Coated Conductors for Applications Workshop 2018

September 10 – 13
Vienna, Austria
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PROGRAM BOOK

The organizers would like to thank the sponsors of the CCA 2018:

Program at a Glance

	Monday	Tuesday	Wednesday	Thursday
8:30–8:45		*Registration*		
8:45–9:00		*Welcome*		
9:00–9:15			**Characterization and Modeling**	
9:15–9:30				
9:30–9:45		**Magnet Applications**		**Characterization and Modeling**
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17:15–17:30		**Fabrication and Processing: Research**		
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18:15–18:30			*Social Dinner Viennese Heuriger* (until 22:00)	
18:30–18:45	*Welcome Reception* (until 20:00)			

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Please note that for your convenience the listed presentation titles are linked to the respective abstracts.

Monday, Sept. 10

Registration

16:00 – 18:30

For participants arriving on Monday afternoon or earlier, we recommend registering during the specified time slot to avoid a rush for the registration desk on Tuesday morning. Registration is mandatory for attending the Welcome Reception.

Welcome Reception

18:00 – 20:00

Drinks and finger food will be served during the Welcome Reception at Schloss Wilhelminenberg.

Tuesday, Sept. 11

Registration

8:30 – 8:45

For all participants who could not make it by Monday afternoon, the registration desk will be open for a brief duration on Tuesday morning.

Welcome

8:45 – 9:00

Before the technical sessions start, the organizers would like to welcome all participants.

Magnet Applications

9:00 – 12:00 *Chairperson: TBA*

9:00 – 9:30	*W. Goldacker (Karlsruhe Institute of Technology, Germany)* HTS Roebel cables, a qualified solution for advanced high field magnets	***INVITED***
9:30 – 10:00	*D. Larbalestier (National High Magnetic Field Laboratory, Tallahassee, USA)* World record DC magnetic field using an $REBa_2Cu_3O_x$ (RE = Y, Gd) superconducting magnet	***INVITED***
10:00 – 10:15	*D. van der Laan (Advanced Conductor Technologies / University of Colorado)* Recent progress on CORC® cable and wire development for magnet applications	
10:15 – 10:30	*T. Mulder (CERN / University of Twente)* ReBCO CORC cable-in-conduit conductors for large-scale magnets and bus lines	
10:30 – 11:00	**Coffee Break + Posters I**	
11:00 – 11:15	*N. Bykovskiy (CERN)* ReBCO tape based thermally activated superconducting switches and rectifier for charging high current magnets	
11:15 – 11:30	*F. Grilli (Karlsruhe Institute of Technology, Germany)* Real time simulation of current ramps in large HTS coils: no longer a computational dream	
11:30 – 12:00	**Discussion**	
12:00 – 14:00	**Lunch Break + Posters I**	

Fabrication and Processing: Industry

14:00 – 15:45 *Chairperson: TBA*

14:00 – 14:30	*A. Usoskin (Bruker HTS GmbH)* PLD/ABAD based technology of long-length YBCO coated conductors for ultra-high field applications	***INVITED***
14:30 – 14:45	*S. Moon (SuNAM)* Coated conductors by RCE-DR: process details and scale-up issue	
14:45 – 15:00	*M. Bauer (THEVA Dünnschichttechnik GmbH)* Recent progress of HTS wire production at THEVA	
15:00 – 15:15	*D. W. Hazelton (Superpower Inc.)* Progress of 2G HTS (RE)BCO conductor development at SuperPower	

15:15 – 15:30 *A. Molodyk (SuperOx)*
Status of 2G HTS wire production at SuperOx

15:30 – 15:45 *M. Bäcker (Deutsche Nanoschicht GmbH)*
HTS wire production at Deutsche Nanoschicht in 2018: non-magnetic substrates, improved processing, and scale-up to 40 mm tape width

15:45 – 16:00 *V. I. Pantsyrny (Bochvar High-technology Research Institute of Inorganic Materials, Moscow, Russia)*
Materials for coated conductors: tapes and targets

16:00 – 16:30 **Coffee Break + Posters I**

Fabrication and Processing: Research

16:30 – 18:45 Chairperson: TBA

16:30 – 17:00 *T. Puig (ICMAB-CSIC, Spain)* ***INVITED***
Growth of high current nanocomposite $YBa_2Cu_3O_{7-x}$ coated conductors from colloidal solutions: TFA versus TLAG process

17:00 – 17:15 *T. Izumi (AIST, Japan)*
R&D of coated conductors for applications

17:15 – 17:30 *M. Erbe (Karlsruhe Institute of Technology, Germany)*
Suitability assessment of different REBCO compounds (RE = Yb, Er, Ho, Y, Dy, Gd, Sm, Nd) for the fabrication of CSD-based coated conductors

17:30 – 17:45 *V. Selvamanickam (University of Houston, USA)*
Fabrication of high performance REBCO tapes and round wires for high field applications

17:45 – 18:00 *M. Osofsky (Naval Research Laboratory)*
Scalable process for producing striated 2G tapes for low AC loss applications

18:00 – 18:15 *K. Ohki (Sumitomo Electric, Japan)*
An intermediate grown superconducting (iGS) joint between REBCO coated conductors

18:15 – 18:45 **Discussion**

Wednesday, Sept. 12

Characterization and Modeling

8:30 – 12:00 Chairperson: TBA

8:30 – 9:00 *F. Gömöry (Institute of Electrical Engineering, Slovak Academy of Sciences)* ***INVITED***
Characterization of the local critical current fluctuation along the length in industrially produced CC tapes

9:00 – 9:15 *F. Grilli (Karlsruhe Institute of Technology, Germany)*
Length uniformity of the angular dependences of I_c and n of commercial (RE)BaCuO tapes with artificial pinning at 77 K

9:15 – 9:30 *D. Abraimov (National High Magnetic Field Laboratory, Tallahassee, USA)*
Transport critical currents of modern ReBCO conductors in high magnetic fields up to 45 T

9:30 – 9:45 *R. Hühne (IFW Dresden)*
Effect of granularity on local transport properties in pure and doped YBCO films grown on technical templates

9:45 – 10:00 *A. Ichinose (Central Research Institute of Electric Power Industry, Japan)*
Microstructures and superconducting properties of several coated conductors

10:00 – 10:30 **Coffee Break + Posters I**

10:30 – 10:45 *S. Kauffmann-Weiss (Karlsruhe Institute of Technology, Germany)*
Advanced long-length GdBaCuO tapes with high homogeneity and mechanical-electrical performance for DC-FCL applications

10:45 – 11:00 *O. Dicuonzo (EPFL-SPC)*
Transverse pressure and bending tests on modified twisted stacked strands

11:00 – 11:15 *N. Amemiya (Kyoto University, Japan)*
Experimental study on controlling factors of quench protection of conduction-cooled RE-123 coated conductors

11:15 – 11:30 *A. Romanov (ICMAB-CSIC)*
$REBa_2Cu_3O_7$ coated conductors as a coating for the FCC-hh collider beam screen: Assessment of the classical rigid-fluxon model for RF surface resistances

11:30 – 12:00 **Discussion**

12:00 – 14:00 **Lunch Break + Posters II**

Flux Pinning

14:00 – 17:15 Chairperson: TBA

14:00 – 14:30 *K. Matsumoto (Kyushu Institute of Technology, Japan)* ***INVITED***
Flux pinning of REBCO coated conductors with segmented BHO nanorods

14:30 – 14:45 *Y. Yoshida (Nagoya University, Japan)*
Fabrication of REBCO coated conductor doped with artificial pinning centers using vapor-liquid-solid growth method

14:45 – 15:00 *J. Banchewski (ICMAB-CSIC)*
Enhanced pinning performance of CSD $YBa_2Cu_3O_{7-x}$ thin films via ultrafast liquid assisted growth and preformed nanoparticles

15:00 – 15:15 *J. Diez-Sierra (University of Ghent, Belgium)*
Pinning enhancement in $YBa_2Cu_3O_{7-\delta}$ nanocomposite thin films with preformed perovskite nanocrystals using low fluorine chemical solution deposition

15:15 – 15:45 **Coffee Break + Posters II**

15:45 – 16:00 *M. Lao (Karlsruhe Institute of Technology, Germany)*
Assessment of the $I_c(B,T,\theta)$ characteristics of PLD-GdBCO tape with columnar $BaSnO_3$ nanoprecipitates

16:00 – 16:15 *T. Okada (Institute for Materials Research (IMR), Tohoku University, Japan)*
Consideration on angular dependent pinning properties in $REBa_2Cu_3O_y$ coated conductor containing $BaHfO_3$ nanoparticles fabricated by UTOC-TFA-MOD process

16:15 – 16:30 *P. López-Domínguez (University of Ghent, Belgium)*
Nanometer-sized perovskites for pinning in coated conductors

16:30 – 16:45 *D. X. Fischer (TU Wien, Atominstitut, Austria)*
Effect of neutron irradiation on the superconducting properties of REBCO tapes

16:45 – 17:15 **Discussion**

Social Dinner

18:00 – 22:00

On Wednesday evening a social dinner will take place at a Viennese Heuriger (lit. "new wine"), where typical Austrian food and wine will be served.

Thursday, Sept. 13

Characterization and Modeling

8:30 – 11:00 Chairperson: TBA

8:30 – 9:00 *T. Kiss (Dept. of Electrical Engineering, Kyushu University, Japan)* ***INVITED***
Significant improvement of robustness of current carrying capabilities in coated conductors by use of face-to-face double stacked architecture

9:00 – 9:15 *H. Kitaguchi (National Institute for Materials Science (NIMS), Japan)*
Development of a joint resistance evaluation system (1) concept, design, and manufacture

9:15 – 9:30 *K. Kobayashi (National Institute for Materials Science (NIMS), Japan)*
Development of a joint resistance evaluation system (2) commissioning results

9:30 – 9:45 *J. Gutierrez (Institut de Ciència de Materials de Barcelona, Spain)*
Coated conductors for the CERN's Future Circular Collider beam screen chamber

9:45 – 10:00 *M. Kapolka (Institute of Electrical Engineering, Slovak Academy of Sciences)*
3D modelling and measurements of cross-field demagnetization in stacks of tapes

10:00 – 10:15 *D. van der Laan (Advanced Conductor Technologies, LLC, University of Colorado Boulder, USA)*
Electromechanical performance of CORC® cables and wires under axial tension and transverse compression

10:15 – 10:45 **Discussion**

10:45 – 11:15 **Coffee Break + Posters II**

Power Applications

11:15 – 13:15 Chairperson: TBA

11:15 – 11:45 *J. Kephart (Naval Surface Warfare Center Philadelphia Division Machinery Research)* ***INVITED***
Naval applications and challenges of superconducting systems

11:45 – 12:00 *S. Pamidi (FAMU-FSU, USA)*
Second generation high temperature superconducting gas-insulated power cable

12:00 – 12:15 *M. Iwakuma (Kyushu University, Japan)*
Development of REBCO fully superconducting motors for electric aircrafts

12:15 – 12:30 *M. Vojenciak (Institute of Electrical Engineering, Slovak Academy of Sciences)*
REBCO coated conductor for fault current limiter application in cryogen free conditions

12:30 – 12:45 *J. D. Weiss (University of Colorado / Advanced Conductor Technologies)*
Development of CORC® power transmission and fault current limiting cable systems

12:45 – 13:15 **Discussion**

Closing

13:15 – 13:30

The organizers would like to direct some final remarks at the audience, including an outlook on the next CCA workshop. Lunch will be served after the closing.

Posters I

Tuesday + Wednesday morning

Magnet Applications

M. Solovyov (Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia)
Replacing the bulk superconductor tube in AC magnetic shield by a multilayer CC tape structure

J. Gnilsen (Bruker HTS GmbH, Germany)
Comparison of in-field performance of Bruker HTS coated tapes at 77 K and 4.2 K

J. Šouc (Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia)
CORC® cable production and its use in the coil winding

Fabrication and Processing

A. Markelov (SuperOx, Russia)
Optimisation of fabrication technologies for high quality, low-cost 2G HTS wire

T. Mulder (CERN / University of Twente)
Thin and flexible ReBCO CORC wires - coil and joint technologies

E. Mikulášová (Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia)
Low temperature bonding of superconducting tapes covered by Ag layer

K. Sakuma (Seikei University, Japan)
The structure and superconducting properties of trifluoroacetates metal organic deposition derived $(Y_{0.77}Gd_{0.23})Ba_2Cu_3O_y$ on annealed CeO_2 buffered substrates

W. Freitag (Karlsruhe Institute of Technology, Germany)
In-situ precipitation of $BaHfO_3$ nanoparticles in REBCO films deposited by TFA-MOD on CeO_2-buffered Ni-5at%W tapes via reel-to-reel process

Characterization and Modeling

M. Bäcker (Deutsche Nanoschicht GmbH, Germany)
Industrial-scale resistive I_c measurement device

T. Kujovič (Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia)
Local deformations created during the assembling of CC tapes into a round cable

R. Ries (Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia)
Characterizing of superconducting tape quality by measuring magnetic AC susceptibility

M. Osipov (National Research Nuclear University MEPhI, Moscow, Russia)
The effect of temperature on the levitation properties of CC-tapes stacks

Power Applications

C. Morais (Itaipu Binacional)
Evaluation of existing coated cabling of Itaipu hydroelectric power plant after years of operation: aspects to be considered for technological updating

K. Sato (Seikei University, Japan)
The longitudinal magnetic field dependence of critical current density in multilayered TFA-MOD $REBa_2Cu_3O_y$ coated conductors

M. Mošať (Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia)
Importance of stabilization layer homogeneity for coated conductors used in fault current limiter

Posters II

Wednesday afternoon + Thursday

Flux Pinning

J. Kawanami (Seikei University, Japan)
The effect of intermediate heating treatment temperature on in-field J_c for TFA-MOD $BaHfO_3$ doped $(Y_{0.77},Gd_{0.23})Ba_2Cu_3O_y$ CCs

E. Seiler (Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia)
Angular I_c anisotropy and pinning properties of coated conductors in moderate magnetic fields at temperatures close to 77 K

P. Degtyarenko (JIHT RAS / JSC SuperOx, Russia)
The influence of artificial pinning centers on the irreversibility temperature of 2G HTS wire in magnetic field

J. Nishimura (Seikei University, Japan)
The effect of $BaHfO_3$ nanorods on J_c in the longitudinal magnetic field for $EuBa_2Cu_3O_y$ coated conductors derived from PLD

Fabrication and Processing

M. Skarba (Slovak University of Technology, Bratislava, Slovakia)
Overlap joints of CC tapes tested by thermal cycling and mechanical load

S. Funaki (Shimane University, Japan)
Superconducting joint for REBCO coated conductors by low-temperature liquid phase growth reaction

X. Obradors (ICMAB, CSIC, Barcelona, Spain)
Advances in deposition and growth of all-chemical high $YBa_2Cu_3O_{7-x}$ films and coated conductors

A. Kirchner (IFW Dresden, Institute for Metallic Materials, Germany)
Superconducting joints between REBCO coated conductors prepared by melt joining of superconducting soldering films

H. Ha (Korea Electrotechnology Research Institute)
Multi superconducting layer coated conductor for high engineering critical current density

Characterization and Modeling

S. Pokrovskii (National Research Nuclear University MEPhI, Moscow, Russia)
Investigation of non-stationary processes in HTS tapes under impulse current loads

S. Li (Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia)
Coupling and superconductor loss in soldered 2G HTS stacks and multi-tape-conductor racetrack coils

I. Rudnev (National Research Nuclear University MEPhI, Moscow, Russia)
Levitation properties of the coated conductor compositions in the gradient magnetic field of various geometries

E. Pardo (Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia)
3D modeling of macroscopic force-free effects in thin films and rectangular prims under tilted applied magnetic fields

Power Applications

M. Pekarčíková (Slovak University of Technology, Faculty of Materials Science and Technology, Trnava, Slovakia)
Investigation of CC tapes with soldered metallic high heat capacity layer suitable for superconducting fault current limiters

J. Mišík (Slovak University of Technology, Faculty of Materials Science and Technology, Trnava, Slovakia)
Resistive composite heat sink material for superconducting tape in FCL applications

P. N. Degtyarenko (JIHT RAS / JSC SuperOx)
Design optimization of flat HTS three-phase cables based on coated conductors

Book of Abstracts

In the following, all submitted abstracts are listed, each on an individual page, sorted by topic. For the page number where a specific topic starts, please refer to the table of contents on page 1.

Magnet Applications

Transverse pressure and bending tests on modified twisted stacked strands

Ortensia Dicuonzo, Davide Uglietti, Rainer Wesche, Pierluigi Bruzzone

EPFL-SPC, Switzerland

The original SPC design of the Twisted Stacked-Tape Conductor (TSTC), consisting of REBCO tapes enclosed between two annealed copper shells, has been modified to improve the tolerance to mechanical loads. New design options include for example a different arrangement of the tapes, the presence of a wrapping tape and the not annealed copper shells. The critical transverse load and critical bending (measured at 77 K, s.f.) of the new options are compared to the previous one by a careful analysis of the irreversibility point. The critical current was also measured on the individual tapes before the test and after disassembling the strand to verify the reversible or irreversible nature of the I_c reduction. The feedback of the strand investigations on the design of the new cable prototypes is discussed.

Replacing the bulk superconductor tube in AC magnetic shield by a multilayer CC tape structure

Mykola Solovyov[1], Martin Kucharovič[2], Ján Šouc[1], Fedor Gömöry[1]

[1]Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia
[2]Faculty of Electrical Engineering and Information Technology STU, Bratislava, Slovakia

Some applications of superconducting magnetic shields, like the magnetic diverter in accelerator or the inner part of a magnetic cloak, required superconductors formed in the shape of a tube. The melt-cast processed BSCCO-1112 tube is a good option for low DC magnetic fields, however, for AC applications and stronger magnetic fields the CC tapes seem to be a favorable solution. On top of a lower energy dissipation and better infield performance, another advantage of using ReBCO tapes in shielding application is a lower cost, less sensitive mechanical handling and the possibility to arrange tapes easily to specified geometric shape and dimension.

Actually, we present the results for two tested configurations made of commercially available 12 mm wide superconducting tapes: in the first one the tapes were wound helically on a cylindrical former, and in the second one the tapes were placed on it in parallel to the cylinder axis. The maximal number of layers in case of both manufactured arrangements was six. We compare complex magnetic susceptibility of the CC tape configurations with that of the BSCCO-1112 tube of similar dimensions. Measurements were performed for AC magnetic field with amplitudes up to 13 mT at the 72 Hz frequency.

Comparison of in-field performance of Bruker HTS coated tapes at 77 K and 4.2 K

Johannes Gnilsen[1], *Alexander Usoskin*[1], *Michael Eisterer*[2], *Ulrich Betz*[1], *Klaus Schlenga*[1]

[1]*Bruker HTS GmbH, Germany*
[2]*Atominstitut, TU Wien, Austria*

Short fractions of long, up to 600 m, YBCO coated tapes were investigated regarding correlation of in-field critical currents measured at two different temperatures of 77 and 4.2 K. The tapes were manufactured via ABAD-PLD processing route employing a stainless steel substrate.

Impact of defects of different art was studied. Both (i) integral deviation of HTS composition, crystallinity, level of oxygen index and (ii) local defects as scratched, “spot” defects etc. were considered. Abnormal behavior of critical current caused by inhomogeneities in functional layers at gradient of magnetic field was found and analyzed. Results were always compared with current performance in self-field at 77 K.

