The Effect of Magnetic Field Orientation on the Critical Current of HTS Conductor and Coils

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Abstract*—The critical current of short samples of HTS multifilamentary conductor and ring-shaped coils has been measured at helium temperatures with varying magnetic field orientation with respect to the conductor. The samples and coil conductor consist of a multifilamentary composite of BSCCO-2223 filaments in a silver matrix. Short conductor samples were tested in a variable temperature system with up to 8 T background field using a sample rotational system. Ring-shaped coils made from the sample type of conductor were exposed to a large background field at liquid helium temperatures and critical current was measured with the ring located at various axial positions within the bore. As the ring moves closer to the end of the magnet, the measured critical current decreases, even though the magnitude of the field to which the ring is exposed decreases. This decrease in J_c is due to the strong anisotropy of the superconductor and is consistent with short sample measurements.

I. Introduction

High temperature superconducting materials, such as the bismuth-, thallium-, and yttrium-based superconductors, have a critical current that is dependent not only on the operating temperature and magnitude of the magnetic field to which it is exposed, but is also strongly dependent on magnetic field orientation [1]. For the magnet and systems engineer, this results in additional constraints on the design of a superconducting magnet system, because the magnitude and orientation of the field varies with position within a given magnet winding. The present study correlates the performance of high-temperature superconductor (HTS) in a magnet winding with short sample measurements of critical current as a function of magnetic field amplitude and direction. Unlike conventional low field magnets, the end turns of an HTS winding limit the overall critical current of a magnet due to the strong orientation dependence of the critical current density of the HTS material [2].

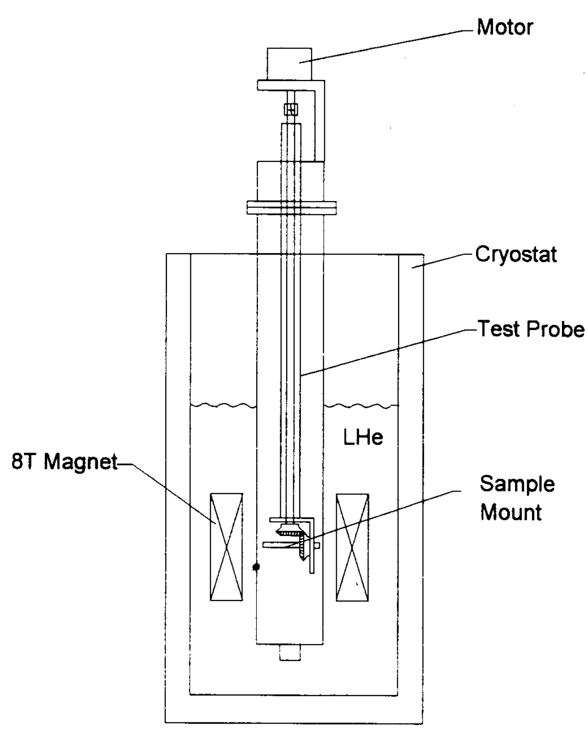
II. Short Sample Measurements

A. Measurement Apparatus

The test apparatus depicted in Fig. 1 consists of a 4-inch bore, 8 tesla low-temperature superconducting magnet with a variable temperature insert. The test probe has an angular motor control and right angle gear drive which allows the sample to be rotated in the applied field. By adjusting the flow valve on the helium cryostat and the vaporizer heater, the sample tube can be filled with either liquid helium or helium vapor.

The sample mount shown in Fig. 2 allows two 7.5-cm long samples to be measured at the same time. In order to match the thermal contraction of the HTS samples and provide good thermal stability, the sample mount is comprised mostly of silver, except for a G-10 spacer which is used to direct the flow of current through the two samples. The silver cover piece inserts into the bottom piece providing sample support under the Lorentz forces. A flexible copper braid is used for the current leads. These leads provide adequate cross-sectional area to limit the ohmic heating, while still allowing rotation of the sample mount.

Fig. 1. Angular dependence test apparatus.



