ROEBEL CABLE FOR HIGH-FIELD LOW-LOSS ACCELERATOR MAGNETS *

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Abstract

In the past 40 years, the high energy physics (HEP) program has driven the development of superconducting magnet technology. NbTi and Nb_3Sn have reached their performance limits with upper critical fields (H_{c2}) of 14 T and 29 T, respectively, limiting magnetic field generation to about 10.5 T and 20 T [1-3]. YBa_2Cu_3Oy (YBCO) coated conductors are capable of generating very high magnetic fields, but are limited by a flat tape geometry and subsequent high AC losses. Roebel cables create a filamentary type structure and provide transposed current percolation paths, reducing these AC losses. Performance testing of YBCO Roebel cables exist only for high temperature (50-77 K) regimes in self-field and are limited to studies on critical current density and AC losses. There exists a need to characterize YBCO Roebel cables at low temperature (4.2 K) and varying magnetic fields to determine their electromagnetic and mechanical properties, and evaluate their viability in high field low loss accelerator magnets.

INTRODUCTION

In the twenty years since the discovery of high temperature superconductors (HTS), significant progress has been made in their technology and a number of potential conductors are now industrially manufactured in sufficient lengths for the development of magnets. Of the various HTS materials discovered, two in particular have significant potential for HEP magnets: $Bi_2Sr_2CaCu_2O_x$ (Bi2212) and YBCO. Both Bi2212 and YBCO have very high critical current density (Jc) at 4.2 K in background magnetic fields of at least 45 T. They have both been used to generate magnetic fields of at least 25 T, clearly surpassing what is possible with Nb_3Sn, and are thus also considered now to be high field superconductors (HFS). With the development of these conductors, electrical performance may no longer be the primary limitation to the generation of high magnetic fields. Figure 1 summarizes the engineering current density (J_E) as a function of applied magnetic field for useful superconducting materials. Note that in the high current density, high magnetic field regimes, Bi2212 and YBCO are the only viable candidates.

In comparing Bi2212 and YBCO, one finds that neither conductor has a clear advantage; each has its strengths and weaknesses for HEP magnets. Bi2212 is the only HFS conductor with high Jc in an isotropic round wire; this is its primary advantage. Bi2212 is plagued, however, by relatively poor electromechanical performance and the need for a final heat treatment at about 890°C in pure oxygen, which limits its construction to a wind-and-react process. YBCO conductors are fully processed into a final product before magnet construction begins; thus they are capable of react-and-wind magnet construction. Additionally, YBCO conductors have significantly better mechanical properties than Bi2212, and because the YBCO layer is on or near the neutral axis, the bending stress in the YBCO layer associated with winding is minimized. Owing to the Ni-alloy substrates that dominate the cross-section, YBCO coated conductors have the highest ultimate tensile strength, yield stress, strain tolerance and fatigue resistance of any HFS conductor [4-7]. YBCO conductors, however, can only be manufactured as wide, thin tapes, with significant electromagnetic anisotropy and a very low YBCO fraction within the conductor (~1%). This geometrical restriction limits its ability to be cabled, resulting in high AC losses and a lack of design freedom for magnet applications. The absence of a reliable, high-performing cable has been one of the key limitations of YBCO coated conductors for high field magnet applications.

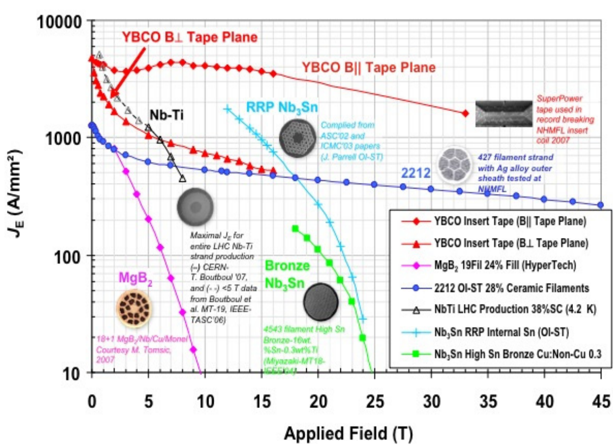

Figure 1: JE(B, 4.2K) for superconducting materials; courtesy of Peter Lee, NHMFL ASC

Roebel cables

Roebel cables were originally introduced in 1970 to solve AC loss problems for high current copper cables for generator applications. Roebel cables create a filamentary type structure and provide transposed current percolation paths, reducing the AC losses; thus the Roebel cable geometry is a promising solution to YBCO cabling issues.

YBCO Roebel cables are constructed by first precision punch processing a specific meander-like shape into YBCO coated conductor; these strands are then sequentially wound around each other, often around a mechanically stabilizing substrate. Figure 2 shows a single Roebel strand and an example of assembled Roebel cable is illustrated in Figure 3. Despite the inherent complexity of the winding approach, the last four years has seen significant progress in the production of YBCO-based Roebel cables and they are now available commercially in long lengths [8-10]. These advances in YBCO Roebel cables address two key technological challenges: the ability to manufacture a cable with not only high J_c but also high critical current I_c, and reduced AC losses. Both of these accomplishments could prove pivotal to the ultimate market success of YBCO coated conductor applications.

