinning centers in RCE-DR, but to our disappointment, it does not reach the value required by the fusion reactor.

We've set up PLD system to address the problem and we're in the final stages of optimization before the mass production of the qualified CCs. Here we report how we optimized the process using electrical, micro-structural data as well as a variety of parameters we're engaged with. We also present our efforts to further reduce the cost; wider-web process and process automation through machine learning.

Part of this work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2022M3I9A1076681).

Session:

Conductor Manufacturing

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Superconductivity Global Alliance

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Area: High Field Applications

The Superconductivity Global Alliance (ScGA) is a community of institutes and companies in the superconducting domain that aim to increase the adoption of superconducting technologies and applications. The alliance's main goals are to A. Establish a stronger superconductivity community, B. Plan with big industry for R&D developments, C. Incentivize expanded public and private funding opportunities, all while contributing heavily to the UN SDG 17 goals for a more sustainable future.

With over 140 members globally, including industry, universities, and research institutes, the ScGA works on expanding superconducting applications in fusion, energy & power, transport, healthcare, electronics & quantum, science discovery, and material applications.

After publishing white papers highlighting development challenges in these superconducting application domains, the ScGA now plans to create global events, pulling the community together to expand efforts toward a common goal.

Session:

Accelerator Applications

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Study of jointless coils for fully superconducting magnetic bearings

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Commonly used superconducting magnetic bearings (SMB) are built from bulk superconductors and permanent magnets. In general, the levitation force of a SMB is determined by the magnetic flux density applied to the superconductor and its spatial gradient. When using permanent magnets, the levitation force is limited due to their confined field generating capabilities. To overcome this limitation, a fully superconducting magnetic bearing was designed combining a passive levitating coil with an active stationary coil, both made from coated conductors. The active coil is powered by a superconducting dynamo to minimize losses. Therefore, a short circuit coil is required, which might be realized as a wind and flip coil to avoid unfavorable normal conducting joints.

To test the design, small wind and flip coils were produced with tapes from different coated conductor

manufactures and charged afterwards with a superconducting dynamo to determine the generated magnetic flux density in the coil center. Additional simulations were used to estimate the maximum magnetic field. The simulations were carried out for different operation temperatures between 77 K and 20 K using the coated conductor data from the public HTS wire database. The simulations indicate a maximal flux density up to 4 T inside a coil with 20 mm inner diameter, 30 mm outer diameter using a stack of four 6 mm wide layers. The test coils formed a first fully SMB together with a cylindrical bulk superconductor. This bearing featured a low magnetic field decay after charging. The levitation force is stable after an initial magnetization of the coil but increases for a magnetization with opposite polarity, similar to a conventional SMB under lateral displacement.

For further tests, a larger prototype of the fully SMB was built. This prototype included conventional double pancake coils in the active stator and open coils in the passive rotor. The conventional coil design was necessary since the first wind and flip coils degraded over time due to unprotected slit surfaces. With this prototype, first levitation force measurements were made and the stability of the force magnitude was studied. The magnetic field in the prototype coil was less stable due to the incorporated normal conducting joint. However, the realized magnetic field was higher and therefore levitation forces increased in comparison to the jointless test coil.

Session:

Power and Mobility applications

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Advances and perspectives at Faraday Factory Japan

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Faraday Factory Japan (FFJ) has been evolving to reflect and adapt to the evolution of the HTS applications market. In 2019-2024, an explosion of demand on HTS tape occurred thanks to one major customer, CFS, placing two consecutive major orders that completely dominated the market: one for TFMC and the other for SPARC. The successful tests of TFMC demonstrating over 20 T magnetic field at 20 K, at fusion-relevant size, generated huge investments into high-field compact fusion. This revitalised interest to other HTS applications because with the recently increased production volumes the price on HTS tape started to decrease.

In 2025, a significant change in the HTS market landscape is going to happen: a transition from one major project/customer to several medium- to large-scale projects, with prospects to develop into several huge projects. As new large-scale projects appear, the demand on HTS tape will exceed worldwide supply drastically. This highly probable scenario dictates creating strategic partnerships between customers and HTS suppliers, in order to increase the security of future supply.

