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A possible solution to reduce magnetic losses in transformer cores working at liquid nitrogen temperature

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The efficiency of power transformers should be always taken in account when design and operation conditions parameters are chosen. In high temperature superconducting transformers (HTS transformers), normally cooled by liquid nitrogen at 77 K, cores are usually kept at room temperature in order to minimize total magnetic losses, losing the possibility to use the cooling liquid to minimize electric risks and to cool the core, and increasing the complexity of the cryostats that, in these cases, must only embrace the superconducting windings. This work try to evaluate the magnetic core losses increasing at 77 K, for different magnetic materials, and the possibility of reducing these losses under some specific manipulation of magnetic materials. For this purpose, several low temperature measurements are presented to characterize the magnetic behavior of four electrical steels usually used in transformer cores. The chosen magnetic materials are three crystalline materials, two grain-oriented and one non oriented steels, and an amorphous electrical steel. The most significant results show that grain oriented steels have lower losses increasing at cryogenic temperature, comparing with the other two magnetic materials, and that above a certain value of magnetic induction, *B*, total magnetic losses at 77 K became smaller than room temperature losses. Results interpretation is presented and some suggestions are made concerning production of magnetic materials for applications at 77 K.

Mechanical tests of ITER TF Conductors jacket materials.

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The set of very tough requirements have been formulated for TF jacket materials with extremely high plasticity at liquid helium temperature. The stainless steel 316LN-IG is recommended to be used for TF jacket tubes. The samples of 316LN-IG tubes produced by three different Manufacturers have been tested in different conditions – virgin tubes and tubes after the prescribed low deformation and annealing at 650^{o}C 200 h. The testing has been done at room temperature and at cryogenic temperatures. The ASME and ASTM methods of testing were used. The details of low temperature equipment used for testing are given. Some differences in mechanical properties of the tubes produced by different suppliers have been revealed and analyzed. The data on the subsize samples and full sized samples have been compared. The formation of the ferrite inclusions have been shown at the areas of welding in all investigated samples.

Cryogenic Properties of Cold-deformed High Strength Conductors

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Cold rolled composite conductors was characterized and the effects of crystallographic structural anisotropy and microstructure refinement on cryogenic properties of the composite were studied. Characterization was carried out with high resolution scanning electron microscopy (SEM), x-ray diffractometer and mechanical testing. It was observed that the smaller the thickness of the lamellae, the higher the cryogenic strength and the electric resistivity. The property changes with cold deformation strain were related to the microstructure scales. All the deformed samples exhibited strong texture that had impact on the anisotropic properties of the materials. The thickness of the lamella was inversely proportional to the deformation strain. A closer examination of the components in the composites revealed that while the lamellae were well aligned in the one direction, they were curved in the other direction. The curved lamellae observed were attributed to the development of shear bands during the deformation. Both the texture and shear bands were related to the anisotropy of the properties.

Mechanical Properties of Cold-Rolled and Aged MP35N Alloys for Cryogenic Magnet Applications

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MP35N is a high-strength Nickel-Cobalt base alloy that has numerous applications at both room and elevated temperatures due to its ultra high strength, high modulus and outstanding corrosion resistance. The National High Magnetic Field Laboratory (NHMFL) further explored the use of MP35N in cryogenic temperature applications. Currently, the material has a practical application as a structural reinforcement component for high field pulsed magnets at 77 K. This paper reports the tensile properties of cold-rolled and aged MP35N at both room and liquid nitrogen temperatures. Optimized fabrication methods developed by the NHMFL and H.C. Starck have improved the material's 77 K properties with ultimate tensile strengths exceeding 2500 MPa and a Young's modulus higher than 200 GPa. Closer examination of the stress-strain curve reveals that the materials exhibit internal stress which is attributed to the development of nanoplatelets during the fabrication process. The NHMFL is also pursuing the application of MP35N below temperatures of 77 K. Therefore, this paper discusses the potential of age-hardened MP35N to be used as either reinforcement or substrates for high temperature superconducting (HTS) magnets.