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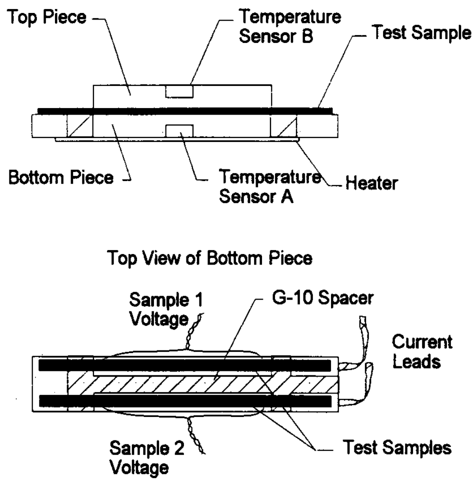

Fig. 2--Angular dependence sample mount.

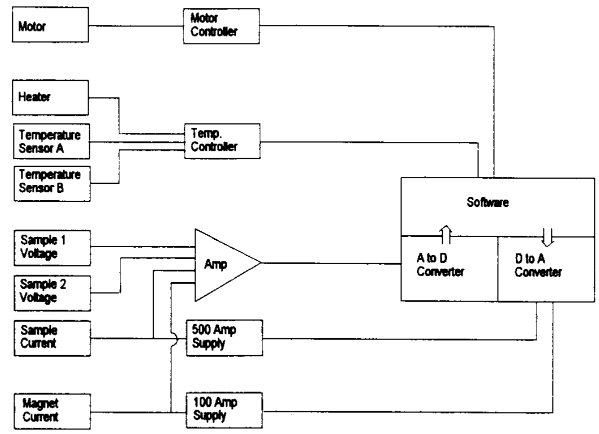

Fig. 3. Instrumentation and computer control layout.

For temperature control, two resistance temperature sensors, which are insensitive to magnetic fields, and one thin-film heater are used. Sensor A is used to control the heater, while sensor B is used to monitor the sample temperature. Tests showed good temperature stability at low temperatures even with currents greater than 100 A.

Samples are soldered to the silver end tabs with low-temperature (< 100 C) indium-bismuth solder. After the top piece is set in place, the voltage taps are soldered onto each sample. The silver cover piece and voltage leads are secured to the sample mount with tape. The entire mount is then inserted into the gear and locked in place with a set screw.

Data acquisition and computer control software is used to operate this measurement system. A block diagram of the instrumentation and computer control is provided in Fig. 3. The software directly controls the motor and temperature controllers. The sample voltages and shunt voltages from the sample and magnet power supplies are amplified before going into the A to D converter, while a D to A converter sends out voltages to control the two power supplies.

B. Sample Data

For this report, the test samples were divided into two categories--test samples and magnet wire samples. The test sample data is included to demonstrate the overall performance of the test system, while the magnet wire sample data is provided to explain the performance of the ring coils.

1) Test Samples: Two 85-filament BSCCO-2223 wire test samples (2.54-mm wide by 0.20-mm thick) were measured at various temperatures and fields to test the measurement technique. Initially, the samples were cooled to 20 K at an angle of -90 degrees, and the field was ramped to 1 tesla. With the field held constant, data was taken at angles ranging from -90 to +90 degrees. Then, data was taken from +90 to -90 degrees. These data are provided in Fig. 4 showing the angular hysteresis.

In an alternative measurement procedure, the samples were cooled down to 77 K, and a scoping test was run to find the true 0-degree angle. After adjusting the samples to this true 0-degree angle, the samples were cooled to 20 K, and the field was ramped to 1 tesla. Data was taken at angles ranging from 0 to +90 degrees. Next, the angle was rotated back to 0 degrees, and the samples were warmed to 120 K (above Tc) and allowed to cool down to 20 K. Then, measurements were taken from 0 to -90 degrees. These data are also plotted on Fig. 4 showing the expected symmetry of angular dependence.

2) Magnet Wire: A 19-filament BSCCO-2223 wire (4.32-mm wide by 0.15-mm thick) was measured at 4.2 K in background fields of 1, 2 and 4 tesla and at angles of -3 to +90 degrees (Fig. 5). After running a scoping test to find the true 0-degree angle, the samples were cooled to 4.2 K, turned to an angle of -3 degrees in order to ensure that the peak was captured. Next, the field was ramped to 1 tesla, and, with the field held constant, data was taken at angles ranging from -3 to +90 degrees. After these tests, the samples were rotated back to -3 degrees, warmed to 120 K (above Tc) and allowed to cool back down to 4.2 K. Then the field was ramped to 2.0 T, and the tests continued.