Quantification of critical currents’ correlation, which existence was independently confirmed within earlier studies, allows predicting the performance of the HTS tape at helium temperature employing a feasible technique operating at liquid nitrogen environment.

This work was supported in part via EASITrain: European Union’s H2020 Framework Programme Grant Agreement no. 764879; and AREAS EC Project, Grant Agreement no. 730871.

ReBCO tape based thermally activated superconducting switches and rectifier for charging high current magnets

Nikolay Bykovskiy, Alexey Dudarev, Diego Davalos, Herman ten Kate

CERN, Switzerland

Aiming at design improvements for the International Axion Observatory (IAXO), a 22 m long helioscope for searching solar axions, equipped with a 360 degree rotating superconducting toroidal magnet, alternative options for powering of the 20 kA magnet are under consideration. Use of high-temperature superconductors (HTS) in a superconducting transformer-rectifier system cooled by a single stage cryocooler at 40-50 K level is a promising option thereby avoiding massive movable bus bars, current leads and related services. The overall efficiency of such a magnet powering system is determined by the properties of thermally activated HTS switches that operate in a fast synchronous manner. We investigated, both experimentally and numerically, the switching performance of copper-coated and etched tapes, conduction cooled at 77 K in contact with low-mass heaters perfectly matching the tape surface. The transition metrics such as time constants to toggle between 'on' and 'off' states, time delays between heater pulse and onset of gate resistance, and the 'off' state resistance have been evaluated as a function of heater power and cooling conditions. Based on the obtained agreement between measurements and simulation, the performance of the powering circuit at high operating currents, order of tens kA, is predicted from the numerical model. Using a superconducting rectifier comprising an HTS transformer and two HTS thermal switches operating at 40-50 K level is a promising option for charging large magnets at a slow ramp-rate, as for example in particle detector magnets.

Real time simulation of current ramps in large HTS coils: no longer a computational dream

Edgar Berrospe[1], Frederic Trillaud[1], Victor Zermeno[2], Francesco Grilli[2]

[1]*National Autonomous University of Mexico*
[2]*Karlsruhe Institute of Technology, Germany*

Simulation of large scale superconductor systems made of HTS tapes is a high memory- and time-consuming task. Methods like homogenization and multi-scale modeling using the H formulation of Maxwell's equations have already shown a substantial reduction on the memory demand and the computation time. Recently, a strategy based in the T-A formulation and using a 1D approximation for the tapes has been proposed to model large scale devices. In this work, we propose the application of the multi-scale and homogenization methods to the T-A formulation to analyze large magnets, made of hundreds or thousands of turns. A large HTS coil is used as case study, and the strategy is validated by comparing the results of the proposed strategy with those of the well-known H formulation used as a reference model. Once the strategy is validated, we simulate the case study during a ramping up and down cycle. The time needed to perform this simulation on a standard professional laptop [Intel Core i7, 16 GB of RAM] is comparable to that of the typical operation for such large magnets. The proposed strategy makes it therefore possible to simulate these large HTS magnets almost in real time. Previous results have shown that when the T-A formulation is used, the current density distributions present some non-physical ripples at sub-critical current densities. As an additional contribution of this work, the presence of these ripples is analyzed to understand its origin and strategies are proposed to avoid them and obtain physical solutions.

CORC® cable production and its use in the coil winding

Ján Šouc[1], Fedor Gömöry[1], Mykola Soloviov[1], Michal Vojenčiak[1], Tomáš Kujovič[1], Ján Kováč[1], Lubomír Frolek[1], Eva Michalcová[2], Jozef Mišík[2], Marcela Pekarčíková[2], Michal Skarba[2]

[1]Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia
[2]Faculty of Materials Science and Technology, Slovak University of Technology, Trnava, Slovakia

We report about the manufacturing of CORC® (Conductor On Round Core) cable consisting in CC (Coated Conductor) tapes helically wound in several layers on Cu tube. The production machine designed and assembled for this purpose allowed to make in one run the cable with two layers each comprising four superconducting tapes. The cable of length 40 m was made at the production rate of 6 m/hour by this machine. Eight Furukawa-SuperPower *RE*BCO tapes SCS4050AP and 50 m long were deposited in two layers on the Cu tube with outer diameter 6.35 mm. The produced cable was utilized for making the superconducting solenoid with 12 cm bore diameter. The winding of four layers each containing 20 turns has the height of 15 cm. In order to assess the influence of the cabling technology and subsequent coil winding on the superconducting tapes properties, their critical currents were measured individually after immersing the coil into the liquid nitrogen bath. The results from this characterization exclude critical current degradation for any tape of the cable used for solenoid preparation. Afterwards the critical current of the solenoid was measured by monitoring of the voltages on all tapes during the increasing coil current. For the determination of coil’s critical current the average of these voltages in dependence on coil current was evaluated. The coil critical current determined in this way is 623 A i.e. lower than 1240 A which is the simple sum of individual tapes critical current as declared by producer. This difference can be explained by the tape critical current dependence on magnetic field. In addition the critical current dependence on the axial and bending load of REBCO CC tapes at room temperature, finite element method (FEM) simulations were performed.

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-14-0438.

HTS Roebel cables, a qualified solution for advanced high field magnets

Wilfried Goldacker, Anna Kario

Karlsruhe Institute of Technology, Germany

HTS-REBCO-tapes used at lHe temperatures are the mandatory material enabling an increased magnetic field in future advanced high field magnets. Beside energy applications, the HTS Roebel cable qualified recently as applicable choice for the insert coils of magnets with favorable properties as narrow bending radius (>20 mm), high filling factor (>90%) and high transverse stress tolerance (>200 MPa) with resin impregnation, as learned from the successful demonstrator dipole magnet project of CERN (EUcard2). So far 30 m-class cables were fabricated in good quality. Future full size insert magnets however need longer lengths exceeding 100 m. For this purpose the fabrication accuracy of the strand geometry was optimized with an upgrade and extension of the KIT equipment with a RTR punching tool. The punching process itself, depending sensitively on the tape performance and material configuration, had to be adapted specifically to the selected tape material to minimize degradations. An innovative punch and coat (Cu plating) strategy seals the strand and leads to a robust strand performance blocking delamination effects. Major remaining hints come from the still insufficient homogeneity of the transport currents in the tapes which has impact on thermal stabilization, current redistribution, strand coupling and quench detection issues. Advanced and new characterization tools at Kit, as delamination test rig and RTR transport current analysis allow extended investigations of tape and cable properties to raise the performance of the cable step by step. In this contribution we like to report about the actual state of knowledge on the Roebel cable topic reviewing in particular bending effects, applied transverse stresses, delamination behavior, the strand punching procedure, influence of current anisotropy (pinning situation), transport currents and their further potential, strand coupling, the cable behavior in coil geometry and the influence of the specific tape properties (different manufacturers) on the cable performance in the different application regimes. Future prospects of the Roebel approach in competition to other solutions will be discussed.

Thin and flexible ReBCO CORC wires - coil and joint technologies

T. Mulder[1,3]*, J. Weiss*[2]*, D. van der Laan*[2]*, M. Dhallé*[3]*, A. Dudarev*[1]*, H. H. J. ten Kate*[1]

[1]*CERN, Switzerland*
[2]*Advanced Conductor Technologies, USA*
[3]*University of Twente, Netherlands*

ReBCO-CORC is a versatile multi-tape round conductor developed for application in high-field magnets for 20 T at 5 K, as well as for magnets, bus-bars and superconducting links operating in the 20 to 50 K range. So-called CORC "cable" has a diameter of 5 to 8 mm and uses standard for example standard SCS4050 tapes from Superpower Inc. The cable is relatively flexible, can carry high current, but lacks in current density due to its metallic core and relatively thick substrate. The recent reduction of tape substrate thickness from 100, via 50, now down to 30 μm, as well as tape width reduction from 4, via 3, now to 2 mm provided a boost in tape current density and at the same time a reduced minimum bending radius. Consequently, CORC conductors can be made smaller allowing flexible high-current CORC round wires of 2 to 4 mm in diameter. Such CORC wires can now be used in compact high-field magnets, in for example accelerator magnets and insert coils.

For CERN's magnet development program, four CORC wires, prepared by Advanced Conductor Technologies, were tested in the shape of a short solenoid at the University of Twente to demonstrate their high performance and flexibility and to pin-point aspects of improvement in handling, layout and production process. The latest tested CORC wire, with 3.5 mm diameter, showed a critical current of 3970 A at 4.5 K and 10 T, corresponding to a current density of 412 A/mm^2. The wire has a critical current retention of 84%.

Recent developments in tape technology now allows for an even further substrate thickness reduction from 30 to 25 μm and tape width reduction from 2 to 1.5 mm. CORC wires based on this will show current densities of 400 to 500 A/mm^2 at 20 T and 5 K. State of the art ReBCO wires and various performance demonstration tests are reported. Research on CORC wires and demonstration coils at CERN is in full swing and exciting new developments can be expected in the near future.

ReBCO CORC cable-in-conduit conductors for large-scale magnets and bus lines

T. Mulder[1,3]*, J. Weiss*[2]*, D. van der Laan*[2]*, M. Dhallé*[3]*, A. Dudarev*[1]*, H. H. J. ten Kate*[1]

[1]*CERN, Switzerland*
[2]*Advanced Conductor Technologies, USA*
[3]*University of Twente, Netherlands*

The ReBCO CORC Cable-In-Conduit Conductor is a high-current multi-strand conductor aimed for application in large scale magnets, for example in particle detectors and fusion experiments, but also for use in bus lines feeding high currents to magnets or other devices. ReBCO based conductors open up the operating temperature range of 20 to 50 K allowing significant reduction in cooling cost and simplification of the refrigeration plant. ReBCO CORC also enables a magnetic field in large magnets far beyond 20 T at 5 K and a significant increase in thermal stability compared to NbTi or Nb_3Sn superconductors.

Three unique, first-in-the-world, CORC Cable-In-Conduit Conductors were developed at CERN. The first CORC CICC is a 1.7 m long sample rated 42 kA at 5 K and 12 T. This conductor, successfully tested in 2016 demonstrated the feasibility of CORC in CICC and allowed exercising all preparation techniques. The next two conductors, designed for fusion and detector magnets, show a current rating of 80 kA at 5 K and 12 T. The fusion magnets type of conductor features a stainless steel jacket to cope with the large electro-magnetic loads in such magnets and it has internal forced-flow cooling allowing direct surface contact between helium gas and CORC strands. The second conductor for detector magnets and bus bars has a copper jacket allowing conduction cooling through the jacket via an external cooling line, an elegant cooling method offering significant simplification of coil windings and cooling infrastructure.

Both conductors have been tested in fall 2017. The stainless steel jacketed conductor showed excellent performance, no degradation, demonstrating its high performance thereby validating predictions and preparation techniques. The copper jacketed variant, however, showed significant degradation and a final critical current retention of only 35%. The defect was traced back to a non-optimal strand cabling parameter causing tapes to buckle. Currently, a new CORC Cable-In-Conduit Conductor is prepared with improved CORC strands for testing in fall 2018. Further research on CORC CIC-Conductors is in progress of which results will be published in the years to come.

Recent progress on CORC® cable and wire development for magnet applications

Danko van der Laan[1], Jeremy Weiss[1], Dustin McRae[1], Xiaorong Wang[3], Hugh Higley[3], Soren Prestemon[3], Tim Mulder[4], Alexey Dudarev[4], Herman ten Kate[4], Ramesh Gupta[5]

[1]Advanced Conductor Technologies, USA
[2]University of Colorado, USA
[3]Lawrence Berkeley National Laboratory, USA
[4]CERN, Switzerland
[5]Brookhaven National Laboratory, USA

Advanced Conductor Technologies has been developing high-temperature superconducting Conductor on Round Core (CORC®) cables and wires wound from REBCO coated conductors for use in high-field magnets. Magnet applications on which the conductor development is focused on include compact fusion magnets that operate at currents between 50 and 100 kA at fields of 12 – 20 T and accelerator magnets that operate at currents exceeding 10 kA and engineering current densities (J_e) of over 600 A/mm^2 at 4.2 K in a background field of 20 T.

Here, we outline the latest progress on CORC® cable and wire development. We'll discuss the latest results of the 6-around-1 cable-in-conduit-conductor (CICC) based on CORC® cables developed for fusion magnets and discuss methods to increase the CORC®-CICC flexibility that would allow bending to diameters in the order of 1 meter. The latest results on CORC® wire development for accelerator magnets will be discussed, including in-field measurements of CORC® wires that have demonstrated a projected J_e at 20 T of more than 400 A/mm^2.

The next step in CORC® cable and wire development is underway, which is their incorporation into high-field demonstration magnets. Here we outline the latest results of high-field insert magnet development using CORC® cables and wires. Several magnet programs will be discussed, including those focused on the development of accelerator magnet inserts for canted-cosine theta (CCT) and Common Coil magnets that would generate 5 T in a 10 T background field within the next 2 – 3 years.

World record DC magnetic field using an $REBa_2Cu_3O_x$ (RE = Y, Gd) superconducting magnet

Seungyong Hahn, Kwanglok Kim, Xinbo Hu, Thomas Painter, Iain Dixon, Seokho Kim, Kabindra Bhattarai, So Noguchi, Jan Jaroszynski, David Larbalestier

National High Magnetic Field Laboratory, Tallahassee, USA

The use of superconductors to generate powerful magnetic fields has had major impacts on many fields, above all medicine (MRI), pharmacy (NMR), particle accelerators (e.g. the Large Hadron Collider), fusion devices (e.g. ITER), as well as many other diverse scientific and industrial uses. Using Nb-Ti and Nb_3Sn low temperature superconductors (LTS), fields up to 23 T have been achieved but higher fields from purely superconducting magnets were until recently impossible due to the upper critical field $H_{c2}(0)$ of Nb_3Sn being only 30 T. The MagLab's hybrid LTS/HTS all-superconducting 32 T magnet has recently broken through the 23 T barrier but higher DC fields still require very powerful resistive magnets. 41 T was achieved in 2017 with a purely resistive magnet dissipating ~30 MW, but the highest DC field has for 17 years remained at 45 T using a hybrid 31 MW/33.6 T resistive insert inside a large bore 11.4 T superconducting magnet. Such high power resistive magnets are only available in a few places in the world, while superconducting magnets are pervasive due to their small power requirements. Here we report on the test of a 14.4 T HTS solenoid inside a 31.1 T resistive magnet that together generated 45.5 T. This solenoid uses a recently developed REBCO coated conductor with a very thin (30 μm) Hastelloy substrate which enabled operation at the extremely high conductor current density of 1420 A/mm^2 under a magnetic stress of 691 MPa at 45.5 T. Operation at such extremely high current density is possible only because the magnet was wound without insulation. Such a "no-insulation (NI)" design can allow rapid and safe quench from the superconducting to the normal state. Demonstration of a working magnet at such high current density allows design of new superconducting magnets with unprecedented compactness, affordability and high field. The tests validate some of the great hopes for HTS materials by demonstration of a twice higher field than is possible with any low temperature superconductor.

Fabrication and Processing

Growth of high current nanocomposite $YBa_2Cu_3O_{7-x}$ coated conductors from colloidal solutions: TFA versus TLAG process

Teresa Puig[1], Ziliang Li[1], Cornelia Pop[1], Bohores Villarejo[1], Flavio Pino[1], Ferran Valles[1], Bernat Mundet[1], Laia Soler[1], Julia Jareno[1], Silvia Rasi[2], Juri Banchewski[1], Natalia Chamorro[3], Roger Guzman[1], Max Sieger[1], Adria Pacheco[1], Mariona Coll[1], Anna Palau[1], Susgana Ricart[1], Jaume Gazquez[1], Jordi Farjas[2], Pere Roura[2], Josep Ros[3], Xavier Obradors[1]

[1]ICMAB-CSIC, Bellaterra, Spain
[2]GRMT, U. de Girona, Spain
[3]Dept. Quimica, UAB, Bellaterra, Spain

Coated conductors of $YBa_2Cu_3O_7$ (YBCO) have emerged as the most attractive opportunity to reach unique performances for large scale power applications and high field magnets, though reducing the cost/performance ratio continues to be a key objective at present. Chemical solution deposition (CSD) is a very competitive cost-effective technique which has been used to obtain nanocomposite films and CCs. In the recent years we have been able to demonstrate the unique potentiality of CSD techniques based on Ink Jet Printing deposition to achieve low cost, low anisotropy and high critical current coated conductors. In this presentation, I will report on the latest progress on the development of the growth process and enhanced vortex pinning of CSD nanocomposite YBCO films obtained from colloidal solutions, where preformed oxide nanoparticles (NPs) are stabilized in the YBCO precursor solutions. This standard TFA-route will be then compared with our recent new approach to reach CSD nanocomposites through transient-liquid assisted growth (TLAG), enabling ultrafast growth rates in the range of 50 nm/s. This novel TLAG process combines the advantages of the CSD with the ultrahigh growth rates of liquid-mediated techniques. We will present the different strategies we are following to control supersaturation in the liquid assisted nucleation and growth, the new defects landscape and the role of the preformed nanoparticles in the vortex pinning of TLAG-nanocomposites.

This research has been funded by EU-ERC_AdG-2014-669504ULTRASUPERTAPE project, EU-FP7 NMP-LA-2012-280432 EUROTAPES project and Excellence Program Severo Ochoa SEV2015-0496.

Recent progress of HTS wire production at THEVA

Markus Bauer, Markus Bendele, Therese Chabert, Veit Große, Georg Sigl

THEVA Dünnschichttechnik GmbH, Germany

An overview on recent improvements of coated conductors (CC) manufactured using the all E-beam PVD pilot production line at THEVA will be given.

Due to a continuous optimization of equipment as well as processes, the critical current of the wires was continuously increasing during the last year. Recently, 500 A/cm have been surpassed at high yield production conditions and already 650 A/cm have been demonstrated on production length. In addition to the critical current, also several further requirements must be considered and are actually necessary to use the wire in electrical devices. The copper stabilization layer, necessary in most applications, often has an inhomogeneous thickness which impedes the use of the conductor e.g. in coils. The recent progress with copper coated conductors towards a smaller thickness variation of the copper will be presented. Further requirements are stress, strain and bending tolerance as well as delamination strength which were measured using several types of the stabilization.

Finally, a recently developed joining technique for long-length CCs is discussed in terms of resistance and mechanical properties for various joint configurations.

Scalable process for producing striated 2G tapes for low AC loss applications

Michael Osofsky[1], *Joseph Prestigiacomo*[1], *Raymond Auyeung*[1], *John Claassen*[2], *Martin Rupich*[3], *Jozef Kvitkovic*[4], *Sastry Pamidi*[4]

[1]*Naval Research Laboratory, USA*
[2]*NOVA Research, Inc., USA*
[3]*AMSC, Inc., USA*
[4]*Center for Advanced Power Systems, Florida State University, USA*

The use of Second Generation High Temperature Superconducting wires in power applications requires that the conductor be engineered to minimize AC losses. This can be accomplished by dividing the YBCO film into thin filament arrays and the periodic introduction of filament bridges along the conductor length to emulate geometries present in twisted conductors. In this work, we explore the use of laser lithography of commercial Ag coated 2G YBCO produced by AMSC. Laser lithography enables the formation of these filaments with sharp edges in a controlled manner without metal splatter. This technique is a data driven materials process that can be scaled up for industrial production. In this talk we will present a low AC loss tape design, details of the laser lithography process, results of I_c measurements on samples with various striation widths, AC loss data to validate the efficacy of the process, and details of a method to form the edge filament bridges.

