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Study of HTS Wires at High Magnetic Fields

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***Abstract*—Fermilab is working on the development of high field magnet systems for ionization cooling of muon beams. The use of high temperature superconducting (HTS) materials is being considered for these magnets using Helium refrigeration. Critical current (I_c) measurements of HTS conductors were performed at FNAL and at NIMS up to 28 T under magnetic fields at zero to 90 degree with respect to the sample face. A description of the test setups and results on a BSCCO-2223 tape and second generation (2G) coated conductors are presented.**

***Index Terms*— High temperature superconductor, BSCCO, coated conductor, critical current**

I. INTRODUCTION

THE main application of High Temperature Superconductor (HTS) magnets at Fermilab is presently in the realm of Muon Colliders, which require high field solenoids for muon beam cooling. This includes the high field sections of a 6D Helical Cooling Channel [1, 2] and high-field solenoids (> 30 T) for the final, low emittance stage of the muon cooling channel [3-5]. These ambitious goals require strong HTS magnet and conductor programs, to be conducted in close collaboration with other U.S. National Labs, Universities and Industry.

A main mission of the conductor program is that of monitoring and studying the best performing HTS's on the market, including state-of-the-art Second Generation (2G) coated conductors, but also Bi-2212 round wire and cables [6] together with the U. S. National Collaboration. Characterizing HTS materials, the engineering current density (J_E) as a function of magnetic field, temperature, field orientation, as well as transverse, longitudinal and bending strain/stress is essential input to practical magnet design. HTS tapes just need extensive evaluation of the aforementioned properties to monitor industry progress. Based on conductor results, the best performing HTS conductors will be selected to be used in the magnet program.

BSCCO-2223 and 2G HTS are typically produced in the form of tapes, which are anisotropic and exhibit the highest critical current when the magnetic field is applied parallel to the tape face (B_{PAR}) and the lowest one when the field is perpendicular to it (B_{PERP}). Fig. 1 shows the geometrical configuration of a tape and relative directions of magnetic field. Earlier 1G tapes have been tested at various temperatures in both field directions [7,8]. Angular measurements on 2G have been performed at higher temperatures [9, 10].

A sample holder designed to perform I_c measurements of HTS tapes under externally applied magnetic fields, with orientations Θ varying from zero to 90 degrees with respect to the c-axis (see Fig. 1), was used in this study. The I_c angular dependence was measured at FNAL at temperatures from 4.2K to 33 K up to 15 T, while providing up to 1400 A of current to a 2G sample by SuperPower (SP). To complement similar studies on two HTS conductors by American Superconductor (AMSC) [11], the latter plus a sample by SP were tested in parallel and perpendicular field configurations up to 28 T at NIMS.

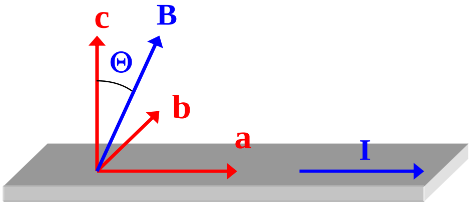

Fig. 1. HTS superconductor with current direction and relative direction of magnetic field B. B is always perpendicular to the current direction (Schematic is courtesy of C. Thieme, AMSC).

II. SAMPLES DESCRIPTION

First Generation (1G) multi-filamentary HTS are composites of silver or silver alloy matrix and BSCCO [12]. 2G HTS conductor is based on a thin film approach, and it is now seen as a major candidate for an effective replacement of 1G wire. 2G has excellent mechanical properties, and allows a react-and-wind technique for magnet construction.

TABLE I HTS SPECIFICATIONS

Strand ID	Hermetic 1G	2G 348	2G SCS 4050
Company	AMSC	AMSC	SuperPower
Min I_c (77 K, self-field)	115	110	100
Average thickness t_T	0.31 mm	0.2 mm	0.145 mm
Average width w_T	4.8 mm	4.8 mm	4.4 mm
Laminate	stainless	copper	copper
Laminate thickness	2 x 0.037 mm	2 x 0.050 mm	2 x 0.020 mm
YBCO layer thickness		1.4 μm	1.2 μm
Min. critical bend diameter	50 mm	50 mm	20 mm
Max. rated tensile strain	0.3 %	0.3 %	0.45 %

A BSCCO-2223 Hermetic tape and a 2G 348 Coated conductor by AMSC, as well as a 2G SCS 4050 conductor by SP were used in this study. Their specifications are given in Table I. A schematic of the SP conductor is shown in Fig. 2.