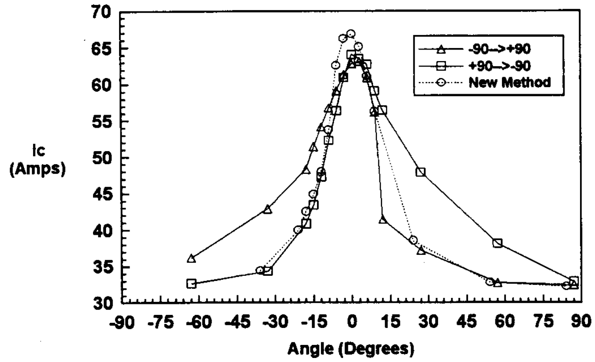

Fig. 4. 85-filament test sample angular dependence data (20 K).

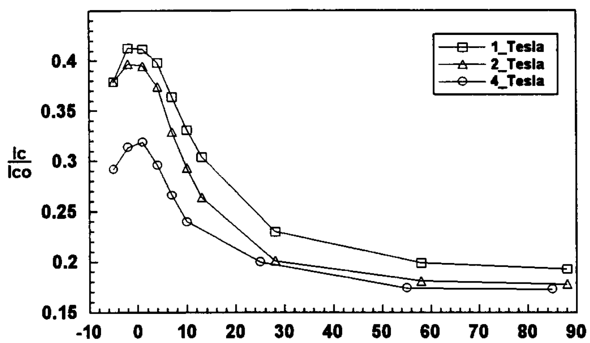

Fig. 5. 19-filament magnet wire angular dependence data (4.2 K). Data are normalized to the 4.2 K, zero-field Ico of 90 amps.

III. Ring-Shaped Coils

A. Sample Preparation

The superconducting composite ring coil was fabricated using the react-and-wind fabrication method with a continuous 22.25 meter length of a 19-filament HTS wire (2.54-mm wide by 0.2-mm thick). This wire was processed similarly to the magnet wire mentioned previously (Fig. 5.) The wire used to wind this coil had a critical current of 15.9 A at 77K, which corresponds to a 4.2 K critical current of 82.7 A, compared to values of 20.4 Amps at 77 K and 90.0 Amps at 4.2 K for the test sample. The ring coil has an outside diameter of 152 mm, an inside diameter of 140 mm and axial length of 14 mm.

Before layer winding the wire into the coil geometry, a 25 μm-thick layer of insulation was applied to each side of the wire using a UV-coating method developed at ASC. During the winding process, epoxy was applied to the windings, or "wet wound," to give the coil mechanical strength. A fiberglass wrap was added to the outside diameter of the magnet. The ring coil has 49 turns and a weight of 150 g.

This coil was thermally cycled fifteen times at 77 K showing little degradation in critical current (7.24 to 6.98 A; 3.6%). A 4.2 K measurement was also performed, yielding a critical current of 40.2 amps.

The advantage of this ring coil, as compared to a more compact solenoid, is that in the test environment, the magnetic field is roughly constant in amplitude and direction over the entire volume of the coil.

B. In-Field Measurements

The 49-turn BSCCO coil was tested by placing it on a holder in the bore of a large solenoidal background magnet, as shown in Fig. 6. The coil holder was designed so that the coil could be moved up and down along the axis of the background magnet, enabling the critical current to be measured in the different field orientations and magnitudes that occur close to the inner windings of the magnet.

All measurements were carried out at 4.2 K using a critical-current criterion of 1 μV/cm. Voltage taps were attached to the test coil about 3 cm from where current was introduced. Because the test coil contained many turns, induced voltages were high and so a counter-wound coil approximately matching the number of turns in the test coil was used to null out much of the induced voltage noise.

The sample coil was cooled in zero field, the background magnet was energized to a central field of 4 T, and the V-I curve of the sample coil was measured. The sample coil was then moved axially toward one end of the background magnet and the V-I curve was measured again. This procedure was repeated until the sample coil eventually reached the fringing field at the end of the background coil. The hysteresis of the measurement was less than 1% as the coil was moved to the end of the magnet and back again. As the coil is moved, the field orientation changes from being parallel to the axis of the test coil, to impinging on it at an angle to the axis, and the magnitude of the field at the test coil decreases. A second experiment was conducted in the same way, except that the current in the background coil was increased as required to keep the magnitude of the background field constant at the sample coil. The required increase in current was determined from a magnetic-field profile of the background coil.