PLD/ABAD based technology of long-length YBCO coated conductors for ultra-high field applications

Alexander Usoskin, Ulrich Betz, Sonja Noll-Baumann, Klaus Schlenga

Bruker HTS GmbH, Germany

An alternating beam assisted deposition (ABAD) employed for processing of bi-textured buffer layer as well as pulsed laser deposition (PLD) used for HTS layer deposition represent a large area deposition tools not only regarding the area of processed tape but also in sense of size of deposition windows. In case of ABAD, the deposition area is roughly determined by aperture of ion-beam sources yielding about 100 – 200 cm^2. By PLD, deposition area corresponds to 50-100 cm^2 how it was shown in our recent study where lateral flows of laser plasma are taken into account.

Energy balance defined by heat flows together with energy flow introduced by ion/molecular beam and condensation energy was evaluated for both of these processes. Influence of relatively low heat capacity of substrate tape (made of stainless steel of Hastelloy) is taken into account in evaluation of stability of substrate temperature. For PLD, such analysis was done in both cased of "confined" area deposition and deposition employing lateral flows.

It is found that activation of the lateral flows of laser plume is determined by a degree of "tightness" of tape windings against the guiding drum employed as a tape carrier within PLD processing. Guiding of plasma plume by smooth substrate surface as well as influence of surface macro-relief including "external" mechanical elements that create a barrier for lateral flow propagation are investigated. Critical geometries for plasma flow propagation in lateral direction as well as flow penetration length are evaluated using a consideration of compressible flows with variable Mach numbers. Comparison of reel-to-reel and drum based tape transport is discussed in a view different art of ion/molecular flow propagation in the course of long-length tape processing.

Recent results on processing of long YBCO coated conductors for ultra-high field applications will be demonstrated and discussed.

This work was supported in part via AREAS EC Project, Grant Agreement no. 730871.

Low temperature bonding of superconducting tapes covered by Ag layer

Edita Mikulášová, Fedor Gömöry, Rastislav Ries, Tomáš Kujovič, Marek Mošať, Michaela Sojková

Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia

In this study are investigated the possibilities of bonding two tapes together to create one single conductor with double critical current. We use high temperature superconductor tapes with Ag cap layer only. Bonding will be achieved by applying pressure on tapes where contacted surfaces will be either etched, covered by silver powder or heat treated. Bonding configurations with different mutual orientation of superconducting layers are considered. We report influence of bonding process on the superconducting properties of the resulting conductor. For evaluation were used magnetic susceptibility and transport current measurements.

The structure and superconducting properties of trifluoroacetates metal organic deposition derived $(Y_{0.77}Gd_{0.23})Ba_2Cu_3O_y$ on annealed CeO_2 buffered substrates

Keita Sakuma, Yoshinori Kamada, Masashi Miura

Seikei University, Japan

Trifluoroacetates metal organic deposition (TFA-MOD) derived $(Y_{0.77}Gd_{0.23})Ba_2Cu_3O_y$ [(Y,Gd)BCO] coated conductors (CCs) is a promising candidate for power and magnet applications because of a low production cost and high critical current densities (J_c) under magnetic field [1,2]. To further improve J_c, the quality (crystallinity and surface roughness…) of CeO_2 buffered substrates is one key factor. We have reported that annealing treatment of CeO_2 buffered substrate is one of important approaches for improvement of crystallinity and surface roughness for CeO_2 buffered substrate [3]. However, the effects of the annealing treatment of CeO_2 buffered substrates on superconducting properties of TFA-MOD (Y,Gd)BCO films is not clear.

To investigate the effects of anneal treatment of CeO_2 buffered substrates on the crystallinity and superconducting properties for TFA-MOD (Y,Gd)BCO films, we fabricate the (Y,Gd)BCO films on as-grown and various annealed CeO_2 buffered substrates [annealing temperature (T_A) = 600 – 1000ºC]. The optimal annealed CeO_2 buffered substrate showed high crystallinities and flat surface. The appropriate annealing treatment of CeO_2 buffered substrates makes the enhancement of J_c for TFA-MOD (Y,Gd)BCO films. The present results will be discussed in terms of correlation between crystallinity and J_c for TFA-MOD (Y,Gd)BCO films.

Acknowledgements: KS is supported by PMAC Scholarship Fund for Young/Women Researchers. MM is supported by JSPS KAKENHI (17H03239 and 17K18888). A part of this work was supported by Kato Foundation for Promotion of Science (KJ-2744).

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R&D of coated conductors for applications

Teruo Izumi[1], *Takato Machi*[1], *Akira Ibi*[1], *Koichi Nakaoka*[1], *Takeharu Kato*[2], *Masataka Iwakuma*[3], *Masashi Miura*[4], *Takanobu Kiss*[3], *Satoshi Awaji*[5]

[1]*AIST, Japan*
[2]*JFCC, Japan*
[3]*Kyushu University, Japan*
[4]*Seikei University, Japan*
[5]*Tohoku University, Japan*

In the R&D of coated conductors (CCs), the requirements from the applications have to be satisfied. The requirements include not only in-field performance and low ac loss etc. but also uniformity, reproducibility, reliability and low cost.

In this paper, the recent progress on the R&D of coated conductor considering the above background is reviewed.

For example, the improvement of uniformity of $I_c(B)$ distribution even in the CCs including APC materials as well as realization of higher in-field performance is necessary. It is obvious to be important for low ac-loss in magnetic applications such as motor, however, it is also necessary for reproducibility, reliability and low cost. In the PLD process, it was found that the plane plume system is effective to fabricate the uniform $I_c(B)$ performance and high uniformity in the distribution of filament-I_c values in the scribed CCs.

Concerning the combination of in-field performance and low cost, the remarkable progress in the micro-structure control was achieved for TFA-MOD process, which is the UTOC (Ultra-Thin Once Coating)-MOD process. The TFA-MOD has been recognized to be cost effective. However, the in-field performance had been lower than those by the vapor process. The new process (UTOC-MOD) makes the BMO particles as APC finer very much. As a result, a dramatically high $J_c(B)$ value of 4 MA/cm^2 @ 65 K, 3 T was achieved.

As mentioned above, the scribed CCs is beneficial for lowering ac-loss. However, the development of the high processing speed is necessary for minimizing the cost for filamentation. For this purpose, the multi-beam scribing system has been developed. As a first step, the effectiveness of the dual beam was already confirmed.

The details on the progress of the R&D will be reported in the presentation.

This paper has been supported by METI, NEDO, AMED and AIST.

In-situ precipitation of $BaHfO_3$ nanoparticles in REBCO films deposited by TFA-MOD on CeO_2-buffered Ni-5at%W tapes via reel-to-reel process

Wolfram Freitag

Karlsruhe Institute of Technology, Institute for Technical Physics, Germany

Commercial power applications using high-temperature superconductors such as $RE\mathrm{Ba_2Cu_3O_{7-x}}$ (*RE*BCO, *RE* = Y, Gd) Coated Conductors require a good performance in magnetic fields as well as a low-cost and high-speed fabrication process. Chemical solution deposition (CSD) based on metalorganic deposition (MOD) of trifluoroacetates (TFA) is an attractive method capable of achieving all those requirements. Upscaling to a continuous industrial reel-to-reel process with high throughput is rather uncomplicated for CSD because of the technical convenience and economic efficiency of this synthesis route. An improvement of the pinning properties is accessible through the incorporation of spontaneously segregating, highly dispersed nanoparticles in the *RE*BCO matrix by providing the starting solution with respective precursor salts.

Our previous results [1] demonstrated a significant performance improvement for GdBCO films on $SrTiO_3$ and $LaAlO_3$ single crystal substrates when hafnium is added to the precursor solution. Nano-scale $BaHfO_3$ (BHO) precipitates form during the crystallization of the *RE*BCO phase which leads to an increase in pinning force densities by a factor 4 compared to pristine samples. Also the critical current density J_c at self-field and 77 K rises significantly (to 7 MA/cm²), while a very low anisotropy is observed in applied magnetic fields caused by a J_c increase in a wide angular range around $B||c$. As a next step, those results are transferred to long length coated conductors. For this, the reel-to-reel process for *RE*BCO-BHO-nanocomposites on CeO_2-buffered Ni-5at%W tapes is optimized. First results on short tape samples show T_c values comparable to those on single-crystal substrates. A detailed analysis of the microstructure by X-ray diffraction, scanning electron microscopy, atomic force microscopy as well as of the electrical transport measurements will be given.

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An intermediate grown superconducting (iGS) joint between REBCO coated conductors

Kotaro Ohki, *Takashi Yamaguchi, Tatsuoki Nagaishi*

Sumitomo Electric, Japan

The superconducting joint of $REBa_2CuO_y$ (REBCO, RE: rare earth elements) coated conductors (CCs) is one of the key technologies to realize persistent current operations of prominent HTS magnets. In 2014, Park et al of Korea University succeeded in developing the superconducting joint of REBCO CCs [1]. This technology was a technical breakthrough in the operation of the permanent current mode of the HTS magnets.

However, the total processing time is too long for applications that require many joints such as nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI).

We have developed a superconducting joint technology for REBCO CCs with a simple and short processing time concept [2]. The key point of this joint technology is a microcrystalline REBCO precursor layer for joining. The REBCO precursor can be crystallized epitaxially and connected by performing heat treatment at 800°C for 20 minutes in an atmosphere of 100 ppm oxygen with external mechanical pressure applied. This intermediate grown superconducting (iGS) joint gives a critical current of > 100 A at 77 K in a self-field. The joint resistance is less than 10^{-12} Ω and the joint boundaries are atomically connected.

In this presentation, we will discuss the processing time, especially oxygen introduction processing time. We believe the superconducting joint technology is promising for realization of the persistent current mode operation of NMR and MRI.

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Acknowledgements:

This work was supported by the JST Mirai-Program Grant Number JPMJMI17A2.

Overlap joints of CC tapes tested by thermal cycling and mechanical load

Eva Cuninková[1], Marcela Pekarčíková[1], Lubomír Frolek[2], Martin Necpal[1], Jozef Mišík[1], Fedor Gömöry[2], Michal Skarba[3]

[1]Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology, Trnava, Slovakia
[2]Slovak Academy of Sciences, Institute of Electrical Engineering, Bratislava, Slovakia
[3]Slovak University of Technology, Bratislava, Slovakia

The resistance of the joint often plays a crucial role in the design of a superconducting device. The overlap joining method using lead-free solders as well as lead solder itself was adopted in this study, and several samples were produced under the same conditions during soldering processes to ensure the same initial state. A thermal cycle ranging from -196°C to 55°C with 10 min dwell at the peak and the lowest temperature was used, the cooling and heating (ramp) rate was 25°C/min. The electrical properties of the jointed samples were evaluated from the current-voltage curves measured in liquid nitrogen bath, i.e. at 77 K. The electrical resistance of soldered joint was determined, and the possible degradation of superconducting tapes was tested by comparing the critical currents and *n*-values before and after the thermal cycling. Further, direct current (DC) transport characteristics of soldered overlap joints of REBCO CC was performed, after they were subjected to uni-axial tensile stresses in the longitudinal direction. In addition to the electrical measurements, microstructural evolutions of solder joints during thermal cycling were investigated and correlated with the electrical resistance.

Status of 2G HTS wire production at SuperOx

Alexander Molodyk[1], Alexey Mankevich[1], Anton Markelov[1], Valery Petrykin[2], Sergey Lee[2], Svetlana Martynova[1], Sergey Samoilenkov[1]

[1]SuperOx, Russia
[2]SuperOx, Japan

In response to the increased demand on 2G HTS wire, both external and internal, the SuperOx group of companies installed new PLD HTS facility in Moscow, in addition to the existing similar facility in Japan, which remained in operation. As a result, the wire production capacity was doubled, and we are on the way to manufacture 100 km of 12 mm wide wire in 2018. Wire produced at each location is of identical high quality.

Each unit of production reel-to-reel equipment at every stage on the wire fabrication route is capable of handling one- to a few kilometer-long pieces of wire. Typical lengths of continuous pieces of finished wire that come out of production are 300-400 m.

An in-line quality management system, especially important at the early fabrication stages such as substrate electropolishing and buffer layer deposition, ensures high yield of finished wire and helps reduce cost by eliminating defective pieces of wire from further processing. A new approach for finished wire yield assessment has been developed, which facilitates quality management, economic analysis and stock and new order management.

The main directions for new product development are: (1) enhance wire performance in magnetic field, without compromising the wire property reproducibility, (2) use thinner substrate for higher engineering current density, and (3) make narrow wire, in widths smaller than 4 mm.

Optimisation of fabrication technologies for high quality, low-cost 2G HTS wire

Anton Markelov, Alexey Mankevich, Roman Valikov, Vsevolod Chepikov, Andrey Petrzhik, Burkhan Massalimov, Artem Lednev, Ivan Kulemanov, Alexey Soldatenko, Pavel Degtyarenko, Sergey Samoilenkov

SuperOx, Russia

In this talk we will report recent activities undertaken at SuperOx aimed at increasing the I_c and uniformity, enhancing manufacturing yield and throughput, and thus at reducing the cost of 2G HTS wire.

The wire's buffer layer texture is continuously monitored during production by taking real-time RHEED patterns of the IBAD-MgO layer. Automated closed-loop control of the process is implemented using the buffer layer texture quality parameter derived from the RHEED patterns. We will present the results of a systematic study into the dependence of the finished wire I_c on the RHEED texture quality parameter.

Another innovation resulting in 20-30% production throughput increase has been to simplify the SuperOx buffer layer stack by eliminating the previously used CeO_2 cap layer. The present SuperOx buffer layer architecture terminates with $LaMnO_3$ layer, without compromising the finished wire I_c and uniformity.

An almost linear dependence of the wire I_c on the HTS layer thickness is observed up to 3 micron HTS layer thickness. For cost-effectiveness considerations, at present we make 1.5-1.8 micron thick HTS layer delivering wire with an I_c level in the 500-600 A/12 mm range.

Superconducting joint for REBCO coated conductors by low-temperature liquid phase growth reaction

Shuhei Funaki[1], Yugo Miyachi[1,2], Yasuji Yamada[1], Jun-ichi Shimoyama[3]

[1]Shimane University, Japan
[2]JSPS Research Fellow
[3]Aoyama Gakuin University, Japan

To achieve a practical application of REBCO-CC, development of superconducting-joint method is needed. Recently, many groups have investigated the superconducting-joint methods, and several novel techniques for jointing were suggested. However, these techniques include long-time annealing to compensate oxygen deficiency of REBCO due to high process temperature. Consequentially, it is considered that the development of superconducting-joint methods with feasible process at On-site are required. We have suggested the "KOH flux method", which is production method of REBCO film by using low-temperature molten alkaline hydroxide. The KOH flux method can grow biaxially crystal-aligned RE123 and RE124 films on single crystalline substrates below 600°C. RE124 has a rigorous stability in oxygen stoichiometry and shows no structural phase transition as opposed to RE123 phase. Moreover, stable temperature of RE124 phase is far lower than that of RE123 in the ambient atmosphere. Although the T_c of RE124 is inferior to RE123, Y124 has an important phenomenon that T_c was improved up to 91 K by Ca substitution for RE site. On the other hand, synthesis of twin-free and orthorhombic Eu123 single crystal was reported by Marquez. This result indicates that the Eu123 synthesized at 450°C by using NaOH–KOH eutectic flux is grown with sufficient amounts of oxygen in Cu–O chain. In this presentation, in order to establish superconducting-joint method that requires no oxygen annealing process, we endeavored to develop a superconducting-joint between two REBCO-CCs by low-temperature liquid phase growth reaction.

Jointed samples were prepared in three steps. The first step is that RE–Ba–Cu–O raw materials were placed between RE123 films of CC. In the second step, REBCO-CCs were pressed by two plates of metal. Finally, REBCO-CCs were heat treated at 525°C in KOH vapor. All steps were performed at ambient pressure.

Obtained REBCO-CCs were bonded finely, and showed T_c^{onset} = 76 K, T_c^{zero} = 60 K inclusive of jointed region. From XRD observation, jointed region contained RE123 and RE247 phases.

This work was supported by JST-Mirai Program Grant Number JPMJMI17A2, Japan.

Fabrication of high performance REBCO tapes and round wires for high field applications

Venkat Selvamanickam

University of Houston, USA

University of Houston has developed an advanced metal organic chemical vapor deposition (MOCVD) process for thick film REBCO tapes with superior in-field performance over a wide range of temperatures for applications ranging from next-generation electric machines operating at 65 K, 1.5 T to accelerator magnets at 4.2 K, 15-30 T. The Advanced MOCVD process enables excellent control of pure c-axis REBCO film growth of even 5 μm in thickness with nanocolumnar pinning centers that are just 2 – 3 nm in diameter. Such a unique microstructure has resulted in critical currents as high as 8700 A/12 mm at 30 K, 3 T (J_c of 15 MA/cm^2 and J_e of 7250 A/mm^2) which are more than a factor of two higher our previous results. Additionally, pinning force levels of 1.8 TN/m^3 have been achieved in the 5 μm thick films which are at the same level as that reported previously in 1 μm thick films. At 4.2 K, the tapes processed by Advanced MOCVD exhibit a record-high engineering current density (J_e) of 5200 A/mm^2 at 4.2 K, 15 T (corresponding critical current density (J_c) of 10 MA/cm^2) which is more than a factor of five better than the J_e of the best Nb_3Sn wires and 10 times better than the J_e of commercial REBCO tapes. Using innovative designs, the efficiency of precursor use in the Advanced MOCVD reactor has been tripled to 45% which has an immense impact on REBCO tape cost and throughput. Novel in-line quality control tools using two-dimensional X-ray Diffraction (2D-XRD) are being developed for real-time monitoring of the film composition, texture as well as the size and orientation of $BaZrO_3$ nanocolumns all of which can enable high-yield manufacturing.

We have also developed a Symmetric Tape Round (STAR) wire technique to fabricate 1.6 to 1.9 mm diameter round REBCO wires with high J_e and excellent tolerance to bend strain. STAR REBCO wires can be bent to a radius of just 15 mm while sustaining a J_e above 400 A/mm^2 at 4.2 K, 20 T which meets key stringent requirements of accelerator magnets. Our recent results on high performance REBCO tapes and round wires will be presented.

Advances in deposition and growth of all-chemical high $YBa_2Cu_3O_{7-x}$ films and coated conductors

X. Obradors[1], *T. Puig*[1], *Z. Li*[1], *B. Villarejo*[1], *C. Pop*[1], *N. Chamorro*[1,2], *F. Pino*[1], *F. Vallés*[1], *B. Mundet*[1], *P. Barusco*[1], *J. Gázquez*[1], *M. Coll*[1], *A. Palau*[1], *S. Ricart*[1], *J. Ros*[2], *J. Farjas*[3], *P. Roura*[3], *A. Usoskin*[4]

[1]*Institut de Ciència de Materials de Barcelona, ICMAB-CSIC, Bellaterra, Catalonia, Spain*
[2]*Departament de Química, Universitat Autònoma de Barcelona, Bellaterra, Catalonia, Spain*
[3]*GRMT, Department of Physics, Catalonia, Spain*
[4]*Bruker HTS, Alzenau, Germany*

Achieving high critical currents on thick films of $YBa_2Cu_3O_{7-\delta}$ derived from low cost and versatile Chemical Solution Deposition (CSD) methodology is still an open issue which requires advanced investigation of the ink deposition and film growth.

