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The Performance of Bi-Sr-Ca-Cu-O Superconducting Quadrupole Coils

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***Abstract*—A small saddle coil for quadrupole magnets was made in industry from BSCCO-2223 high temperature superconducting tape. The coil was made to help develop methods for winding the ends of small-aperture magnets. This coil has a radius of 35 mm. It was tested in liquid helium, and liquid nitrogen. Voltage taps have been installed so that V-I characteristics of both straight and curved elements can be examined. The performance of the coil will be compared to short sample measurements of pieces of conductor taken from the start and finish of the windings.**

I. INTRODUCTION

The technology of superconducting magnets has played a critically important role in the development of current high-energy particle accelerators. The application of this technology in accelerators to date has been limited to the use of low-temperature superconductors (LTS), such as Nb-Ti. The development of magnetic devices using high-temperature superconductors (HTS), with their higher critical fields and higher operating temperatures, could provide substantial advantages over the current LTS technology.

The higher operating temperature of HTS systems (relative to LTS systems) allows a simpler and less expensive cryogenic system to be used. A specific example of an application in which this could be an important advantage is provided by the magnet system for a possible upgrade [1] of the CESR storage ring at Cornell. For this application, compact dual-bore superconducting quadrupole magnets [2] are required. These magnets have a length of about 40 cm, a small magnetic bore (35 mm radius), and a field gradient of 10 T/m. The required field quality and the small bore dimension rule out the use of flat coils. However, saddle coils made from BSCCO-2223 tape, operated at about 30° K and providing 5500 A-turns, would satisfy the geometric constraints and meet the field gradient requirements. The peak field seen by the coils is modest, about 0.37 T (in the "bad" direction, i.e., perpendicular to the tape surface).

II. SADDLE COIL DESIGN

The basic parameters of the coils are fixed by the magnet requirements discussed above. The coil inner radius is 35 mm, and its width is the width of the BSCCO tape (2.7 mm). The overall length is 380 mm, of which 334 mm is straight

In the straight part, the coil has a rectangular cross section, with a height of 15.0 mm. The rectangular cross section is chosen because it provides the best field quality. Field quality requirements also set the tolerance on the coil dimensions: ± 0.2 mm on the height, and ± 0.1 mm on the width.

The end coil design is shown in Fig. 1. The principal constraint on the design of the coil end was to minimize the strain experienced by the tape during coil winding. To this end, the winding mandrel was designed [3] to provide a constant perimeter surface. The smallest bend radius (experienced by the first tape layer) is 12 mm. Since this first layer of tape is wound on the constant perimeter mandrel, it will not experience any bending strain in the "hard" direction (parallel to the tape surface). As subsequent layers in the coil block are wound on top of each other, they do not lie precisely on constant perimeter surfaces and so experience some additional strain due to bending in the "hard" direction. This is partially compensated by the fact that these layers have a larger bend radius.

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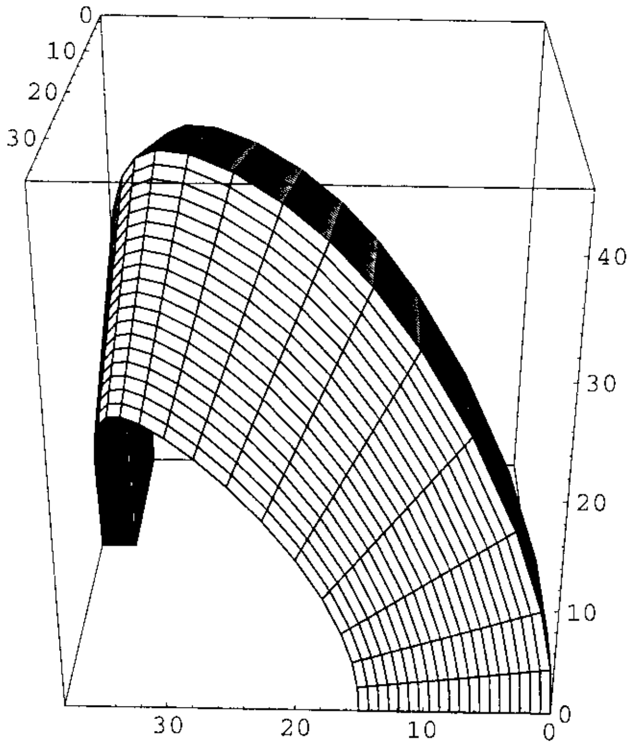

Fig. 1
Design of the end section of the saddle coil.
The numbers shown are millimeters.

III. COIL FABRICATION

The HTS saddle coil was fabricated using the react & wind process [4][5] with multifilamentary BSCCO 2223 tapes, nominal dimensions of 2.7 mm x 0.18 mm. A standard Oxide-Powder-In-Tube (OPIT) process was used to manufacture the HTS conductor with critical currents greater than 50 A at 77 K (1 μV/cm, self-field) [6].