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Pictures of the AMSC conductors can be found in [11].

For both 2G conductors, the active component is the YBCO ($YBa_2Cu_3O_7$), which is only about 1 µm thick. AMSC uses a bi-axially textured substrate approach onto which a thin epitaxial oxide buffer layer is deposited (RABiTS^{TM}) [13, 14]. SP uses the IBAD technique [15, 16].

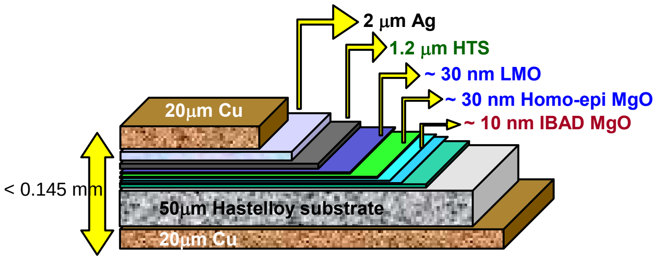

Fig. 2. Schematic of a 2G coated conductor by SuperPower showing an YBCO layer 1.2 µm thick obtained with the IBAD technique.

III. EXPERIMENTAL SETUPS

A. *Measurement Procedure at FNAL*

The samples used at FNAL were straight and 38 mm long. The sample, supported in its middle part by G-10, was soldered within a groove on two Cu half cylinders using a splice length of 12 mm at each sample end to control contact resistance and heating power. The sample holder was placed at the desired angle within cylindrical holes in the probe Cu lugs [11]. The distance between the voltage taps was of 10 mm.

At FNAL measurements were obtained at a number of temperatures in a Variable Temperature Insert (VTI) with an inner diameter of 49 mm, within a 15/17 T magneto-cryostat and 2000 A current leads to the sample. The temperature was controlled using a LabView PID routine and a LakeShore218 monitor to read the Cernox^{TM} sensor on the sample. The average temperatures at which the measurements were performed in parallel field were 4.234 K ± 0.019 K, 14.113 K ± 0.037 K, 22.212 K ± 0.134 K and 33.082 K ± 0.074 K. The average temperature variation during the superconducting to normal transition was negligible at 4.2 K, 0.126 K at 14.113 K, 0.097 K at 22.212K, and 0.116 K at 33.082 K. For the angular dependence measurements, the angle Θ was changed in steps of 11.250 and 22.50 degrees. First, critical current measurements were performed in liquid nitrogen (77 K) at self-field. Next, voltage-current (VI) characteristics were measured in He (liquid or vapor) at a magnetic field between 0 and 15 T. The critical current I_c was determined using the 1µV/cm criterion [17]. Critical currents have not been corrected for self-field effects which can be substantial at low fields.

B. *Measurement Procedure at NIMS*

The sample holder used at NIMS is shown in Fig. 3. Six samples were tested in series. Three were mounted in a parallel field configuration and three in a perpendicular field configuration. Samples were straight and 30 mm long. They were supported on G-10 5 mm wide holders ending with Cu caps. Splice length was 5 mm at each sample end. The distance between the voltage taps was 5 mm. The critical current I_c was determined using the 1 µV/cm criterion. At NIMS the VI characteristics were measured in liquid He at magnetic fields up to 28 T in the 30 T Hybrid magnet with a 52 mm warm bore. The equipment power supply limit was 500 A.