Here we report, on one hand, a study of the solution deposition and growth conditions to achieve $YBa_2Cu_3O_{7-\delta}$ thick films (>1 µm) using single pass Inkjet Printing and multideposition. The solution deposition and pyrolysis conditions were investigated through in-situ analytical tools to assure homogeneous and high quality microstructures. The growth conditions of thick $YBa_2Cu_3O_{7-\delta}$ layers were investigated on $LaAlO_3$, CeO_2/YSZ and CeO_2/sapphire single crystal substrates and to the coated conductor architecture $^{CSD}YBa_2Cu_3O_7/^{CSD}CZO/^{ABAD}YSZ/SS$, where ABAD stands for Alternating Beam Assisted Deposition. The nucleation conditions of $YBa_2Cu_3O_{7-\delta}$ films on top of CSD-CeO_2 – based cap layers have been investigated to delay the formation of $BaCeO_3$ phase at the interface and hence keep high quality $YBa_2Cu_3O_{7-\delta}$ epitaxial films. We will show how ~1 µm-thick $YBa_2Cu_3O_{7-\delta}$ films and coated conductors can be obtained by IJP with high critical currents (I_c^{sf} = 390 and 100 A/cm-w, respectively, at 77 K and self-field).

We also show that this approach can be extended to the preparation of "all-chemical" nanocomposite thick films and coated conductors using preformed $BaMO_3$ (M=Zr, Hf) nanoparticles. On the other hand, we will show that a novel "Flash heating" approach leads to a novel nanostructure in pristine and nanocomposite films and coated conductors which enhance vortex pinning efficiency. The advanced processing methodologies lead to accurate control of microstructure and properties of "all-chemical" $YBa_2Cu_3O_{7-\delta}$ coated conductors.

This research has been funded by EU-FP7 NMP-LA-2012-280432 EUROTAPES and H2020- 721019 FASTGRID projects and Excellence Program Severo Ochoa SEV2015-0496.

Superconducting joints between REBCO coated conductors prepared by melt joining of superconducting soldering films

A. Kirchner, K. Nielsch, R. Hühne

IFW Dresden, Institute for Metallic Materials, Germany

In the future, $REBa_2Cu_3O_{7-x}$ (REBCO; RE = Y, Gd) coated conductor wires of several kilometers length are needed for resistance-free energy transmission lines as well as for the realization of large superconducting magnet coils. However, the length for the production of high quality wire is currently limited to about 1 km. Therefore, persistent current joints between coated conductors are a crucial prerequisite for the application of REBCO coated conductors in large scale devices. At the same time, it is desirable that the joints exhibit similar superconducting properties (i.e. electrical resistance and critical current density) as the coated conductor itself, since the quality of the complete wire depends on the weakest point in the wire architecture. So far, ohmic low resistance PbSn soldering joints between Ag/Cu stabilized REBCO coated conductors are state of the art, which lead to losses in the current transport.

In this study, we joined two commercial REBCO coated conductors by a two-step procedure. At first, a superconducting soldering solution was developed and deposited on un-stabilized commercial REBCO coated conductors. The soldering precursor solutions consist of the metal cations RE (= Y, Yb), Ba and Cu in a Cu-rich 1:2:4 ratio. This solution was deposited via the Chemical Solution Deposition (CSD) process by dip-coating on un-stabilized REBCO coated conductors. Afterwards, we measured the superconducting properties in the resulting films. Secondly, the joining of the two coated conductor pieces covered by the soldering layers was realized using a lap joint approach by annealing at 820°C under pressure. It is expected from the pseudo-binary phase diagram [1] that a Cu-rich barium-cuprate "liquid phase" forms beside the superconducting RE-123 compound during the melt-process at 820°C resulting in a mechanical stable joint.

[1] D. A. Cardwell, A. D. Bradley, N. H. Babu, M. Kambara and W. Lo: "Processing, microstructure and characterization of artificial joins in top seeded melt grown Y-Ba-Cu-O", Supercond. Sci. Technol. 15 (2002) 639 – 647.

Suitability assessment of different REBCO compounds (RE = Yb, Er, Ho, Y, Dy, Gd, Sm, Nd) for the fabrication of CSD-based coated conductors

Manuela Erbe, Pablo Cayado, Wolfram Freitag, Bernhard Holzapfel, Jens Hänisch

Karlsruhe Institute of Technology, Germany

The introduction of $RE\mathrm{Ba_2Cu_3O_{7-x}}$-based (*RE*BCO, *RE* = rare earth elements) Coated Conductors (CC) into commercial applications requires reliable, cost-effective growth processes and in many cases a good performance in applied magnetic fields. Chemical solution deposition methods, such as the TFA-MOD process using metal-organic trifluoroacetates or low-fluorine routes, are absolutely capable of meeting those requirements. The simplicity of the fabrication process renders them cheap and versatile. Composition and stoichiometry of the precursor solutions can be readily modified, and artificial pinning centers are conveniently introduced via the solutions. This allows for an easy adaption of the CC performance to the demands of the according applications.

So far, YBCO has been the compound with the farthest popularity, since it has been one of the first known systems with T_c values above 90 K and, therefore, has gone through thorough investigations. Yttrium is also comparably well available and amongst the rare earth elements the least expensive. However, other *RE* elements promise further performance enhancements in consequence of higher T_c values, but also process simplification and an increase of the reproducibility due to broader processing windows.

Here, we show our investigations on different single-*RE*-BCO compounds, both to establish clarity about their according T_c values when grown by the same MOD process, since literature values are rather contradictory, and to develop a deeper understanding of their processing windows with respect to formation temperatures and optimal process gas compositions ($p(O_2)$, $p(H_2O)$). We focused on Yb, Er, Ho, Dy, Gd, Sm and Nd as substituents for Y and investigated their growth behaviour and resulting physical ($J_c(B)$, T_c) and structural properties (XRD, SEM) when grown as pristine films on single-crystalline $LaAlO_3$ and $SrTiO_3$ substrates and compare them to similar films with 12 mol% BHO.

HTS wire production at Deutsche Nanoschicht in 2018: non-magnetic substrates, improved processing, and scale-up to 40 mm tape width

Michael Bäcker, Ron Feenstra, Mariusz Mosiadz, Brygida Wojtyniak, Jan Kunert, Oliver Brunkahl, Mark Rikel, Martina Falter, Mario Sadewasser

Deutsche Nanoschicht GmbH, Germany

Since the commissioning of an Extended Pilot Line production facility in 2016, Deutsche Nanoschicht (DN) has continued to make significant progress in the development of all-CSD HTS wire manufacturing. DN has implemented chemical solution deposition (CSD) techniques for all layers of the conductor architecture: buffer, HTS, and thin Ag contact layer, seeking advantages of reduced cost and material usage. Notable highlights of the past two years, discussed in this presentation, include:

- Successful development of a non-magnetic and stronger alternative to Ni-W(5 at%) (Ni5W) substrate tapes in the form of Ni alloy with larger W concentration of 9 at% (Ni9W). This development was realized in partnership with an outside vendor on an industrial scale of 1 ton of hot-rolled material, taken from a larger 2-3 ton melt. The final texture anneal is performed at DN. The texture quality of Ni9W matches closely the Ni5W texture. This correspondence is further borne out by initial YBCO deposition tests indicating comparable I_c performance on the Ni9W substrate compared to Ni5W.

- DN has taken steps to exploit the flexibility of CSD technology by increasing the width of its deposition platform from 10 to 40 mm. At the time of writing the transition is nearly complete for LZO and CeO buffer layers. For YBCO major progress has been achieved in the form of homogeneous epitaxial growth and I_c performance over the full 40 mm width, at levels comparable to 10 mm-width processing. Key to this development has been engineering control of laminar gas flow in the YBCO reaction furnace. The 10 to 40 mm transition is on track to be completed by the end of 2018 for all layers of the wire architecture.

- The I_c performance of 10 mm wide tape has steadily increased from 250-270 A in 2016, to 330-350 A recently, and even up to 400-420 A (77.3 K, sf). Using a newly acquired variable-temperature I_c measurement system it is found that, parallel to the I_c enhancement, the (ab)/c-axis anisotropy in magnetic field has also increased. The origin of the anisotropy increase and its relation to the overall I_c improvement is presently not understood.

Progress of 2G HTS (RE)BCO conductor development at SuperPower

Drew W. Hazelton

Superpower Inc., USA

Developments in 2G HTS conductor performance continue to drive the design and operating limits for a broad range of demanding applications. The design, testing and fabrication technology of 2G HTS (RE)BCO conductors is presented, highlighting the ability of 2G HTS wire to function under a wide range of operating conditions. SuperPower continues to address 2G HTS conductor development and production methods to improve characteristics and performance of the wire and provide technical support in its use. In particular, extensive studies on wire properties have been carried out and processing upgrades implemented to improve both the base performance of the conductor, as well as its functionality by enhancing key characteristics such as piece length, mechanical properties and uniformity of critical current and performance in magnetic fields. Updated measurements on recent production material are presented and plans for future performance targets discussed.

Materials for coated conductors: tapes and targets

V. I. Pantsyrny, I. M. Abdyukhanov, D. N. Rakov, M. M. Potapenko, P. V. Konovalov

Bochvar High-technology Research Institute of Inorganic Materials, Moscow, 123060, Russia

The specific features of manufacturing processes of initial materials for coated conductors fabrication developed in SC "VNIINM": metal substrate tapes and targets for laser and magnetron sputtering are reviewed. Two types of metal substrate tapes were developed: textured Ni-W alloy substrate and non-textured ones with lengths of up to 200 m and 1000 m correspondingly. Homogeneous substrates from Ni-5 at.% W (Ni-5W), Ni-7W, Ni-9W alloys with 70 µm thickness and composite 3-layers substrate with 2 outer thin layers (thickness of 20 µm each) of Ni-6W alloy and inner thick layer of paramagnetic stainless steel (thickness of 60 mm). All types of substrates have texture with more than 99% grain orientation along {100} direction. The fabrication process of non-textured stainless steel Cr25Ni18 (analogue to DIN T1.4845) tapes with lengths more than 1000 m, has been analysed. The alloys with W content of more than 8 at.% are proved to be paramagnetic at 77 K while Ni-9W alloys are paramagnetic also at 4.2 K. The composite tapes with good workability like in Ni-5W but with M_{sat} value about 8 emu/g (2 times lower than homogeneous tapes) could be treated as compromise material. The process of fabrication of homogeneous metallic Zr-Y targets with Y content of 15±1 at.% for buffer YSZ layer by magnetron ABAD deposition was developed. Plate form targets with dimensions of 400 x 100 x 5 mm and tube form targets with 50 mm in diameter and length up to 1300 mm. Zr-Y alloy plates and tubes were soldered to the copper base to remove heat flux that could be very high during high speed deposition process. The fabrication aspects of ceramic disk-shaped (diameters of up to 160 mm) and rectangular targets (that consist of multiple parts with nearly no size limitation) for CeO_2 buffer layer and superconducting Y-123 or Gd-123 layer deposition by PLD technique are considered. The density of the fabricated superconducting targets has 90±3% of theoretical limit and buffer targets – 90 - 95%. The possibility to attain the amorphous state of the magnetron sputtered Gd-Ba-Cu-O layer was experimentally evaluated with targets produced in SC "VNIINM".

Multi superconducting layer coated conductor for high engineering critical current density

Hongsoo Ha[1], Jaehun Lee[2], Seung-hyun Moon[2], Sangsoo Oh[1]

[1]Korea Electrotechnology Research Institute
[2]SuNAM, Republic of Korea

Superconducting coated conductors are currently commercialized and have been developed to optimize for various applications.

Especially, a number of studies have been carried out to develop high-performance conductor by bundling of coated conductors that has high operating current over thousands ampere at high magnetic field to apply large devices such as an accelerator and a fusion reactor. Several types of conductors using coated conductors such as CORC cable, Roebel conductor, HTS CroCos and TSTC have been developed.

In this study, multi- superconducting layered coated conductor has been suggested as a high current transport conductor with high engineering critical current density. Coated conductor has usually low c-axis strength and is easily delaminated between superconducting layer and ceramic buffer layers. In order to make multi-superconducting layered coated conductor, delaminated superconducting films are used to stack on a coated conductor. The transport current of multi-superconducting layered coated conductor can be increased with the number of superconducting layers.

The critical current of two superconducting layered coated conductor was measured 1000 A/cm, which is almost twice to the critical current of a coated conductor. And also engineering critical current density becomes almost twice because two superconducting layered coated conductor shows within 10 micron thicker than that of conventional coated conductor. If ten superconducting layered coated conductor can be made, it is assumed that it will exhibit very high critical current up to ten thousand ampere.

Coated conductors by RCE-DR: process details and scale-up issue

Seung-hyun Moon

SuNAM Co. Ltd, Ansung, Gyeonggi-Do 430-817, Republic of Korea

For the mass production of coated conductor, it is essential to choose raw materials with low prices and high-yield synthesis process for a superconducting layer. In this point of view, E-beam co-evaporation is one of the most promising method because simple elemental metal sources—Gd (Y), Ba, Cu, are employed. However, we should answer the question of whether there is a thermodynamic reaction path from single element of Gd (Y), Ba, Cu to a superconducting $Gd(Y)Ba_2Cu_3O7_{-\delta}$ (123) phase. In addition, growth kinetics are also greatly emphasized for the high-yield process. In the presentation, we will show the thermodynamic route for the RCE-DR process, which is essentially identical to the melt-textured growth, where a biaxially textured substrate plays a role of a seed for the growth of the superconducting layer. The route for the high-quality superconducting layer with the high growth rate will be discussed based on the phase diagram.

Usually scale-up of deposition system needs a variety of technical considerations, and we should consider the benefit of scale-up. Based on the potential application/market analysis, we'll discuss the suitable ways of CC production scale-up. And also we'll show the some recent progress of SuNAM's CC and magnets.

Experimental study on controlling factors of quench protection of conduction-cooled RE-123 coated conductors

Naoyuki Amemiya, Xijie Luo, Satoru Inoue, Yusuke Sogabe

Kyoto University, Japan

Quench protection is a serious issue in magnets made with RE-123 coated conductors. If we apply a classical quench protection scheme with which the store energy is dumped in an external resistor, the following factors should determine whether the magnet can be protected or not: threshold voltage of quench detection; time required for quench detection and activation of circuit breaker; decay time constant of current which is determined by magnet inductance and dump resistor; operating current; thickness of copper stabilizer; cooling condition. The objective of this study is sorting out the influences of these factors and showing the boundary in which the classical quench protection is applicable.

If we neglect the influence of the thermal conduction between turns, the electrical and thermal behavior of the quench initiation phase of a long coated conductor in a magnet can be simulated by an experiment using a short piece of coated conductor due to slow normal zone propagation. We conduction-cooled 200 mm-long coated conductor samples, and initiated quenches using small resistive heaters. An FPGA module enabled us monitoring the sample voltage and controlling the output current of a power supply. Once the monitored sample voltage reached a threshold value (simulating a quench detection in a magnet), we waited a certain period (simulating the time required for quench detection and activation of circuit breaker), and, then, decreased the output current of the power supply exponentially (simulating the decay of the magnet current by a dump resistor). The critical currents before and after a quench were compared to see whether the conductor was degraded or not. We varied the threshold voltage, the time constant of decreasing current, the operating current, the thickness of copper stabilizer etc. to look for the boundary in which the conductors are not degraded. For example, when the threshold voltage is 100 mV, the waiting period is 0.1 s, and the decay time constant of the current is 1 s, the coated conductor which is plated with 41 μm-thick copper did not degrade even if it carried 290 A at 30 K, 2 T.

This work was supported by the JST under its S-Innovation Program.

$REBa_2Cu_3O_7$ coated conductors as a coating for the FCC-hh collider beam screen: assessment of the classical rigid-fluxon model for RF surface resistances

Artur Romanov[1], Joffre Gutierrez[1], Patrick Krkotic[2], Joan O´Callaghan[3], Francis Perez[2], Montse Pont[2], Xavier Granados[1], Sergio Calatroni[4], Mauro Taborelli[4], Teresa Puig[1]

[1]*ICMAB-CSIC, Bellaterra Spain*
[2]*ALBA synchrotron, Spain*
[3]*Universitat Politècnica de Catalunya, Spain*
[4]*CERN, Switzerland*

In attempt to continue the progression in experimental particle physics beyond the lifetime of the Large Hadron Collider, CERN kicked off a R&D initiative of a new 100 TeV proton-proton collider of 80-100 km circumference, the so-called *Future Circular Collider* (FCC). Part of this study is to rethink the design of the beam screen which is supposed to shield the cold bores of steering magnets from the increased synchrotron radiation.

The design concept of the FCC-hh beam screen is based on an octagonal shaped stainless steel tube coated in its interior with copper. In the foreseen operating conditions of 40-60 K, 16 T and 0-1 GHz proton bunch frequency, the intended Cu coating might not guarantee an impedance sufficiently low for a stable beam. This motivates the exploration of high-temperature superconducting coated conductor (HTS-CC) tapes as an alternative coating. As a first test for the suitability of this approach, the surface resistance of conventional YBCO is estimated with the classical rigid-fluxon model. At the operating conditions of the FCC, it exhibits a lower surface resistance than Cu.

In this contribution, we present the surface resistance of commercially available $REBa_2Cu_3O_7$ CCs from different manufacturers calculated from transport properties results using the classical rigid-fluxon model. Their applicability as a coating for the beam screen is evaluated by discussing the frequency and magnetic field behavior at 50 K. The accuracy of the model is assessed by correlating those results with surface resistance measurements obtained using a RF dielectric resonator constructed to operate at 8 GHz, up to 9 T and as a function of temperature. Frequency and magnetic field limiting cases have helped to define a validity window for the model.

A key quantity of the classical rigid-fluxon model is the depinning frequency. It is defined as the current frequency at which the vortex motion becomes as dissipative as in the flux-flow regime. The depinning frequency can be related to transport properties that are correlated to the material's microstructure. Thus, when experimentally verified, this theoretical approach gives prospect to an exciting opportunity. It can generate knowledge on how to tailor the microstructure of CCs around a new field of surface resistance dependent applications.

Advanced long-length GdBaCuO tapes with high homogeneity and mechanical-electrical performance for DC-FCL applications

<u>Sandra Kauffmann-Weiss</u>[1], Mayraluna Lao[1], Roland Gyuráki[1], Quoc Pham[1], Simon Otten[1], Veit Große[2], Markus Bauer[2], Christian Lacroix[3], Frederic Sirois[3], Jens Hänisch[1]

[1]*Institute for Technical Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany*
[2]*THEVA Dünnschichttechnik GmbH, Ismaning, Germany*
[3]*Department of Electrical Engineering, Polytechnique Montréal, Montréal, Canada*

A promising solution for transporting renewable electrical energy over long distances is the realization of high-voltage DC super-grids, but the management of fault currents remains an issue even if DC circuit breakers have emerged. Superconducting Fault Current Limiters (SCFCLs) using *RE*BCO tapes have proved their outstanding performance for fault current limitation on medium-voltage AC systems, and the production of these *RE*BCO tapes in the necessary length for FCL applications has already been demonstrated. However, to realize cost-effective *RE*BCO tapes, first the characteristics of the tapes have to be improved further.