Effect of cryogenic treatment on thermal conductivity properties of copper

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Copper is well known for its high thermal conductivity properties and hence it is extensively used in many cryogenic applications like cold fingers, heat exchangers, etc. During the development of such components, copper undergoes various machining operations from the raw material stage to the shape of the final product to serve for the intended purpose. During the machining process, stresses are induced within the metal, resulting in internal stresses and strains. These strains distort the atomic structure and result in build up of resistance path for heat carriers which transfer thermal energy from one location to the other. The induced resistance for the heat carriers results in reduction of thermal conductivity of the conducting metal and as a result the developed component will not perform as per expectations. Cryogenic treatment is a popularly employed technique where the metal samples are gradually cooled to cryogenic temperature (around 100K), soaked for extended duration of time ranging between 16-24 hours and warmed to room temperature slowly. During this process, the internal stresses and strains are reduced and dislocations are minimized with refinement of the atomic structure. These combined effects improve the path for heat carriers and hence enhancement in thermal conductivity properties. In this experimental work, effects of cryogenic treatment and tempering on the electrolyte grade copper are studied and discussed.

Magnetoresistance of 5N, 6N and 6N8 High Purity Aluminum

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Magnetoresistance of electrical conductor in cryogenic applications is an important issue. The electrical resistivity of 5N, 6N and 6N8 high purity aluminum was measured in magnetic field up to 15T at 4.2K by four probe method. Specimens were set on quartz holder, and annealed with holder to avoid accidental stress. Magnetoresistance were measured in both perpendicular and parallel direction. Effect of purity was investigated using three kinds of aluminum samples; 5N and 6N, which are commercially available, and 6N8, which was further purified from 6N aluminum. Specimens of commercial 5N copper were also tested for comparison. When magnetic field is applied perpendicular to the current direction, RRR (residual resistivity ratio) declined with increasing field and the RRR at 15T was about a third of the RRR at 0T. When magnetic field is applied parallel to the current direction, RRR tended to show higher values than the former case, and the behavior of RRR with field depended on purity. While the RRR of 5N dropped sharply below 1T and almost constant over 1T, the RRR of 6N and 6N8 increased with magnetic field and maintained high RRR value. Estimated mechanisms of these behaviors and the effect of the specimen size will be reported.

Determination of mechanical and thermal properties of electrical insulation material at 4.2 K

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For the electrical insulation of superconducting magnets or magnet components different insulation materials are used that ensure mechanical stability and good electrical insulation properties at low temperatures. Especially glass-fiber-reinforced or sand-filled epoxies are typical material composites that can be used at temperatures down to 4.2 K.

For current lead construction within fusion technology, an optimized filled epoxy with respect to mechanical shear strength had to be identified. Therefore different steel/epoxy compositions where examined using the standardized three point bending method. The test specimens were formed putting five layers of glass-fiber lubricated with epoxy between two 1.4429 steel frames. The epoxy facing surface of the steel was blasted with glass or corundum. A systematic investigation was performed using different epoxies to get an optimized mechanical performance. The results will be discussed together with data from a sand-filled epoxy compound. For the latter compound beside the mechanical properties thermal conductivity and expansion is given in addition.

Effect of 12 MeV electron irradiation on properties of electrical insulations for Nb3Sn based magnet coil cables

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One of the goal of European Coordination for Accelerator Research & Development (EuCARD) project realized under Framework Programme 7 of European Commission is design of high field Nb3Sn magnet model what allows development of technology to be used in future particle accelerators. One of a critical issue of Nb3Sn magnets working in the circular accelerators will be a resistance of the magnet coil cables electrical insulation against the high energy irradiation. Paper presents experimental investigation of the influence of 12 MeV electron irradiation on thermal, electrical and mechanical properties of insulation material. The material samples have been irradiated in near to 80K temperature conditions. The thermal properties have been investigated in pressurized superfluid helium conditions, while mechanical and electrical properties in LN2 environment.

