ABSTRACTS

Speakers and Presenters, by Session

TUESDAY, APRIL 4

Plenary Session (PL)

4PL1 Developing Coated Conductor based Magnets for Spherical Tokamaks

Rod Bateman, Tokamak Energy, United Kingdom

On route to developing zero carbon emission commercial electrical power generation, Tokamak Energy (TE) is developing Spherical Tokamak (ST) technology. A key enabling technology for ST machines is the development of HTS magnets. TE has embarked on a program of developing HTS magnets based on REBCO coated conductors for ST's up to fusion reactor scale magnet sets. This presentation will summarise the challenges and the progress of that program to date.

4PL2 High Magnetic Field Applications for Coated Conductors

Mark Bird, National High Magnetic Field Laboratory | Florida State University

There is a revolution underway in high field magnet technology that has been enabled by coated conductors (CC) becoming viable for high field applications. Recently the record field made an unprecedented jump from 23.5 T to 32 T in less than twelve months. The previous increase of 8 T took approximately 40 years! While only three groups worldwide have delivered magnets operating beyond 23.5 T to date, there are at least seven groups working on such magnets presently with multiple ones anticipating completion this year.

This dramatic increase in field is due partly to the current-density of CC but mainly due to the high mechanical strength and stiffness and the relative ease of coil fabrication. While CC is being productively employed presently, there are still significant challenges that limit application. In particular, the predictability of the critical current of the CC, the presence of screening currents in the CC, and the means of protecting the CC during high current-density quench are matters presently being addressed. The presentation will focus on magnets presently being developed for operations at fields higher than 23.5 T along with how the various groups are addressing these critical challenges.

4PL3 ASCEND: Cryogenic and Superconducting Powertrain for the Propulsion of Electrical Aircraft

Alexandre Colle, Airbus UpNext, France

The storage of liquid hydrogen (LH2) is becoming a serious candidate for the electric aircraft of tomorrow. In a possible scenario, fuel cells produce the electrical energy to propel the aircraft. This architecture is fully electric and emission free during the operation of the aircraft. In order to reduce the mass and gain in efficiency at the system level, ASCEND is a 3-year project to investigate the possible synergy between the LH2 onboard and a cryogenic and superconducting (SC) powertrain. A ground demonstrator of 500 kW is being manufactured/assembled and is expected to be tested in mid-2023. It will be composed of a SC DC cable, a cryogenic motor control unit, a SC AC cable and a SC motor.

The first part of the presentation will give an overview and the objectives of the project. Then, the requirements on the SC conductors for each component will be presented. A SC fault current limiter with a high electrical field during fault to increase its compactness, a flexible SC cable for aircraft integration, degradation of the SC performances under vibration/mechanical constraints or high performance conductors to reduce the AC losses in the SC motors are some examples of those requirements. This part intends to initiate a discussion between the SC manufacturer and us to share the needs and understand the limits.

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Conductor Manufacturing (CM)

4CM1 New horizons for PLD-based technology of 2G HTS tapes

Sergey Lee, Faraday Factory, Japan

Pulsed laser deposition (PLD) technique is an extremely efficient tool for deposition of inorganic thin films with multi-element chemical composition, complex crystal structure and specific defect landscapes. Although PLD is widely used in laboratories, there were no successful examples of PLD mass production so far. In this light, utilization of PLD technology for pilot scale reel-to-reel fabrication of high-temperature superconducting wires of second generation (2G HTS) is an exceptional case.

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Conductor Manufacturing (CM)

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Hundreds of kilometers of 2G HTS tapes were produced by PLD recently, making it an enabling material for ultra-high field fusion magnets with operating temperature around 20K. Material demand for emerging fusion industry became a main driver for 2G HTS production scale-up efforts by companies developing various MOCVD, RCE, MOD and PLD techniques.

Faraday Factory Japan (FFJ) is a new industrial and R&D entity that sets an ambitious goal to bring annual production beyond 1000 km/12mm level, serving the market with hundreds of megaAmpere-meters (MAm) of HTS tape with typical minimum Ic level of 200 A/4 mm at 20K, 20T.Multiple industrial PLD units operating 24/7 are the essence of FFJ technological process.

Further development of advanced PLD chambers and new platforms of excimer lasers is a critical issue for PLD-technology survival in competition with other manufacturing techniques.

In this talk we will present our vison of the new Factory space, its equipment, utilities, operation and management, which can be considered as a standard production unit for further multiplication.

4CM2 Coated Conductor R&D at Shanghai Superconductor Technology and discussion for fusion application

Yutaka Yamada, Shanghai Superconductor Technology, China; Chubu University, Japan

Recent progress of HTS magnets for compact fusion and the mass production of HTS-CC (Coated Conductor) attracted much interest in HTS industry as well as in the energy business community. Here in this presentation, I first summarize the recent effort at Shanghai Superconductor Technology for the low-cost and mass production especially for fusion application as well as Ic and Jc properties.

Recently we have organized the "HTS conductor R&D committee for fusion application" in Japan to discuss what we need in CC R&D for this application. At the end of 2022 we visited QST (National Institutes for Quantum Science and Technology) and discuss HTS system possibility with QST members. JT60SA at QST is a most advanced Tokamak type system made of NbTi and Nb_3Sn conductor for TF and CS coils and much more compact than ITER. This system completed in 2020, and now ready in operation. They have solved many problems in the conductor or magnets such as strength, size accuracy, AC loss and so on, which was critical to the realization of the whole system.

In the latter half of this talk, on behalf of the above committee, I will especially introduce some discussion about the important R&D issues for fusion application. Also, expected price or cost of REBCO conductor will be discussed using low temperature fusion systems of JT60SA or ITER.

4CM3 Homogenous REBCO Coated Conductor Production Developed by Using IBAD and Hot-wall PLD Process

Yasuhiro Iijima, Fujikura Ltd., Japan

REBCO coated conductors by IBAD/PLD process have excellent and uniform in-field Jc properties with robust mechanical strain strength. They are suitable to high field applications as high-end NMR systems, which strongly requires good transporting and dimensional uniformity in long piece length. Moreover, tremendous REBCO conductor demands emerged for “compact” nuclear fusion research which requires quite high in-field Ic even at 20 K, 20 T, with affordable Ic variations and neutron radiation durability. This talk describes current status and perspectives of REBCO coated conductor by mass productive PLD process at Fujikura Ltd.

Pulsed-laser-deposition (PLD) is a non-equilibrium vapor process characterized to have high growth rate with quite largely supersaturated conditions though it has also excellent controllability of varied deposition conditions for complexed multi-element oxide films. It allows to control high density dislocations and small-size secondary phase particles, dispersed inside good textured REBCO films growing at very high rates. In order to obtain longitudinal stability of thus optimized process conditions, we had designed and developed “Hot-Wall Type” reel-to-reel PLD apparatuses, which realized quite robust and reproducible temperature uniformity by furnace like heating system. Thus we succeeded to commercialization of long length and uniform REBCO wires including $BaHfO_3$ doped artificial pinning type lineups, preserving deposition conditions of narrower windows. RE elemental dependence would be also reviewed on crystalline growth stability for c-axis aligned thick films, in-field Jc performance in wide temperature and field range, and also shortly on neutron radiation damage.

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We are now continuing to develop productivity and quality control of those wires with varied width, toward large capacity and long piece length industrialization.

A part of this work is based on results from a project subsidized by the New Energy and Industrial Technology Development Organization (NEDO), and results performed at the High Field Laboratory for Superconducting Materials, IMR, Tohoku University.

4CM4 Recent Progress in Coated Conductor at SuNAM : Production Scale-up and Customer-oriented Development

Seung Hyun Moon, SuNAM Co. Ltd., South Korea

We have demonstrated that co-evaporation and growth of superconducting phase utilizing liquid phase produces high performance Coated Conductor (CC) at high throughput and low cost. We supplied hundreds of kilometers of CC for various applications, including grid use in the domestic market. Increasing demand from domestic market such as cables, Fault Current Limiters (FCLs), high speed railways, and global demand for high field magnet and fusion applications let us install 2nd co-evaporation system. In the 2nd system, with improved stability and controllability of e-gun and added feedback-control system, we stressed uniform critical current both length-wise within run and also between runs, addressing customer requirements. Post-processing for protection layer is also modified to get uniformity in the physical dimension of the final product.

We tried to include BMO_3(M = Zr, Hf, …) in our CC from the 2nd co-evaporation system and relation between critical property and micro-structure was analyzed. We're setting up a PLD system to further our effort to make CC with excellent in-field properties. Other scale-up issues are also discussed.

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

4CM5 REBCO HTS wire manufacturing at SuperPower for high-field magnet applications

Yifei Zhang, SuperPower Inc., United States

In the last several years, the practical applications of REBCO HTS wire have been realized in a number of fields where high-field (around 30T) hybrid magnets with REBCO HTS inserts were successful built for scientific research magnet systems and for commercial NMR systems. It is worth noting that in these applications REBCO HTS wire is an enabling material rather than a substitute. The achievements in these applications have triggered a great interest in using REBCO HTS wire for the development of compact fusion reactors in which high-field magnets are critical for plasma confinement. With the huge amount of wires now being needed for fusion reactor construction (hundreds to thousands of kilometers per reactor), for the first time since the REBCO wires became commercially available, the demand for this material is now outpacing its production.

Higher in-field performance and higher mechanical strength are the basic reasons why REBCO HTS wire is adopted by the compact fusion technology development. Continuous efforts are being made at SuperPower to improve the performance and quality of our products. With an increased Zr doping level and optimized composition the new (HM) REBCO formula has showed greatly improved in-field Ic values at lower temperatures and higher fields compared with the previously developed AP formula. For the HM wires, the average Ic at 4.2K-17T//c is about 450 A/4mm and the average Ic at 20K-20T//c is estimated at 160 A/4mm. With an ongoing plan to increase our production capacity, we are also focused on improving the processing stability and increasing the manufacturing yield. R&D efforts are being made as well to extend our capabilities to produce REBCO HTS wires that can meet different requirements

4CM6 Production of technical HTS wire for magnet and cable applications

Cornelia Hintze, THEVA Dünnschichttechnik GmbH, Germany

Using a unique PVD technology THEVA has prevailed as the only commercial manufacturer of second-generation (2G) HTS wire in Europe. The main drivers for the incipient commercialization of HTS are magnetic field applications and the use of HTS cables for power transmission. Hence, in recent years, developments at THEVA have been focused on the improvement of wire performance in magnetic field and towards high yield in the HTS wire production line.

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The engineering current density and magnetic field resilience have been addressed by addition of artificial pinning (AP) particles to the HTS evaporation material. Thus, the performance below 40 K could be increased by a factor of 2–3 compared to standard HTS wire without AP. At 20 K, 20 T the engineering current density could be pushed beyond of 750 A/mm^2 and is exceeding the in-field performance of every other established superconductor wire material. Consequently, 2G HTS wire is about to trigger a revolution in magnet technology.