The aim of the European project FASTGRID (Cost effective FCL using advanced superconducting tapes for future HVDC grids) is the property improvement of the $GdBa_2Cu_3O_7$ tapes in order to significantly enhance their electric field limit which will enhance the economical attractiveness of SCFCL for high-voltage DC applications. High critical currents will help to reduce the cost as the absolute length of the tapes is reduced for a given design and the device size will decrease. Furthermore, the metallic stabilization layer has to be suitable for good electrical contact and optimal quench propagation and detection. The process and architecture developed on short lengths were implemented for the long-length production.

This presentation focusses on (micro-)structural, mechanical-electrical characterization and (optical) measurement of quench propagation of THEVA tapes and shows promising results of structural and electrical homogeneity in combination with high critical current densities (> 1000 A/cm-width at 65 K, self-field).

Acknowledgements:

This project has received funding from the European Union's Horizon 2020 research and innovative program under grant agreement No 721019.

Effect of granularity on local transport properties in pure and doped YBCO films grown on technical templates

Patrick Pahlke[1], Max Sieger[1], Mayraluna Lao[2,3], Michael Eisterer[2], Paul Chekhonin[4], Werner Skrotzki[4], Alexander Meledin[5], Gustaaf Van Tendeloo[5], Kornelius Nielsch[1], Ludwig Schultz[1], Ruben Hühne[1]

[1]IFW Dresden, Germany
[2]Atominstitut, TU Wien, Austria
[3]Karlsruhe Institute of Technology, Germany
[4]TU Dresden, Germany
[5]University of Antwerp, Belgium

$YBa_2Cu_3O_{7-x}$ (YBCO) and related compounds are the most promising materials for energy applications at 77 K or high field magnets at lower temperatures. The required flexible conductors are realized with the coated conductor technology. Over the last 20 years, significant efforts have been made to develop the necessary biaxially textured templates for a long length conductor manufacturing. One of the technological approaches is the preparation of biaxially textured buffer layers on arbitrarily textured metal tapes by methods like ion beam assisted deposition (IBAD), alternating beam assisted deposition (ABAD) or inclined substrate deposition (ISD). Alternatively, highly textured metal templates are fabricated by the rolling assisted biaxially textured substrate (RABiTS) route. More recently, significant efforts are devoted to enhance the current transport capability of the superconducting layers in magnetic fields by engineering the microstructure using nanometer-sized artificial pinning centers with an optimized density and distribution in the YBCO matrix.

Nevertheless, grain boundaries with low misorientation angles (typically below 10°) are still present in the superconducting layer of such coated conductors with a distribution strongly dependent on the template used. To study this dependency in more detail, we deposited YBCO layers with different thicknesses on $SrTiO_3$ single crystals, buffered Ni-W RABiTS substrates and ABAD-YSZ templates using pulsed laser deposition. Additionally, $BaHfO_3$ artificial pinning centers were incorporated in some of these YBCO layers. We analyzed the local texture and microstructure of the superconductor using electron backscatter diffraction as well as scanning and transmission electron microscopy. The local critical current density was analyzed by high resolution Hall scans with a resolution down to 2 µm. By overlapping structural information with local J_c mappings we will discuss the influence of the texture distribution and the grain boundary properties on the critical current density on the grain level. Furthermore, it will be shown that the granularity of the YBCO layers is significantly changed with increasing thickness or with the incorporation of $BaHfO_3$ pinning centers.

The authors acknowledge financial support from EUROTAPES, a collaborative project funded by the European Union's Seventh Framework Programme (FP7 / 2007 - 2013) under Grant Agreement no. 280432.

Characterization of the local critical current fluctuation along the length in industrially produced CC tapes

Fedor Gömöry, *Asef Ghabeli Juybari, Miroslav Adámek, Ján Šouc*

Institute of Electrical Engineering, Slovak Academy of Sciences

Fluctuation of critical current along the length of conductor is a common feature of commercially available CC tapes manufactured by an industrial process. Efforts dedicated to the elimination of this adverse effect have reached certain success, however it would be sensible to incorporate its description in the standard tape characterization. In particular, it would be interesting to establish a procedure for predicting - using a minimum set of tape characteristics - the critical current defined at the electrical field criterion over its whole length, the quench current characterizing certain power dissipation or the current at which the hot spots will lead to a local damage.

We have analyzed the data on longitudinal I_c fluctuations provided by tape manufacturers in terms of Gaussian and Weibull distributions. Along with the standard parameters describing these distributions (e.g. the mean and standard deviation in case of the Gaussian distribution) we have checked the possibility to predict the tape behavior using the weighted mean and the weighted coefficient of variation. Sets of data artificially modified in order to model the appearance of non-statistical defects have been analyzed in an analogous procedure. We discuss how valid are the various statistical parameters in case of three objects: CC tape of production length, a superconducting cable where all the tapes are fully transposed and a superconducting coil with rather different exposition of the tapes placed in various parts of the winding.

Length uniformity of the angular dependences of I_c and n of commercial (RE)BaCuO tapes with artificial pinning at 77 K

Krzysztof Kubiczek[1], *Francesco Grilli*[2], *Anna Kario*[2], *Aurelien Godfrin*[2], *Victor Zermeno*[2], *Mariusz Stepien*[1], *Marian Kampik*[1]

[1]*Silesian University of Technology, Poland*
[2]*Karlsruhe Institute of Technology, Germany*

One of the most significant and basic parameters connected with the performance of rare earth-based high temperature superconductor (HTS) tapes is the angular dependence of their critical current in external magnetic field. Because of the complex tape architecture and complicated production process of coated superconducting tapes, the homogeneity of the angular dependence of the critical current $I_c(B,\theta)$ along the conductor's length needs to be evaluated.

The characterization of the $I_c(B,\theta)$ dependence along the tape's length is important in order to predict the performance of applications (such as cables and coils) made of HTS tapes. For this purpose, the typically adopted procedure is the following: the $I_c(B,\theta)$ dependence of a short tape sample is measured, and the results are used as input for numerical simulations of applications made of that tape. But how representative of the whole tape length is the short-sample measurement? Does the $I_c(B,\theta)$ angular dependence simply vary along the tape length by a variable scaling factor or does it change its functional dependence on B and θ?

The present work aims at answering those questions by evaluating the uniformity of the angular dependence of the critical current $I_c(B,\theta)$ and of the power-index $n(B,\theta)$ in external magnetic field (up to 600 mT) at 77 K of several pieces of three coated conductor tapes with artificial pinning manufactured by SuperPower, Inc. between 2008 and 2014.

The possibility of exploiting the lack of 180-degree symmetry (typical of samples with artificial pinning) for building tape assemblies with high effective critical current is also investigated.

Local deformations created during the assembling of CC tapes into a round cable

Tomáš Kujovič, Fedor Gömöry, Ján Šouc

Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia

Coated conductors need to be assembled into cables in order to achieve the properties required for specific application, for example the critical current higher than one tape can provide. Tapes are arranged into cables using different procedures. Commonly during the manufacturing process a mechanical stress is introduced. This could affect negatively the electrical properties of superconductor, or even lead to a mechanical damage because of creation and propagation of cracks in the tapes. In addition to an overall loading, local deformations can damage the superconductor long before a simple tension or bending stress reaches critical point for the tape under investigation. In consideration of these facts a detailed mechanical modelling is desirable.

We present the results of mechanical finite element analysis using the software Ansys. In the study of mechanical stress distribution we pay particular attention to the investigation of local deformations. Such locations with enhanced deformation pressure are created already during the cable assembling. The analysis is performed in conditions relevant for the manufacturing of a round cable by placing tapes in helical manner on a round metallic tube. We have found that the effect of the local deformations appearing in this arrangement at the crossings of tapes from adjacent layers can be controlled to some degree. We present a simulation model for simplified evaluation of local deformations and their influence on tape deformation.

Industrial-scale resistive I_c measurement device

Michael Bäcker[1], Thomas Braun[1], Ruslan Karabalaev[1], Roger Woerdenweber[2]

[1]Deutsche Nanoschicht GmbH, Germany
[2]Forschungszentrum Jülich, Germany

A high-speed – high-current quality control is mandatory for the production and sales of long length HTS tapes. Reel-to-reel resistive measurements provide the only failsafe technique for detecting faults and dropouts. Inductive measurements are reliable but not 100% secure. Some defects are overestimated and others underestimated. Overly sensitive settings lead to an over-interpretation of I_c drops while coarse settings raise the risk of missing serious dropouts. On the other hand, the method is well-established; its non-contact nature is convenient and safe, and the technique is fast.

In contrast to the commercial availability of inductive measurement systems, resistive measurement systems are often home-made and may not be suitable usable for industrial 24/7 quality control. The measurement principle is either based on a stop-and-go mode, whereby the tape motion is periodically stopped to perform the I_c measurement over a given tape section and then moved forward, or the measurements are continuous but either slow and restricted to low current values or faster but lacking information such as *n*-values, which are essential for a proper evaluation of the tape quality.

These limitations illustrate the big challenges in realizing an industrial scale (i.e. 24/7, fast and continuous) resistive I_c measurement device. Deutsche Nanoschicht GmbH has constructed and realized such a device with a measurement capability of 1000 m/h for critical currents up to 1000 A. Major challenges tackled with the new design include: a radical suppression of ohmic heating at the current feeding units which could cause unacceptable quenches and temperature spikes during the measurement, reduced friction and tensile stress while moving the tape over the current injection units, *n*-value derivation without stopping the tape, and measures to avoid of frequent LN_2 refills.

The new design comprises horizontal current transfer wheels with current feeding and active motors outside the cryostat to minimize tensile stress, sub-cooling of the current injection section, and a measurement section with boiling LN_2 at 77.3 K and multiple voltage tabs combined with varying currents for the determination of transport I_c and *n*-values.

Details on the design considerations and measurement results will be given in the presentation.

Characterizing of superconducting tape quality by measuring magnetic AC susceptibility

Rastislav Ries[1], Marek Mošat[1], Fedor Gömöry[1], Michal Vojenčiak[1], Eugen Seiler[1], Marcela Pekarčíková[2], Eva Cuninková[2], Jozef Mišík[2]

[1]Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia
[2]UMAT MTF, Trnava, Slovakia

Measurement and analysis of magnetic AC susceptibility is a useful tool in the study of superconducting materials. Exposure of a sample to a magnetic field changing in time generates loops of electrical currents that are detectable in a contactless way with the help of a suitable pick-up system. This measurement makes it possible to compare the measured AC susceptibility of a CC tape with Brandt model and determine its critical current. We report on using this technique in continual checking of tape sample quality during its modification aimed at improving the properties in DC current limitation. In this process a layer of stycast with anorganic filler was applied on the tape surface in order to reduce the temperature rise during the period of current limitation. In several stages of the sample modification its critical current was checked by direct transport measurement, the final limitation performance is tested by applying the pulse of voltage that drives the sample into resistive state. For this purpose as the first step the current terminations have been provided on both ends of the sample by galvanic deposition of Cu. Before and after each modification step, the sample was magnetically measured. Based on these measurements, it is possible to identify the most critical steps in the sample preparation.

Microstructures and superconducting properties of several coated conductors

Ataru Ichinose[1], Kiyosumi Tsuchiya[2], Hdetoshi Oguro[3], Akihiro Kikuchi[4]

[1]Central Research Institute of Electric Power Industry, Japan
[2]High Energy Accelerator Research Organization, Japan
[3]Tokai University, Japan
[4]National Institute for Materials Science, Japan

Long length coated conductors (CCs) have recently commercialized and are candidates for use in superconducting power applications. However, CCs supplied by CC production companies have different characteristics, depending on the manufacturing process, the substrate and the thickness of superconductor, the difference of artificial pinning centers and so on. Therefore, it is important for the application sides to investigate superconducting properties under the same measurement method and condition. Critical current, I_c, of whole tape width approximately 4 mm were measured at 4.2 K and up to 18 T of magnetic field and 77 K and up to 3 T. The magnetic field was usually applied in perpendicular to CCs surface. After measuring the I_c, microstructures of cross-section and plan-view of the CCs were analyzed using a transmission electron microscopy (TEM) with an energy dispersive X-ray spectrometer (EDX). According to the microstructural analysis, it was found that the microstructure varies depending on the manufacturing process of superconducting layer using single-step vapor deposition or two-step deposition which is separated to deposition and reaction steps. Furthermore, it has been found that the I_c of some CCs can be further improved by optimizing manufacturing conditions.

Development of a joint resistance evaluation system (1) concept, design, and manufacture

Hitoshi Kitaguchi, Akira Uchida, Munenori Amaya, Kensuke Kobayashi, Gen Nishijima

National Institute for Materials Science (NIMS), Japan

Superconducting joints between HTS conductors are much interested. Evaluation technique of low resistance ranging 10^{-13}-10^{-9} Ω is important in joint development. The current decay method using LR circuit is well known and widely used. We are developing a joint resistance (R_j) evaluation system and its concept, design, and fabrication are reported in this paper.

The concepts of our system are: (1) R_j can be measured as a function of temperature ranging 4-90 K, (2) R_j can be measured as a function of magnetic field ranging 0-3 T, (3) magnetic field can be rotated to investigate the anisotropy at the joint, (4) electric current up to 200 A can be applied to the circuit including a joint, and (5) R_j can be measured as fast as possible.

In our design, HTS LR closed circuit specimen is composed of a winding part (one or a few turns, inner diameter: 100 mm) with a tail (length: 320 mm). The joint should be located at the end of the tail. Electric current in the specimen can be generated inductively by using a copper solenoid coil set at the center of the winding. Hall sensors are set near the circuit to measure the current in the specimen. The tail goes into external field magnet. The magnet is a Nb-Ti split pair coil with the field direction perpendicular to the tail. The whole sample setting can be rotated along the tail axis. The sample setting and the magnet are cooled independently by using cryocoolers. The system will be assembled and tested in this summer.

A part of this work is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO) [No.16100555-0].

The effect of temperature on the levitation properties of CC-tapes stacks

Maxim Osipov, *Sergey Pokrovskii, Dmitriy Abin, Irina Anishenko, Igor Rudnev*

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Russia

At present, most of the superconducting levitation systems are based on bulk superconductors. Stacks of coated conductors (CC-tapes) have proved their ability to act as an alternative to bulk superconductors as components of a magnetic levitation system. In recent years, the number of publications in this field of research has increased significantly. In our previous works, we have studied the effect of the number of elements in the stack and stack magnetization on the levitation force, as well as the stability of the system in response to lateral displacements and vibrations.

However, all experiments were limited to the temperature of liquid nitrogen. This work continues a series of studies on the levitation properties of CC-tape stacks and is mainly focused on the temperature dependence of the levitation force. Experimental measurements of the dependence of the levitation force of the CC-tape stacks on the number of elements in the stack at various temperatures were carried out. In measurements we used CC-tapes with different critical current values from different manufacturers: Sunam, SuperOx, Theva. The width of the tapes was 12 mm. The tapes were cut into pieces of 12 mm x 12 mm. The number of layers in the stack was from 5 to 100. Cooling of the stack of CC tapes was carried out in a cryostat using a cryocooler. The temperature ranged from 30 to 80 K.

According to the obtained results, the temperature has a strong effect on the levitation characteristics of the stack. With a decrease in temperature, a significant increase in the levitation force is observed, as well as a decrease in the hysteresis of the levitation force. In addition, the temperature change has a different effect on the tapes with different values of the critical current. The experimental results were compared with the results of calculations performed using COMSOL Multiphysics. Analyzes and conclusions of this work can be useful for practical application in the systems based on magnetic levitation.

The study was carried out at the expense of a grant from the Russian Science Foundation (Project No. 17-19-01527).

Investigation of non-stationary processes in HTS tapes under impulse current loads

Sergei Pokrovskii, Igor Rudnev, Irina Anischenko, Dmitry Abin, Maxim Osipov

National Research Nuclear University MEPhI, Russia

An important aspect of the operation of any electrical device is its reliability. For most applications of high temperature superconductors the most unfavorable situation is the moment of transition to the normal state. At the same time, the local heat release is aggravated by the low propagation speed of the hot spot, which leads to damage to the HTS tape and, as a result, the device as a whole.

In this paper we present the results of a study of non-stationary processes second generation HTS tapes heating under the impulse current loads with amplitudes up to 10% above the critical current of the tape (77 K, self-field). Superconducting tapes with a copper protective layer were used as the samples. The I-V characteristics of the samples were measured under the action of current pulses during cooling in liquid nitrogen. Critical parameters (amplitude, rise time of the transport current) of the current pulses, leading to the degradation of the superconductor were obtained. Local current carrying characteristics of HTS tapes investigated using Hall probe magnetometry. The features of the influence of local inhomogeneities in the distribution of the critical current of the tapes on the transition of the superconductor to the normal state are revealed.

Also, the model of the superconducting tape under the action of the transport current pulses was developed. In the model uses the transport characteristics of industrial second-generation HTS tapes and the thermal properties of the tape layers. Simulation was performed using the finite element method. The cooling of a superconductor in liquid nitrogen, as well as cooling by cryocooler systems is considered. Modeling of cooling processes was carried out taking into account the boiling curve of liquid nitrogen. Various cooling regimes for a single tape and a stack of HTS tapes have been investigated. The features of the propagation of a hot spot at different cooling modes at pulse current loads are revealed. The results of the calculation were compared with the experimental data and a good agreement was obtained.

This work was supported by the Russian Foundation for Basic Research (Grant No. 17-29-10024).

Development of a joint resistance evaluation system (2) commissioning results

Kensuke Kobayashi, Akira Uchida, Munenori Amaya, Shinji Saito, Gen Nishijima, Hitoshi Kitaguchi

National Institute for Materials Science (NIMS), Japan

The joint technique between HTS conductors is very important to evolve their applications. Various joint techniques have been proposed in these years. However, quantitative evaluation methods for joint resistance (R_j) with respect to parameters of temperature and magnetic field have not been established. We are developing an evaluation system for superconducting and/or ultra-low resistance joints. In this paper, we report commissioning results and future prospects of our system.

In this system, R_j of an HTS joint is evaluated by a current decay method using LR closed circuit. A test specimen is composed of a one- or several-turn closed-loop coil, i.e. both ends of the conductor are joined together. Typical inductance of the one-turn coil with a diameter of 100 mm is ~0.6 μH. Thus, measurement times, i.e., times to measure the current decay by 10%, are ~2 minutes and ~12 hours for $R_j = 10^{-9}$ Ω and $R_j = 10^{-12}$ Ω, respectively. Using this system, performance of the joint with resistance ranging 10^{-13}-10^{-7} Ω can be quantitatively evaluated as a function of temperature, magnetic field and its orientation.

The commissioning was performed by measuring several REBCO joints. Commercially available REBCO conductors were used for specimens. Joints were made by soldering using Pb-Sn or Bi-Sn solder. Resistances of the soldered joints were in the range of 10^{-8}-10^{-7} Ω at 77 K in self-field. At low temperatures, where the solder is superconducting, much lower resistance is expected. On the other hand, application of magnetic field should easily increase the R_j. We will discuss the temperature and magnetic field dependence of the joint between REBCO conductors.

A part of this work is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO) [No.16100555-0].