ICMC-05 Electrical Insulation Materials at Cryo Temp's

Preparation and cryogenic properties of hollow glass microsphere/epoxy composites

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Epoxy resins have been extensively used in cryogenic engineering areas and their cryogenic mechanical and thermal properties have to be improved to meet the high requirements of cryogenic engineering applications. In this work, glass hollow microsphere (HGM) reinforced triglycidyl-p-aminophenol (TGPAP) epoxy composites have been prepared. The weight content of HGM was from 0 to 20 wt.%. Mechanical behaviors of HGM/epoxy composites at both room temperature (RT) and liquid nitrogen temperature (77 K) were investigated in terms of impact property. The fracture surfaces of neat epoxy and HGM/epoxy composites were examined by scanning electron microscopy (SEM). The results showed that impact strength at room temperature and 77 K are all enhanced by the addition of HGM at appropriate contents. Furthermore, the thermal conductivity and coefficients of thermal expansion of neat epoxy and HGM/epoxy composites were also investigated from 77 K to room temperature. The HGM/epoxy composites showed lower thermal conductivity and coefficient of thermal expansion than neat epoxy. The results suggest that HGM/epoxy composites have potential applications as advanced cryogenic materials in cryogenic engineering areas.

DESIGN AND DEVELOPMENT OF GFRP CRYOSTAT

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Abstract

Glass Fibre-reinforced-plastic (GFRP) cryostats have been developed for various cryogenic fields, such as superconducting magnets and cryogenic electronics. For several applications of superconducting magnets v.i.z. pulsed magnets, SQUID detectors, superconductor transformer, cables, non-metallic and non-magnetic cryostats are required.

Design, development and performance evaluation of a GFRP cryostat for use with liquid nitrogen are studied in this paper. The capacity is about 1 liter for liquid nitrogen with an inner diameter of about 90mm & 180mm in height. The steady state evaporation rate with the dipstick are about 76ml/hr, 102 ml/hr & 165ml/hour of liquid nitrogen for FRE DOBEKOT 505-C, FRE B BOW 42 MA & FRVE cryostat respectively when vacuum valve open and there is continuous vacuum of the doubled wall vessel. Whereas the steady state evaporation rate with the dipstick are about 255ml/hr, 318 ml/hr & 343 ml/hr of liquid nitrogen for FRE DOBEKOT 505-C, FRE B BOW 42 MA & FRVE cryostat respectively when vacuum valve closed. The material problems, possible answers are summarized and the construction of GFRP cryostats is demonstrated.

Submission Category: ICMC-04 Polymers, Resins, and Composites at Cryo Temp's

Low-temperature neutron irradiation tests of superconducting magnet materials using reactor neutrons at KUR

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A superconducting magnet has been used for the high energy particle physics experiments with accelerators, secondary particle beamline and so on. It is recently being required on superconducting magnets to operate in quite severe radiation environment for the accelerator upgrade and the next-generation muon experiments, such as the LHC upgrade project and the COMET experiment at J-PARC . Expected neutron fluence on the superconducting coils in the experiment reaches 10^{21} n/m^2 or higher, therefore the magnet should be designed taking into account the irradiation effects. The irradiation test for superconducting magnet materials has been carried out using reactor neutrons at Kyoto Univ. Research Reactor Institute. As a first step of the experiment, aluminum alloy stabilizers for superconducting cable was exposed to neutrons at low-temperature around 20 K and the resistance has been measured in situ during neutron exposure. The preliminary data and the prospects will be reported.

This work is partly supported by Japan Science and Technology Agency under Strategic Promotion of Innovative Research and Development Program, “Improvement of Utilization on KUR and HL in Research Reactor Institute, Kyoto Univ.(KURRI)” carried out under the Strategic Promotion Program for Basic Nuclear Research by the Ministry of Education, Culture, Sports, Science and Technology of Japan, and CERN-KEK Collaboration on High Field Magnet R&D.

Progress Toward Scale-up Fabrication of A Powder-in-Tube Process with an Advanced Nb_3Sn Superconductor Design

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Powder-in-Tube (PIT) Nb_3Sn conductors have been fabricated with a low-cost intermetallic Cu_5Sn_4 powder as the tin source. PIT conductor designs with 120 and 840 octagonal subelements have been fabricated that incorporate dispersion strengthened copper. In this work, we present the superconducting properties and mechanical properties of the both octagonal PIT designs as a function of subelement diameter and heat treatment conditions.