Figure 2: Single strand of Roebel cable. [8]

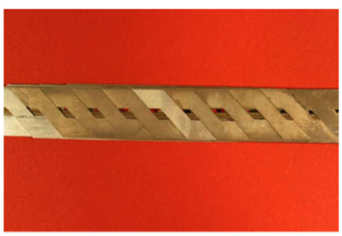

Figure 3: View of a section of sixteen strand Roebel cable with parallel underlying copper stabilizer. [8]

CHARACTERIZING ROEBEL CABLE FOR ACCELERATOR PHYSICS

While certain aspects of Roebel cables, such as critical current density and AC losses, have been studied fairly well, other key issues that influence their viability for HEP applications are not understood. Additionally, existing research focuses largely on high temperature (50-77 K), self- field characterization of Roebel cables. This regime is not appropriate for future high field accelerator magnets. The central mission of the necessary research is to investigate behaviors and determine operational limitations of YBCO Roebel cables at low temperatures (4.2 K) and high magnetic fields.

By investigating operational behaviors and limits of YBCO Roebel cables at low temperatures (4.2 K) and as a function of magnetic fields, their viability for HEP accelerator magnets can be determined.

Technical approach

One of the key goals in characterizing Roebel cable is understanding the distribution of current flow in the strands, both during steady-state operation and during a fault condition. Dynamic magneto-optical imaging (MOI) is a technique based upon Faraday rotation of polarized optical light through a Faraday-active indicator film. By placing the indicator film on the surface of a properly magnetized superconductor under an optical microscope, one can image the distribution of magnetic field within the superconductor [11-18]. Recent results have shown that by using a high speed CCD camera, MOI images can be converted to a time-dependent two-dimensional dataset and the evolution of the magnetic field (and thus current) profile within a conductor can be captured [19]. Through this approach, and by incorporating simultaneous temperature and voltage measurements, dynamic processes such as current redistribution and quench propagation can be imaged and interpreted at the microscopic level. An example of this type of data can be found in Figure 4. MOI can be used to investigate the current distribution during steady-state operation, as well as the current redistribution during a quench occurrence.

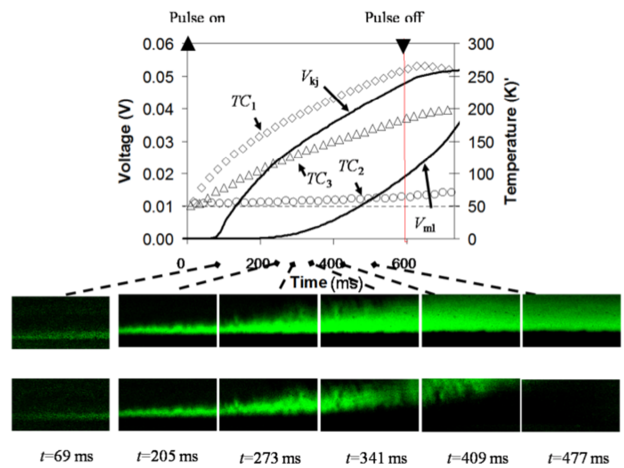

Figure 4: The graph plots the time-dependent voltages and temperatures during a quench with I = 50 A and a heater pulse voltage V_P = 7.5 V at 45 K. t = 0 is defined as the beginning of the heater pulse; the transport current is established prior to that [19]. The corresponding MO images represent the sequential time-dependent images of the magnetic field profiles. These images are manipulated datasets, illustrating the change in magnetic field distribution relative to t = 0 (upper row) and relative to the previous time-step (lower row).

The determination of current flow paths during steady-state operation and during a quench should be performed for both insulated and non-insulated cables. General Cable Superconductor (GCS) specializes in insulation of HFS wire with an acrylate epoxy coating ranging from 10 to 25 nm in thickness. Individual strands of YBCO may be coated with this insulating material prior to winding in the Roebel geometry. The effects of this insulation on the current distribution and quench characteristics will be investigated.

Understanding the mechanical properties of YBCO Roebel cable is essential for magnet design and operation. The key advantages of YBCO coated conductor are the high ultimate tensile strength, yield stress, strain tolerance and fatigue resistance relative to other HFS conductors. These properties need to be investigated and quantified in

YBCO Roebel cable. As YBCO development is primarily driven by high temperature power applications, there is a significant void in the knowledge of the low temperature properties.

There exists a need to know the stress and strain limits and the effects of tension on J_E at 4.2 K for Roebel cables. $I_c(\varepsilon)$ tests should be performed at 77 K for various strain states, including tension, compression, and bending. Axial compressive strain behavior is especially interesting as the geometry of the Roebel cable allows for significant movement of the strands under compressive strain. Effects of this movement on frictional heating and strand contact needs to be investigated.

Additionally, the angular dependence of I_c varies with both magnetic field and temperature for YBCO Roebel cables and this behavior must be examined. $I_c(B)$ tests should be performed at 4.2 K and in a magnetic field ranging up to 20 T at all field angles.

SUMMARY

There is a need to quantify the electromagnetic and mechanical behavior of YBCO Roebel cable in regimes previously unexplored. The information obtained will provide vital missing information necessary to design future high-field low-loss accelerator magnets for high energy physics.

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