For commodity applications competitiveness and cost-efficiency are crucial for success. Although the processes of customization appear simple, the processing chain can become highly cost-intensive if wire is damaged or wasted. We will therefore introduce our well-controlled, reliable processes giving high yield and customization, namely high-speed laser slitting, high-rate PVD metal coating and single-side lamination. These highly optimized products were used to manufacture industrial-scale lengths of material for the SuperLink HTS demo cable to be operated in AC mode and at high voltage level, as well as for an insulated magnet system for an innovative metal billet heater in the RoWaMag project.

For AC applications besides the critical current of the HTS wire the AC-losses are crucial for the wire applicability in industrial projects. Here we will present very recent developments on filamentization techniques for wires optimized aiming at low AC-losses.

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Compact Fusion (CF)

4CF1 HTS Magnets for Fusion Energy

Brandon Sorbom, Commonwealth Fusion Systems. United States

The key performance metrics in magnetically-confined fusion devices called tokamaks scale as the strength of the toroidal magnetic field to the fourth power. One of the most important consequences of these scalings is that increasing the magnetic field in a tokamak enables a much smaller device to demonstrate net-energy production, leading to dramatic reductions in cost, timeline, and organizational complexity required to construct and operate the fusion device. Following the successful demonstration of a large-bore, 20 T, all-REBCO magnet in September 2021, an energy-breakeven fusion device called SPARC has begun construction and will be commissioned in 2025. A fusion pilot plant called ARC will follow, with the aim of putting fusion power on the grid in the early 2030's. This talk will explain why high-field REBCO magnets are a game changer for fusion energy, how the recent 20 T magnet demonstration has opened the path for Commonwealth Fusion Systems (CFS) to build the next generation of fusion devices, and how the REBCO industry can continue to scale up to support the growing demand for the emerging fusion industry.

4CF2 HTS Coated Conductors Pave the Way for Stellarators

Paul Harris, Type One Energy Group Inc., United States

Stellarators derive all their plasma confinement from their magnets. The advent of HTS tape has brought huge gains towards the realization of stellarator fusion power plants. Stellarators arguably offer the best potential for commercialization of fusion with steady state operation and high confidence levels in extrapolating recent performance gains. Historically stellarators have had the reputation of being "hard to build and easy to operate". Type One Energy is leveraging HTS technology combined with additive manufacturing to create a new generation of stellarators that will be easy to build and easy to operate.

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Compact Fusion (CF)

4CF3 **HTS coils without HTS tapes: direct deposition and patterning on wide surfaces**

Alexander Usoskin, Renaissance Fusion, France

At Renaissance Fusion we are dramatically simplifying the manufacturing of High Temperature Superconducting (HTS) coils for magnetic confinement fusion and other applications. We completely bypass the paradigm of HTS tapes and cables. Instead, we directly deposit and pattern multi-layer HTS coils on vacuum vessels or other wide surfaces. After the deposition, a laser selectively removes HTS material from narrow tracks or "grooves" to geometrically constrain the supercurrents. The result is a large, superconducting printed circuit, properly patterned to generate the 3D magnetic field of choice. Surfaces include flexible meter-wide tapes, rigid plates, and rigid cylinders, not necessarily of circular cross-section. This approach could streamline several HTS applications, from Magnetic Resonance Imaging to magnet undulators for synchrotrons, to wind turbines, to magnetic and magneto-inertial fusion. In particular, it could resolve the coil problem of stellarators: fusion devices similar to tokamaks – steadier, more stable, but featuring complicated 3D coils. There has been a tendency to adopt complex "coil winding surfaces" and then simplify the coils on those surfaces. At Renaissance Fusion we do the reverse: we adopt simple, piecewise cylindrical surfaces, at the cost of more complex current patterns on those surfaces. Such cost is negligible for us: just a different programming of the laser engraving. Plans will be presented for a cylindrical demonstrator of a stellarator field. Flowing mesoscale liquid metal walls will fully cover its interior to demonstrate the ability, in a reactor environment, to shield structural materials and delicate HTS from fusion neutrons, as well as extract heat and breed one of the fusion fuels: tritium. Progress will be presented in designing and building Physical and Chemical Vapor Deposition machines for the in-house production of said demonstrator and of meter-wide tapes for other uses. Research needs, challenges, job openings and areas of possible collaboration will also be discussed.

4CF4 **Applicability of large-current HTS STARS conductor to the next-generation fusion experimental devices**

Nagato Yanagi, National Institute for Fusion Science, Japan

Development of the large-current STARS (Stacked Tapes Assembled in Rigid Structure) conductor has progressed to apply to the helical fusion reactor magnets. It has the remarkable feature that REBCO tapes are simply stacked without twisting or transposition. The stack of tapes is embedded into a copper stabilizer and covered by a stainless-steel jacket with laser beam welding for mechanical reinforcement. A 20-kA-class nominal current is a target considering the application to the next-generation fusion experimental devices. A 6-m STARS conductor sample was fabricated with a 600-mm diameter and a coiled structure of 3 turns. It was tested in 8 T, 20 K in a 700-mm bore solenoid coil. A stable operation up to 18 kA current was confirmed, which corresponds to the current density of 80 A/mm2. A series of 100-time repetitive excitations was carried out with a 1 kA/s ramp rate. The low-resistive mechanical lap joints with indium insertion between the current feeders and the conductor terminals played an important role by ensuring no temperature increase from the terminals. A residual magnetic field was observed after the transport current became zero, which might be caused by a circulation current among the simply-stacked REBCO tapes with self-inductance imbalances. A simple circuit model for a two-tape conductor shows a linear dependence of the circulation current as a function of the ramp rate, which matches well with the observation. A second experiment of the 6-m sample is planned to have >1000 times excitations with a precise measurement of circulation currents. From the observed residual magnetic field in the 6-m sample, the level of circulation currents expected in a conductor used for large-scale coil windings in a fusion reactor is estimated, and its effect on stability is discussed.

4CF5 **Coated Conductors and their application for compact fusion**

Yuhu Zhai, Princeton Plasma Physics Laboratory (PPPL), United States

Next-step US tokamak facilities and compact stellarators configured as fusion pilot plants (FPP) to support fusion commercialization are all recommended options by multiple recent consensus studies. The goal for a FPP is to make 50-100 MW net electricity power plants with extended long pulses or steady state options. To meet the challenge of operating a pilot plant by 2040, significant technology maturation efforts are underway by privately funded startups with the goal to demonstrate mature HTS magnet technology.

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Compact Fusion (CF)

4CF5 – *continued*

To de-risk a compact FPP, sustained high power density (SHPD) tokamaks can close system integration and performance gaps for the US to resolve physics and engineering issues. Recent design studies show higher current coated conductors (CCs) can significantly improve the feasibility of all fusion confinement design options. High current density cables consisting of multiple CCs are essential for engineering design of the next step configuration studies to allow space for interior plasma components.

The CC options for SHPD 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 an HTS insert wound with coated conductors or cables meet physics requirements for SHPD plasma startups. Detailed assessment of AC losses during coil current ramping, cooling capability during quench, sizing of the OH and PF coils in the compact radial build and space allocation of structural supports, and expected coil fatigue performance under cyclic loading will be presented to de-couple the OH coil from the inner TF for SHPD. Although the bucked central solenoid (CS) design can be structurally beneficial for stress management in advanced tokamaks, the risk of inner TF legs trapped inside the OH coil is mitigated by the decoupled insert design that is properly sized and validated by engineering.

4CF6 Further progress in high temperature superconducting tapes for practical use of superconducting magnets for nuclear fusion reactors

Arata Nishimura, National Institute for Fusion Science, Japan

To achieve a carbon neutrality, nuclear fusion energy has been considered a powerful next generation energy source that does not consume fossil fuels and does not emit high level radioactive waste. The fusion energy will be produced by the reaction of deuterium and tritium. From the viewpoint of efficient energy production, a compact nuclear fusion reactor is desired. It is also believed that this will contribute to the reduction of construction and operation costs. To realize the compact fusion reactor, it is necessary to establish steady plasma confinement in a high magnetic field and a high temperature operation of superconducting magnets.

The performance of high temperature superconducting tapes represented by ReBaCuO tapes has been steadily improving. It brings new concepts and capabilities to the design and manufacture of large-scale magnets for fusion reactors.

The presentation will introduce and review some aspects of the future fusion magnets. The operation temperature will be 20 K and the maximum magnetic field will be higher than 14 T – 15 T which will be the limit of the Nb_3Sn wire to obtain a certain critical current. The current density of the tape is very high, and the engineering current density of the magnet will be over 50 A/mm^2, hopefully around 80 A/mm^2 to realize a slim magnet design. Since the AC losses must be reduced, VIPER, CORC and HFRC type conductors are available, but the current density becomes lower comparing with a stacked conductor. No insulation magnet is one option to apply the conduction cooling and to provide the effective coil cooling. It is also important to proceed with neutron irradiation effect and a quench detection system.

Some requirements for HTS tapes will be raised and listed at the end of the discussion.

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Magnet Applications (MA)

5MA1 Coated Conductors for Ultra-High-Field NMR Spectrometers

Robert Herzog, Bruker, Switzerland

The reliable supply of ReBCO coated conductors of sufficient length and quality during recent years allowed Bruker to build about ten Ultra-High-Field (UHF) NMR spectrometers, based on a hybrid LTS-HTS technology, and deliver them to customers: 1.1 and 1.2 GHz magnets (25.8 T and 28.2 T), operating at ~2 K, as well as 1.0 GHz magnets (23.5 T) immersed in a liquid helium bath at 4.2 K. These latter, more recent magnets are smaller, lighter and consume less helium than their larger ~2 K cousins, making them attractive to customers with single-story laboratories.

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Magnet Applications (MA)

5MA1 – *continued*

Manufacturing these magnets, we gained considerable experience in handling commercial ReBCO tapes and winding them into HTS coils. Although the performance of the coils reached expectations, we nevertheless realized the importance of the ReBCO tapes fully complying to our requirements to reliably achieve the necessary quality standards. Sufficiently high current densities at low temperatures (4.2 K) and high fields are essential, as are uniform properties over long piece lengths without Ic drop-outs. Our layer-wound HTS coils in addition need a robust electrical insulation to cope with the conditions during quenches. Mechanical strength is not only necessary for withstanding the Lorentz forces, but also advantageous to reduce the risk of damage during all tape handling processes.

5MA2 HTS for Accelerators – Potential and Perspective
Luca Bottura, CERN, Switzerland

HTS is a game changer for many applications of superconductivity, not last particle accelerators and detectors. This talk relates the potential of HTS, and in particular REBCO coated conductors, to the needs and evolution of superconducting magnets for accelerators. HTS already have a spectacular current carrying ability at high field, demonstrated and available on relevant lengths. The main perceived challenges are rather associated with magnet mechanics and quench management. HTS may offer solutions to both, relying on innovative winding technology. Furthermore, the extended range of operating temperature of HTS will benefit energy efficiency and sustainability. This potential is of very high interest towards sustainable large scale research infrastructures such as particle accelerators.