Coated conductors for the CERN's Future Circular Collider beam screen chamber

Sergio Calatroni[1], Paolo Chiggiato[1], Elisa Garcia-Tabarés[1], Pedro Gonzalez[2], Xavier Granados[3], Joffre Gutierrez[3], Ilya Korolkov[2], Patrick Krkotic[4], Ramon Miquel[2], Joan O'Callaghan[5], Francis Perez[4], Montse Pont[4], Teresa Puig[3], Artur Romanov[3], Mauro Taborelli[1]

[1]CERN - The European Organization for Nuclear Research, Geneva, Switzerland
[2]Institut de Física d'Altes Energies, Bellaterra, Spain
[3]Institut de Ciència de Materials de Barcelona, Bellaterra, Spain
[4]ALBA Synchrotron Light source, Cerdanyola del Vallés, Spain
[5]Universitat Politècnica de Catalunya, Barcelona, Spain

The future circular hadron-hadron collider (FCC-hh) is a CERN study for a next generation large proton – proton collider aiming for a 100 TeV center-of-mass collision energy in a 100 (80) km circumference ring. Superconducting magnets operating at 16 (20) T cooled at 1.9 K will steer the beam which will emit 28 W/m/beam of synchrotron radiation. A beam screen held at around 50 K shall absorb the radiation and shield the magnets, thus allowing for a better overall cryogenic efficiency and power consumption. State-of-the-Art technology at CERN relies on a stainless-steel beam screen optimized for operation at 4.2 K coated with an 80-micrometer low-surface resistance Cu layer. The Cu layer is added in order to minimize beam coupling impedance. A high impedance would create large electric fields in the beam screen due to the image currents generated by the accelerated protons. In turn, the electric fields will have catastrophic impact on the proton beam stability. However, copper operating at 50 K may not provide low enough beam coupling impedance in the FCC-hh. The alternative of having the 100 (80) km beam screen operating at 4.2 K is economically and energetically not viable.

Within a consortium formed in 2017 between ALBA synchrotron, the institute of high energy physics (IFAE), the polytechnic university of Barcelona (UPC), the institute of material science of Barcelona (ICMAB) and CERN, we have identified the possibility of using high temperature superconductors, like $REBa_2Cu_3O_{7-x}$ coated conductors, operating above 40 K as potential candidates to substitute Cu in the FCC beam screen chamber. This consortium is committed to develop knowledge of accelerators with thin films and material development and characterization under the extreme conditions found in high energy particle accelerators.

In this talk, we present the consortium goals and the identified challenges for using coated conductors' technology in the extreme environment of the FCC. We will also present the very promising results already obtained on commercially available $REBa_2Cu_3O_{7-x}$ coated conductors from different manufacturers, showing the potential for these materials to substitute copper as the beam screen coating in circular colliders.

3D modelling and measurements of cross-field demagnetization in stacks of tapes

Milan Kapolka[1], *Enric Pardo*[1], *Anup Patel*[2], *Algirdas Baskys*[2], *Francesco Grilli*[3]

[1]*Institute of Electrical Engineering, SAS, Slovakia*
[2]*Department of Engineering, University of Cambridge, UK*
[3]*Institute of Technical Physics, Karlsruhe Institute of Technology, Germany*

Stacks of REBCO coated conductor tapes and bulks have potential to replace permanent magnets in many power applications, such as generators or motors, as well as portable magnets for separators. Both stacks and bulks can trap higher magnetic fields than permanent magnets, the world records being 17.7 T and 17.6 T, respectively. In addition to somewhat higher trapped fields, stacks present several advantages, such as virtually unlimited length, higher width (up to 45 mm), and better mechanical and thermal properties.

The problem of both stacks and bulks is demagnetization by transverse-fields, which are present in any rotating machine. Demagnetization and reduction of the trapped field is one of the main issues for future commercial applications. The demagnetization process must be fully understood, in order to reduce it. Finite size effects are present in most measurements and many applications. Therefore, full 3D models with all finite size effects need to be developed.

The whole demagnetization process of stacks can be modeled by the Minimum Electro Magnetic Entropy Production method (MEMEP 3D), as well as by Finite-Element Methods (FEM) in the H formulation. The work is focused on modeling stacks of up to 5 tapes with various amplitudes of demagnetizing frequencies of the transverse fields. First, we approximate the stack as a bulk separated by isolating thin layers. Later, we decrease the superconductor thickness and increase the air gap in between in order to converge to the situation of a stack made of thin tapes.

The results of the MEMEP method are compared with those obtained with the H-formulation of Maxwell's equations implemented in Comsol Multiphyisics, obtaining good agreement. Both methods also agree with the measurements. We discuss the 3D effects and the validity of the 2D models. We found that the finite length of the tapes causes significant deviations compared to the 3D models.

The results presented in this work show that 3D modeling of the electromagnetic behavior of superconductors has become sufficiently viable to be routinely applied for investigating cases of high practical interest such as cross-field magnetization in stacks and tapes.

Coupling and superconductor loss in soldered 2G HTS stacks and multi-tape-conductor racetrack coils

Shuo Li[1], *Enric Pardo*[1], *Ján Kováč*[1], *Michal Vojenčiak*[1], *Thomas Reis*[2]

[1] *Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia*
[2] *Oswald Elektromotoren GmbH, Miltenberg, Germany*

High power density superconducting motors are the key components for electric and hybrid distributed propulsion for aircrafts, which can drastically reduce commercial flight emissions. Multi-tape conductors are adopted in the stator coils to increase the power density of the motor. Furthermore, two kinds of HTS cable are proposed to decrease the losses of windings. One cable is insulated by epoxy plate, which we call it uncoupled type. Another one is insulated in the same way and soldered at the ends, which we call it coupled type. A 2D detailed model is established with Minimum Electro-Magnetic Entropy Production method (MEMEP) programmed in C++ to estimate the magnetization loss. In the modelling, there are four HTS tapes stacked in parallel. For each tape, there are one superconductor layer, one nonmagnetic substrate layer (Hastelloy C-276) and two copper layers. The HTS layer is considered by power-law non-linear resistivity and the other layers are considered as normal conductor with different constant resistivity. Losses in the superconductor layer and in the other normal conductor layers are carefully calculated. Two short HTS samples are prepared and standard magnetization measurement is performed under various magnetic field amplitude and frequency. The modelling result agrees with measurements very well. The results show that the coupled type cable has much higher magnetization loss than uncoupled type cable under parallel magnetic field. In addition, the coupled type cable has a strong frequency dependency. Then, a real size HTS coil with coupled cable is prepared and measured under AC transport current, where the tape is coupled at the terminals only. Again measurements agree with calculations. Modeling results show that HTS coils with coupled cable present almost the same loss as uncoupled. Therefore, transposing multi-tape cables is not necessary to reduce self-field AC loss in coils.

Levitation properties of the coated conductor compositions in the gradient magnetic field of various geometries

I. Rudnev, M. Osipov, A. Starikovskii, I. Anischenko, S. Pokrovskii, A. Podlivaev

National Research Nuclear University MEPHI (Moscow Engineering Physics Institute), Russia

Both experimentally and theoretically we studied an interaction of the stacks of HTSC tapes with the sets of permanent magnets creating various configurations of gradient magnetic field: array of oppositely oriented permanent magnets, Halbach array, etc. We have analyzed dependences of interaction force on levitation gap (the distance between HTSC tape stack and surface of permanent magnets) for various configuration of magnetic field as well as for various geometries of the HTSC tapes compositions. In the frame of a two-exponential model of the critical state, we have calculated interaction force of the stacks of HTSC tapes with the array of NdFeB permanent magnets of opposite polarity as an example of gradient magnetic field of the simple geometry. Dependences of the interaction force on the distance between the stacks and magnets were obtained for different number of the tapes in the stack N_t = 1 – 50. It was found the decreasing of the levitation force per one tape in the stack as N_t increases. We have studied also the influence of a transverse crack in one of the tape on the total force and found that the character of the levitation curve depends on location of the defective tape in the stack. Obtained results are discussed on the basis of the possibility and efficiency of the use of various geometries of the magnetic field in magneto-levitation application of HTSC tapes.

The study was carried out at the expense of a grant from the Russian Science Foundation (project No. 17-19-01527).

3D modeling of macroscopic force-free effects in thin films and rectangular prims under tilted applied magnetic fields

Enric Pardo, Milan Kapolka

Institute of Electrical Engineering, Slovak Academy of Sciences

When the magnetic field *B* is parallel to the current density *J*, the critical current density J_c is determined by force-free effects, such as vortex cutting and breaking. This causes a macroscopic electric field *E* that is not always parallel to *J*. This situation has not been predicted for finite thin films, such as REBCO coated conductors, or bulks. Computer modeling is necessary to study force-free effects in samples of general shape, enabling to interpret characterization measurements.

In this contribution, we develop a novel numerical modeling method and self-programmed tool to predict the magnetic response with macroscopic force-free effects. The 3D numerical method, which finds the detailed screening current density, is based on a novel variational principle that avoids spending degrees of freedom in the air. For the superconductor, we assume properties similar to the Elliptic Critical State Model but with a smooth *E*(*J*) relation.

We analyze in detail the 3D screening currents and magnetization loops of both square thin films and bulk rectangular prisms under tilted applied magnetic field. For both films and prism, J_c is enhanced at the regions where *J* has a parallel component to *B*, creating asymmetric current paths. This causes an increase in the magnetization of most of the magnetization loop. For thin films, we have found that the magnetization loop presents a minimum at remanence. The cause is that the self-field is perpendicular to the sample, and hence the enhancement of J_c due to the parallel component of *B* to *J* is not present. However, this minimum is strongly suppressed for prisms with finite thickness, since the self-field also presents a *B* component parallel to *J*.

The novel modelling method enables to predict interesting force-free effects in REBCO films and bulks. This opens the door for modelling other 3D situations interesting for applications.

Electromechanical performance of CORC® cables and wires under axial tension and transverse compression

Dustin McRae, Jeremy Weiss, Danko van der Laan

Advanced Conductor Technologies, LLC, University of Colorado Boulder, USA

Advanced Conductor Technologies is developing high-temperature superconducting (HTS) Conductor on Round Core (CORC®) cables and wires from ReBCO tapes for high-field accelerator, fusion and scientific magnets. One of the concerns with operating any HTS conductor in magnets that operate at currents exceeding 10,000 A at fields of over 20 T in future accelerator magnets, or 50,000 A at fields over 12 T in fusion magnets, is the effect of mechanical stress and stress cycling on the conductor performance. Detailed mechanical tests of the conductor performance under axial and transverse stress relevant for magnet operation are thus required to develop robust magnet conductors.

Here we present recent test results of critical current (I_c) degradation as a function of applied transverse compressive stress on CORC® cables and wires as well as axial tension on CORC® wires at 76 K. Additionally, fatigue cycling is performed at different stress levels up to 100,000 cycles to investigate I_c retention beyond the design life of modern user magnets and fusion devices. CORC® cables and wires presently exhibit excellent electrical performance in mechanical fatigue at transverse stress levels where I_c degraded by only 3 – 5%, and even after I_c degraded by as much as 20%. Fatigue cycling in axial tension is ongoing, and preliminary test results are also presented. Initial correlation between the effect of mechanical stress and the conductor layout allows further optimization of CORC® cables and wires. The study presented here expands on established framework for ongoing mechanical characterization and development of CORC® cables and wires and further quantifies their feasibility as a practical magnet conductor.

Significant improvement of robustness of current carrying capabilities in coated conductors by use of face-to-face double stacked architecture

Takanobu Kiss[1], Kohei Higashikawa[1], Yuhei Nishimiya[1], Yukihisa Kumagai[1], Takumi Suzuki[1], Valery Petrykin[2], Sergey Lee[2], Kenji Suzuki[3], Masaru Tomita[3], Akira Ibi[4], Takato Machi[4], Teruo Izumi[4]

[1]Department of Electrical Engineering, Kyushu University, Japan
[2]SuperOx, Japan
[3]RTRI, Japan
[4]AIST, Japan

Spatial homogeneity of critical currents in coated conductors (CCs) is one of the most important issues for practical applications because the minimum I_c in a long length CC will limit the total performance of the tape. This becomes crucial especially in narrower and/or multi-filamentary tapes. In this study, we have investigated current transport properties in face-to-face double stacked (FFDS) CCs by measurements and analysis. Starting from a multi-scale modeling of nonlinear current transport properties in a long length CC strand, we developed a method to analyze detailed properties in the FFDS architecture including contact resistance, local electric field distribution and current sharing among the tapes. It has been shown that the total dissipation, i.e., joint resistance depends on I_c variation and its spatial frequency of the CCs. Based on the measurements on local I_c variation in a 1-mm-wide CC by the reel-to-reel scanning Hall probe microscopy, we analyzed the global current-voltage characteristics of the FFDS CCs at various conditions of joining resistance. Critical current density can be increased by a factor of two effectively and the local electric field concentration can be suppressed one order smaller than that of single strand even though at the same end-to-end voltage criterion of 1 μV/cm. From these analyses, we can lead the conclusion that the FFDS architecture is very effective to suppress the influence of local I_c drop and can improve the robustness and reliability of the CCs.

Acknowledgements: This work was supported by “JSPS KAKENHI (16H02334)” and partly by JST-Mirai Program Grant Number JPMJMI17A2, Japan.

Transport critical currents of modern ReBCO conductors in high magnetic fields up to 45 T

Dmytro Abraimov[1], *J. Jaroszynski*[1], *Y. Zhang*[2], *A. Francis*[1], *A. Constantinescu*[1], *Y. L. Viouchkov*[1], *D. C. Larbalestier*[1]

[1]*National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL 32310 USA*
[2]*SuperPower Inc., Schenectady, NY 12304 USA*

Several manufacturers worldwide are now making ReBCO coated conductors for superconducting magnets, some aiming at ultra-high fields > 25 T. There are several approaches to improve the whole conductor J_e of ReBCO conductors: artificial pinning centers, increased ReBCO thickness, and thinner substrates are three such thrusts being actively studied. We have measured and compared transport critical currents for short samples of conductors produced by SuperPower Inc., SuperOx, SuNAM, and Bruker in very high fields up to 31 T at 4.2 K and in fields up to 15 T at various temperatures. To study J_c properties at the highest fields, ultra-narrow bridges were prepared from 7.5% and 15% Zr doped R&D ReBCO tapes produced by SuperPower Inc. using optical photolithography, wet etching, and final trimming by FIB. We were able to prepare 1.6 – 4.6 μm wide and 60-130 μm long bridges suitable for transport measurements at variable temperatures (4.2 K – 30 K) and field orientations in the NHMFL Hybrid DC magnet up to 45 T. At 10 K and 20 K and fields above 20 T in B || tape orientation, we found that J_c is field independent. As we expected at 42 T $J_c(\theta, 4.2\text{ K})$ 15% Zr ReBCO has a wider *ab*-peak, however slightly lower peak value than for 7.5% Zr doped ReBCO. The full width half maximum for tapes with 7.5% Zr doping is 10.5° and 29.7° for 15% Zr. Near $B \perp$ tape, J_c values for both doping concentrations match. The $J_c(B, 4.2\text{ K})$ dependence for the $B \perp$ tape orientation follows the power function up to 45 T, but $J_c(B)$ drops faster above 10 K. At 4.2 K we observed a wide range over which F_p showed no decrease up to at least 45 T; at 12 K F_p maximum is at 25 T for 7.5% Zr tapes. Critical currents follow well the dependence $I_c(B, T) = I_{co}(B)\exp(-T/T_o)$. We found lower T_o values for tapes with 15% than for 7.5% Zr. Critical currents of tapes with 15% Zr doping decrease faster with temperature than 7.5% Zr. However, the anisotropy of critical currents is lower for 15% Zr than for 7.5% Zr doping.

Acknowledgements: The National High Magnetic Field Laboratory is supported by National Science Foundation through NSF/DMR-1157490 and NSF/DMR-1644779 and the State of Florida.

Enhanced pinning performance of CSD $YBa_2Cu_3O_{7-x}$ thin films via ultrafast liquid assisted growth and preformed nanoparticles

Juri Banchewski[1], *L. Soler*[1], *J. Jareño*[1], *R. Guzmán*[1], *S. Rasi*[2], *J. Farjas*[2], *P. Roura*[2], *S. Ricart*[1], *C. Mocuta*[3], *X. Obradors*[1], *T. Puig*[1]

[1]*Institut de Ciència de Materials de Barcelona ICMAB-CSIC, Barcelona, Spain*
[2]*Univeristy of Girona, Girona, Spain*
[3]*Synchrotron SOLEIL, L'Orme des Merisiers, Saint Aubin, France*

The field of High Temperature Superconductivity (HTS) experienced a rapid evolution of low-cost, high throughput Coated Conductors (CCs) over the past few years. Various fabrication and post-treatment techniques were developed having the same objectives in prospect: Lowering the fabrication costs while enriching the density of flux pinning centers. However, as promising as recent advancements are, the high requirements to push HTS to a broad commercial market still remain to be met. To address this challenge, we are developing a novel growth approach, entitled Transient Liquid Assisted Growth (TLAG), which combines the technological simplicity and upgradability of Chemical Solution Deposition (CSD) with ultrahigh growth rates of liquid-mediated techniques. Growth rates up to 50 nm/s, surpassing any conventional method by one order of magnitude, are already realized and higher values are foreseen. The approach is compatible with the incorporation of preformed nanoparticles (NPs) to further tune the vortex pinning landscape.

In this presentation, we will motivate the relevance and opportunities of growing $YBa_2Cu_3O_{7-x}$ (YBCO) films with TLAG. First, we will demonstrate the high epitaxial quality that can be reached ($\Delta\omega < 0.4°$ and $\Delta\phi < 1°$ up to 24% molar of NPs), though the major part is dedicated to studying the generation of flux pinning defects and their role in enhancing superconducting properties. Low temperature transport measurements reveal high critical temperatures (T_c = 88-92 K) and critical current densities (J_c = 2-6 MA/cm^2 at self-field and 77 K). Linking transport measurements with transmission electron microscopy results suggests that the novel growth approach can naturally drive the YBCO to form a high amount of 124-intergrowths and small ab-oriented particles (5-10 nm). This in turn smoothens the decay of J_c as a function of magnetic field and reduces the effective anisotropy ($\gamma_{eff} \leq 3$) already in pristine TLAG films compared to the conventional TFA-CSD route. Finally, the successful incorporation of NPs into the YBCO matrix promotes the performance at high fields and low temperatures. Combining both, the ultrafast growth and the inclusion of preformed NPs might bear two key aspects: Tailoring a defect landscape with regard to application needs while reducing HTS fabrication costs to a minimum.

Acknowledgements:

Research was funded by the ERC (ERC-AdG-2014-669504ULTRASUPERTAPE_Project), Programa Excelencia Severo Ochoa SEV2015-0496, MECD (FPU13/02638) and Soleil Synchrotron.

Fabrication of REBCO coated conductor doped with artificial pinning centers using vapor-liquid-solid growth method

Yutaka Yoshida[1], *Yusuke Ichino*[1], *Yuji Tsuchiya*[1], *Tomohiro Ito*[1], *Ataru Ichinose*[2], *Kaname Matsumoto*[3], *Satoshi Awaji*[4], *Teruo Izumi*[5]

[1]*Nagoya University, Japan*
[2]*Central Research Institute of Electric Power Industry, Japan*
[3]*Kyushu Institute of Technology, Japan*
[4]*Tohoku University, Japan*
[5]*National Institute of Advanced Industrial Science and Technology, Japan*

We have proposed a vapor-liquid-solid method (VLS) in which a thin liquid layer is interposed in the growth for the purpose of fabricating a REBCO coted conductor at high quality and at high speed. It has been reported that a REBCO thin film grows at relatively lower substrate temperature during the VLS via the pseudo liquid layer. VLS REBCO film have few defect, is similar to the liquid phase epitaxy method (LPE)method. In LPE, mediated growth methods such as liquid phase, in general the growth rate is expected to be improved compared to physical vapor growth (PVD).