Over the past five years, FFJ has increased HTS tape production 20 times. At present, the installed production capacity is over 1,000 km of QA-passed 12 mm wide tape, or over 3,000 km of QA-passed 4 mm wide tape. As of Q1-2025, 100% of the installed capacity for 2025 has been committed, and we are actively negotiating our 2026 production. In case of a moderate additional demand, FFJ can quickly commission additional capacity, which is approximately 50% of the currently installed one. To satisfy the probable significantly larger demand, new investment and approximately 2-year lead time for creating new capacity are required.

In line with the market evolution, FFJ is diversifying HTS tape offer, to include REBCO formulations optimised for low temperature and high magnetic field and for applications at 77 K, and face-to-face stacks of two HTS tapes for improved I_c defect tolerance, mechanical strength and production yield. Our R&D activities are aimed at the continuous improvement of production efficiency and development of new products tailored to specific applications such as, for example, HTS cables and aerospace.

Session:

Conductor Manufacturing

Accelerator Magnet Applications / 125**HTS for high-power RF applications**

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Niobium-based materials have been extremely useful for superconducting RF technology but require low temperature operation. High-Temperature Superconductors (HTS) in the form of Coated Conductors (CCs) soldered to suitable substrates have already proven their potential for selected applications (RF cavities for axion dark-matter detection, beam coupling impedance control for colliders). This work aims to determine the high-power RF performance of HTS at X-band (11.424 GHz). We have tested several types of REBCO HTS materials, such as films deposited by electron-beam physical vapor deposition, CCs soldered to a copper substrate, and solid pucks formed from powder. RF testing was done via a hemispherical TE mode cavity that maximizes the magnetic field and minimizes the electric field on a 2-inch sample region. We report on first HTS measurements at low and high power, and will discuss future experimental plans and strategies, and potential short- and long-term applications.

Session:

Accelerator Applications

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Energy Saving Magnet Design for Next-Generation Particle Accelerators

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The energy consumption of large research centers like CERN represents a critical challenge for particle accelerators' development and sustainability. High-temperature superconducting (HTS) materials improve energy efficiency, operating at higher temperatures compared to LTS conductors, reducing cooling requirements. Superferric magnets, with their iron yoke-based design, simplify assembly and lower costs, enabling sustainable and cost-efficient solutions for future development.

The ESABLiM project focuses on designing superferric MgB₂ or HTS magnet for high-energy, low-field accelerators, replacing high-demand resistive magnets to enhance energy efficiency and affordability. This technology suits existing facilities like CNAO and PSI, potentially making heavy-ion accelerators for medical use more accessible.

For the FCC-ee design study, superferric HTS magnets are explored for quadrupoles and sextupoles to reduce magnet length, increase the collider dipole filling factor, and improve luminosity. A combined quadrupole-sextupole magnet optimizes field quality, independent gradient tuning, and HTS material use, cutting costs while meeting performance requirements for the beam dynamic.

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The technological development of HTS conductors for fusion in the EU-DEMO programme

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Within the EU-DEMO programme an extensive R&D is carried out on HTS conductors for their application in magnets for fusion.

The quench initiation and propagation in different conditions in REBCO conductors have been studied in a 4-years long experimental campaign on seven 15kA-class samples. Tests were successfully carried out in SULTAN facility and the results show that a temperature peak beyond 150 K on the stack of REBCO tapes may lead to the degradation of the conductor DC behavior. Moreover, conductors with a large effective heat capacity are more promising in terms of expected performance in the EU-DEMO Central Solenoid.

Also, full-scale conductors, designed to operate at a current of 60 kA, a peak field of 18 T, an inlet temperature of 4.5 K and a minimum bending radius of 1.5 m, have been manufactured and some of them have been tested to assess the DC performances with electro-magnetic and thermal cycles, as well as the AC losses.

The programme is also supporting experiments on neutron irradiation of HTS tapes under different conditions, addressed to future power plants that could potentially involve HTS conductors in Toroidal Field coils.

On behalf of the Magnet System Work Package team, I will present a brief outline on the development programme of HTS conductors covered in the EU-DEMO project and its strategic interest for fusion.