Phase evolution and morphology studies for Tube-type Nb_3Sn strands

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A Model that predicts the coarse-grain and fine-grain A-15 area from initial Cu/Sn ratio was compared to experimental observations made for three Tube-type Nb_3Sn strands with varying Cu/Sn ratios reacted at several temperatures (615-750C) for various times. Short samples were reacted under flowing argon. The coarse/fine grain A-15 ratio was compared as a function of temperature and initial Cu/Sn ratio. SEM-EDS was used to determine the Sn content in the Cu-Sn core at times near the completion of 6:5 growth and A-15 growth to inform the model. At the point of maximum 6:5 growth and at the completion of the A-15 conversion, longitudinal SEM was taken to observe 3-D morphology of the 6:5 and coarse-grain A-15 respectably. In addition, 6:5 at the Cu-Sn/6:5 interface was investigated with SEM to develop a model for the formation and growth at this boundary.

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The effect of final technological steps on RRR of ITER PF coils relevant NbTi strand

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The residual resistance ratio (RRR) of NbTi strand for ITER poloidal field (PF) coils, has been investigated both during a bare strand processing and after the following chemical cleaning and Ni plating, with the aim to guarantee the required value of RRR > 100 in a final Ni-plated 0.73 mm in dia NbTi strand.

The dependence of RRR in ITER PF NbTi strands on a deformation ranged up to 20% has been established. The significant RRR values reduction to less than 100 has been found after the rather small (0.6%) deformation with the following tendency to saturation. The heat treatment regimes for RRR recovering have been optimized. The RRR reduction in a final strand has been revealed after chemical cleaning and Ni plating in comparison with that in annealed bare strands arrived at Ni plating. As for the effect of Ni plating, the presence of Ni coating with 2 μm thickness could not significantly influence on the conductivity of the stabilizing copper due to the absence of any heat treatment after Ni plating. The decrease of RRR observed for the Ni plated strands is associated with the bending deformation applied by the guiding rolls in the processing of the strands through Ni plating bath. The influence of bending deformation on strands RRR values has been calculated in accordance with the algorithm IEC 61788-4. The correlation between RRR's of virgin strand and Ni plated strand has been also established. It was shown on statistical database that the RRR values larger than 130 measured in the virgin (non Ni plated) strands guaranty the attainment of the RRR larger than 100 in Ni plated strands.

A $Nb_{0.36}Ti_{0.64}$ Superconductor with Ferromagnetic Artificial Pinning Centers for Low Magnetic Field Applications

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Artificial ferromagnetic pinning centers in $Nb_{0.36}Ti_{0.64}$ can attain more than double the critical current density, J_c , values at around 2 tesla compared to conventionally processed niobium-titanium composites. In this paper, we discuss design and performance characteristics for low applied magnetic field utilizing a three step fabrication process.

Modeling of the electrical and mechanical behaviors of Bi2Sr2CaCu2Ox/AgMg round wires based on the statistical characterization of its microstructure

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For multifilamentary Bi2Sr2CaCu2Ox (Bi2212) round wires, cross-sectional SEM and multi-angle SEM on extracted single filaments show that its microstructure is complicated. Specifically, after heat treatment the cross-section is dominated by interfilamentary bridges and the Bi2212/Ag interfaces are irregular and jagged. A fundamental question arises regarding how this unique microstructure affects the transport and electromechanical behavior. To address this question theoretically, two approaches are being developed that depend upon the SEM images as input. In one model, fractal characterization is used to evaluate the rough interfaces and determine the mechanical and electromechanical behavior of the multifilamentary wire at a microscopic level. In the other approach, two-point probability functions are applied to the overall wire cross-section to evaluate the in-plane conductivity, and subsequently in three-dimensions by using serially-sectioned SEM images. By developing multi-scale models of transport in Bi2212, a deeper understanding of transport in a three-dimensional heterogeneous media evolves.