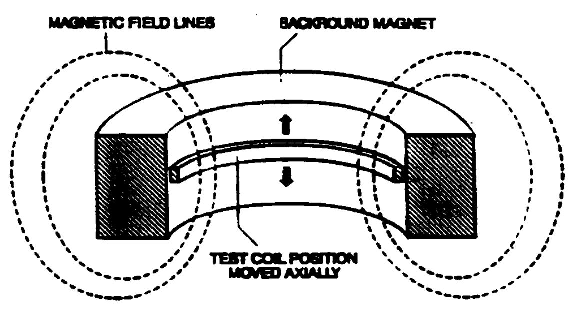

Fig. 6. Ring coil test configuration, with ring coil at zero offset.

IV. Results

The critical current results for these two test cases--constant current and constant field--are provided in Table I. The angle data is the angle between the tape plane and the total magnetic field of both coils, computed using a computer-generated field map of the background magnet and test coil and averaged over the cross-section of the test coil.

In Fig. 7, the critical current values for the two test cases are compared. As the ring coil location is shifted from the middle to the end of the magnet, the critical current of the ring coil at 4.2 K decreases by ~20%. This occurred even though the field magnitude near the magnet end was less than in the middle. Approximately the same result was obtained when the field magnitude was kept constant at the test coil.

In Fig. 8, the constant field test data are compared to the 4.2 K, 4 T short sample data (Fig. 5). The error bars represent the range in field angle over the cross-section of the ring coil.

TABLE I
IN-FIELD RING COIL MEASUREMENTS

Offset Position (cm)	Angle (deg.)	Constant Current	Constant Field
-1	-2.2	26.6	26.9
0	0.0	27.1	27.2
1	2.2	26.4	26.4
2	4.4	25.1	25.1
3	6.9	23.7	23.6
4	9.7	22.6	22.3
5	12.9	21.4	21.2
6	16.6	21.7	21.1
7	20.4	21.7	21.6

V. Conclusion

High temperature superconductors present magnet engineers additional challenges in the design of practical magnet systems. The strong dependence of critical current on magnetic field orientation requires a new design paradigm for magnet windings. As a result of this strong orientation dependence, the end turns of a magnet winding limit the critical current rather than the high field region near the midplane, as is the case with conventional low-temperature magnets. The effect is ascribed to the dependence of critical current density on magnetic field orientation. This can be seen from a quantitative comparison with the short-sample Ic-vs.-angle characteristics of the conductor.

Thus, the effect of angle dominates the effect of reduced flux density at the magnet ends, in contrast to the case for low-temperature superconductors. The ring results shown here were obtained at 4K where angle anisotropy in the Bi-compound is smaller than at higher temperatures; therefore, the effect is expected to be more significant for BSCCO superconductor magnets operating at higher temperatures.

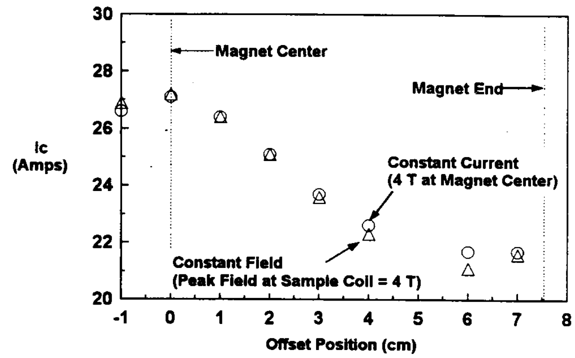

Fig. 7–Comparison of Ic results for the constant current and constant field test cases.

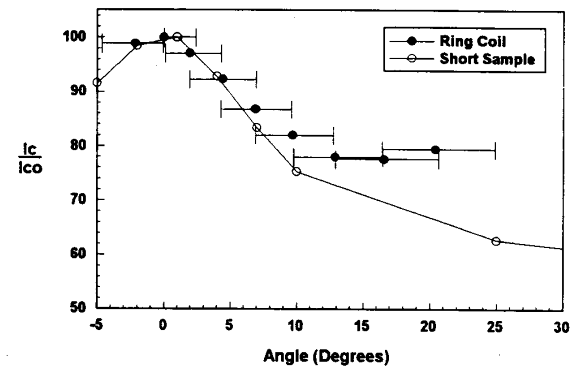

Fig. 8–Comparison of short sample and constant field ring coil results. The data are normalized to the 4.2 K, 4 T, 0-angle values.

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