Session:

Introduction

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Electromagnetic and Mechanical Properties of Edge-impregnated REBCO Coils under High Magnetic Field

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The electromagnetic stress induced with a high current density and a high magnetic field are one of the serious issues in high field superconducting magnet. We have investigated a “Robust coil concept” based on the edge-impregnation with REBCO coated conductors, for a high field cryogen-free superconducting magnet beyond 30 T. The hoop stress distribution can be modified by the edge-impregnation, resulting in the reduction of the maximum hoop stress in the coil. It has been demonstrated in some R&D REBCO coils in the recent decade. In particular, we achieved 25 T under a background field of 14 T with a large scale 20 stacked REBCO prototype pancake coils with a 266 mm in outer diameter. In this case, the reduction of induced strain of the coil was confirmed from 0.31% in BJR to 0.27% experimentally [1]. A 19 T REBCO insert coil for a 33T cryogen-free superconducting magnet (33T-CSM) was designed based on the Robust coil concept and is now under construction [2, 3]. The inner/outer diameters and the height of the 19T REBCO insert coil is 68 mm/300 mm and 300 mm, respectively. The number of single pancakes is 64. The central magnetic field of 19 T can be achieved with 367 A under the background field of 14 T by the LTS outsert under conduction cooling conditions. The maximum hoop strain at the nominal current is estimated to be about 0.29%. The detailed mechanical design strategy will be presented for the 33T-CSM.

[1] K. Takahashi et al., IEEE TAS, 33 (2023) 4601405

[2] T. Uto et al., IEEE TAS in press (DOI: 10.1109/TASC.2024.3524490)

[3] S. Awaji et al., IEEE TAS in press (DOI: 10.1109/TASC.2025.3525608)

Session:

EM & Mechanical Properties

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A comprehensive scaling law for REBCO tapes confirmed by experimental testing

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In this work, we propose and validate a formulation of a scaling law to describe the magnetic field dependence of REBCO tapes from the milli Tesla range up to the irreversibility field, at variable temperatures. The validation of this law was conducted by means of an experimental campaign of testing REBCO tapes from different manufacturers.

Measurements of critical current were done via transport and magnetization methods. Matching of the two methods allows inferring the critical current as a function of field and temperature. A database of the resulting scaling parameters of tapes is currently being launched. Different as well as common patterns in the temperature dependence of the scaling parameters among various manufacturers have been identified and analytical expressions to extend the scaling law to the temperature domain from 4.2 K up to T_c are put forward.

The variations of the scaling law parameters and their temperature dependences could be helpful in further performance optimization, through correlation with the material science and production techniques of the different manufacturers.

Additionally, we propose including the angular scaling by adopting a two-peak description. Measurements to validate such scaling are being conducted in liquid nitrogen, at 77 K, by exposing the tapes

to background fields below 1 T using permanent magnets, as well as in liquid helium, at 4.2 K, up to 15 T in a solenoid facility available at CERN. Both the perpendicular and parallel field orientations are tested using a set innovative sample holders.

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STUDIES AND MEASUREMENTS ON A HTS REBCO TAPE SMALL RACETRACK COIL IN LN₂

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REBCO tapes are highly promising conductors for various applications but remain incompletely understood both theoretically and experimentally. As part of the PNRR-IRIS project, now in its final phase, a 10-T cryogen-free dipole magnet demonstrator, ESMA (Energy Saving Magnet for Accelerators), is being designed and manufactured using HTS technology.

To support ESMA development and improve the understanding of REBCO tapes in practical winding applications for future accelerators, an experimental campaign is underway. This involves validating the performance of a 12-mm Faraday Factory Japan (FFJ) REBCO tape through small-sample testing, racetrack coil production, and LN₂-based tests. These tests include coil charging, discharging at varying rates, transition measurements to the Normal Conducting (NC) state, and overcurrent powering, performed multiple times across several thermal cycles.

Measurement data have been collected using voltage taps, Hall probes, and temperature sensors and then compared with calculated margins and central field values. The findings, along with details of the coil design and manufacturing process, will be presented and analysed in the presentation.

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Accelerator Applications

Electromagnetic and Mechanical Properties 1 / 132

Delamination of REBCO tapes induced by electromagnetic forces: an experimental study.