5MA3 Recent Progress and Challenges in REBCO Magnet
Seungyong Hahn, Seoul National University, South Korea

A notable progress has been made over the last decades in REBCO conductor and magnet technologies. Now multiple companies routinely deliver commercial-level REBCO conductors in different recipes, while various high field REBCO "user" magnets are currently under construction or even in service. Despite the outstanding achievements by our community, we still struggle with critical technical challenges that limit widespread use of REBCO beyond laboratory magnets. This paper reviews the recent progress in REBCO magnets for various applications that include NMR, MRI, high-energy physics, fusion, condensed matter physics, electric propulsion, and environment. Key lessons that we have learned so far and major challenges that we still need to overcome are discussed in detail.

5MA4 Mid-scale REBCO coil with "Robust REBCO coil concept"
Satoshi Awaji, Tohoku University, Japan

Since 25T cryogen-free superconducting magnet (CSM) was made in 2015 [1], we have been developing a robust REBCO coil concept for a next generation of high field CSMs [2]. A 33T-CSM project with a REBCO insert started at HFLSM, IMR, Tohoku University in 2022. The robust REBCO coil consists of two bundle REBCO tape co-winding, all turn separation with fluorine coated polyimide, edge impregnated pancake with a thin FRP plate. A mitigation of a burn-out related to a local degradation of REBCO winding and an optimization of the stress distribution in REBCO pancakes are expected for the robust REBCO coil concept. For R&D study, we made a mid-scale 20 stacked REBCO pancake coil with Robust REBCO coil concept". The height, inner- and outer-diameters of the coil are 101mm, 68 mm and 266 mm, respectively. We achieved total central magnetic field of 25 T with 300 A combined under a 14 T background field without any anomalous voltages. It is found that the hysteresis of magnetic field has two components from a screening current in the REBCO tape and a coupling current between two REBCO tapes, which are opposite field contribution. In addition, we could confirm that the maximum stress in the REBCO coil is reduced because of the optimization of stress distribution in the coil due to the edge impregnation. The detail experimental and simulation results of the mid-scale 20 stacked REBCO pancake coil will be presented as well as the basic concept of the 33T-CSM.

[1] S. Awaji et al., SuST 30 (2017), 065001
[2] S. Awaji et al., IEEE TAS, 31 (2021) 4300105.

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Magnet Applications (MA)

5MA5 REBCO - a silver bullet for our future colliders?

Xiaorong Wang, Lawrence Berkeley National Laboratory, United States

High-field superconducting magnets with a dipole field of 16 T and above enable future energy-frontier circular particle colliders. Although we believe these magnets can be built, none exists today. They can also be a showstopper for the future colliders due to a prohibitively high price tag based on the current conductor and magnet fabrication cost. The high-temperature superconducting REBCO coated conductor can address both the technical and cost issues, a silver bullet to lay both monsters to rest. The challenges and unknowns, however, can be too arduous to make the silver bullet. We propose a potential road forward and key action items. We hope to stimulate more thoughts, discussions and an effective plan from the community that can lead to a cost-effective high-field REBCO magnet technology for future colliders.

5MA6 HTS magnets for future accelerators and the IRIS project

Lucio Rossi, University of Milano and INFN-Milano LASA Laboratory, Italy

Particle accelerator magnets is probably the most difficult domain for application of HTS conductor, very much like LTS. The necessity to couple high overall current density with an excellent field quality near the coils makes use of HTS very problematic at this stge. The need of ramping the magnets, while controlling the field errors at level of 100 ppm is an additional challenge in search of a solid solution yet. Despite these issues, various programs are investigating the use of HTS for accelerators, addressing some of the previous issues. The talk will describe the R&D effort in Europe for high field dipoles for large accelerators and also on possible application of HTS tapes at low field (either in pure superconducting or in superferric mode) and high temperatures.

5MA7 Benefits and Requirements of ReBCO Cables for Accelerator Magnets

Ramesh Gupta, Brookhaven National Laboratory, United States – Withdrawn

To achieve fields greater than 20 T or to operate significant field magnets at temperatures above 20 K, High Temperature Superconductors (HTS) are not only desired but essential. Accelerator facilities with long term horizon are seriously considering such magnet as a part of their overall program. Rare-earth Barium Copper Oxide (ReBCO) cables are already promising an exciting game changing opportunity for future fusion reactors. This presentation will examine the prospects of such possibilities for future accelerators while discussing the broad requirements on ReBCO cables for accelerator magnets. Finally, several R&D accelerator magnets designs and how they use a variety of known architects of ReBCO cables, will be presented.

5MA8 Latest Development of High-field Magnets for Compact Fusion Reactors and Particle Accelerators from CORC ® Cables and Wires

Danko van der Laan, Advanced Conductor Technologies, United States

Advanced Conductor Technologies is developing CORC® cables and wires wound from REBCO coated conductors for use in compact fusion magnets and high-field particle accelerators. An overview of the latest CORC® conductor development and their implementation into prototype high-field magnets is presented.

A concept aimed at narrow Ohmic Heating coils in compact fusion reactors is described in which CORC® cables are wound into grooved mandrels. The concept doesn't require epoxy impregnation, thereby significantly easing magnet manufacturing. The CORC® cable is wound directly into grooved mandrels, where support against hoop stress is provided by the neighboring mandrel. Initial degradation-free tests at current ramp rates as high as 5 kA/s up to 10 kA and under mechanical cycling within a 12 T background magnetic field are discussed.

An overview of high current density CORC® wires with improved bending performance that allows bending to radii below 20 – 25 mm is provided. The CORC® wires are developed specifically for high-field accelerator magnets that ultimately would generate a dipole magnetic field of 20 T. An overview of the development of a 5 T canted-cosine-theta (CCT) magnet from the latest generation of CORC® wires at Berkeley National Laboratory will be provided.

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Magnet Applications (MA)

5MA8 – *continued*

The development of a Common Coil insert magnets, wound from a high-current CORC® cable using a novel winding approach, will be outlined. Insert coils are developed for operation within the 10 T LTS Common Coil outsert at Brookhaven National Laboratory. The performance under quench at currents exceeding 12 kA at 6 T background field of the first, smaller Common Coil CORC® insert magnet is presented. An overview of a more powerful CORC® insert magnet, aimed to generate a dipole field of 3 T within the 10 T Common Coil outsert that will be tested near the summer of 2023, is also provided.

5MA9 A study on transverse resistance of a non-insulated coil wound with (RE)$Ba_2Cu_3O_{7-x}$ coated conductor in high magnetic fields

Jeseok Bang, National High Magnetic Field Laboratory, United States

(RE)$Ba_2Cu_3O_{7-x}$ coated conductor (hereafter REBCO CC) is a promising option for the development of strong magnets for various applications. Indeed, many institutes have ongoing research endeavors to design, construct, and test REBCO magnets. As a result, the world-record high magnetic DC field intensity of 45.5 T has been reached by using REBCO CC. Behind the success, it is noteworthy that the no-insulation (NI) REBCO CC winding technique plays a key role in this remarkable achievement. The NI configuration improves the REBCO magnet operational stability and reliability by providing an electrical current detouring path at a local defect in a coil. Due to this advantage, numerous research endeavors have been made to investigate electric properties regarding the contact between REBCO CCs. However, most of the relevant research is limited to the tape level, so an in-depth study at the coil level has yet to be sufficiently performed. Therefore, in this work, we report on a study of the resistances caused by the mechanical contact between REBCO CC windings at the coil level. We design, fabricate, and test NI coils wound with REBCO CCs. However, different winding tension is applied during the fabrication. Using the coils, experimental studies are performed with various operating temperatures and external magnetic fields. Then, numerical simulations are used to calculate the resistance induced by mechanical contact between REBCO CC windings. Then, simulation results are compared with measured results from experimental studies.

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Conductor Materials Research (CMR)

5CMR1 Ultimate performance of industrial YBCO tapes

Alexander Molodyk, Faraday Factory Japan, Japan

2G HTS tapes based on YBCO have become the leading product for high magnetic field applications market. This is so because YBCO tapes exhibit excellent performance that meets and exceeds most applications requirements and also, not to the lesser extent, because YBCO tape technology is robust enough that it has been successfully scaled to large industrial volumes.

Record R&D results demonstrate the limits of REBCO performance of more than twice that of the average production YBCO tapes. At the same time, the performance of many best production YBCO tapes is superior to the average performance of production YBCO tapes by up to 50%. This shows the potential ultimate performance that shall be achieved in production. The best tapes demonstrate very high Ic values of 350 A/4 mm at 20K, 20 T and of 650 A/4 mm at 4.2 K, 20 T. Making this level of currents average performance will alone reduce the cost of production of YBCO tapes by 30%.

In this talk we will show the data of high magnetic field measurements on YBCO tapes, compare the typical micro- and nano-structure features in the best-, average- and worst-performing tapes and discuss the strategies that will help us reveal the reasons for the different performance and modify the manufacturing technology, to achieve today's best performance routinely.

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Conductor Materials Research (CMR)

5CMR2 Development of Coated Conductors for Electric Propulsion System of Aircraft

Teruo Izumi, Advanced Industrial Science and Technology (AIST), Japan

The REBCO superconducting devices are expected to realize a lightweight and high-power electric propulsion system for aircraft. In our group, the propulsion system including generators, motors, and cable by REBCO coated conductors is being proposed. One of the features of the system is operation in the liquid nitrogen temperature. To realize the system, the high Ic performance even under the magnetic field in the liquid nitrogen are strongly required. Additionally, the low ac loss conductor is also necessary for the fully superconducting rotating machines. In the current national project, the development of the coated conductors for high Ic(B) and low ac loss 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. A high temperature deposition and low temperature O_2 annealing was applied for EuBCO+BHO materials in the PLD development and the UTOC-MOD process was developed for TFA-MOD for realizing high in-field performance. By both approaches, the intermediate goal of the project (300A/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 5-filaments was fabricated by using a pico-sec pulse laser to suppress the dross and it revealed 1/5 loss reduction and high Ic(B) property.

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

5CMR3 Towards a Specification of Coated Conductors for Use in Magnets

David Larbalestier, National High Magnetic Field Laboratory, United States

Coated Conductors (CC) are an amazing materials engineering achievement, but they are still far from easy to specify. Magnet users find it hard even to specify Ic properties because of the huge range of B, T and angle at which they will be used. Other very important properties like the rectangularity and uniformity of Ic across and along the tape can have significant impact on magnet performance but are not easy to measure in any continuous way except at 77 K and low fields. Although very strong in tension, CC are susceptible to out of plane stress that can delaminate the REBCO from its buffer. I will present a viewpoint about how we could better define CC properties from the perspective of our high field test coil program.

5CMR4 Customizing coated conductors to enhance normal zone propagation velocities

Xavier Obradors, ICMAB – CSIC, Spain

Enhancing the normal zone propagation velocity (NZPV) is a critical requirement of $REBa_2Cu_3O_7$ (REBCO) coated conductors (CC), particularly for being used in fault current limiters and magnet applications.