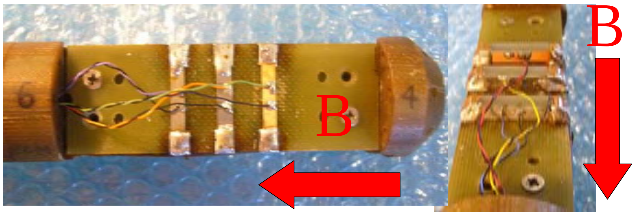

Fig. 3. Sample holder used at NIMS showing six instrumented samples.

IV. RESULTS

A. *Critical Current Data*

Fig. 4 shows I_c results at 4.2 K for the three HTS wires as a function of magnetic field, in the parallel and transverse field configurations, as measured at NIMS and at FNAL [11]. There is a good agreement for the 2G conductors, whereas some discrepancies are apparent, especially at the lower fields, for the 1G hermetic tape.

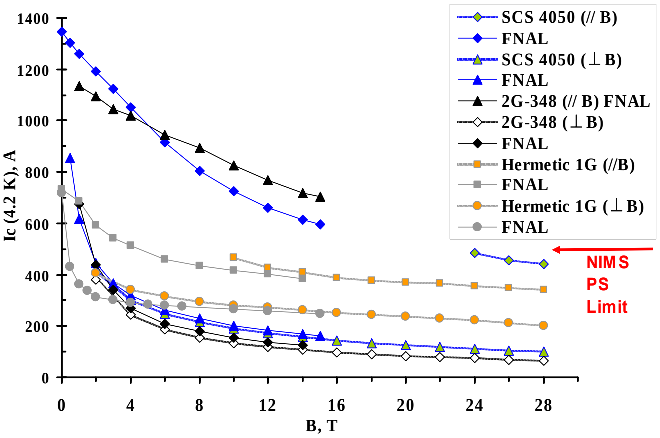

Fig. 4. $I_c(B)$ results of the three HTS tapes obtained at 4.2 K in parallel and perpendicular fields at NIMS, compared with FNAL tests [11].

B. *Measurement of Anisotropy*

Fig. 5 shows I_c results as a function of magnetic field for the 2G SCS 4050 conductor, in the parallel and transverse field configurations, from 4.2 K to 33 K. The performance at self-field and 77 K was 106±1 A. One can see that the I_c dependence in parallel field reduces mostly linearly with field, which indicates that effective pinning is maintained for the parallel direction over the entire field range. For the perpendicular direction pinning is most effective at low fields but then reduces at high fields.

Figs. 6 and 7 show the I_c normalized to I_c(77 K, 0 T) as a function of field and field angle at 4.2 K and 33 K. Most of the

I_c reduction occurs between 90 and 45 degrees.

To gauge field and temperature dependence of the anisotropy, the ratio of I_c, normalized to I_c(77 K, 0 T), in parallel field to that in transverse field as a function of applied magnetic field, or:

$$\frac{I_c(B_{PAR})/I_c(77K,0T)_{PAR}}{I_c(B_{PERP})/I_c(77K,0T)_{PERP}}$$

can be calculated at the various temperatures and fields. This was done in Figs. 8 and 9 for the 2G SCS 4050 and the 1G hermetic tapes, using for data at 4.2 K both FNAL and NIMS results. For the 1G tape, a linear field dependence with a slope increasing with temperature had been produced for this ratio [11]. The NIMS data show a reasonably flat field dependence at 4.2 K (Fig. 9), making it a good choice at 4.2 K. For the 2G SCS 4050 conductor (Fig. 8), the ratio increases fast with field and tends to saturate above 4 T. The NIMS data show that at 4.2 K it actually slightly increases at high field. Contrary to the 2G 348 conductor, where this ratio showed no observable temperature dependence [11], in the case of the 2G SCS 4050, above 4 T the ratio decreases with increasing temperatures. This means that this conductor is less anisotropic at high temperatures.