Transport and Electro-optic Studies of Bi:2212 Conductors with a 2-D Random-Oriented Single-Stack Design

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In this work, a strand design for Bi-2212 conductors which had a single stack approach with randomly oriented but densely packed two-dimensional Bi-2212 filaments, was studied. This Bi-2212 Two-Dimensional Random-Oriented Single-Stack (2D-ROSS) Round Wire design had high levels of grain texture and significant amounts of Ag-superconducting interface within the filaments, and maintained a high strand fill factor. Previous studies had shown that the 2D-ROSS design had higher J_e values than similarly manufactured double stack designs. In the present work, lower C starting powders allowed higher J_c optimizations. Heat treatments were performed under 100% flowing oxygen, and the samples were melt processed in the 888 - 900°C range. Transport results were measured at 4.2 K in fields out to 15 T. D_{eff} values were extracted with the help of magnetic measurements performed to 14 T. Results for transport and magnetic results are reported, and correlated with SEM studies.

Heat treatment studies on roll-processed Bi-2212/Ag textured ribbon

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We have developed a method by which to align the particles of Bi-2212 powder in thin layers having the a-b planes oriented in the flat dimension. In this study, two different heat treatments were applied to optimize the densification and connectivity of textured Bi-2212/Ag ribbons. The first is a solid state reaction which was performed below the Bi-2212 melting temperature. The second is a partial melt process typically used for round wire applications. The influence of the heat treatment procedures on the texture and microstructure are reported.

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Magnetic Measurements of Interstrand Contact Resistances in Nb3Sn Rutherford Cables with Cores of MgO Tape and S-Glass

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Rutherford cables exhibit two classes of parasitic magnetization both of which can distort the bore-field of an accelerator magnet: (1) a *static magnetization* resulting from intrastrand persistent currents, and (2) a *dynamic magnetization* produced by coupling currents passing through interstrand contact resistances (ICR) during field ramping. It has been shown that interstrand coupling can be controlled by placing a core between the layers of the cable. The goal of such modifications to the standard Nb_3Sn Rutherford cable is to adjust the crossover resistance, R_c, while maintaining a relatively small adjacent-strand contact resistance, R_a, to preserve current sharing. Stainless steel ribbon (with its associated native oxide coating) is a frequently used core. Recently, however, MgO-paper tapes and woven s-glass ribbons have been suggested as alternative core materials in the interests of improved flexibility and compatibility with the cabling process. Interstrand contact resistances can be extracted from the results of AC loss measurement. Accordingly pickup-coil magnetization measurements of AC loss have been carried out on a group of cables with paper and ribbon cores. This paper reports on the resulting ICR results compared to those from uncored and stainless-steel-cored cables; it concludes by comparing the LHC-ramp-rate induced coupling magnetization of a typical cored Nb_3Sn Rutherford cable with its transport-current-moderated persistent-current magnetizations.

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Electromechanical properties of recently developed Bi-2212 strand

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High Energy Physics demands magnetic fields above 20 Tesla (T) that are beyond the reach of present Nb-Ti and Nb_3Sn LTS materials. In addition, ultra-high magnetic fields are desirable for other applications such as nuclear magnetic resonance magnets (NMR). Bi-2212 strand is one of the most promising HTS candidates for making high field magnets due to its very high upper critical field, and because it can be made in a round wire conductor form. Owing to the brittle nature of HTS conductor, characterization of the electro-mechanical properties of Bi-2212 strand is important for the magnet design and cabling. New results on axial strain and magnetic field dependence of the critical current for recently developed Bi-2212 conductors will be presented. These measurements were made as a function of tensile and compressive strain in magnetic fields at 4 K. The reversibility aspect of I_c versus strain will be reported in tension and compression. Possible mechanisms of this reversibility/irreversibility will be discussed. We will also present a database of stress-strain characteristics of Bi-2212 strands and various Ag alloys at room and liquid-nitrogen temperatures to identify mechanically strong and chemically compatible materials that could possibly be used for strengthening bismuth-based superconducting strands.

Longitudinal and transverse electro-mechanical properties of PLD-YBCO coated conductor with copper stabilizer

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Coated conductors show fascinating mechanical property in longitudinal (uni-axial) tension/compression. On the other hand, vulnerability for transverse tension has been pointed out. In the present work, longitudinal and transverse electro-mechanical properties were investigated for the PLD-YBCO coated conductor. The conductor width, the substrate thickness and copper stabilizer thickness are 5 mm, 100 μm and 100 μm, respectively. The critical current is 150 A at 77 K, self-field. The longitudinal electro-mechanical property was tested by a conventional tensile test at 77 K, self-field. Strain was measured by the dual extensometers (so-called Nyilas-type). In the case of the transverse electro-mechanical property test, the tensile force angular dependence was investigated. The results will be compared with data in literatures and discussed.

