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STUDY OF HTS INSERT COILS FOR HIGH FIELD SOLENOIDS

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ABSTRACT

Fermilab is currently working on the development of high field magnet systems for ionization cooling of muon beams. The use of high temperature superconducting materials (HTS) is being considered for these solenoids using Helium refrigeration. Several studies have been performed on insert coils made of BSCCO-2223 tapes and second generation (2G) YBCO coated conductors, which are tested at various temperatures and at external fields of up to 14 T. Critical current (I_c) measurements of YBCO short samples are presented as a function of bending stress, magnetic field and field orientation with respect to the sample surface. An analytical fit of critical current data as a function of field and field orientation is also presented. Results from several single-layer and double-layer pancake coils are also discussed.

KEYWORDS: High temperature superconductors, BSCCO-2223, YBCO, angular measurements, bending tests, pancake coils, muon collider.

INTRODUCTION

Ionization cooling for muon beams will require the development of a 6D Helical Cooling Channel [1,2] and high-field solenoids (> 30 T) [3-5]. Both of these configurations might require extensive use of HTS materials to produce the required magnetic fields. HTS tapes are generally high performing at very high fields and do not require reaction. Whereas a rectangular cross section can be limiting for certain coil geometries, it well suits the purpose of winding high J_c solenoids. Both 1G BSCCO-2223 and 2G HTS YBCO tapes show anisotropic behavior with respect to field orientation and this plays a major role in designing solenoids. For this reason, an accurate understanding on how critical current responds to field orientation is needed in order to precisely include this effect into solenoids design.

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CRITICAL CURRENT STUDIES

Several short sample tests were performed at Fermilab up to 15 T to study critical current dependency on magnetic field and field orientation. The standard setup allows for a 38 mm long sample to be mounted on a holder designed to provide a rotation with respect to an external magnetic field [6]. The sample, supported in its middle part by G-10, is soldered within a slot on two copper halves. A splice length of 12 mm was used on each side of the tape. The sample holder is placed at the desired angle and fixed for testing.

Critical Current Experimental Data Fitting

Using Fermilab in-field data [6] complemented with additional data from new samples, YBCO tapes critical current as a function of magnetic field and field orientation has been fit using the following analytical expression [7]:

$$I_c(B,\theta) = \frac{k(B)}{\sqrt{\sin(\theta)^2 + \frac{\cos(\theta)^2}{\varepsilon(B)^2}}} + \left(a(B)\sin(\theta)\right)^2 \tag{1}$$

In FIGURES 1, 2 and 3 expression (1) is plotted as a solid line against some angular data acquired at Fermilab at several different magnetic fields.

Anisotropy effects are noticeable, especially at the highest fields where even small angles are found to sensibly influence the overall performance of the conductor. This plays a major role in designing solenoids because of the magnetic field distribution at the edges of the coil.

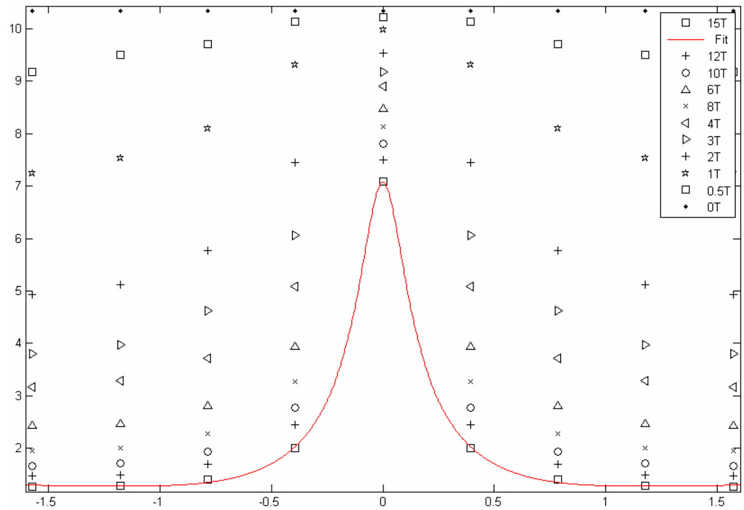

FIGURE 1. I_c(4.2 K,15 T)/I_c(77 K,0 T) fitting curve.