The Current Flow Diverter (CFD) and buffer-CFD (b-CFD) concepts are customizations of the CCs that have proven to increase the conductor's robustness against hot-spot regime [1, 2]. The modified CC architecture works by creating a high resistive interface between the metallic shunt and the superconducting REBCO layer either in the central section of a conventional CC tape or in the whole width. In this presentation we will present several strategies to customize the contact resistance between the REBCO superconducting layer and the metallic shunt to succeed in enhancing the NZPV.

Different approaches to generate high interfacial resistances have been considered, including additional nanolayers or modified metallic shunts (Y_2O_3, AgS, Ag alloys), which minimize the manufacturing changes [3]. The success in enhancing the NZPV has been tested through Current Transfer Length (CTL) measurements or by determining the NZPV dependence with the applied current [4]. The experimental effectiveness of the processes was tested using Scanning Hall Probe Microscopy to assure that the critical current homogeneity is preserved while the interfacial electrical resistivity was measured at different temperatures. We have demonstrated that the NZPV value is enhanced by a huge value of a factor 17 when compared to conventional CCs. The advantages and hindrances of the different CFD manufacturing approaches will be discussed in connection to the performance demand of different applications, such as Fault Current Limiters and magnets.

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Conductor Materials Research (CMR)

5CMR5 Transient Liquid Assisted growth (TLAG), a method to increase Coated Conductors throughput and meet applications requirements

Teresa Puig, ICMAB – CSIC, Spain

$REBa_2Cu3O_7$ coated conductors (REBCO CCs) are unique advanced materials capable of being integrated in different emerging applications such as fault current limiters, compact fusion, electric aviation, or high-field NMR, among others, so much effort is being devoted to meet the different requirements. However, the community is facing a global need to reduce the cost/ performance ratio of REBCO CC manufacturing processes, especially when CCs are to enter the market with a large number of devices. Therefore, we are developing a scalable high-throughput growth approach, called "Transient Liquid Assisted Growth (TLAG)" [1,2], which uses multifunctional colloidal inks for chemical solution deposition (CSD) [3] and features ultra-high growth rates of over 1000 nm/s with high critical current densities of 3 MA/cm^2 at 77 K [4]. TLAG is a high non-equilibrium liquid-solid growth process where nucleation and growth are kinetically controlled, so rapid in situ techniques were required to understand the growth mechanism and determine the correlation of the kinetic process parameters with epitaxy and growth rate. In this presentation, I will discuss the current understanding of the TLAG process, relevant process parameters for growth of CC nanocomposites, advances in growth rates and the TLAG vortex pinning capabilities. The use of fast acquisition in situ XRD imaging (<100 ms/frame) under synchrotron radiation, transmission electron microscopy, in situ resistivity experiments, and angular transport measurements have been crucial for this study. The liquid-solid TLAG process will be compared with other existing gas-solid and solid-solid growth methods.

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

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5CMR6 Multilayer BZO/YBCO thick films for high Ic in high fields

Judy Wu, University of Kansas, United States

Judy Wu*[1], Victor Ogunjimi[1], Mary Ann Sebastian[2], Di Zhang[3], Bibek Gautam[1], Mohan Panth[1], Jie Jian[3], Jijie Huang[3], Yifan Zhang[3], Timothy Haugan[2], HaiyanWang[3]

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A multilayer (ML) scheme was recently developed to facilitate diffusion of Ca from two thin $(Ca_{0.3}Y_{0.7})$BCO layers sandwiched with three BZO/YBCO layers and the consequent dynamic Ca/Cu substitution on tensile strained YBCO lattice during the growth of c-axis aligned $BaZrO_3$ dimensional artificial pinning centers (BZO 1D-APCs) in BZO/YBCO nanocomposite films. The substitution of smaller Cu ions by larger Ca ones is found energetically preferable by inducing c-axis elongation of the YBCO lattice near the BZO 1D-APC/YBCO interface to enable a coherent interface via reducing the BZO/YBCO lattice mismatch from originally 7.7% to 1.4%, leading to significantly enhanced pinning efficiency of BZO 1D-APCs, especially at high magnetic fields. In this work, the ML scheme is applied to thick BZO/YBCO films with total thickness in the range from 150 nm to 750 nm. Remarkably, comparable Jc (B) was observed in these ML samples while at lower temperature and higher fields, the thicker BZO/YBCO ML films outperform their thinner counterparts in both higher value and less anisotropy of Jc (B). At 750 nm thickness, Jc (65K, 9T) is >1.2 MA/cm^2 and Jc (30K, 9T) reaches up to 12 MA/cm^2 with a variation of ~25% over the entire angular range of B field orientations. This result illustrates the critical role of the BZO 1D-APC/YBCO interface in the pinning efficiency of BZO 1D-APCs.

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Conductor Materials Research (CMR)

5CMR7 Nanorod-layered structure transition in GdBCO thin films with BHO addition

Kaname Matsumoto, Kyushu Institute of Technology, Japan

The development of REBCO tapes has been progressing, and its current-carrying properties are being improved for application in superconducting devices at 20 K and 65 K. Previous studies have shown that high Jc performance in magnetic fields can be obtained by introducing APC nanorods and nanoparticles into REBCO. In NbTi metallic wires, the effective pinning center is a normal-conducting precipitate with an upper limit of about 25 % by volume. On the other hand, the upper limit for the volume fraction of APC in REBCO films is much lower, around 5 %. In this study, we investigated the microstructure of REBCO thin films with an APC concentration near 5 % to find a clue to solving the problem. In the samples prepared by the PLD method, the growth of nanorods parallel to the c-axis was observed at an APC concentration of 5 %, but when the concentration was increased above 5.5 %, the nanorod structure collapsed and an APC multilayered structure horizontal to the substrate plane was observed. Simultaneously, a degradation of the Jc property was also observed along with a decrease in Tc. In order to understand the above structural transition, we developed a local strain energy analysis method based on micromechanics theory and found that the structural transition is caused by the relaxation of the increase in strain energy due to the addition of APC. The above findings can be used to improve the performance of the REBCO wire in the future.

5CMR8 Status and prospects of REBCO conductors for ultra-high magnetic field applications

Venkat Selvamanickam, University of Houston, United States

Because of the tremendous pull from compact fusion, REBCO tape supply is significantly trailing demand. There is also a need to substantially reduce the cost of REBCO tapes, now greater than $100/kA-m, to a level comparable with low temperature superconductors for widespread use in many applications. A challenge with REBCO tapes is the high capital equipment cost, about $30M for a 1000 km/year production capacity. A better approach needs to be developed to increase throughput by several-fold without a large increase capital investment. Another approach to reduce cost and address the tape availability issue is to increase the critical current. Today's cables made for compact fusion magnets use over 200 tape strands, so increasing the critical current by 10x can reduce the number of tapes by about 10-fold which will reduce cost and alleviate availability concerns. Critical current levels up to 5x higher than that of commercial tapes have been achieved in short REBCO tapes and more than 3x higher than that of commercial tapes have been demonstrated in 50-m-lengths. These processes need to be scaled up to commercially-usable lengths of 300 – 500 meters. Some high magnetic field applications that use complex coil geometries such as particle accelerators require round conductor architectures with excellent bend tolerance. Round STAR® wires have been developed with engineering current density over 1,100 A/mm^2 at 4.2 K, 20 T at a bend radius of 15 mm and have been wound into compact, transposed, multi-strand cables. The state-of-the-art REBCO tapes and round wires being developed for ultra-high magnetic field applications will be presented.

5CMR9 The role of small defects on the degradation of coated conductors in radiation environments

Michael Eisterer, TU Wien, Atominstut, Austria

Magnets for fusion reactors and particle accelerators are promising applications for coated conductors. However, the superconductors will be exposed to high-energy neutrons during the operation of these magnets. Fast neutrons induce damage primarily by direct collisions with the lattice atoms that lead to a variety of defects, ranging from so-called collisions cascades with a diameter of a few nanometers down to single displaced atoms and the respective lattice strain. While the large defects are beneficial for the critical currents by serving as pinning centers, the small defects mainly enhance scattering of the charge carriers which is pair breaking in cuprate superconductors; thus reducing both, the transition temperature and the superfluid density. These competing effects lead to a maximum in the critical current as a function of neutron fluence. Unfortunately, the individual contributions of large and small defects cannot be resolved in fast neutron irradiation experiments. Gadolinium containing tapes offer this opportunity by an additional -low-energy neutron induced- point defect producing mechanism. Some Gadolinium isotopes absorb low energy neutrons and the recoil of the following emission of a high-energy phonon is sufficient to displace the respective nucleus.

WEDNESDAY, APRIL 5

Conductor Materials Research (CMR)

5CMR9 – *continued*

Our experiments show that simultaneous irradiation with low- and high-energy neutrons results in a much faster degradation than fast neutron irradiation. This difference can be ascribed to the small defects resulting from the neutron capture reactions. These results are complemented by data of annealing experiments, where defects are partly healed out and the superconducting properties recover. The superconducting transition temperature turns out to be a suitable parameter to monitor impurity scattering for a description of the degradation of the critical currents in radiation environments.

5CMR10 Fluorine-Free MOD REBCO tape with BaMO3 (M = Zr, Hf) artificial pinning center

Tatsuoki Nagaishi, Sumitomo Electric Industries, Japan

Low cost REBCO tape is anticipated for superconductor applications such as fusion magnets, MRI, and NMR. Reasons for the present high cost of REBCO tape are expensive processed source materials, the low yields for film preparation from them and the high running cost of energy sources. In this regard, fluorine free MOD (FF-MOD) is the most promising technique aiming for low cost because of inexpensive material solutions, nearly 100% material yield and no special energy source requirement except for a conventional tube furnace. It used to be hard to include artificial pinning centers (APCs) in the process needed for high magnetic field applications. However, as we reported in [1], [2], we have succeeded in making FF-MOD films with added $BaMO_3$ (BMO, M = Hf, Zr, etc.) nanoparticles as APCs by applying a poly-crystallization sintering process along with other processes. We developed BMO nanoparticles with a minimum diameter of 2 nm by utilizing the solvothermal method [3]. The poly-crystallization sintering process was introduced to decompose $BaCO_3$ completely because residual $BaCO_3$ inhibits film growth. So far, we have succeeded in fabricating epitaxial REBCO films which contain more than 7 mol% BMO on a clad type tape with buffer layers [4]. 120-m-long REBCO tapes with Ic exceeding 200 A/4 mm-width at 77 K have been achieved. The highest Ic at 20 K, 20 T (B//c) is 230 A/4 mm with 2.7 mol% $BaHfO_3$.

A part of this work was performed at the High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University (Project No. 202112-HMKPC-0006).

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5CMR11 Are 15% Zr doped ReBCO tapes with the natural spread of Ic as useful as graded Ic tapes with 7.5% Zr doping?