We investigated the possibility of PLD-VLS REBCO coated conductor from the viewpoint of the growth rate. By using the VLS growth method, it was confirmed that REBCO coated conductor with less *a*-axis oriented grains can be fabricated at a wider region of the growth temperature and oxygen partial pressure compared with the conventional PVD growth at a high growth rate.

Furthermore, we studied control technologydoping artificial pinning centers (APC) into REBCO coated conductor using high speed fabrication technology for high performance in magnetic field and cost reduction.

In this work, we will investigate challenges such as VLS-REBCO coated conductor doped with APC on IBAD tape for high performance in the magnetic field by using liquid phase during VLS growth method. We improved the fabrication method, for example the thickness and the stability of the liquid layer in the growth. We confirmed that BHO nanorods grow continuously in superconducting layer using VLS growth from results of surface observation, microscopic observation and superconducting properties in magnetic field.

This work was partly supported by the ALCA project of the Japan Science and Technology Agency (JST) and NU-AIST alliance project.

The effect of intermediate heating treatment temperature on in-field J_c for TFA-MOD $BaHfO_3$ doped $(Y_{0.77},Gd_{0.23})Ba_2Cu_3O_y$ CCs

Junya Kawanami[1], Kazuki Shimizu[1], Michio Sato[1], Masashi Miura[1], Koichi Nakaoka[2], Teruo Izumi[2]

[1]Seikei University, Japan
[2]AIST, Japan

$REBa_2Cu_3O_y$ coated conductors (CCs) derived from the trifluoroacetate metal organic deposition (TFA-MOD) process are one of candidates for magnet application because of the low-cost and the high critical current density (J_c). We have succeeded in obtaining high in-field J_c by addition of $BaHfO_3$ (BHO) nanoparticles (NPs) into $(Y_{0.77},Gd_{0.23})Ba_2Cu_3O_y$ ((Y,Gd)BCO+BHO) films [1]. For further enhancement of J_c, controlling the size and density of the BHO NPs is one of key factors. Recently AIST group successfully controlled the size of $BaZrO_3$ NPs by introducing an intermediate heat treatment (IHT) process [2]. However, the effect of IHT temperature (T_{IHT}) on in-field J_c for (Y,Gd)BCO+BHO CCs is not clear.

In this work, in order to investigate the effect of IHT temperature on superconducting properties, we fabricated (Y,Gd)BCO+BHO CCs using various IHT temperatures. These CCs have almost the same critical temperature. The (Y,Gd)BCO+BHO CC with T_{IHT} = 570˚C shows a higher magnetic field dependent J_c and less angular dependent J_c compared to that of T_{IHT} = 550˚C and T_{IHT} = 600˚C. Our results demonstrate that the IHT temperature has an important role in improving in-field J_c of TFA-MOD (Y,Gd)BCO+BHO CCs.

Acknowledgements: This work is supported by JSPS KAKENHI (17H03239 and 17K18888). A part of this work was supported by Kato Foundation for Promotion of Science (KJ-2744).

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Pinning enhancement in $YBa_2Cu_3O_{7-\delta}$ nanocomposite thin films with preformed perovskite nanocrystals using low fluorine chemical solution deposition

Javier Diez-Sierra[1], *P. López-Domínguez*[1], *H. Rijckaert*[1], *K. De Keukeleere*[1], *M. Falter*[2], *J. Bennewitz*[3], *M. Hemgesberg*[3], *A. Meyer*[3], *H. Huhtinen*[4], *P. Paturi*[4], *S. A. Schunk*[5], *M. Bäcker*[2], *I. Van Driessche*[1]

[1]*University of Ghent, Belgium*
[2]*Deutsche Nanoschicht GmbH, Germany*
[3]*BASF SE, Germany*
[4]*University of Turku, Finland*
[5]*hte GmbH, Germany*

In order to meet the requirement for power applications, scalable and low-cost fabrication of high-quality $YBa_2Cu_3O_{7-\delta}$ (YBCO) nanocomposite films is required in coated conductor architecture. Up to now, textured superconducting YBCO films with the desired properties are produced via costly processes such as pulsed laser deposition or metal-organic chemical vapor deposition which limits their competitivity and availability. However, the introduction of the chemical solution deposition approach can fulfill the demand of high-quality epitaxial YBCO films with high performance and lower manufacturing cost.

On the other hand, the implementation of YBCO coated conductors in moderate-to-high magnetic field applications such as windmills or electrical generators is limited due to the strong reduction of the critical current density (J_c) when the magnetic field is increased. However, this reduction of the J_c can be minimized by the introduction of nanometer-sized defects in YBCO matrix that prevent vortex motion. The introduction of preformed nanocrystals as artificial pinning centers offers more control of the crystallinity, size and shape of these pinning centers and thus a better control of the microstructural properties of the final nanocomposite films.

In this work, bimetallic perovskite oxide nanocrystals were synthesized by heating of various bimetallic alkoxide precursors. After the synthesis, the resulting nanocrystals are added to the low-fluorine YBCO precursor solution. Afterwards, these YBCO nanosuspensions were deposited on single crystal $LaAlO_3$ substrates via spin-coating. After the thermal treatment, superconducting YBCO nanocomposite films with a thickness of around 300 nm and a J_c of around 5 MA/cm^2 were obtained. These YBCO nanocomposite films also showed a much smoother decay of the J_c with increasing magnetic field which confirms the pinning enhancement produced by the introduction of preformed nanocrystals.

Bimetallic perovskite oxide nanocrystals in combination with low fluorine chemical solution deposition methods show good potential as a cost-efficient, reproducible and high quality industrial pathway to superconducting nanocomposites capable of meeting the larger market demands.

Angular I_c anisotropy and pinning properties of coated conductors in moderate magnetic fields at temperatures close to 77 K

Eugen Seiler, Rastislav Ries, Fedor Gömöry, Michal Vojenciak

Institute of Electrical Engineering, Bratislava, Slovakia

We report the results of angular anisotropy measurements on three commercial 4 mm wide coated conductors from different manufacturers – SuperOx, SuNAM and Superpower companies. The critical current (I_c) was measured on full width samples of the coated conductors in magnetic field applied at varying angle (theta) with respect to the flat face of the conductor. The measurements were performed at constant temperatures of 77 K, 70 K and 65 K with applied magnetic field magnitudes from 0.3 T to 2 T. The experimental results were analyzed employing the Blatter scaling method as well as the vortex path model / maximum entropy approach. The Blatter scaling approach suggests one anisotropic pinning mechanism dominating over the entire explored domain of fields and temperatures, most likely different for each of the coated conductors. The analysis according to the vortex path model indicates a few contributing pinning mechanisms (defect structures) and certain evolution of their relative strengths with increasing applied field magnitude is observed.

Assessment of the $I_c(B,T,\theta)$ characteristics of PLD-GdBCO tape with columnar $BaSnO_3$ nanoprecipitates

Mayraluna Lao[1], *Jens Hänisch*[1], *Alexander Molodyk*[2], *Vsevolod Chepikov*[2], *Sergey Lee*[3], *Valery Petrykin*[3], *Bernhard Holzapfel*[1]

[1]*Karlsruhe Institute of Technology, Germany*
[2]*SuperOx, Russia*
[3]*SuperOx, Japan*

The addition of artificial pinning centers (APC) is an inevitable path towards the improvement of the in-field performance of coated conductors. A lot of work has already shown that in this way the critical current, I_c, under an applied magnetic field, can be increased and the anisotropy regarding the direction of the field can be decreased, which are both desirable for applications. Recently, SuperOx has explored the effects of incorporating perovskite compounds of $BaSnO_3$ (BSO) and $BaZrO_3$ (BZO) in their pulsed laser deposited $GdBa_2Cu_3O_{7-x}$ (PLD-GdBCO) tapes. These compounds form nanosized columnar precipitates roughly parallel to the *c*-axis of GdBCO. An enhancement of up to 80% in I_c of the BSO-doped sample with respect to the undoped tape has been achieved at 4.2 K and in an applied field of 2 T perpendicular to the tape surface.

In this work, detailed measurements of the angle dependence of I_c of the BSO-doped tapes will be presented. The critical current is measured using a system equipped with current leads able to conduct currents of up to 1000 A. The sample holder is mounted in a helium gas flow cryostat with a split coil magnet for fields up to 6 T and stable temperatures between 2 K and 80 K. The sample holder can be continuously rotated with respect to the direction of the field, thus allowing measurement of $I_c(\theta)$. With the high-current capacity of the setup, transport critical currents of full-width 4 mm wide tapes are measured at a wide range of field, angle and temperature.

The presence of non-superconducting nanocolumns acting as correlated vortex pinning centers is known to alter the anisotropy of I_c drastically. Thus, this work will impart how the $I_c(\theta)$ of the BSO-doped GdBCO evolves with field and temperature, which contributes further understanding of the resultant effects of adding APCs to the enhancement of the critical current of industrially produced coated conductors.

The influence of artificial pinning centers on the irreversibility temperature of 2G HTS wire in magnetic field

Gavrilkin Sergey[1], Nikolay Mineev[2], Vsevolod Chepikov[2], Sergey Lee[3], Valery Petrykin[3], Alexander Molodyk[2], Sergey Samoilenkov[2], Igor Rudnev[4], Alexei Tsvetkov[1], Pavel Degtyarenko[2,5]

[1]LPI RAS, Russia
[2]JSC SuperOx, Russia
[3]JSC SuperOx, Japan
[4]NRNU MEPHI, Russia
[5]JIHT RAS, Russia

We systematically studied the resistive transition in magnetic field of 2G HTS wire samples with and without artificial pinning centers (APC) in the GdBCO layer. The samples were fabricated by PLD, using commercial production equipment and conditions at SuperOx Japan and contained 0, 6, 12 and 18% (molar) of $BaSnO_3$ (BSO) and 6% (molar) of $BaZrO_3$ (BZO). Superconducting properties of the samples were measured using PPMS in the field range from 0 to 9 T, and the samples were rotated from orientation $H||c$ (θ = 0°) to $H||ab$ (θ = 90°) at 15° increments. The resistivity curves were obtained by the 4-probe technique with a 100 mA measuring current. From these curves the irreversibility temperature, T_{irr}, was derived as the beginning of the resistive transition. We observed a T_{irr} peak in the $H||ab$ orientation. We replotted the $T_{irr}(H)$ curves as irreversibility field lines H_{irr}(T) and scaled those data using the relation for the effective field for rotated sample: The $H_{irr}(T)$ curves (at a fixed field orientation) of the undoped sample collapsed into one master-curve, which corresponded to the anisotropy parameter of about 4.5 ± 0.3. All curves for the APC-doped samples were also rescaled with the calculated anisotropy factor, but they collapsed only in the 60-90° angle range, which was expected as $BaZrO_3$ and $BaSnO_3$ nanocolumns act as pinning centers along the $H||c$ direction (0°). The activation energy derived from the $\log(\rho/\rho_0)$ against $1/T$ plots was almost constant in the whole angular range, with a small peak at $H||ab$. The $U_a(\theta)$ curves looked similar for all doped samples; the activation energy as well as the critical temperature decreased with increasing doping level. The logarithmic resistivity plot of the undoped sample looked differently, with a kink and two different slopes corresponding to two regions with different activation energy values. We speculate that that could be related to a different pinning landscape in the undoped sample. For instance, the grain boundaries between the *c*-oriented and *a*-oriented GdBCO grains, appreciably present in the undoped sample and almost absent in the APC-doped samples, may contribute to the observed differences.

Consideration on angular dependent pinning properties in $REBa_2Cu_3O_y$ coated conductor containing $BaHfO_3$ nanoparticles fabricated by UTOC-TFA-MOD process

Tatsunori Okada[1], Satoshi Awaji[1], Koichi Nakaoka[2], Takato Machi[2], Teruo Izumi[2]

[1]Institute for Materials Research (IMR), Tohoku University, Japan
[2]National Institute of Advanced Industrial Science and Technology (AIST), Japan

Trifluoroacetate based metal-organic deposition (TFA-MOD) method is a powerful way to fabricate $RE\mathrm{Ba_2Cu_3O}_y$ coated conductors (*RE*BCO-CCs) with low fabrication cost. Recently, some of authors developed a new method to make $\mathrm{Ba}M\mathrm{O_3}$ (*M*: metal) nanoparticles finer by reducing the once-coating thickness in the multiple-coating process. We call this UTOC (Ultra-Thin-Once-Coating) process, and the miniaturization of $BaZrO_3$/$BaHfO_3$ nanoparticles by the UTOC process was confirmed [1,2].

To understand pinning properties of $BaHfO_3$ nanoparticles (radius $R \lesssim 10$ nm) in UTOC-TFA-MOD *RE*BCO-CCs, we measured field angle, θ, dependence of J_c under conditions of 4.2 K ≤ T ≤ 90 K and B ≤24 T. We found a noble depression of $J_c(\theta \sim B||ab)$ only in high temperatures (T = 65 K, 77.3 K) and low field ($B \lesssim 5$ T) regions [3]. Similar depression can be seen in the case of $BaZrO_3$ (R ~ 10 nm) but not in cases of $BaSnO_3$ (R ~ 20 nm) and $BaNbO_3$ (R ~ 40 nm) [4], suggesting that sizes of vortex core and nanoparticle play a key role.

To understand observed $J_c(\theta)$, we calculated the pinning potential by $BaHfO_3$ nanoparticle under condensation energy interaction *with kinetic-energy term*, which is usually omitted in widely used model (*e.g.* local model) to calculate the elementary pinning force, f_p. In our calculation, we found that f_p (hence J_c) becomes smaller around $\theta \sim B||ab$. This can be understood as that energy losses due to kinetic energy increased since vortex core shrinks in one direction when magnetic field approaches the *ab* plane.

At the conference, we would like to report detailed information on experiments and calculations of $J_c(\theta)$ in UTOC-TFA-MOD *RE*BCO-CCs with $BaHfO_3$ nanoparticles.

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Effect of neutron irradiation on the superconducting properties of REBCO tapes

David X. Fischer, Rainer Prokopec, Johann Emhofer, Michael Eisterer

Atominstitut, TU Wien, Austria

Nuclear fusion could be a valuable contribution to future CO_2-neutral electricity production. In a power plant, superconductors will be needed to produce the strong magnetic field for confining the fusion plasma. While current research reactors (like Wendelstein 7-X and ITER) use NbTi and Nb_3Sn for the magnet coils, future fusion reactors might use coated conductors because of their superior superconducting properties that potentially allow operation at higher magnetic fields and higher temperatures.

In the fusion process (D+T $\rightarrow$ He+n) high energy neutrons are released which cannot be entirely shielded from reaching the magnet coils. This gradually changes their microstructure and therefore the superconducting behavior. Neutron irradiation studies are essential to anticipate these effects.

In this study, commercially available coated conductor tapes form several manufacturers were irradiated to neutron fluences of up to 4.9×10^{22} m^{-2} in the TRIGA-MARK II reactor at Atominstitut. After each irradiation step, the critical currents were obtained using transport current measurements in background fields of up to 15 T.

The change in anisotropy of the critical currents after neutron irradiation was studied on patterned tapes down to 4.2 K. Many factors influence the radiation robustness coated conductors. The results show that a lower operation temperature postpones the degradation of critical currents. The opposite effect has the presence of artificial pinning centers in the superconducting layer – it decreases the radiation resistance. A model to understand this behavior will be presented.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. We want to thank the manufacturers AMSC, SuNAM, SuperPower and SuperOX for providing us with samples of their coated conductor tapes.

Nanometer-sized perovskites for pinning in coated conductors

Pedro López-Domínguez[1], Javier Díez-Sierra[1], Katrien De Keukeleere[1], Sebastian Schäfer[2], Hannes Rijckaert[1], Stephan Andreas Schunk[2], Michael Bäcker[3], Isabel Van Driessche[1]

[1]*Ghent University, SCRiPTS, Department of Chemistry, Ghent, Belgium*
[2]*hte GmbH, Heidelberg, Germany*
[3]*Deutsche Nanoschicht GmbH, Rheinbach, Germany*

High-temperature superconducting materials as YBCO ($YBa_2Cu_3O_{7-x}$) exhibit properties adequate for their use in power applications and magnets. The technology for their industrial manufacturing is already developed, with chemical solution deposition (CSD) as one of the most cost-effective approaches. However the performance of such materials is limited by vortex movement at medium to high magnetic fields. Those vortices can be immobilized by introducing artificial pinning centers (APCs), which have the ability to pin and restrict their movement. The spontaneous segregation of secondary phases during the YBCO heat treatment has already been described in literature. This approach has limitations in terms of nanocrystal formation and reaction control. For that reason, we have focused on the preparation of preformed nanocrystals as APCs. Here we present a powerful approach for the preparation of very small perovskite nanoparticles, with general formula ABO_3. These inert materials are suitable for growing a high-quality YBCO film with nanocrystals homogeneously distributed on it. Ligand test screening has been performed to prepare stable colloidal solutions which have been successfully used for the deposition process.

Flux pinning of REBCO coated conductors with segmented BHO nanorods

Kaname Matsumoto[1], Yutaka Yoshida[2], Satoshi Awaji[3]

[1]Kyushu Institute of Technology, Japan
[2]Nagoya University, Japan
[3]Tohoku University, Japan

Research and development of REBCO coated conductors (CCs) is progressing, and application development to MRI, SMES, motors, etc. is expected. The REBCO CC already exhibit a high J_c reaching 20% of the theoretical depairing current density at 4.2 K in zero magnetic field, and a huge macroscopic pinning force F_p of 1 to 2 TN/m^3 have been confirmed even in the high magnetic fields ($B||c$). $F_p(B||c)$ exceeding 100 GN/m^3 is also reported at 65 K. These excellent performances are achieved by introducing high-density columnar $BaMO_3$ (BMO; M = Hf, Zr, etc.) artificial pinning centers (APCs) into the REBCO thin film with a gas phase method such as PLD method or MOCVD method. However, at the production level, as the production rate of the CC is increased, the surface diffusion of BMO becomes insufficient, so that the nanorods are covered with the REBCO layer, and the BMO nanorods are broken into segments and dispersed in the REBCO film. In the case of producing coated conductors at high speed, it is difficult to introduce ideal BMO nanorods into the REBCO films. Therefore, taking into account the pinning effect due to the segmented BMO APCs and additional crystal defects, it is necessary to proceed with the development of REBCO CCs. In this study, we discuss the effects of segmentation of BMO nanorods in REBCO thin films during high speed deposition, from the viewpoint of experimental results and analysis of magnetic flux dynamics using time dependent Ginzburg-Landau simulation.

Power Applications

Evaluation of existing coated cabling of Itaipu hydroelectric power plant after years of operation: aspects to be considered for technological updating

Cláudio Morais[1], *Eli Marcos Finco*[1], *Angelo Eduardo Roselli Rosolem*[2]

[1]*Itaipu Binacional, Brazil*
[2]*WorleyParsons, Brazil*

Itaipu is currently the world's largest generator of renewable clean energy and plans the modernization of its equipment, because many of them are obsolete and at the end of its useful life. Equipment with new functionalities must be installed during the "Technological Updating", including the existing coated cabling.