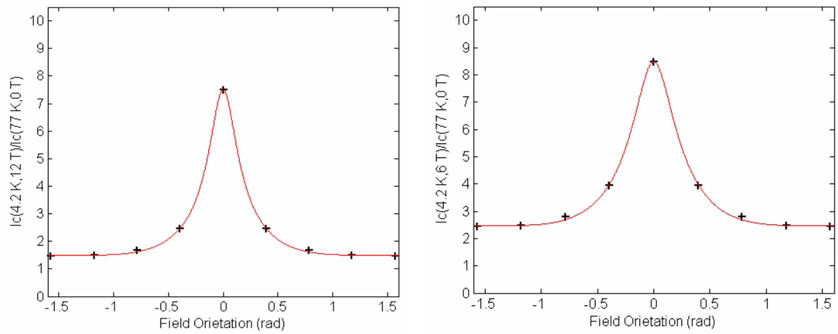

FIGURE 2. YBCO critical current ratio fit against experimental data at 12 T (left) and 6 T (right).

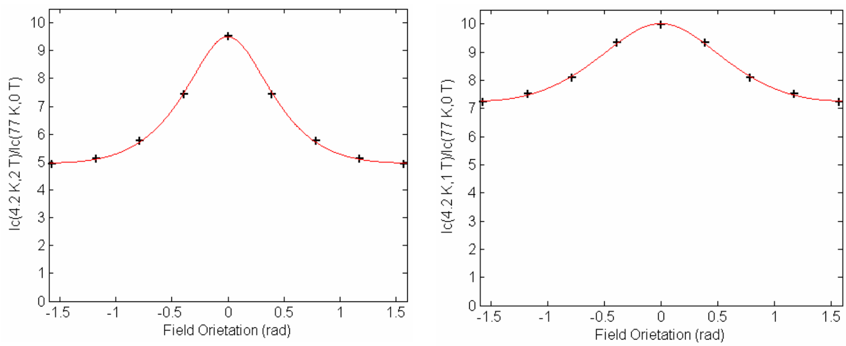

FIGURE 3. YBCO critical current ratio fit against experimental data at 2 T (left) and 1 T (right).

The behavior of the three parameters *k(B), a(B)* and $\varepsilon(B)$ in expression (1) as a function of magnetic field can be easily fit as sums of exponential terms or rational polynomial functions. As a result, a self contained expression describing critical current behavior as a function of field and field orientation was obtained. A full 3D plot is shown in FIGURE 4.

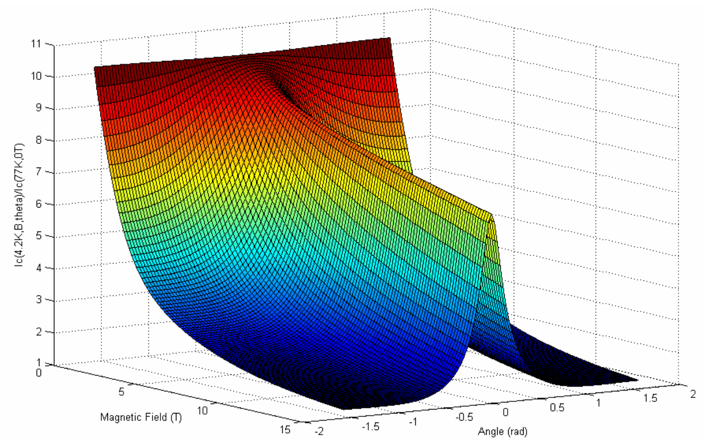

FIGURE 4. $I_c(B,\theta,T)/I_c(77K,0T)$ fitting curve.

BENDING STUDIES

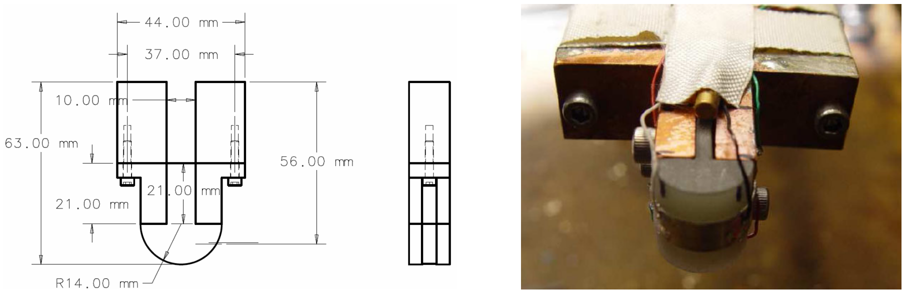

FIGURE 5. Bending Sample Holder (left); Mounted Sample for bending test (right).

