Cold Densification of long lengths of industrial *in situ* MgB_2 wires with improved J_c and B_{irr} values

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A strong enhancement of J_c in monofilamentary *in situ* MgB_2 wires over lengths exceeding 10 meters by means of the Cold High Pressure Densification (CHPD) technique recently developed in Geneva is reported. By means of a newly developed prototype machine, pressures around 1 GPa were applied before reaction on the four sides of a square wire produced by Hyper Tech, USA. Densification occurred by a sequence of pressing steps with overlapping regions of 20 mm. On $C_4H_6O_5$ added wires of a final dimension of 0.5x1 mm^2, J_c(4.2K) = $1x10^4$ Acm^{-2} was obtained at a field $B(10^4)^{//}$ of 13.1T (0.1 μV/cm), i.e. close to the values obtained on short samples. For monofilamentary wires, almost isotropic J_c values were obtained, with $B(10^4)^{//}$=13.4 and $B(10^4)^{//}$=13.1T at fields parallel and perpendicular to the wider surface, respectively. At 20K, both values are close to 6.4 T, the value of $B_{irr}^{//}$ at 20K being 11.0T. By applying the criterion of 1 μV/cm, the $B(10^4)$ are even 0.4 T higher, thus confirming the presence of a marked T_c distribution inside the MgB_2 filaments which was confirmed by specific heat measurements. The observed enhancement of J_c is correlated to the enhancement of mass density and to improved connectivity in the MgB_2 filaments, as shown by electrical resistivity and specific heat measurements.

We also report strongly enhanced J_c values for CHPD treated multifilamentary MgB_2 wires. The present results are very promising in view of the industrial application of CHPD, the extension to wire lengths of several hundred meters being now possible.

Critical Current and *n*-values of MgB2 strands in a range of B-T

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Critical current and index values were measured for a set of high performing MgB2 materials over a large range of B-T space. Applied fields ranged from 0-15 T, and temperatures from 4 K -40 K. Several different versions of powder-in-tube (PIT) samples were measured, including those with binary MgB2 compositions (no doping) as well as SiC and intrinsic C doping (C doping added to the starting B during formation). These were compared to strands with selected “non-reactive” pinning centers included both metallic and ceramic dopants. Magnetic and transport results for critical current were compared, as well as n-values. The electric field dependence of n was investigated and the functional form described. The differences in transport and magnetic critical current results were interpreted in terms of connectivity. Differences between n-values from the two different techniques was attributed to a comparison of flux creep effects to those of extrinsic (e.g., wire sausaging) effects.

MgB_2 grain refinement for ex-situ Powders-in-Tube superconducting tapes.

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Grain refinement of MgB_2 powders is one of the key parameters to increase the in-field critical current density of ex-situ tapes. Here we will revue the recent activities on this topic at the CNR-SPIN (former INFM-LAMIA) laboratories. We will show the advantages to use different techniques, i.e.: high-energy ball milling, low synthesis temperature and controlled oxidation of the MgB2 powders. All these methods produce enhanced performances at higher fields although the causes for the improvements can be different. These methods were studied with a wide variety of experimental techniques including in-situ synchrotron x-ray diffraction in the various steps of the realization of the tape. Moreover the powder's granulometry can play a crucial role in obtaining multifilamentary conductors with a large number of very fine filaments useful to reduce the AC losses. We have studied the relationship between grain and filament size in terms of transport properties and have shown that the optimization of this ratio is possible in order to obtain suitable conductors for AC industrial applications.

Optimization of Transport Properties of Multifilamentary MgB_2 Strands with Different Strand Designs

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Various strand designs, as well as the influence of these designs on critical current density J_c, have been investigated for MgB_2 strands. The strands were designed with different number of filaments, powder fraction, monofilament sheath materials, outer sheaths, and filament placements. Pre- and post-reaction microstructural texture and density were evaluated and correlated with transport properties. In some cases, longitudinal and transverse “cracks” were observed in SEM images. Then the relative influence of starting (green) density vs powder fraction and sheath hardness are compared on both J_c and n-value. Various heat treatments were applied in order to determine the optimum heat treatment conditions for various powder types. Finally, a set of wires designed for enhanced bending strain tolerance were studied by reacting the wires straight, assembling them onto curved bend test fixtures and measuring J_c. The influence of strand count and filament placement on bending strain tolerance is discussed.

The cabling of MgB_2 hollow wires by react and wind process

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Several architectures of superconducting MgB_2 multiwires cables have been manufactured in order to test the viability of a "React & Wind" process, to be used to build large superconducting magnets or high current transport cables and busbars. Round wires precursors are drawn with an internal Mg core, in order to produce an hollow superconducting phase by the "in situ" Reactive Mg Liquid Infiltration process. The precursor has been drawn to small diameters, of the order of half a millimetre, then it is braided according to various transposition geometries to realize a precursor cable. To obtain the superconducting cable, a final heat treatment is applied batch wise or continuously in tunnel furnaces. Finally, the cable may be thermal stabilized by cladding it with low melting metals. All the cabling operations are done taking into account the mechanical characteristics of the wires and assuming a safety margin in the applied flexural strains. The transport superconducting properties of the cables are measured at different temperatures and magnetic fields and, in some specific cases, are checked also after small mechanical deformations of the cables. The deformation analysis is intended to determine the limiting strains that these superconducting cable can sustain.