Dmytro Abraimov, National High Magnetic Field Laboratory, United States

Even if a uniform ReBCO conductor were used, the local critical current Ic in a magnet would be highly non-uniform due to the strong in-field angular dependence of ReBCO. Ic would be smaller in regions exposed to the substantial radial field. To reduce the effect of screening currents and unify Ic in the magnet, graded Ic tapes have been used. SuperPower Inc. targets grow tapes with different ReBCO thicknesses. However, tapes from different growth runs may lead to production tapes with different properties. We observe variations of the spread of slopes in transport Ic vs. B in log-log graphs that suggest variations in pinning for films with the same thickness and grading. Variation of pinning properties complicates the scaling of Ic for modeling. For more than 70 tapes, we analyze deviations of the in-field Ic from target values, end-to-end variations, and slit-to-slit variations. End-to-end relative variations of Ic are similar at 77K; SF and at 4.2K, B⊥tape for most tapes less than +/- 5%. However, due to the strong angular dependence of in-field Ic and existing variations of ab-plane tilt angle, relative variation of Ic at 4.2K, 18o are larger, with the majority of tapes roughly staying within +/- 10%. Transport in-field Ic for tapes with 7.5% and 15% Zr doping were compared. Tapes with 15% Zr had composition adjusted for high Ic at high fields and 4.2K-20K temperature range suitable for fusion applications. Lower average values of Ic at 77K, self-field and larger □-values were detected for 15% Zr doped tapes. We observed that these tapes have considerably higher values of in-field Ic due to higher artificial pinning center density and increased ReBCO thickness. The natural spread of parameters of 15% Zr doped tapes is comparable with the intentional spread for 7.5% Zr doped graded Ic tapes.

WEDNESDAY, APRIL 5

Poster Session (PO)

5PO1 Measurement of Transverse REBCO Delamination Strength of Conductors from Multiple Sources

Takanobu Mato, National High Magnetic Field Laboratory, United States

In 2017, the Applied Superconductivity Center at the National High Magnetic Field Laboratory successfully generated a record high magnetic field of 45.5 T, in which 11.4 T was generated by the 'Little Big Coil', a stack of small REBCO coils, within a 31.1 T background by a resistive outsert. After the operation, the post-mortem revealed that the REBCO tape was mechanically damaged. The REBCO tape was plastically deformed, displaying waviness and potential buckling of the conductor. It was also observed that the REBCO layer delaminated from the buffer layers in many areas and certainly degraded the critical current of the REBCO magnet. In order to not only understand but also mitigate this form of damage, the delamination strength of REBCO CC needs to be studied. Since 2013, numerous researchers have measured the REBCO delamination strength in transverse direction and found large variations. However, one study eliminated the large scatter of the measured values by removing the copper edge of the REBCO tape and using a new experimental setup made of epoxy resin. The copper edge plays a significant role in the REBCO delamination strength due to its non-interfacial elastoplastic deformation.

In our study, we adopt this method for the measurement of the delamination strength of REBCO tapes designed for new versions of Little Big Coil. We are attempting to measure the critical current under transverse stress by using the epoxy-made experimental setup. The difference between the previous studies is discussed.

5PO2 2D Reel-to-Reel Scanning Raman Spectroscopy of REBCO Conductor for Quality Control, Process Control Feedback and Prediction of In-Field Jc(B,T) Performance

Nathaly Andrea Castaneda Quintero, University of Houston

The demand for scaling up the manufacturing of REBCO coated conductors has increased dramatically in recent years. The main requirements include high manufacturing yield and consistent performance along long lengths at field and temperature of interest. Therefore, implementing a high throughput characterization technique for quality control becomes essential. In this study, we report on the development of a 2D Reel-to-Reel Scanning Raman Spectroscopy system for characterization of long lengths of REBCO conductors. Detailed 2D maps of over 14 detected Raman peaks in the REBCO/BZO/REO system can be obtained simultaneously resulting in 3x14 maps of intensity, wavenumber peak width distribution. The wealth of information obtained through the scans can be analyzed to provide insight ranging from identification of the origin of defects or dropouts to prediction of in-field performance Jc(B,T) in non-defective tapes. Results on both defects characterization and correlation of Raman features to in field performance will be presented and discussed.

5PO3 A fast, novel, and coupled Electro-Magnetic and Electro-Thermal model for metal-insulated high field magnets

Anang Dadhich, Slovak Academy of Sciences, Slovakia

High-field REBCO magnets contain several coils with many turns, and electro-thermal quench is an issue that is required to be taken into account while designing such magnets. Thus, there is a need for fast and accurate software to numerically model the overall performance of full-scale magnets. High temperature superconductors can be modeled using different techniques for electro-magnetic (such as H-formulation and A-V formulation) and thermal (finite element method) analysis. However, it takes a lot of time to model the electro-magnetic and electro-thermal behavior of superconductors simultaneously in a commercial software, specially for non-insulated or metal-insulated coils. We have developed a novel and fast model programmed in C++, which performs coupled electro-magnetic and electro-thermal analysis using variational methods based on Minimum Entropy Production [Minimum Electro-Magnetic Entropy Production (MEMEP) and Minimum Electro-Thermal Entropy Production (METEP), respectively]. The models are applied to axi-symmetric full scale magnets of more than 30 T field strength for transient design (thermal quench reliability), taking screening currents into account. The electro-magnetic formulation has been benchmarked with H-Formulation in our previous works. The electro-thermal model in our software, using METEP, is benchmarked with a Finite-Difference method, showing good agreement. The model developed is faster than commercial software and conventional methods and can be used for a quick and complete electro-magnetic and electro-thermal analysis of practical superconducting applications such as rotating machines and coils for high field magnets.

WEDNESDAY, APRIL 5

Poster Session (PO)

5PO4 Optimization of ReBCO CORC®-based Cable-In-Conduit-Conductors for fusion

Arend Nijhuis, University of Twente, The Netherlands

For magnet fields in the 20 T range, Conductor on Round Core (CORC®) cables and wires, composed of spiraled high-temperature superconducting (HTS) REBCO tapes, wound in multiple layers, is one of the options in fusion high field magnet technology. They combine isotropic flexibility and high resilience to electromagnetic and thermal loads. Finite element (FE) and analytical models are developed to predict the performance of CORC® under axial and transverse load aiming for optimal cabling layout of ReBCO based Cable-In-Conduit Conductors (CICC) for fusion magnets. The large electromagnetic load for 100 kA/20 T class conductors, requires a systematic analysis on tape and cable level to determine the optimum between reliable operation and minimal production and operation cost.

As a basis for the models, extensive experimental REBCO tape and CORC® cable characterisation and FE modeling has been performed to study the performance under axial, transverse contact and torsional loads. With CORC®-based models, parametric analysis is carried out by varying winding angle, core's Poisson's ratio, core diameter, friction coefficients, and tape width. The models build at the University of Twente are used for analysis of the present series of ReBCO CORC® based CICCs that are being tested in the Sultan facility at PSI (Switzerland). The combination of experimental test results from different conductor layouts and model computations, may offer important guidelines for further optimisation of the first-generation high-performance ReBCO prototype superconductors for fusion.

5PO5 Superior critical current of long length 4 µm thick REBCO tapes

Chirag Goel, University of Houston, United States

$REBa_2Cu_3O_{7-\delta}$ (REBCO, RE = rare earth)-based tapes with high critical current can be very impactful in high magnetic field applications at low temperatures and power applications at high temperatures. A pilot-scale Advanced Metal Organic Chemical Vapor Deposition (MOCVD) method was used to fabricate 50-m-long, 4+µm thick REBCO tape in a single pass. Critical currents 3.3x that of commercial HTS tapes were achieved at 20 K, 12 T in these 50-m-long tapes. A 20-m-section from a 50 m tape was tested over its entire length by reel-to-reel (R2R) scanning Hall-probe microscopy (SHPM) at 65 K, 0.25 T, 2 T, and 4 T. The 4-mm-wide strand showed mean critical currents at 65 K of 530 A, 200 A, and 104 A at 0.25 T, 2 T, and 4 T respectively.

This work was supported by the U.S. Department of Energy Advanced Manufacturing Office award DE- DE-EE0007869 and the U.S. Department of Energy Office of High Energy Physics award DE-SC0016220.

5PO6 REBCO films on flexible dielectric substrates for microwave applications

Jithin sai Sandra, University of Houston, United States

Rare Earth Barium Copper Oxide (REBCO) superconducting thin film with significantly low surface resistance, grown on flexible, dielectric template has a strong potential in microwave frequency applications. In this work, flexible yttria-stabilized-zirconia (YSZ) ribbon is being used as a suitable dielectric substrate for high frequency applications due to its low dielectric loss, low thermal conductivity, chemical and thermal compatibility with REBCO and oxide buffer thin films. A 40 µm thick, flexible YSZ substrate was planarized to ~ 1 nm roughness, facilitating the growth of a high-quality, biaxially-textured magnesium oxide (MgO) by ion beam assisted deposition (IBAD) followed by magnetron-sputter-deposited homo-epitaxial MgO and $LaMnO_3$ (LMO) layers. The LMO films on flexible YSZ with an out-of-plane texture 3.1° and an in-plane texture of 6.7° served as a good template for high-quality REBCO film growth. 350 nm REBCO films grown by metal organic chemical vapor deposition (MOCVD) were characterized using Scanning Hall Probe Microscopy (SHPM) for uniformity in critical current density (Jc) at 77 K. RF performance characterized using quality factor (Qf) measurements of REBCO films on flexible YSZ at 8-8.3 GHz and 20-75 K are positively correlated with Jc (77K) and found to be superior to that of high-quality REBCO films on sapphire substrate.

WEDNESDAY, APRIL 5

Poster Session (PO)

5PO7 Electromechanical and Electromagnetic testing of Advanced MOCVD REBCO tapes

Vamsi Yerraguravagari, University of Houston, United States

High critical current density (Jc) of High Temperature Superconductor Coated Conductor (HTS CC) tapes based on REBCO (RE = rare earth) are being widely used for high magnetic field applications such as compact fusion, nuclear magnetic resonance spectroscopy, and particle accelerators. Commercially available REBCO tapes based on Hastelloy substrates permanently degrade in Jc at a strain higher than 0.6% which corresponds to a stress value of 700MPa. In this work, we have evaluated the electromechanical properties of REBCO CC (commercial tapes and tapes made at UH using advanced MOCVD) in different composites forms. The objective of this work is to develop higher yield strength tapes to withstand large forces in even high magnetic fields. We are also evaluating the performance of long length REBCO tapes fabricated using Advanced MOCVD using a Reel-to-Reel(R2R) Scanning Hall Probe Microscopy (SHPM) fields from 0.05T to 4T at 65K. This data is used to design the REBCO deposition process to achieve the desired in-field performance uniformly over long lengths.

This work was supported by Advanced Research Projects Agency-Energy (ARPA-E) award DE-AR0001374, U.S. Department of Energy Office of High Energy Physics award DE-SC0016220, and the U.S. Department of Energy Advanced Manufacturing Office award DE- DE-EE0007869.