Before winding actual solenoids, some effort has been put into understanding conductor behavior under bending conditions. In order to do so, sample holders ranging from 30 mm down to 4 mm in bending diameter have been designed and used with both American Superconductors BSCCO-2223 and Superpower SCS4050 YBCO tapes. In FIGURE 5 the sample holder design and a mounted sample are shown. Tapes are bent to the needed diameter on a G10 support and then soldered on each side allowing for a pair of 15 mm splices to the copper. The G10 holders and the copper parts were designed with slots to accommodate the sample in order to facilitate the mounting procedure and prevent lateral shifting or misalignment with respect to the magnetic field.

American Superconductor BSCCO-2223 Tape

In FIGURES 6 and 7, test results are presented for American Superconductor Stainless Steel reinforced BSCCO-2223 Tape. The nominal critical current at 77 K under self-field conditions for straight samples was measured to be equal to 147 A. The tape has an overall thickness of 0.3 mm and a nominal width equal to 4.3 mm. A new sample was mounted for each of the bending diameters.

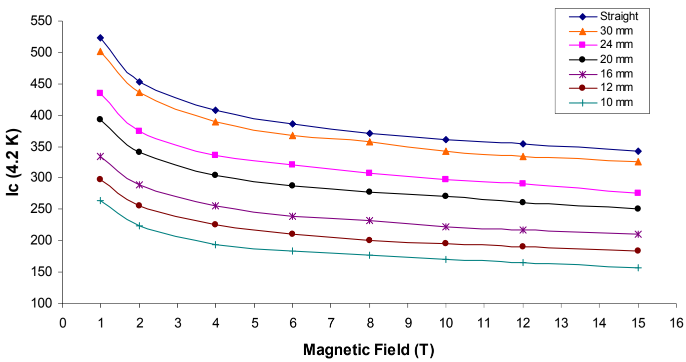

FIGURE 6. Critical current at 4.2 K for BSCCO-2223 bent samples obtained by ramping the field down.

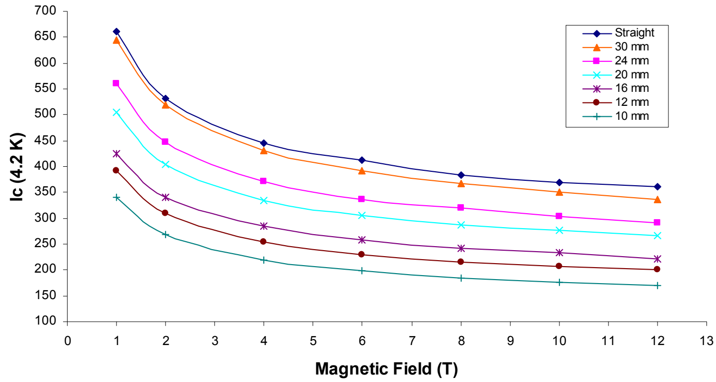

FIGURE 7. Critical current data at 4.2 K for BSCCO-2223 bent samples obtained by ramping the field up.

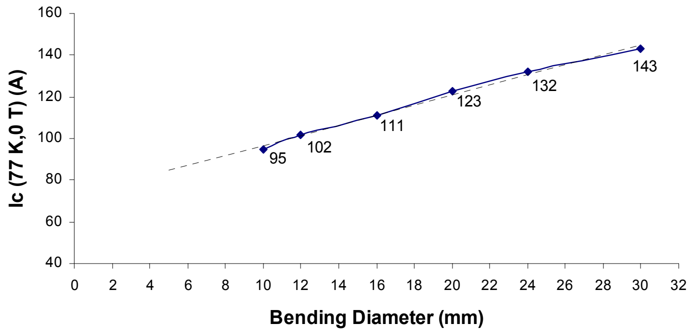

FIGURE 8. Critical current data at 77 K for BSCCO-2223 as a function of bending diameter.