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The remarkable superconducting properties of REBCO tapes in high magnetic fields render them highly suitable for applications such as fusion magnets and particle accelerators. However, their mechanical limits under transverse tensile stresses from Lorentz forces and screening currents in high-field coils must be addressed for reliable performance. This study investigates the delamination behavior of commercial REBCO tapes subjected to transverse tension induced by an electromagnetic force. Magnetic fields up to 19 T and currents up to 2 kA generated transverse tensile stresses of the order of 10 MPa in 4 mm-wide samples. A custom-designed sample holder was developed, with the aid of numerical analyses, to minimize the hoop stress component. The reduction in critical current after delamination was assessed at 4.2 K and 77 K. Additionally, post-experiment analyses using inductive mapping of the local critical current density and SEM/EDX were performed, providing insights into distribution, mechanisms, and chemical nature of the damage. Forensic analyses revealed regions with changes in elemental composition, indicating quench events concomitant with the induced delamination.

Session:

EM & Mechanical Properties

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Is transposition necessary in superconducting cables? Consequences of lack of transposition on AC losses and current distribution in coated conductor cables

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Transposition means that the strands periodically exchange their position in the cable; in electrical terms, it means equalizing the strand impedance. Most of the LTS (Nb₃Sn and NbTi) cable concepts are transposed, but when looking at the finest structure, i.e. the filaments, even LTS conductors are not transposed. In contrast with LTS, most of the cable concepts for coated conductors are non-transposed. Transposition reduces total AC losses by uncoupling the strands (thus reducing the coupling losses) and ensures a uniform current distribution, which in turns improve the field quality. What happens to AC loss and current distribution in non-transposed coated conductor cables? Coated conductor cables have naturally large AC losses because of the large hysteretic losses in tapes. In non-transposed cables, the fully coupled losses component would increase even more the total AC loss. AC loss upper limits can be set by the electric power consumed to remove the heat and by stability. About the latter, coated conductors can sustain much larger transient heating, because their temperature margin is much larger than in LTS. There are examples of REBCO magnets that functions despite extremely large AC losses.

Regarding current distribution, non-transposed concepts are prone to current ramp limitations and worse field quality. Examples from the fusion magnets in the 1970's to the newest coated conductor magnets for fusion show that non-transposed coated conductor cable can sustain very faster current ramps. Regarding field quality, coated conductors have much larger magnetization than fine twisted multifilamentary wire. The large magnetization affects the spatial and temporal field quality. In non-transposed cables, large coupling currents also worsen the field quality; examples in a dipole and in a high field solenoid insert are shown.

Even if the physical mechanisms in coated conductors and LTS materials are the same, the consequences are not: coated conductors have larger temperature margin (much more stable) and thus can sustain larger AC losses and current imbalances than LTS. For this reason, non-transposed concepts for coated concepts are being used in the most recent large and high field magnets.

Session:

Cables for magnets

Accelerator Magnet Applications / 134**Construction Technology for the 10 T HTS Energy Saving Dipole Magnet of the Italian Facility IRIS**

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The Innovative Research Infrastructure on Applied Superconductivity (IRIS) is a project funded by the Italian Minister for University and Research, with leadership assigned to INFN and LASA laboratory serving as its coordinator. This project, currently in its final phase, involves the design and construction of an Energy Saving, fully high-temperature superconducting dipole Magnet for Accelerators (ESMA). This magnet has been designed by ASG Superconductors S.p.A. with the support of INFN LASA Team. The fabrication will take place in ASG Superconductors S.p.A. Genova.

This contribution covers the final design of the dipole and its construction technology, covering electromagnetic, mechanical, and thermal aspects.

Magnetic wise, 12 racetrack coils will be wound using a metal-as-insulation winding technology. The overall coil stack (6+6) will be nearly 1 meter long and will feature a 70-mm-wide free bore with a maximum central field of 10 T. To wind the coils, a dedicated winding machine have been designed and purchased.

To withstand such a field a mechanical structure made by high-strength alloys is being produced. ESMA will be a conduction cooled cryogen free magnet and will operate at 20 K, significantly reducing costs associated with cryogenics.