5PO8 Electromagnetic Properties of 2 μm thick 15% Zr-doped $REBa_2Cu_3O_{7-\delta}$ Double-Sided Tapes

Bhabesh Sarangi, University of Houston, United States

High Temperature Superconducting (HTS) Coated Conductors (CCs) based on epitaxial $REBa_2Cu_3O_{7-\delta}$ (REBCO, RE = rare earth) films with superior mechanical strength and high current carrying capacity are being developed for use in ultrahigh-field superconducting magnets such as dipoles and quadrupoles for particle accelerators, and for compact fusion. In this work, we modified our advanced metal organic chemical vapor deposition (A-MOCVD) reactor to deposit 1–2 μm thick REBCO films on both sides of a double-sided buffered substrate in a single pass. Double-sided REBCO tapes with about 2 μm thick films on each side showed critical current of 530 A/4mm at 20 K, 20 T which is 3.5x that of commercial REBCO tape performance.

This work was supported by Advanced Research Projects Agency-Energy (ARPA-E) award DE-AR0001374.

5PO9 Quality assessment of long REBCO coated conductors by offline/inline characterization techniques augmented by machine-learning models

Siwei Chen, University of Houston, United States

The increasing prevalence of large-scale, high-magnetic-field superconducting applications increases the demand for high-volume of uniform and high-performance REBCO coated conductors. For quality control/assessment of long REBCO coated conductors, the magnetization method has replaced the transport current measurement in numerous recent consensus studies due to its non-contact and non-destructive nature. It has been demonstrated to profile self-field and in-field critical current density (Jc) distributions at high testing speed and spatial resolution. A fly in the ointment is the compromised sensitivity of Jc at the center of width in REBCO tapes. This low sensitivity can be attributed to the intrinsic property of the current loops in magnetized REBCO tapes under external dipole fields during testing. A complimentary quadrupole external magnetic field has been devised and verified to induce mirror-symmetric current loops in REBCO tapes to compensate for the sensitivity. In conjunction with the dipole magnetization measurement results, the recovered Jc in the middle of the tapes can identify any defects in long REBCO tapes offline. To also enable critical current (Ic) monitoring of REBCO tapes during manufacturing, the inline two-dimensional X-ray diffraction (2D-XRD) technique was employed. Machine-learning-based regression models were trained to predict Ic at different temperatures and magnetic fields. The performance of the obtained models was auspicious, giving over 85% of predictions falling within the range of offline measured Ic. The combination of offline/inline characterization techniques and the machine-learning-based Ic predictors provided an indirect approach to assessing long REBCO tapes during manufacturing. It will serve as a reliable feedback source for real-time quality control in a scaled-up REBCO tape deposition process, thereby providing longer and more uniform high-performance REBCO tapes for large-scale, high-field superconducting applications.

WEDNESDAY, APRIL 5

Poster Session (PO)

SPO10 Correlation of microstructural and transport characteristics of REBCO conductors with variable Jc(4.2 K) and variable superconducting layer thickness

Yavuz Oz, National High Magnetic Field Laboratory, United States

Stable and predictable Jc(B,**θ**,T) behavior along the entire coil is crucial for designing and building very high field magnets. However commercially available REBCO tapes can exhibit significant Jc(B,**θ**,T) variation. Moreover, due to the need for variable Ic in some magnet designs manufacturers produce tapes with different superconducting layer thickness (t_REBCO), which can result in more undesired Jc(B,**θ**,T) variation. We have observed significant Jc(B,**θ**,T) variation in REBCO tapes with variable t_REBCO produced by SuperPower Inc. delivered to both the 32 Tesla and 40 Tesla all-superconducting magnet projects, accompanied by dense arrays of micron sized blocking defects and precipitates on the REBCO layer surface. In addition to reducing the surface area available to supercurrent flow, blocking defects produce large strain fields around them which can also affect vortex pinning. To understand how defects and precipitates affect Jc and in particular vortex pinning, we characterized and correlated surface defect type, size and density with transport Jc(4.2 K , 14 T ⊥ tape), the slope of the Ic(B) curve (alpha) and t_REBCO in more than 60 tapes produced by SuperPower delivered to the 40 Tesla all-superconducting magnet project. We found a non-uniform distribution of a-axis grains, porosity, and copper oxide grains in almost all the studied samples, which had 0.6 microns < t_REBCO < 1.9 microns and 2.5 MA/cm^2 < Jc (4.2 K, 14 T ⊥ tape) < 6.5 MA/cm^2. Jc and alpha vary significantly at the same t_REBCO, with a maximum of ± 30% and ± 10% respectively. Surprisingly, Jc and alpha did not decrease with increasing t_REBCO as usually reported in the literature. Jc scaled linearly with increasing alpha, and we found a correlation between defect type and t_REBCO, and between defect type and the Jc versus alpha range.

5PO11 Design of a 40-MW-class Electric-Wire-Interconnect-System for Liquid-H2 Fuel-Cell Propulsion

Timothy Haugan, U.S. Air Force Research Laboratory, United States

The aerospace industry is the last major transportation industry working to implement hybrid-electric technology for propulsion. Nearly exponential growth is occurring recently for electric aircraft development, with reportedly with more than 300 startup companies worldwide formed in the last 2-3 years. As of April 2022, pre-orders for electric aircraft exceeded 5,500 aircraft and $29B sales, even though only a handful of electric aircraft have been certified for flight so far. The goals for electric drivetrain components established by the NASA SUSAN and ARPA-E ASCEND programs are aggressive and challenging, to simultaneously achieve highest power densities possible simultaneous with highest efficiencies, for major components; e.g. for SUSAN > 30 kW/kg and > 99%. While strong efforts worldwide are considering different technology approaches; however, it is generally understood that cryogenic/superconducting technologies can meet the specific goals set.

The electric-wire-interconnection-system (EWIS) of an electric drivetrain is known to have by-far the largest mass fraction of all components. This paper studies the EWIS of a 40-MW-class electric drivetrain, and compares different wire technologies including cryogenic metals, superconductors, and 'conventional' metals at ambient temperatures. The mass and heat loss scaling laws of the components of the electric drivetrain are presented for varying power/voltage/ampacity levels (0-20 kA) and power-wire distribution architectures. Electric power system components studied thus far include metal conductors (Cu-clad-Al (CCA), Al 99.999% 'hyperconductor'), busbars, current leads, metal/superconducting tee-joints, high temperature superconducting (HTS) Y,RE-Ba-Cu-O cables, low/high voltage insulation, and cryoflex tubing. A weight and efficiency analysis of a 40 MW EWIS system will be provided, and material options for will be compared.

Acknowledgments. This research was funded by the NASA University Leadership Initiative (ULI) #80NSSC19M0125, AFOSR LRIR #18RQCOR100, and the Air Force Research Laboratory/Aerospace Systems Directorate.

WEDNESDAY, APRIL 5

Poster Session (PO)

5PO12 Screening Current Induced Strain in Ultra-High-Field REBCO-Coated-Conductor Magnets

Yi Li, Princeton Plasma Physics Laboratory, United States

Rare-earth-based barium copper oxide (REBCO) coated conductor (CC) outstands high-temperature superconductor (HTS) candidates in terms of high in-field performance, critical current density, tensile strength, and commercial availability, making it the conductor of choice for ultra-high-field (UHF) magnet applications. REBCO CC is also considered the enabling technology for cost-effective, compact fusion systems because of its potential for low-cost production and liquid-helium-free operation. However, technological challenges pertaining to the large screening currents still remain. The major issues caused by the screening currents in REBCO conductors in high-field applications involve two aspects: the screening current-induced magnetic field (SCF) and the screening current-induced stress (SCS). In the past decades, extensive research has been devoted to the SCF, offering a variety of possible remedies. With the latest advances in the construction and testing of high-field magnets, new observations of the SCF involving REBCO coils were reported. The SCS was identified in recent years and has raised growing concerns. The excessive and highly concentrated Lorentz force, rooted in the high magnetic field and the screening currents, poses threats to the structural integrity of REBCO coated conductors. Here we review recent research efforts in understanding and tackling the screening current-related technological issues. We present studies, including recent developments at Princeton Plasma Physics Laboratory, on numerical modeling, experimental characterizations, and possible countermeasures. It is still an open question to precisely predict the SCS in large-scale HTS magnets. How to minimize the influence of SCF and SCS is one of the key technical challenges for the design of future UHF REBCO magnets.

5PO13 Design and Analysis of an Axial Flux High-Temperature Superconducting Motor

Jun-Yeop Lee, Changwon National University, South Korea

In line with global environmental regulations, the demand for eco-friendly and highly efficient aircraft propulsion systems is increasing. The combination of axial flux motors and superconductors could be a key technology used to address these needs. In this paper, an axial flux high temperature superconducting (HTS) motor for aircraft propulsion was designed and its characteristics were analyzed. A 2G HTS wire with high magnetic flux characteristic was used for the field winding of the 120 kW axial flux HTS motor, and the rotational speed and rated voltage of the motor were 2,000 rpm and 220 V, respectively. In this axial flux HTS motor, the revolving armature type was adopted for stable cooling of the HTS field coil. The design and analysis related to the electromagnetic and thermal characteristics of the motor were performed using a 3D finite element method program. The HTS coil was maintained at the target temperature by effectively designing the current lead and cooling system to minimize heat loss. These results can be effectively used in the design of propulsion systems for large commercial aircraft in the future as well as for the design of small aircraft with less than 4 seats.

5PO14 FEM Modeling of heating effects during current sharing in REBCO cables containing faulty strands

Milan Majoros, The Ohio State University, United States

Superconducting cables have to be used in high field magnets to reduce their self-inductances and enable their fast ramping. REBCO Roebel and CORC cables have their strands transposed or twisted to reduce ac loss, magnetization, and improve field homogeneity and ramp rate sensitivity. Stability and current sharing are important. Here we present the results of thermal FEM modeling of current sharing in tape-stacks containing degraded or faulty elements. The FEM model assumed a magnetic field of 8 T at a temperature of 4.2 K, stack of 11 non-insulated REBCO tapes containing defects located in their centers and immersed in a liquid He bath. The effects of contact resistance on stability and current sharing were explored.

5PO15 Glassy and plastic vortex creep regimes in superconducting (Y,Gd)$Ba_2Cu_3O_y$ films and coated conductors

Leonardo Civale, Los Alamos National Laboratory, United States

Large thermal fluctuations in high temperature superconductors give rise to fast vortex dynamics that promotes the time relaxation of the metastable supercurrents, which is detrimental for power applications.