Itaipu carried out the evaluation of the current condition of the cables installed about 30/35 years ago. Twenty-four samples of cables up to 1 kV were taken from different installation sites. Such samples were chosen considering the most critical conditions imposed on the cables, such as: mechanical stresses, humid environments, operating temperatures, exposure to sunlight, etc. In addition, 11 samples were collected, which were stored in the warehouse for about 30/35 years, that is, 35 samples were evaluated in total in the physical, electrical, mechanical, chemical and thermal aspects.

Several tests were carried out, such as: loss of mass in the sheathing , insulation resistance, water absorption by the gravimetric method, flame resistance, thermal shock, traction and elongation of the sheathing and the insulation before and after ageing, hot deformation, ozone resistance, traction and elongation after immersion in oil, traction and elongation after ageing in air pump, oxygen index, etc.

The evaluation showed that of the 35 samples, 20 were reproved at least one or more of the standards requirements. Most of the observed failures have focused on the characteristics of insulation and cable sheathing. Considering that the failure rate in the 35 samples tested was significant, that is, 20 samples presented nonconformities, which compromises the use of the cables for failing to meet the mechanical, thermal, and chemical characteristics required for a new cable, it is recommended that during the update, all existing cabling be replaced by a new one, in order to not compromise the quality and reliability of Itaipu's electrical installations. It should be noted that despite of the results obtained in this evaluation, Itaipu has never had any problem or fail due to functioning and operation of its cabling system. New technologies of cables will be adopted during the updating.

Second generation high temperature superconducting gas-insulated power cable

Sastry Pamidi[1], *Peter Cheetham*[1], *Chul Han Kim*[2], *Lukas Graber*[3]

[1]*FAMU-FSU College of Engineering and Center for Advanced Power Systems, Florida State University, USA*
[2]*Center for Advanced Power Systems, Florida State University, USA*
[3]*Georgia Institute of Technology, USA*

Second Generation High Temperature Superconducting (2GHTS) power cables are being developed for a variety of applications including the electrical power grid, industrial applications, data centers, high energy physics, electric ships and electric aircrafts. Currently the most common method to insulate HTS power cables is to use lapped tape insulation, which was successfully used in multiple liquid nitrogen (LN_2) cooled HTS power cables and gaseous helium cooled power cables. However, when helium gas is used as the cryogen high voltage rating cannot be achieved due to the occurrence of partial discharge in the lapped tape at < 10 kV. Therefore, new insulation design concepts are needed for helium gas cooled HTS power cables.

We at Florida State University's Center for Advanced Power Systems and Georgia Institute of Technology have been working on cryogenic dielectric designs for 2GHTS cables. We have recently proposed a novel helium gas cooled HTS cable concept, referred to as Superconducting Gas-Insulated Transmission Line (S-GIL), in which the cryogen functions as both the coolant and the dielectric medium for the cable. The S-GIL design provides several benefits compared to lapped tape insulated cables such as higher voltage ratings, superior heat transfer, elimination of solid insulation, and ability to test the dielectric performance at room temperature. Proof of concept experiments performed on S-GIL demonstrated the potential of this design to operate at significantly higher voltages than what is currently possible with gaseous helium cooled HTS cables. The proof of concept experiments showed that the voltage rating of the S-GIL is dependent on the dielectric strength of the cryogen used. Thus one can use helium gas mixtures with higher dielectric strength than pure helium as the cryogens. The paper will discuss the details of the design optimization process with regards to geometry, materials selection, and the cryogen used. Results on several 1 m long model cables will also be discussed.

Development of REBCO fully superconducting motors for electric aircrafts

Masataka Iwakuma[1], Teruo Izumi[2], Akira Tomioka[3]

[1]Kyushu University, Japan
[2]AIST, Tsukuba, Japan
[3]Fuji Electric Co. Ltd, Japan

The most important issue for the propulsion system of electric aircrafts is light weight. The output power density should be higher than conventional jet engines with around 5 to 6 kW/kg. Conventional motors which are composed of copper wires and iron cores have much smaller output power density than that. In the case of small motors with an output power of several tens to hundreds kW, it may be realized by increasing current density and cooling. However it is impossible to realize for MW-class. It seems that only fully superconducting motors can realize it since no iron core is needed. In this study, REBCO fully superconducting motors are developed under the support of JST.

Our research group developed a 3φ-66 kV/6.9 kV-2 MVA REBCO superconducting transformer. The AC loss of REBCO superconducting tapes was successfully reduced by scribing and special winding technique. First the applicability of the technique to the armature winding was investigated. A 100 W fully superconducting motor was designed with REBCO superconducting tapes. Four-filament REBCO superconducting tapes were wound into 6 pieces of armature coils. One phase was composed of the two pieces of armature windings in the opposite side. Field winding was wound with non-scribed REBCO tapes. Current sharing properties among the filaments in every phase were investigated by using Rogowsky coils. As a result, almost even current sharing was observed within an error of 20%. It means no coupling current among the filaments since coupling current is a loop current. It suggests that AC loss consists of only hysteresis loss inside each filament. Now a cryostat for a fully superconducting motor is studied out and is being made for test.

The effect of $BaHfO_3$ nanorods on J_c in the longitudinal magnetic field for $EuBa_2Cu_3O_y$ coated conductors derived from PLD

Jun Nishimura[1], *Kenji Miyata*[1], *Keiichi Sato*[1], *Kota Hirai*[1], *Masashi Miura*[1], *Akira Ibi*[2], *Teruo Izumi*[2]

[1]*Seikei University, Japan*
[2]*AIST, Tsukuba, Japan*

$REBa_2Cu_3O_y$ (REBCO, RE = rare earth element) coated conductors (CCs) derived from the Pulse Laser Deposition (PLD) process are promising candidates for power applications, such as superconducting DC cables because they are high reproducibility and high superconducting performance. T. Matsushita proposed that a superconducting DC REBCO cable using the longitudinal magnetic field (i.e. a Lorentz force-free cable) can achieve higher current-carrying capacity compared with a conventional superconducting cable [1]. However, for a practical force-free cable using the PLD-REBCO CCs, it is necessary to further enhance the critical current density (J_c) in the longitudinal magnetic field. Recently, artificial defects in PLD-REBCO films have been found to be effective for enhancement of J_c in the longitudinal magnetic field [2].

In this work, we prepared $BaHfO_3$ (BHO) nanorods doped PLD-$EuBa_2Cu_3O_y$ (EuBCO+BHO) CC. The critical temperature of the EuBCO+BHO CC is almost the same as that of standard EuBCO CC; indicating that even with the introduction of BHO nanorods, the crystallinity and the composition of the matrix hardly change. The EuBCO+BHO CC shows the J_c of 4.3 MA/cm^2 at 77 K and 0.5 T in the longitudinal magnetic field, which is 1.2 times higher than that of standard EuBCO CC. By using T. Matsusita's force-free cable calculation model [1], we calculated that the current-carrying capacity by using the EuBCO+BHO CC is 1.5 times higher than that using standard EuBCO CC.

Acknowledgements: This work was supported by a research grant from the Japan Power Academy. A part of this work is supported by JSPS KAKENHI (17H03239 and 17K18888).

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The longitudinal magnetic field dependence of critical current density in multilayered TFA-MOD $REBa_2Cu_3O_y$ coated conductors

Keiichi Sato[1], Jun Nishimura[1], Kota Hirai[1], Keita Sakuma[1], Masashi Miura[1], Masaru Kiuchi[2]

[1]Seikei University, Japan
[2]Kyushu Institute of Technology, Japan

The critical current density (J_c) for superconductor coated conductors (CCs) in the longitudinal magnetic field is higher than that in the transverse magnetic field, because the longitudinal magnetic field is a Lorentz force-free state [1]. T. Matsushita suggested that a superconducting $REBa_2Cu_3O_y$ (REBCO) DC cable using the longitudinal magnetic field effect and it can realize high current-carrying capacity compared to a conventional superconducting cables [2]. The TFA-MOD process derived REBCO CC is one of the attractive candidates for a LFF DC cable because they are low-cost and high superconducting performance [3,4]. However, for practical LFF DC cable, further enhancement of J_c in the longitudinal magnetic field is required. Recently, Nagoya University Group reported that multilayered SmBCO films derived from pulsed laser deposition show higher J_c in the longitudinal magnetic field than that of standard SmBCO film [4]. However, the influence of the multilayered structure on J_c in the longitudinal magnetic field for TFA-MOD REBCO CC has not yet been clarified.

In this work, in order to investigate the effect of multilayered structure on the longitudinal magnetic fields of J_c property, we fabricated the ((Y,Gd)BCO/(Y,Gd)BCO+BaHfO3) multilayered CC on metallic substrates derived from TFA-MOD. The critical temperature of multilayered (Y,Gd)BCO CC is the same as that of standard (Y,Gd)BCO CC. The J_c in the longitudinal magnetic field at 77 K for multilayered (Y,Gd)BCO CC is 5.81 MA/cm^2 at 0.5 T, which is 1.92 times higher than that of standard (Y,Gd)BCO CC. Our present results indicate that the introduction of $BaHfO_3$ nanoparticles and multilayered structure for TFA-MOD (Y,Gd)BCO CC play an important role in the enhancement of the J_c also in the longitudinal magnetic field.

Acknowledgements: This work was supported by a research grant from the Japan Power Academy. A part of this work is supported by JSPS KAKENHI (17H03239 and 17K18888).

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Importance of stabilization layer homogeneity for coated conductors used in fault current limiter

Marek Mošať[1], Michal Vojenčiak[1], Fedor Gömöry[1], Christian Lacroix[2], Frédéric Sirois[2]

[1]Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia
[2]Department of Electrical Engineering, Polytechnique Montréal, Canada

Superconducting fault current limiters (SCFCL) based on high temperature superconductors (HTS) potentially offer inherent protection from overcurrent. The superconducting layer is important when the transport current is smaller than the critical current and to trigger the limitation of the current in case of fault. However, fault currents typically reach amplitudes that can be several times higher than the critical current, in less than one millisecond. In this case, the fault current limitation is controlled by the non-superconducting parts of the composite coated conductor. This work focuses on the impact of the homogeneity of the silver stabilization layer on thermal dissipation during fault current limitation. Indeed, the very few micrometers of silver used as stabilizing layer carry almost the whole electric current during limitation. The associated local heat generation depends solely on the resistivity and the thickness of this silver layer. The effect of the layer homogeneity has been examined with the help of the finite element method as well as experimentally. Silver homogeneity was obtained from variation of the resistance over the tape length at room temperature. Variations in the range of 20 percent have been observed. Such variations significantly affect the maximum temperature reached during the current limitation. We saw that the increase in heat generation in areas with higher resistance led to damages of superconducting layer. The quench properties and local critical current degradation of the superconducting tape resulting from this overheating are also analyzed.

Investigation of CC tapes with soldered metallic high heat capacity layer suitable for superconducting fault current limiters

Marcela Pekarčíková[1], Eva Cuninková[1], Jozef Mišík[1], Michal Vojenčiak[2], Marek Mošat[2], Michal Skarba[3], Juraj Halanda[1], Martin Necpal[1], Fedor Gömöry[2]

[1]Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology, Trnava, Slovakia
[2]Slovak Academy of Sciences, Institute of Electrical Engineering, Bratislava, Slovakia
[3]Slovak University of Technology in Bratislava, Slovakia

High-temperature superconductors produced as coated conductors (CC) are attractive materials for high voltage resistive fault current limiters (FCL). However, the commercially available CCs cannot withstand the limitation of electric current at electric fields higher than 100 V/m for sufficiently long time. One of the possibilities to enhance the electric field level is modification of CC by adding a thick layer from Ni-based alloy or stainless steel, with both of them possessing enhanced heat capacity (c_p). We prepared several samples by soldering of CC tape with tape from pure Hastelloy tape or stainless steel tape covered with thin Ag layer. Four lead-free and two lead-based solders with low temperature of liquidus were used for this purpose. The formed solder layers were investigated in cross-section regarding to their thickness and microstructure. Limitation experiments have shown that additional high c_p layer reduces the maximum temperature of superconductor, despite of enhanced heat generation resulting from the lower resistance of the modified tape. Limitation behaviour of the selected samples with metallic high c_p layer was compared with a sample prepared by coating of CC tape with composite containing ceramic powder particles in epoxy matrix.

Acknowledgements

This work was supported by the European Union's Horizon 2020 research and innovative programme under grant agreement No. 721019, by the Slovak Research and Development Agency (APVV) under contract no. APVV-14-0438, and by the Grant Agency of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences (VEGA) under Contract 1/0151/17.

Resistive composite heat sink material for superconducting tape in FCL applications

Jozef Mišík[1], Marcela Pekarčíková[1], Marián Drienovský[1], Jozef Krajčovič[1], Eva Cuninková[1], Michal Vojenčiak[2], Fedor Gömöry[2]

[1]Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology, Trnava, Slovakia
[2]Slovak Academy of Sciences, Institute of Electrical Engineering, Bratislava, Slovakia

For purposes of heat sinking during the limitation of excess current in Fault Current Limiters (FCL), several coatings on the superconducting tape were investigated as possible and suitable material. The main requirements were addressed to achieve six crucial properties: high electric resistance, high thermal capacity, high thermal conductivity, cryogenic suitability, similar thermal expansion with superconducting (SC) tape in operating temperature range, and good adhesion to the silver layer of SC tape. One of the promising ways to achieve all these properties in a single layer is to make a composite of polymeric epoxy matrix with its good heat capacity, high electrical resistance and adhesion to the tape, and ceramic powder filler to compensate different thermal expansion. As a good candidate, after careful research of possible materials and their compositions, the commercial Stycast 2850 FT and SiC powder of < 60 μm particle size were chosen. The poster reveals the results of all investigated combinations of composite components regarding their thermal and mechanical properties.

REBCO coated conductor for fault current limiter application in cryogen free conditions

Michal Vojenčiak, Marek Mošať, Marek Buran, Fedor Gömöry

Institute of Electrical Engineering SAS, Bratislava, Slovakia

High temperature superconductors in form of coated conductors are usual choice for construction of resistive fault current limiters. Their advantages are the critical temperature allowing to use liquid nitrogen as coolant and a relatively high electrical resistance in normal state keeping the prospective current low. Good dielectric strength and high latent heat of evaporation are in favour of using liquid nitrogen as a coolant in fault current limiters. However, besides these advantages it has two significant drawbacks. First, the operating temperature is restricted to the range between 80 K and 65 K. Also the gas evaporated during current limitation forms a layer that insulates the conductor from cold ambient causing in this way a danger of overheating.

In this contribution we show the possibility to widen the range of operating temperatures by cooling the tape by cryocooler and using an aluminium nitride heat conducting elements. Parallel tests at 77 K of tapes cooled by liquid nitrogen and by cryocooler have been carried out.

Experimental results show significantly different cooling performance in these two concepts. The solid aluminium nitride elements increase effectively the heat capacity of superconducting tape because acting as a reservoir ready to accumulate heat. In this way they reduce the maximum temperature of the superconductor and protect it against overheating.

Furthermore, superconducting tape was cooled down to temperature of 50 K at which it has 2.5 times higher current carrying capacity in comparison to 77 K performance. The superconducting tape proved correct functionality at this temperature showing that the fault current limiters can be built as cryogen free devices. Our calculations show that the experimental findings from short samples could be extrapolated to more complex devices.

Design optimization of flat HTS three-phase cables based on coated conductors

V. A. Altov[1], N. N. Balashov[1], P. N. Degtyarenko[1,2], S. S. Ivanov[1], S. I. Kopylov[1], S. V. Samoilenkov[1,2], V. V. Zheltov[1], V. E. Sytnykov[3]

[1]JIHT RAS, Russia
[2]JSC SuperOx, Russia
[3]JSC R&D Center, FGC UES, Russia

In the laboratory of applied superconductivity of JIHT RAS are steadily in progress works on the optimization of various HTS cables designs by numerical simulation, aimed, first of all, to the minimization of AC losses. To this end, are varied dimensions and shapes of cables cross-section, mutual positions of current-carrying HTS elements and stabilizers, and cable phases themselves are sectioned. Shared usage of all these methods allows decreasing of AC losses by an order of magnitude as compared with conventional cable designs. In this work we are considered designs of flat three-phase cables with the highly extended rectangular cross-section shape. The current-carrying elements are coated conductors. A flat unipolar cable has a magnetic field component perpendicular to the HTS layer what significantly increases the AC losses and decreases the critical current. On the contrary, in three-phase cables this field component is suppressed due to the interaction of phases. As a result, a flat cable becomes similar to a coaxial one having the same field penetration conditions and, hence, approximately the same AC losses level. But flat cables have a lot of advantages, i.e., higher flexibility, better mass/dimension ratio and phase cooling conditions, etc. For the rectangular cross-section shape are absent any problems of phases critical currents matching and matching of section dimensions when sectioning cables as well. As the most effective optimization methods we consider here sectioning of cable phases together with their ends screening and using of modified HTS tapes having copper layer on the substrate side. This allows the development of cable designs with AC losses no more than natural cryostat heat losses. E.g., in cables with the critical current of a phase 5.1 kA at the rated phase current amplitude 4 kA the specific AC losses are within 2.5 – 1 W/m. This makes three-phase flat cables more preferable than DC cables for the transmission line lengths up to 150 km, since the total losses in AC-DC-AC converters necessary for DC cables are ca. 2% of rated power.

Development of CORC® power transmission and fault current limiting cable systems

Jeremy D. Weiss[1,2], *Danko van der Laan*[1,2], *Chul Kim*[3], *Sastry Pamidi*[3]

[1]*University of Colorado, USA*
[2]*Advanced Conductor Technologies*
[3]*Center for Advanced Power Systems, Florida State University, USA*

Next generation electric power systems require higher capacity, efficiency, and stability to meet the demands of increasingly complicated grid systems. High-temperature superconducting (HTS) Conductor on Round Core (CORC®) power transmission cables provide unique solutions by offering high operating currents and current densities in a very small cable cross-section, which can also include the ability to protect electric power apparatus and systems from large currents that can develop during a fault.

Advanced Conductor Technologies is developing 2-pole dc and 3-phase ac power transmission cables, cable terminations, and connectors to be cooled with pressurized cryogenic helium gas for shipboard use. The development and successful test results of a 10 meter long, 2-pole dc CORC® power transmission cable, rated at 4,000 A per phase, will be discussed. The development is not limited to only the power transmission cables, but also includes CORC® feeder cables that form the connection between the room temperature bus bar and the CORC® power transmission cable located inside the helium gas environment. Methods to significantly increase the current rating to exceed 10 kA per phase, and current densities of over 500 A/mm^2 will be discussed.

In addition, the inherent fault current limiting capabilities of a short kA-class CORC® wire of less than 4 mm thickness are demonstrated in liquid nitrogen, developing nearly instantaneous voltages in excess of 20 V/m that increased to about 70 V/m within 15 ms of applied overcurrents up to 250% of the critical current. Enhanced current sharing between tapes enabled by the CORC® cable topology appears to mitigate the issue of hot-spots caused by inhomogeneities on the HTS tape level by providing several alternate superconducting routes for current to bypass low I_c sections of the tapes. Operation of the CORC® FCL conductor in stand-alone operation and operated as part of a hybrid-cable system, in which the overcurrent is redirected to a normal conducting path outside of the cryogenic environment, are demonstrated without any degradation of the CORC® wire performance. The results show that highly flexible CORC® wires with record current densities are able to function as fault current limiters without the need for resistive laminates.