Minimum quench power and current non-uniformity in ITER NbTi Cable-In-Conduit Conductors for DC conditions

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The stability and quench behaviour at high currents, in particular for large NbTi cabled conductors like the ITER PF type of conductors, is strongly correlated with the level of current non-uniformity. The joints at the extremities of the cable-in-conduit conductor (CICC) in coils and short samples can introduce a non-uniform current distribution among the strands, for which the degree of non-uniformity mainly depends on the design of the joint. A detailed study down to strand level provides quantitative data leading to a better understanding of the implications for short sample and coil tests as well as on magnet performance limitations. This study is performed with the JackPot cable model and based on PFIS and PF2 short sample tests in SULTAN and the PFCI Model Coil Insert test.

JackPot is an electromagnetic cable model, which incorporates the trajectories of all individual strands. Based on the joint design, cabling configuration, magnet field profile, sample geometry and by using experimentally determined cable and joint interstrand resistance distributions, we are able to calculate representative values for the local quench power and its location of origin. The eventual aim is to find general applicable criteria for quantification of the minimum quench power of ITER NbTi CICCs and to assess the baseline requirements for optimum performance of ITER magnets.

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Cable for the LARP Long-Quadrupole Magnets

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About 4 kilometers of Nb3Sn Rutherford keystone cable in minimum unit lengths of 240 m have been fabricated for the LARP 90 mm aperture Long-Quadrupole (LQ) magnet development. These cables used 0.7 mm diameter RRP® wire of 54/61 and 108/127 design from Oxford Superconducting Technology. The cabling procedure adopted is a two stage process to control the width, mid-thickness, and the strand deformation at the edges of the cable. The cable parameters in the difference runs are compared to provide an understanding of variation in the production. Strands were extracted from the finished cable, reacted on stainless steel barrels and its critical current, Ic, measured on Ti-alloy barrels. Based on measurements of the round wires and that of the extracted strands, the degradation due to cabling was estimated to be in the range of 3-9%. Details of the cabling parameters and results of low temperature measurements of Ic and the residual resistance ratio, RRR, of the copper stabilizer are presented. The implications of these findings are discussed.

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Coated Conductor Rutherford Cables (CCRCs): mechanical and electrical performance of coated conductor tapes, strands and Roebel sub-cables

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In order to increase the efficiency and to reduce the complexity of future fusion reactors, high-temperature superconducting (HTS) magnets are desirable. However, this requires superconducting cables with current carrying capacity exceeding 10 kA in magnetic fields above 10 Tesla, with low ac-losses and with good mechanical performance to withstand the huge Lorentz forces which occur in the magnet system of fusion machines. Coated Conductor Rutherford Cables (CCRC) using low-ac-loss Roebel sub-cables as strands are a concept for realization of high-current low-ac-loss HTS cables which could fulfill the requirements. Depending on width, thickness and cabling angle of the CCRC the Roebel sub-cables can experience large bending strains leading to degradation of the superconducting properties. We developed a special edge-bending device which simulates bending around the edges of a CCRC former. V(I) measurements reveal strong degradation of the critical current for small former thickness and large cabling angles. We present a subsize CCRC demonstrator cable and results from bending and edge-bending experiments on tapes, strands and Roebel sub-cables. The electric performance and influence of self-field effects will be discussed.

Electro- Mechanical Analysis of Roebel Cables with Different Geometries

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For coming fusion applications HTS Roebel cables with high effective current densities are required. Due to the enormous Lorentz forces of fusion magnets these cables must also be able to withstand high mechanical loads. Different types of coated conductor material are produced and there are some which are very resistant to tensile stress. However the Roebel structure increases the mechanical stress at the crossing sections for a given load. This weakens the tape and makes it more susceptible to tensile load in these regions. This increase in mechanical sensitivity depends on geometry parameters as angle, thickness and inner radius of the Roebel structure and can be reduced with an optimized geometry.
In this work different Roebel geometries were investigated with FEM models in Comsol to evaluate their resistance to tensile load and the space they require per winding. An optimized geometry was found which should strongly increase the resistance to tensile load of the whole cable.
Further the electro-magnetic properties of the 2D cross section of a Roebel cable were simulated. From these simulations a change of the Roebel geometry was derived which should increase the current carrying capabilities of the cable.
To verify the results of these simulations, Roebel structured tapes with different geometries will be mechanically weakened by fatigue cycles and their degradation optically and electrically measured.

Compact $GdBa_2Cu_3O_{7-\delta}$ coated conductor cables for electric power transmission and high-field magnet applications

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Bundling high-temperature superconductors together to form high-current cables is required in, for instance, power transmission and low-inductance magnet applications. Cabling techniques that have been applied so far have not resulted in compact, mechanically robust, high-current cables that remain flexible. Here, we demonstrate that the cabling technique that we have introduced only recently enables the construction of cables from high-temperature superconducting coated conductors that meet these requirements. We present details of a cable, wound from $GdBa_2Cu_3O_{7-\delta}$ coated conductors, that has an outer diameter of 7.5 mm and a critical current of about 2800 A at 76 K and self-field. We will discuss how the compact size and flexibility make the cable suitable for Navy and Air Force power transmission, and would allow superconducting power transmission lines that have been installed in the electric power grid to be reduced in diameter. We will also discuss the potential of raising the engineering current density of the cable, while maintaining flexibility, which makes this concept suitable for high-field magnet applications.