WEDNESDAY, APRIL 5
Poster Session (PO)

5PO15 – *continued*

We are pursuing a general understanding of the lowest achievable flux creep rate (S) for any superconductor at any temperature (T) and magnetic field (H). Initially, we found that there is a universal lower limit for S in the Anderson-Kim (A-K) regime at T<<Tc (Eley et al., Nat. Mat. 2017). Later, we expanded our quest to higher T and H conditions outside the A-K limit, where the universality is lost and different single-vortex and collective regimes may occur. In this poster we will present results on (Y,Gd)$Ba_2Cu_3O_y$ coated conductors with randomly distributed BaHfO3 nanoparticles. These samples are ideal for this purpose, as they exhibit extremely strong vortex pinning, with critical current densities among the highest in any known superconductor. We identify several glassy and plastic dynamics regimes, the boundaries among which are determined either by intrinsic vortex properties or by thickness effects. In particular, we find a thickness-controlled "second A-K regime" at high T, which sets the lowest S(T,H) limit in thin samples in technologically relevant T-H conditions.

Work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Materials Sciences and Engineering Division.

5PO16 Experimental Design and Simulation for Testing Current Redistribution in a REBCO Tape-Stack Cable
John Rogers, Texas A&M University and Accelerator Technology Corporation, United States

Recent theoretical studies have suggested the feasibility of using a non-insulated, non-transposed REBCO tape-stack cable in a high-field magnet winding. Due to the variation in magnetic field across the cable, each tape in the cable has a different critical current. As cable current is ramped, currents naturally redistribute due to the dynamic rise in resistivity near critical operation thus preventing premature quench and optimizing the cable current capacity. A lumped network circuit model, coupled with magnetic field simulation, has been studied to predict the behavior of current redistribution in such a cable. An experimental design and simulations are presented to test for current redistribution at liquid nitrogen temperatures. Simulations imply that, if predictions given by the circuit model are accurate, current redistribution can be experimentally verified. Fabrication and operation of the planned experiment is detailed including structural, material, electrical, and magnetic design.

5PO17 Conceptual design of a ReBCO non-insulated ultra-high field solenoid for the Muon Collider
Bernardo Bordini, CERN, Switzerland

The international particle physics community considers a Muon Collider as a possible option for the successor of the Large Hadron Collider at CERN. Recently, an international collaboration has been set up to produce a conceptual design study of a Muon Collider. One of the main challenges is the need of an ultra-high magnetic field solenoid for the final cooling of the muons. This magnet must have a bore aperture of about 5 cm and a 1 % magnetic field homogeneity over 0.5 m of length. CERN is exploring the possibility of developing such a magnet by only using a stack of ReBCO tapes as conductor. The main idea driving the study is to produce a modular compact magnet constituted by an assembly of identical pancakes electrically connected in series. Quench protection and stress management are the biggest design challenges. To cope with them, we are investigating the option of Non-Insulated (NI) pancakes, each made of a single coil (i.e., discarding concentric coils), inserted in a stiff outer disk that provides a sufficient precompression to the coil (~ 200 MPa). To protect the magnet and to ramp up the field sufficiently fast, the NI coil interlayer electrical resistance must be optimized and controlled. In this paper we present a preliminary design of this concept. If successful, this type of design will contribute to the development of high-field solenoids for particle accelerators and promote the use of ReBCO tapes in compact windings needed for different applications such as electrical generators and fusion reactors based on magnetic confinements.

THURSDAY, APRIL 6

Power Applications (PA)

6PA1 Application of HTS Coated Conductors to Overhead Power Lines with Distributed, Evaporative, Cryogenic Cooling – Lessons Learned

Franco Moriconi, VEIR Inc., United States

VEIR has developed a technology that enables overhead and underground power transmission lines utilizing a novel, propriety cooling system. VEIR's long-length superconducting transmission lines are cooled by a distributed, evaporative cooling architecture that uses a liquid nitrogen open-loop system that is 20-times more effective than conventional cryogenic cooling technology. VEIR's lines require small liquid nitrogen flow, resulting in long-length line deployments with HTS conductors and cables that are smaller and lighter than traditional superconducting cables. The novel HTS conductors can be suspended from poles and towers in an overhead transmission line that can carry five times the power of normal conductors. A technology demonstrator of a 30 m. long suspended overhead line was constructed and tested by VEIR in Woburn, Massachusetts. The line operates at low voltage with a current capacity of 3,000 ADC. The HTS conductor uses 4mm wide REBCO tapes in a multi-bundle configuration, and the line operates at 77-78K with cooling provided by VEIR's innovative liquid nitrogen evaporative system. In this paper, we present some of the results and lessons learned from using HTS CC tapes in bundle configurations, and from testing HTS bundles in overhead power lines.

6PA2 US Navy Developments in Large-Scale Superconducting Applications

Peter Ferrara, NSWCPD (Naval Surface Warfare Center, Philadelphia Division), United States

The US Navy has been investing in superconducting technology for the past 80 years. The most recent developments have been in the area of low- and medium-voltage direct current (DC) cables and large-bore magnets, and superconducting magnetic energy storage (SMES). Low-voltage DC cables are most useful in the control of a ship's magnetic signature as part of a degaussing system. Significant progress towards implementing this aboard US Navy vessels has been made and is currently being installed. Medium-voltage power system components have been under development the past several years through programs aimed at dielectrics, warm-to-cold transitions, connectors, etc.; as well as cryogenic refrigeration. Large-bore magnets have been a focus over the past decade and are planned to transition in the next five years. Additionally, the Navy has launched an investigative study on the relevance of SMES for use in applications aboard naval vessels. The invited talk for CCA 2023 will include current status of the Navy's recent transition of low-voltage DC cables to the Fleet, topics on medium-voltage power system components, the next stage of development and potential transition of large-bore superconducting magnets, and initial results and potential use of SMES in naval applications.

6PA3 Development and Needs of Coated Conductors for Air and Space Applications

Timothy Haugan, U.S. Air Force Research Laboratory

The increasing electrification of aerospace industries is driving a need for much lighter and more efficient electric power generation and distribution systems. For example, the goals for electric drivetrain components established by the NASA SUSAN and ARPA-E ASCEND programs are aggressive and challenging, to simultaneously achieve highest power densities possible simultaneous with highest efficiencies for major components, e.g., for SUSAN > 30 kW/kg and > 99%.

In addition to hybrid-electric propulsion, there are many other technologies and applications being studied such as for space and utilizing high field magnets including 1-5 MW microgrids for nuclear propulsion, ion propulsion magnets, magneto-hydrodynamics, magnetocalorics, high-field magnets for radiation shielding, energy storage and transmission for lunar base stations, and beamed power for connecting base stations and powering small spacecraft or transport vessels.

Herein we present some case studies of varying high power technologies, and how the use of coated conductors can strongly impact the performance. Specifically, the weight and efficiency analysis of a 40 MW electric-wire-interconnect-system (EWIS) microgrid system will be provided for liquid-H_2 and fuel-cell propulsion, and material options for will be compared.

THURSDAY, APRIL 6
Power Applications (PA)

6PA3 – *continued*

The development of a 1 MW flux-switching electric motor and drive for electric propulsion will be presented, which demonstrates the need for the highest power density conductor, to achieve filament sizes less than 50 microns for AC loss reduction, and other properties including mechanical strength, low cycling fatigue, and reliability.

Acknowledgments: This research was funded by the NASA University Leadership Initiative (ULI) #80NSSC19M0125, AFOSR LRIR #18RQCOR100, ARPA-E Subaward #89703021SAR00022 for contract #DE-AR0001355, and the Air Force Research Laboratory/Aerospace Systems Directorate.

6PA4 Development of Electric Propulsion System for Aircraft by REBCO Superconducting Devices
Masataka Iwakuma, Kyushu University, Japan

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 comparing the conventional Cu-wire. In our previous efforts in the national projects, 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 which 1kW fully superconducting motor was really manufactured. In the current project, we have the two large research themes. One is the development for fundamental technologies of elemental functions and the other is the verification of device & system function, which consists of verifications of 500kW-class fully superconducting motor and 1MW-class propulsion system. Now, the production of the 500kW-class fully superconducting motor is in the final stage.

We are planning to show the progresses of the current project, which includes the major results in the development for fundamental technologies and the verification of the fully superconducting motor.

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

6PA5 Electric power grid applications of coated conductors – What is available and What is missing?
Sastry Pamidi, FAMU-FSU and the Center for Advanced Power Systems

REBCO coated conductors are being manufactured with increasingly long piece lengths and high current density. Several HTS cables have been demonstrated for a variety of electric power grid applications. They include DC, AC, and transmission and distribution voltages. Some of the demonstration projects operated for long periods, and a few are currently operational. The operations have been satisfactory and demonstrated that the basic cable technology is ready for market. The question then is why we do not see HTS cable in the power grid. Similar questions arise on other coated conductor power applications such as fault current limiters, wind generators, and superconducting magnetic energy storage. The presentation will discuss the missing elements to make HTS power applications attractive. The missing elements include reliable power interfaces, low-maintenance cryogenic equipment, and electrical insulation for cryogenic applications. Recent developments in some of the areas will be discussed along with the need for further technology advancements. The presentation will end with the need to use the increasing worldwide interest in hydrogen to bring superconductivity to the forefront of emerging technologies that can support the push for a sustainable electrical grid with zero emissions.

6PA6 Testing of the HTS magnets for wind generators using a performance evaluation system
Chang-Hyun Kim, Changwon National University, South Korea

This paper deals with the experimental test and characteristic analysis results of a real scale HTS coil for a 10 MW HTS generator using a performance evaluation system (PES). We have proposed a method to evaluate the characteristics of large-scale HTS wind turbine generators using a PES. The PES is designed and manufactured to examine the electromagnetic properties, stability and cooling performance of a full-scale 10 MW HTS coil.

THURSDAY, APRIL 6
Power Applications (PA)

6PA6 – *continued*

Three HTS coils and corresponding armature modules were designed and manufactured to confirm the characteristics of a real-scale generator using the PES. The system was assembled to withstand the force equivalent to one pole of a 10 MW HTS wind turbine under load conditions. The HTS coil was cooled to 35 K through a neon helium cooling system. The HTS coil operates at a rated field current and generates the same force by flowing a DC current through the armature, which corresponds to the rated armature current of a 10MW generator.

THURSDAY, APRIL 6
Electromagnetic & Electromechanical Properties (EEP)

6EEP1 High throughput operando measurements on current transport properties in long REBCO coated conductors and its contribution to tape modeling and process optimization

Takanobu Kiss, Kyushu University, Japan

We have succeeded in developing high-throughput measurement and evaluation of local current transport characteristics of long CC tapes in practical environments. It is relevant to understand current transport properties of REBCO coated conductors (CCs) at actual operation conditions such as low temperature and in-field not only self-field critical current, Ic, at liquid nitrogen temperature. To grasp such Ic as a function of temperature, T, and magnetic field, B, the implicit assumption is, in general, that the sample has a constant tape width and thickness as specified and is sufficiently uniform in the longitudinal direction. Full-length test of Ic is widely conducted as a shipping test, however, it is limited near the self-magnetic field in liquid nitrogen. Regarding T- and B-dependency, it is often defined as a lift factor based on measurements using a short piece sample. Although the full-length inspection in liquid nitrogen is certainly useful for verifying the absence of significant defects, it does not sufficiently capture Ic reduction caused by local defects hidden by the Ic fluctuation and/or the temperature-change of magnetic flux-pinning properties at lower temperature. Therefore, it is not yet clear whether the lift factor is position dependent or not in the long tape. For the tape manufacturing process, high speed operando characterizations are also necessary in order to accelerate process optimization. In this study, we have developed high-throughput measurement and evaluation of current transport characteristics of long CC tapes in practical environments based on in-field reel-to-reel magnetic microscopy coupled with machine learning based analyses. Based on a large number of measured data obtained from long tapes, we discuss the impact of novel data-driven approaches on modeling of transport characteristics in long length tapes as well as optimization of tape fabrication processes.