Session:

Accelerator Applications

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Perspective in NMR: REBCO coated conductors in Bruker Ultra-High-Field NMR Magnets

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The development of HTS coated conductors over the last two decades has enabled the Bruker Ultra-High-Field (UHF) Program to offer magnets with fields exceeding 1.0 GHz. Since 2019, Bruker has delivered 15 subcooled 1.1 and 1.2 GHz magnets to customers worldwide, along with 3 compact 1.0 GHz systems operating at 4.2 K. The maturity of both HTS coated conductor technology and Bruker's magnet development has led to the record 1.3 GHz all-superconducting NMR magnet prototype, which successfully reached field and demonstrated NMR field quality in 2024. This contribution will cover the current status of the UHF program, highlighting recent advances such as the 1.3 GHz magnet and the requirements for HTS coated conductors in NMR applications.

Session:

High Field Applications

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Development of high-field dipole and solenoid magnets using the latest generation of CORC® cables and wires

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Dipole magnets that approach or surpass magnetic fields of 20 T for use in future particle circular accelerators, and high-field solenoids that operate at 20 K, such as envisioned in a multi-TeV muon collider, require the use of high-temperature superconductors (HTS). Several prototype magnets based on high-current HTS CORC® cables and wires, wound from REBCO coated conductors, have been demonstrated in recent years. Although considered one of the most flexible HTS cables, previous-generation CORC® wires degraded by 20–30 % when bent to a 30 mm radius. The limited bending flexibility required rather conservative magnet designs, limiting the magnetic field generated by these early prototype magnets.

Advanced Conductor Technologies (ACT) has recently developed CORC® wires with improved bending flexibility that now allow bending to a 20 mm radius without significant degradation. Very-high current CORC® cables were also developed that have an expected critical current (I_c) of over 30 kA at 10 T at a temperature of 20 K, or at 20 T at 4.2 K. Although the cable contains 96 REBCO tapes of 4 mm width, it allows bending to a 125 mm radius.

The much higher bending flexibility of CORC® conductors allows for more efficient CORC®-based dipole magnets that would ultimately generate 20 T, such as canted-cosine-theta (CCT) magnets under development at Lawrence Berkeley National Laboratory (LBNL) and Conductor on Molded Barrel (COMB) magnets under development at Fermilab. An overview will be provided of the dipole magnet development at both laboratories in support of which ACT will deliver a total length of 225 meters of CORC® wire in the coming months.

The improved bending flexibility and in-field performance of CORC® conductors also allows for the development of low-inductance, high-field solenoids. An overview is presented of the initial designs of 35–40 T solenoids in which several series-connected CORC®-based inserts are operated within a low-temperature superconducting (LTS) outsert, or as a stand-alone HTS solenoid. An overview of the initial design of a 1.2 meter bore 20 T target solenoid for the muon collider, wound from very-high current CORC® cables, will also be provided.

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Session:

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Manufacture and preliminary AC tests of insulated pancakes for fast ramping magnets

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In the framework of the SMILE (Superconducting Magnets to Improve Large Research Facility Efficient) initiative at the Paul Scherrer Institute, we are developing HTS technologies for compact cryocooler-based AC magnets for the HIPA (high intensity proton accelerator) and PROSCAN accelerator complexes. In this presentation, we show the first steps of this AC research program related to HTS pancakes. We present the optimized fabrication process that guarantees the insulation with a small gap between turns together with a good thermal conduction. We will then focus on the first results in terms of AC losses and the efficiency of different cryocooler-based cooling methods, such as copper conduction and cryogenic pulsating heat pipes (PHP).

Session:

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Conductor Material Research / 138

Multi-faceted assessment of structural correlations to superconducting properties of coated conductors for high field applications