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Plastic modeling of superconducting Rutherford-type cable fabrication

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An important part of superconducting accelerator magnet work is the conductor. To produce magnetic fields larger than 10 T, brittle A15 conductors are typically used. The original round wire, in the form of a composite of Copper, Niobium and Tin, is assembled into a so-called Rutherford-type cable, which is used to wind the magnet. The magnet is then subjected to a high temperature heat treatment to produce the chemical reactions that make the material superconducting. At this stage the superconductor is brittle and its superconducting properties sensitive to strain. This work is based on the development of a 2D finite element model, which simulates the mechanical behavior of Rutherford-type cable before heat treatment. To validate the critical criterion, adopted into the Nb-Sn wire analysis, the strain results of the model were compared with those measured experimentally on cable cross sections. The model was then applied to a number of different cable architectures.

Fundamental evaluations of transverse load effects on Nb_3Sn strands using finite element analysis

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The performance of superconductor Nb_3Sn is sensitive to the strain state. Large cable-in-conduit conductors (CICC) used, for example, in ITER has about 30% void fraction to provide good cooling. This design allows for strands movement during operation under the natural Lorentz load causing large local transverse compression and bending. Those effects are believed to cause a significant performance degradation. In this paper 2D finite element elasto-plastic analysis is conducted to simulate the transverse compression on basic elements of a CICC: a single strand and a 3-strand cable. A parametric study of the stress-strain characteristics of copper at 4 K is considered. Areas in which superconducting filaments lie are assigned a uniform Nb_3Sn material property or a composite material property in the finite element model. The results show a strong sensitivity to the elasto-plastic material properties. The twisting of the wires in a 3-strand cable results in different strain state of the individual wire when the cable is under uniform transverse compression along the longitudinal direction. Different cross sections of the 3-strand cable are analyzed to determine the strain distribution in each strand. The analysis predicts where the highest strain occurs and consequently where the highest risk of performance degradation is located in the cable.

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Compact 20 T superconducting magnet for a 50 T-class hybrid magnet

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The repeated prebending treatment for internally reinforced Nb_3Sn wires with CuNb reinforcing stabilizer (CuNb/Nb_3Sn) extremely enhances the critical current. Since the employment of the high strength CuNb/Nb_3Sn wire is very effective for a react-and-wind processed Nb_3Sn superconducting magnet, we focus on the application of this prebending effect to the react-and-wind process development of high-strength strand cables. The Rutherford flat cables composed of 16 CuNb/Nb_3Sn strands were fabricated. High-strength CuNb/Nb_3Sn strand cables will exhibit the critical current of I_c = 1890 A at 13 T and 4.2 K.

In order to construct a compact and energy-saving hybrid magnet, a 20 T-440 mm room temperature bore superconducting magnet consisting of two layers YBCO coils, three layers CuNb/Nb_3Sn coils and two layers NbTi coils is designed, using such Rutherford flat cables in pool- boiling liquid helium. The coil parameters are inner diameter 480 mm, outer diameter 1283 mm, coil height 1302 mm, inductance 232 H and magnetic stored energy 94 MJ at 900 A operation current. A 20 T wide bore superconducting outsert will be combined with a 15 MW-27 T water-cooled resistive insert as a 47 T hybrid magnet.

Study of YBCO tape anisotropy as a function field, field orientation and operating temperature

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Superconducting magnets with magnetic fields above 20 T will be needed for a Muon Collider and possible LHC energy upgrade. This field level exceeds the possibilities of traditional high field Low Temperature Superconductors (LTS) such as Nb_3Sn and Nb_3Al. Presently the use of high field high temperature superconductors (HTS) is the only option available for achieving such field levels. Commercially available YBCO come in tapes and show noticeable anisotropy with respect to field orientation, which needs to be accounted for during magnet design. In the present work, critical current test results are presented for the last generation of commercially available tape from American Superconductors. Short sample measurements results are presented up to 14 T, assessing the level of anisotropy as a function of field orientation and operating temperature.