Acknowledgements: This work was supported by JSPS KAKENHI Grant Number JP19H05617.

6EEP2 Fabrication, characterizations, and design studies of SCSC cables

Naoyuki Amemiya, Kyoto University, Japan

We have been developing the Spiral Copper-plated Striated Coated-conductor cable, abbreviated to the SCSC cable or the double "SC" cable, which is flexible high-current cables, whose distinguished characteristics are low ac losses and small shielding current induced fields (SCIFs). The former is important for armature windings and fast-exciting field windings of motors and generators, CS coils and PF coils of tokamaks, and magnets of rapid-cycling synchrotrons. The latter is important for various accelerator magnets. We installed a reel-to-reel (RTR) cabling machine at Kyoto University, and we are now able to fabricate long pieces of cables. We typically use 2 mm-wide, 10-filaments coated conductor with 0.01 mm-copper plating on both sides and wind them in multiple layers on a round flexible metal core. Using SCSC cable samples, the following characterizations have been conducted: magnetization loss measurements, ac loss measurements in a sample carrying ac current in ac magnetic fields, dynamic resistivity measurements, and current transport experiments. We also conducted design studies of SCSC cables in order to clarify their applicability to practical windings and magnets.

This work was supported mainly by JST-Mirai Program Grant Number JPMJMI19E1, partly by JSPS KAKENHI Grant Number JP20H00245 and partly by Japan-U.S. Science and Technology Cooperation Program in High Energy Physics.

THURSDAY, APRIL 6

Electromagnetic & Electromechanical Properties (EEP)

6EEP3 Could AC loss in coated conductor cables decrease to the level acceptable for pulsed magnets?

Fedor Gömöry, Slovak Academy of Sciences, Slovakia

Because of the ability of to transport large currents at temperatures in the 20-40 K range, the use of REBCO superconductors in place of low-temperature superconductors (LTS) is considered an option when aiming at reduction of operation cost in large machine like a particle accelerator or a fusion tokamak. Substantial part of the cooling budget for the magnetic systems producing pulsed magnetic fields is spent to remove AC loss. The physics of AC loss has been thoroughly studied during the development of LTS wires, and the acquired knowledge is valid also for coated conductors (CC). It can be shown, that the level of expected AC loss depends slightly on the configuration of the cabled conductor, but substantially on the transversal dimension of the primary superconducting element: the filament diameter in case of a multifilamentary wire, and the tape width in case of non-striated coated conductor.

We estimated the AC loss for a 20 kA cable operating in a 5 T magnet at 4 T/s, using a straightforward AC magnetization model that was experimentally verified on short cable samples at 1 T, 4.2 K. The AC loss expected when using NbTi wire with 3 μm filaments is compared with the estimated result for a round cable utilizing a 3 mm wide coated conductor tape. The unavoidable loss component is generated by the magnetic hysteresis caused by flux pinning. We found that in the CC alternative the hysteresis loss is ~500 times higher. Obviously this is a showstopper when considering state-of-the-art CC technology for LTS magnet upgrades. Therefore, it is necessary to search for possible ways to reduce the hysteresis part of AC loss in CC tapes, cables and magnets. We discuss how much can be achieved in this regard by tape filamentization, dedicated cable architecture, and optimised magnet design.

6EEP4 Quench Detection in REBCO Conductor by Using the Wire Itself as a Microwave Transmission Line

Goran Majkic, University of Houston, United States

We present results on utilization of REBCO coated conductor itself as a quench detection medium by exploiting its transmission line properties. The REBCO coated conductor architecture (REBCO/Buffer dielectric/Substrate layers) constitutes a transmission line, which will naturally be sensitive to any local disturbances of homogeneity of material properties including REBCO conductivity change upon transition from superconducting to normal state, change of dielectric constant of buffer layer due to localized heating, as well as any other relevant effects. This makes it possible to utilize the wire itself as a quench sensing transmission line circuit. The development of localized quench leads to local change of the transmission line impedance, which can be near-immediately sensed by a network analyzer, resulting in formation of new peaks, Q-factor changes and frequency shifts of existing peaks and frequency shifts of peaks. We present both numerical simulation and experimental results on the characteristic changes of the rf response signature upon transition from superconducting to normal state. The results are analyzed in terms of sensitivity and response magnitude, as well as in terms of possible optimization of wire architecture for quench detection capabilities.

6EEP5 Continuous measurement on critical current of coated conductors based on a pulsed current inductive method

Xiao-Fen Li, Shanghai Jiao Tong University, China

At the edge of large-scale applications of high-temperature superconducting (HTS) coated conductors (CCs) towards magnets for motors, magnetic levitation, and especially compact fusion, the continuous characterization of the CCs gains more practical importance than ever. Compared to its low-temperature counterpart, the yield of HTS material production is lower due to the composite structure and more complicated manufacturing process, which makes the continuous measurement necessary at least for the moment. On the other hand, the high critical temperature also makes routine characterization of the CCs economically acceptable. The present transport measurement technique has a certain risk of sample damage, which brings considerable loss when applied to the product of kilometer length. An apparatus that continuously measures the critical current of long CCs was developed based on the pulsed current inductive (PCI) method, which is safe for the samples thanks to the short load time of less than 10 ms. During the measurement, a pulse of increasing current is applied to the sample. The measurement of the critical current utilizes the inductive voltage peak due to the abrupt rush-in of magnetic flux when the pinning force is overcome by the Lorentz force. The method's principle, the apparatus, the statistical behavior of the measurements, and the measurement of defect samples are discussed.

THURSDAY, APRIL 6

Electromagnetic & Electromechanical Properties (EEP)

6EEP6 Critical currents in pulsed fields from non-linear electrical transport

Boris Maiorov, NHFML and Los Alamos National Laboratory, United States

A detailed understanding of vortex pinning and dynamics is imperative for technological applications of type II superconductors. One particularly powerful approach to probe vortex physics is nonlinear electrical transport measurements. Achieving non-linear curves and the extraction of the critical current density (Jc) and n-value in pulsed magnetic fields provides key tools for these studies. Using Fast Programmable Gate Array electronics we measured reproducible current–voltage curves (I-V) in different superconducting thin films on single crystals and metal substrates grown by different methods. We show it is possible to measure Jc in high pinning coated conductors up to 65T, if the rapid vortex movement occurring during field pulses is considered to analyze the results. We compare measurements in three magnet systems with different maximum magnetic fields (H), duration and dH/dt at Los Alamos Pulsed Field Facility of the National High Magnetic Field Laboratory, here t is the time. We show the ability to measure Jc and n up to the highest accessible fields as well as to determine Jc and n continuously as a function of H in our newly commissioned mid-pulse magnet (300ms long pulse). We determined the window of dH/dt where meaningful data can be obtained. We also explore the effect of sample geometry in vortex dynamics and show what are the maximum currents we can apply. We compare the Jc performance of standard samples and those with nanoparticle additions, correlating linear and non-linear results in pulsed fields.

6EEP7 Novel angular and lengthwise critical current assessment in REBCO CC

Jan Jaroszynski, National High Magnetic Field Laboratory, United States

A simple torque magnetometer allows for the direct measurement of the torque arising from macroscopic screening currents in REBCO (CC). The angular critical current Ic(B,T,**θ**) is assessed from torque data over the full angular (**θ**) range, magnetic fields (B) up to 45 T, and temperatures (T) up to 50 K. We have got Ic(B,T,**θ**) from ~100 conductors from different vendors. We found that Ic at the ab plane decays with B exponentially Ic(B,T) ~ exp(-B/B0) rather than as power function, as it was assumed so far. In turn, Ic around the ab plane decays with T as stretched exponent exp[-(T/T0)n], and as simple exponent elsewhere. This device also allows to study AC loses and thermo-magnetic instabilities (flux jumps). Compared to transport technique, it is very fast, drastically reducing LHe consumption. It routinely delivers conductor parameters for magnets construction at the NHMFL.

However, substantial Ic variation is observed in short samples cut from different positions along the REBCO CC tapes, especially around the ab plane. Thus, lengthwise characterization is also needed. Here we show initial data from novel reel-to-reel approach. The tape runs through the small but strong magnet. The induced screening currents always oppose this movement. Ic is then determined from the tape tension. That method allows measurements at low temperatures (as 20 K) where Ic is high and delivering high transport current to the tape is virtually impossible. This force magnetometry method is possible for both B||ab and B||c.

A-M. Constantinescu, A. Xu, G. Miller, D. Larbalestier, A. Francis, T. Murphy, D. Kolb-Bond, V. Chabanenko contributed to this work funded by NSF DMR-1644779, User Collaboration Grants Program Project #5206, and the State of Florida.

Jaroszynski et al. 2022 Supercond. Sci. Technol. 35 095009, patents pending 35

6EEP8 Comparison of Electromagnetic, Geometrical, and Microstructural Characteristics of REBCO CC from Prominent Manufacturers

Griffin Bradford, National High Magnetic Field Laboratory, United States

ReBCO Coated Conductor (CC) from various manufacturers is being purchased in large quantities to construct large scale electric machines and scientific user magnets requiring high magnetic fields and tolerance of a variety of stress conditions. While each manufacturer would like to claim that the conductor meets their specification and is a uniform product ready for purchase, rarely is the conductor the ideal cartoon that is often associated with ReBCO CC. To investigate the degree of deviation from ideality, extensive microscopy and electromagnetic characterizations were performed on recently received ReBCO CC from five manufacturers. These characterizations reveal that while some manufacturers meet the requested specification in several areas, all conductors studied had quirks and irregularities which could prove detrimental to use in high-field magnets. Specifically, the geometry of the conductor is shown to contain artifacts and asymmetries, mechanical and laser slitting is still quite destructive to the edge of ReBCO CC, and significant variation of electromagnetic properties along a single tape is shown to be present.

THURSDAY, APRIL 6

Electromagnetic & Electromechanical Properties (EEP)

6EEP8 – *continued*

The heterogeneous nature of ReBCO CC's properties needs to be better understood and mitigated to be able to construct reliable high-field devices utilizing it. Overall, the goal of this study is to: advocate for a standard set of parameters characterizing the geometrical and electromagnetic properties of ReBCO CC, and to better inform the usage of REBCO CC from several vendors and understand their differences best use cases.

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