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HTS high field magnets are one of the technological enablers for medical research, high energy physics, and more recently fusion energy. Especially, recent increasing public interests in the HTS fusion magnets prompt full cross-cutting understanding at all levels of technologies such as the HTS materials, conductors, cables and magnets. No magnet can be better than the conductor, but it is also true that there are unique technological challenges for using HTS in the high field applications because there are still many “missing links” between the conductor technologies and cable/magnet technologies, and most of them are derived from the structure-related property variabilities. The

coated conductor (CC) is currently the most dominant HTS, and there are 7 manufacturers worldwide. But their geometry of thin tape ribbon inevitably makes them anisotropic in the superconducting and mechanical properties. Concerning the superconducting anisotropy, our multi-facet testing revealed significant variabilities of $J_c(\theta, T, H)$ between different CCs that largely depend on temperature and field and the pinning nanostructure. Also, the field angle which produces the highest J_c can be variable not only between the manufacturers but also between the production batches or along the length of each CCs. For the high field magnets, the delamination-induced fracture is a serious issue under high field operations. In addition to pre-existing mechanical damage caused by slitting, our recent nanostructure analysis indicated a strong variability in the buffer layer integrity between the production batches and potentially between the manufacturers. This presentation will discuss further such recent multi-faceted assessments of structural correlations to the coated conductor property variabilities.

Session:

Conductor Material Research

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Cryogenic irradiation reduces radiation resistance of REBCO tapes**Author:** David Fischer^{None}**Co-authors:** Alexis Devitre ¹; Ben Clarke ; Kevin Woller ¹; Zach Hartwig ; Zoe Fischer¹ *Massachusetts Institute of Technology***Corresponding Authors:** devitre@mit.edu, zlfisher@mit.edu, kbwoller@mit.edu, benclark@mit.edu, hartwig@psfc.mit.edu, dafisch@mit.edu

While the interest in fusion energy increases, exemplified by the growing number of fusion startups and rising annual budgets for fusion research, many issues remain unresolved. One major challenge is quantifying the radiation resistance of REBCO tapes in fusion magnets, which are subjected to high-energy fusion neutrons.

The current estimate for the radiation limit of REBCO tapes is about $3 \times 10^{22} \text{ m}^{-2}$, based on room-temperature irradiation results. However, REBCO fusion magnets are subject to radiation damage at their operational temperature of around 20 K. To investigate the effects of low-temperature irradiation, we used MIT's cryogenic ion irradiation setup to expose REBCO tapes to 1.2 MeV protons. For irradiations at 20 K, we observed a 40% higher degradation rate of all investigated superconducting parameters compared to irradiations at 300 K. This might suggest that the observed reductions of critical current, n-value, and transition temperature can all be traced back to the same origin - the breaking of Cooper pairs caused by scattering at small defects.

Our results further indicate, that fusion magnets could already cease operation at fast neutron fluences of $2 \times 10^{22} \text{ m}^{-2}$, given the accelerated defect accumulation at low temperatures. We showcase the new cryogenic neutron irradiation facility, currently under construction at the MIT reactor, which will allow to investigate the actual fluence limits of REBCO tapes under fusion-realistic conditions.

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EM & Mechanical Properties

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Status and Perspective for Superconducting Power Transmission at VEIR

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VEIR Inc., a U.S.-based company, is dedicated to rapidly accelerating transmission capacity using High-Temperature Superconducting (HTS) power cables. HTS materials sustainably minimizes power losses, facilitate the integration of renewable energy sources, and enable efficient grid capacity expansion to meet the growing demands of electrification.

Our proprietary technology employs a passive periodic cryogenic cooling system to maintain operating temperatures, enabling reliable performance over extended distances and reducing the need for frequent intermediate cooling stations. These advancements make VEIR's solution well-suited for modernizing power grids and supporting dedicated transmission capacity, helping hyperscalers achieve 100% renewable energy operations and reduce carbon footprints.

In 2024, VEIR energized a first-of-its-kind 100-foot outdoor overhead superconducting transmission line, is actively executing a NYSERDA state-awarded project focused on installation and repair processes for superconducting cables and has recently been awarded funding under the Department of Energy's Grid Resilience and Innovation Partnership (GRIP) program to deploy an innovative superconducting power line connecting a utility-scale solar facility to the grid. Each of these milestones is validating the ability of VEIR's technology to deliver energy efficiently. This presentation will highlight the current development status, key performance metrics, and perspectives on the adoption of HTS technology to enhance global transmission capacity.

Session:

Power and Mobility applications

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Towards a 3D Thermal-Electrodynamics Simulation of Non-Insulated ReBCO Coils

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Accurately modeling the transient behavior of non-insulated (NI) ReBCO superconducting coils is crucial for fully assessing their potential for high-field magnet applications. While 3D Finite Element (FE) models are among the most promising approaches for capturing the thermal-electrodynamics dynamics of these coils, the widely used $H-\varphi$ formulation of Maxwell's equations remains computationally prohibitive for large-scale applications.