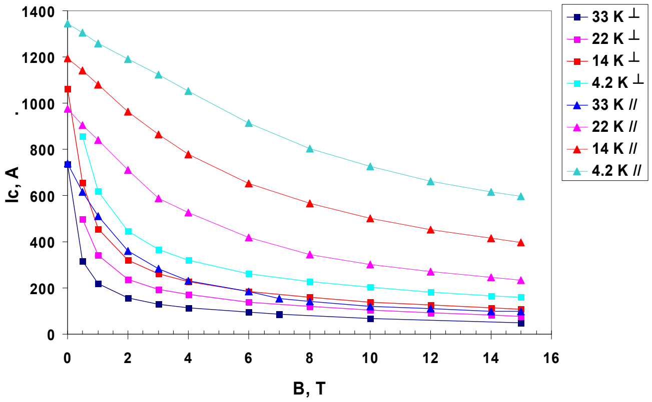

Fig. 5. I_c(B,T) of the 2G SCS 4050 coated conductor in parallel and perpendicular fields, from 4.2 K to 33 K.

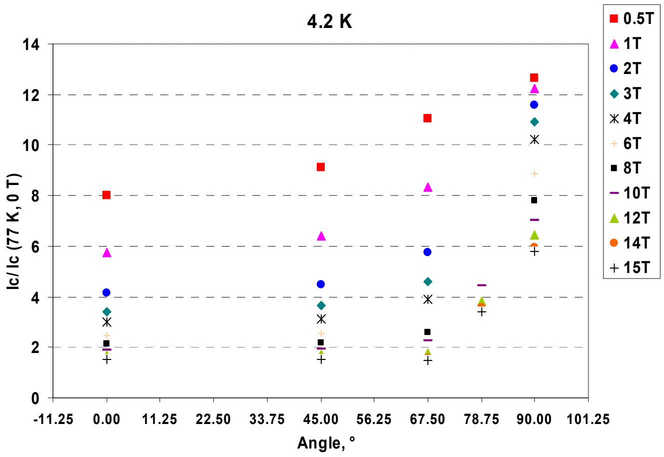

Fig. 6. Normalized I_c (4.2 K) of the 2G SCS 4050 coated conductor versus B and Θ.

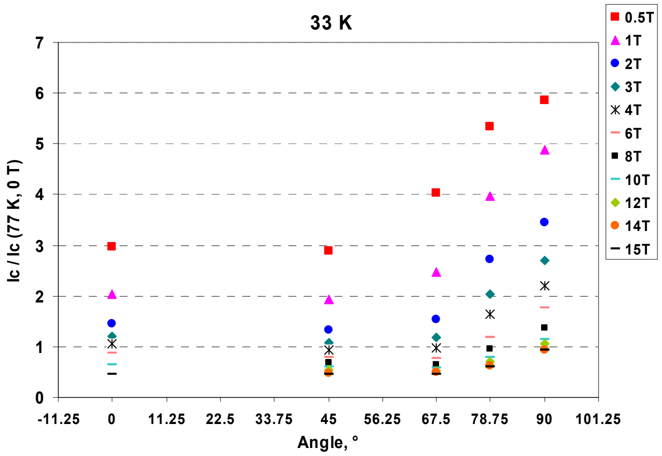

Fig. 7. Normalized I_c (33 K) of the 2G SCS 4050 coated conductor versus B and Θ.

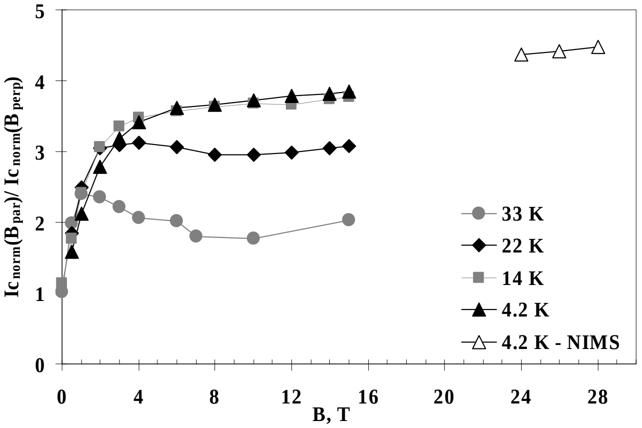

Fig. 8. Ratio of normalized I_c in parallel and perpendicular fields, from 4.2K to 33 K, for the 2G SCS 4050 tape.