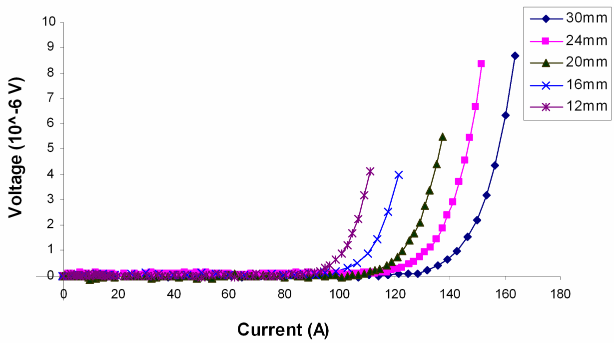

FIGURE 9. Voltage-current curves at 77 K of BSCCO-2223 tested straight after bending stress is released.

In FIGURE 8 critical current values in Nitrogen are plotted against bending diameter, showing a linear degradation as the diameter was reduced below 30 mm. When degradation is present due to bending, retesting the sample straight did not help in restoring the nominal critical current. Voltage-current curves showing this effect can be found in FIGURE 9.

Superpower SCS4050 YBCO Tape

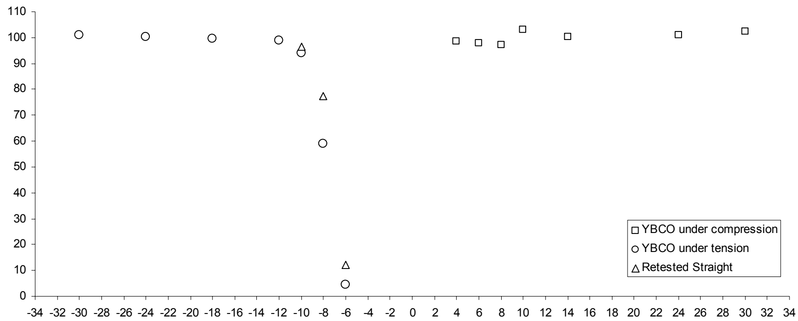

FIGURE 10. Critical Current (77 K,0 T) of Superpower YBCO samples under bending conditions.

Using the same set of setups and procedure, several Superpower tapes samples were tested under bending conditions. Given the asymmetry in the cross section of the tape [8], tests were run both with YBCO under tension and under compression. The tests were run on standard Superpower SCS4050 samples with nominal overall thickness of 0.1 mm and nominal width of 4 mm. All tested samples had 1 micron thick ybco layers and nominal critical current in Nitrogen under self-field conditions of 100 A. As shown in FIGURE 10, when the YBCO layer is put under tension, no critical current degradation occurred down to 12 mm, whereas 95% of critical current is still in the tape when bent to 10 mm. Retesting the bent sample on a straight sample holder generally showed an improvement in critical current, but no full recovery occurred for all of the tested samples.

A complete set of Helium tests have been performed on bent samples under tension and are presented in FIGURE 11. Data refer to magnetic fields parallel to the face of the tape. A very high degree of reproducibility was observed for all the samples that showed no degradation. A drop in critical current is noticeable for diameters below 10 mm both in Helium and in Nitrogen tests.

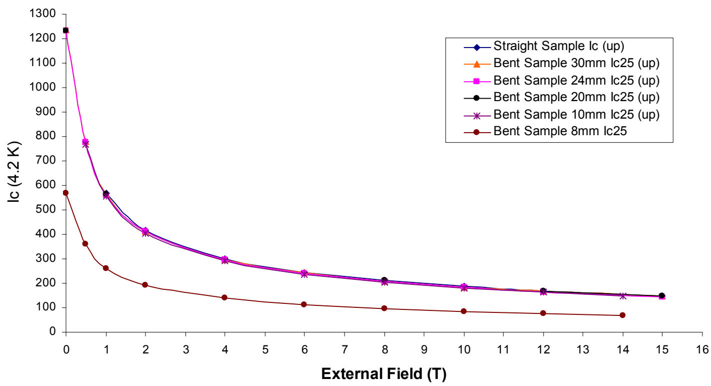

FIGURE 11. YBCO critical current data in Helium under bending conditions (ybco under tension).