To address this challenge, we present a novel mathematical formulation that couples a 3D FE magnetic module with a 1D FE + 2D Finite Differences (FD) electric module, implemented in COMSOL Multiphysics. The formulation has been used to develop a model that simulates the electrodynamic

of large ReBCO NI pancake coils. Although still under development, the model has been validated against other models across various test cases, and preliminary results demonstrate its ability to efficiently capture critical phenomena such as persistent current effects while significantly reducing the computational time required for large-scale 3D FE transient simulations.

The formulation has then been applied to simulate the energization of the Muon Collider 40 T Solenoid, offering valuable insights into: (1) the relationship between energization time and turn-to-turn contact resistance, and (2) the impact of magnetization on the Lorentz forces acting on the conductor. These findings highlight the potential of this 3D magnetic and electric coupling approach to advance the understanding of NI superconducting coils.

Future model developments will incorporate thermal behavior to investigate quench phenomena and evaluate advanced protection strategies.

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Spatial Variation of in-Field I_c in PLD-REBCO Coated Conductors Studied by Reel-to-Reel Hall-Probe Magnetic Microscopy up to 5 T of External Magnetic Field

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Spatial Variation of in-Field I_c in PLD-REBCO Coated Conductors Studied by Reel-to-Reel Hall-Probe Magnetic Microscopy up to 5 T of External Magnetic Field

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Proposed area of relevance: Electromagnetic and Mechanical Properties

Spatial homogeneity is one of the most important requirements of coated conductors as an industrial material, however, the behavior of spatial variation of critical current, I_c , and its controlling factor under practical operation conditions with external magnetic-field and/or at low-temperature are not yet fully understood. The definition of the homogeneity is not well standardized neither. In this study, we have succeeded in measuring position dependent in-field I_c in PLD processed REBCO coated conductor (CC) reel-to-reel manner up to 5 T of external magnetic field at 4.2 K. This allows us to collect detailed data of magnetic field dependence of local I_c as a function of position. By comparing field dependent I_c at each position, we found that the field dependence was almost collapsed on the same curve up to 5 T independent on the position, and the position dependence itself was reproducible as similar to that of 77 K. This indicates that the spatial variation of the local I_c is dominated separately from that of magnetic field dependence. We investigated the origin of such spatial variation by machine learning based magnetic image analyses in order to clarify the influence of local obstacles in the tape. To study further the influence of spatial resolution of the measurements, we carried out spatial frequency, f , analysis and found that the spatial fluctuation of I_c shows $1/f$ dependence. From that, we derived the relationship between standard deviation of the I_c fluctuation and spatial resolution in the measurements. It should be noted that the value of standard deviation in the I_c fluctuation has a meaning only if it was defined together with the spatial resolution in the measurement. These insights would be essential for quality assessment of REBCO CCs.

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Mechanical limitation of stack type Coated Conductor cables for magnet applications

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Electromagnetic and Mechanical Properties of Edge-impregnated REBCO Coils under High Magnetic Field

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Lessons learned from ultra high-field, high-stress REBCO coil tests

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Measurement and FE modelling critical transverse loading limits of REBCO CORC[®]-like cables for fusion

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Demonstration of high critical current on REBCO tapes fabricated by FF-MOD method

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Conductor Material Research / 149

Pinning Mechanisms, Lengthwise Fluctuations, and Flux Jumps in REBCO Coated Conductors: A Torque Magnetometry Study up to $B = 45$ T

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Tape performance specification and performance vs. production

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Delamination of REBCO tapes induced by electromagnetic forces: an experimental study

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Progress in 2G-HTS Tape Development at High Temperature Superconductors, Inc. (HTSI)

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Fusion Magnet Applications / 153

HTS materials and magnets R&D at Renaissance Fusion

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Multi-faceted assessment of structural correlations to superconducting properties of coated conductors for high field applications

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Advances in HTS magnets for fusion at CFS