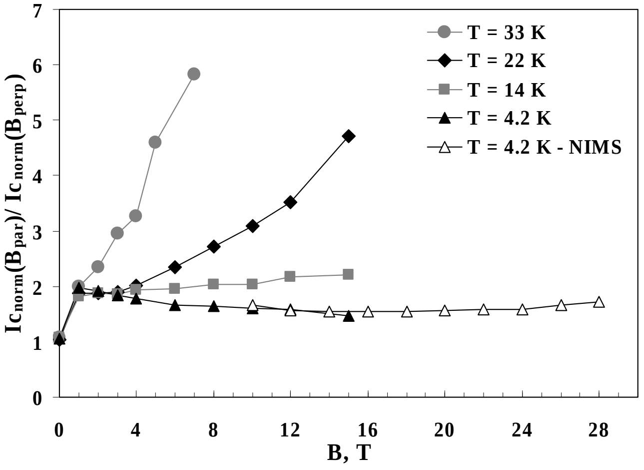

Fig. 9. Ratio of normalized I_c in parallel and perpendicular fields, from 4.2K to 33 K [11], for the 1G hermetic tape.

C. Comparison with LTS

Fig. 10 shows the engineering critical current J_E at 4.2 K and magnetic fields up to 28 T for the three HTS tapes, compared with that of round Bi-2212 (OST), Nb_3Sn and NbTi wires. For the calculation of J_E the entire cross section of each conductor was used. Below 15 T, the J_E of the RPP Nb_3Sn

wire exceeds that of all HTS at 4.2 K. Above 17 T the Bi-2212 round conductor shows a good overall performance. The 2G superconductors have a much higher current density in parallel fields, indicating excellent potential for high current density insert magnets for very high fields. For complete solenoids in which end sections operate with high perpendicular field components, the B_{PERP} performance is currently too low and needs further pinning enhancement for this field direction. It is interesting that the Bi-2223 conductor, which at lower fields has a lower J_E than other HTS's, actually recovers at the highest fields.

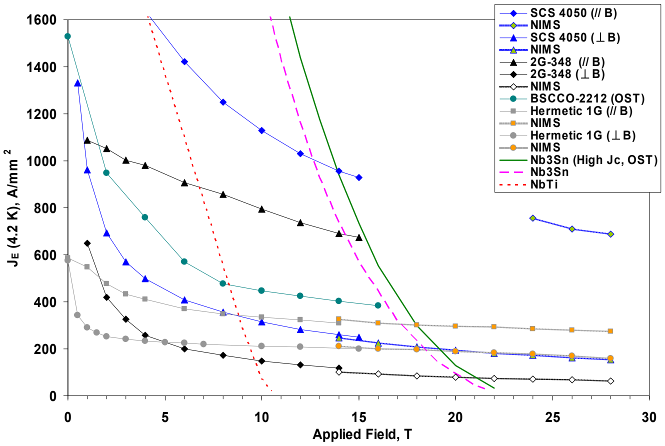

Fig. 10. J_E(B) at 4.2 K for HTS coated conductors, Bi-2223 tape, and Bi-2212, Nb_3Sn and NbTi round wires [11].

V. CONCLUSION

The I_c angular dependence on field orientation was measured at FNAL at temperatures from 4.2 K to 33 K up to 15 T, while providing up to 1400 A of current to a 2G sample by SuperPower (SP). To complement similar studies on two HTS conductors by American Superconductor (AMSC) [11], the latter plus a sample by SP were tested in parallel and perpendicular field configurations up to 28 T at NIMS.

The low anisotropy and reasonably flat field dependence at 4.2 K of the 1G hermetic wire makes it a good choice at 4.2 K. On the other hand, the anisotropy of the 2G SCS 4050 conductor decreases with increasing temperatures, making it a good choice at high temperatures.

The J_E in parallel magnetic field of state-of-the-art coated conductors has dramatically increased in recent years. However, solenoids with strong perpendicular field components in the end sections are limited by the current in perpendicular field. Reducing conductor anisotropy would considerably increase the performance of these magnets.

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