SMALL HTS COILS

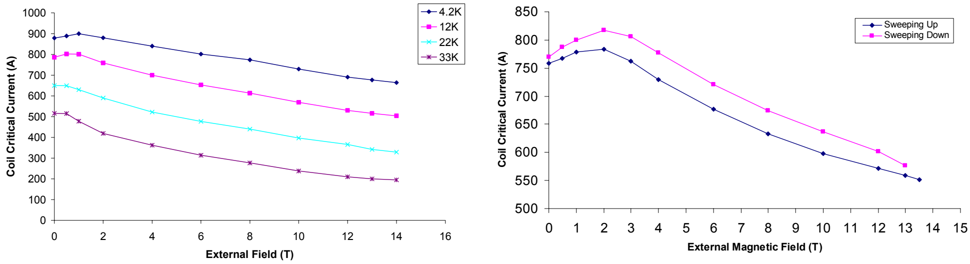

FIGURE 12 AMSC 348 YBCO Single Pancake Test results. Coil ID/OD: 38 mm/43 mm (left); AMSC BSCCO-2223 Single Pancake Test results. Coil ID/OD: 38 mm/43 mm (right).

To practice winding and evaluate conductors, some small coils have been built and tested as inserts in a 14 T Nb_3Sn/NbTi magnet with a 77 mm cold bore. First coils were built as single pancakes using American Superconductor YBCO 344 and BSCCO-2223 tapes. In FIGURE 12 the performances of such coils is presented as a function of field and operational temperature, which ranged from 4.2 K to 33 K. All coils showed results comparable with short sample expectations.

A double pancake unit made of Superpower SCS4050 (4mm by 0.1 mm with 2x20 µm of copper stabilizer) has been built and tested. A small geometry (ID=60 mm, OD=62 mm) was chosen to check winding procedures, turn to turn insulation, instrumentation and joints techniques.

The coil was made out of tape with nominal critical current in Nitrogen of 130 A. The coil carried the expected 1000 A in self-field at liquid Helium temperature. Details of the instrumented coil and voltage-current curves at 4.2 K in self-field conditions are shown in FIGURE 13.

Splices to the copper were performed bridging each of the 4 mm coils to the respective lead using Superpower SCS12050 tape. 1.5 mil adhesive Kapton was chosen as turn to turn insulation. A total of three pairs of voltage taps were mounted to monitor voltages for both top and bottom coils, as well as lead to lead signal.

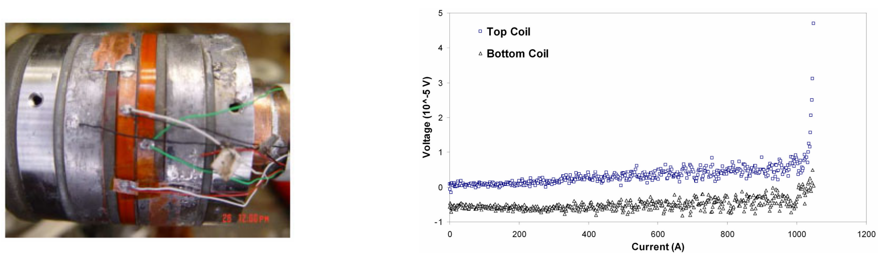

FIGURE 13 YBCO double pancake instrumented coil (left) and voltages for top and bottom coil (right)

CONCLUSIONS

In this paper, the critical current behavior as a function of field and field orientation for 2G YBCO samples has been studied and an analytical fitting has been proposed and shown on a set of in-field experimental data collected at Fermilab. The expression can be easily used, for instance, for critical current mapping of different coil geometries and short sample limit calculations.

Studies of critical current degradation due to bending strain for both 1G BSCCO-2223 and 2G YBCO conductors have been performed. While BSCCO-2223 shows larger critical bending diameter but linear I_c degradation, YBCO samples shows a much smaller critical bending diameter but a sudden drop in critical current.

Several small coils with different geometries have been built and tested to finalize winding procedures, joints techniques and turn to turn insulation. Some more effort is currently being put into finalizing impregnation techniques and scaling up to larger coil geometries.

ACKNOWLEDGMENTS

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