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Commonwealth Fusion Systems (CFS) is building the world's first compact net energy fusion device, SPARC, by utilizing recent advances in the commercial production of 2G REBCO coated conductors. SPARC's delivery and operation will inform the design of ARC, the world's first fusion power plant, scheduled to come online in the early 2030s. The SPARC magnet systems use two magnet technologies: Partitionally Insulated and Transposed (PIT VIPER) cables for the Central Solenoid (CS) and Poloidal Field (PF) magnets, and No-Insulation No-Twist (NINT) coils for the Toroidal Field magnets. The two magnet technologies were proven using model coil programs, TFMC and CSMC. CFS has constructed a manufacturing facility to build the SPARC magnets including facilities to test them at the sub-component scale in LN₂ along with 2 large, cryogenic test stands for full testing of all PF, CS, and TF coils at low temperature and high field before delivering them to SPARC. This talk will provide an overview of the magnet build and tests to date.

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Fusion Applications

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R&D studies on coated conductors relevant for compact fusion magnets

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Commonwealth Fusion Systems (CFS) is building the world's first compact net energy fusion device, SPARC, by utilizing recent advances in the commercial production of 2G REBCO coated conductors. SPARC's delivery and operation will inform the design of ARC, the world's first fusion power plant, scheduled to come online in the early 2030s. The design, safe operation, and quench protection of high field fusion magnets requires the detailed characterization of the field (B), angle (Θ), and temperature (T) dependence of the critical current (I_c) of these tapes at the operational range for each magnet system, which is in the range of 20K, 20T. User facilities for characterizing HTS at very high fields are limited, and measurement standards do not currently exist. Users rely on the critical current measurement systems built in house at each facility for characterization inputs for magnet design and modeling. CFS has started an inter-laboratory comparison study at various laboratories across the world to compare the results measured on the same samples at 20K, B_{||} tape orientation at fields between 5T-30T (or as high field as the facility can support) using the CFS 12T Supercurrent system built at RRI/HTS110 as the benchmark. In this talk, results taken to date will be compared and discussed.

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Mechanical limitation of stack type Coated Conductor cables for magnet applications

Author: Anna Urszula Kario¹

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The critical surface of the ReBCO superconductor enables magnets featuring 20 T + in the future when, in particular, mechanical issues can be overcome. When designing a high-field magnet of significant size, a cabled conductor needs to be used, due to current magnitude, required current sharing and limitation of self-inductance of the magnet in order to achieve acceptable ramp time and quench protection. There are few concepts of coated conductor cables existing as Roebel, CORC and stack type of cable. Currently the Roebel Assembled Coated Conductor cable is on standby, and only a few scientific works have been published. CORC, Cable on Round Core in few variations is being further developed for various applications. Currently, the most widely researched conductor is stack cable, primarily motivated and researched for fusion magnet application.

Since stack type (sub-)cable is the one currently intensively explored, in this presentation the present understanding of the mechanical properties and constraints of stack (sub-)cables for magnet applications will be summarized. Effects of the various components of Lorentz force, taking into account different magnet geometries, are discussed. An overview of experimental and theoretical aspects to understand mechanical questions so far published in literature on stack coated conductor cables is given. Finally, the eventual mechanical limitations of the technology for future high-field magnets will be highlighted.

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Cryogenic and Superconducting Powertrain for Electric Aircraft Propulsion

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To meet climate neutrality in the aviation industry by 2050, technology development is one of the major pathways. Airbus has the ambition to develop a hydrogen powered aircraft by 2035. Hydrogen stored at 20 K can be used as a heat sink to cool electric components of the powertrain. Due to their high current density, high temperature superconducting materials may be particularly interesting to use in DC cables and electric motors.

In this talk we summarize the results and lessons learned from the 500 kW ground-based Advanced Superconducting and Cryogenic Experimental power train Demonstrator (ASCEND), which was finalised in 2023. Following the technology development, Airbus UpNext launched the CryoProp demonstrator in 2024 with the objective to develop and mature a MW-class laboratory superconducting electric propulsion system at cryogenic temperature to be tested in 2026. The goal is also to demonstrate the performance in the specific environmental constraints. We present the specific needs for high temperature superconductors for electric aircraft propulsion.

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Introduction

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TEST

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Conductor Manufacturing