The saddle coil is a single pancake winding with two tapes in parallel. Electrical insulation was co-wound into the coil structure for layer to layer voltage protection. The insulation was nominally 0.25 mm wider than the HTS tapes to protect against electrical shorts around the end turns. Voltage taps were installed in eight locations, four around the inner most turn and four around the outer most turn. The voltage taps were placed at each end of the straight elements to isolate the operating voltage of straight elements from the end turns, as shown above in Fig. 2.

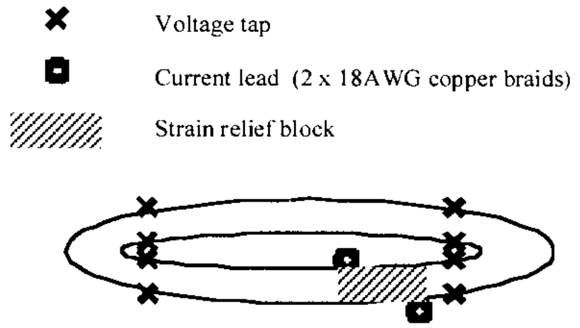

Fig. 2
Voltage tap configuration for comparing coil sections.

The winding procedure was based on existing winding technology used for Nb-Ti quadrupole magnet fabrication at Fermilab. The design of the winding mandrel is described in section II above and the fabrication of the mandrel was performed at Fermilab. The tooling to support the winding mandrel was designed and fabricated by American Superconductor Corporation (ASC). The tooling was designed to pivot and hold the winding surface along the straight elements perpendicular to the angle of the tapes as they are fed in from the pay off spools. As the tapes were laid around the end turns, the mandrel was pivoted simultaneously to maintain perpendicularity of the winding surface along the straight elements.

The coil winding procedure was developed as a two-person operation. The first person was responsible for maintaining the proper angle of the winding mandrel while the second person was responsible for placing the HTS tapes down onto the winding surface. The winding mandrel was pivoted by hand while laying down the end turns. Spring plunger pins were used to lock in the perpendicular angle of the straight elements.

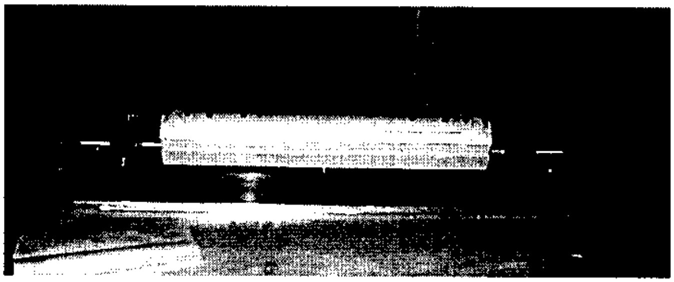

Fig. 3
The winding mandrel and tooling mounted on the winding table.

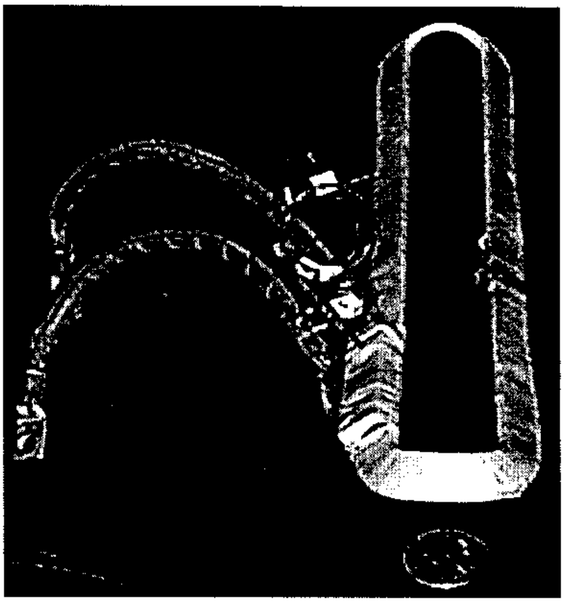

Fig. 4
HTS saddle coil .

Two 30 m strands of HTS tapes were wound into 32 turns. Quick connect clamps were used to support the windings in the straight elements. Temporary leads were then installed to check the windings for any shorted turns using an inductive pick-up sensing technique. No shorted turns were detected before wrapping the windings in fiberglass and vacuum impregnating with epoxy. The coil was impregnated and molded directly on the winding surface to ensure proper conformance to the 35 mm magnetic bore. The quick connect clamps were left on the straight elements during the cure cycle to ensure good uniformity of the windings. Following the impregnation, flexible current leads and voltage taps were installed to begin initial testing.

Dimensional measurements along the straight elements were made after impregnating the coil with epoxy. The dimensions include the bulk composite structure of HTS, glass, and epoxy. The average dimension of the straight elements measured 4.3 mm (+/- 0.1) in width and 15.2 mm (+/- 0.05) in height. Dimensional tolerance of a full quadrupole coil set would have to be controlled using rigid molding techniques.

IV. PERFORMANCE OF THE COIL

The performance of the coil at 77 K is shown in Fig. 5. Eight coil sections were measured for comparing straight elements with end turns. The 1μV/cm criteria is used for comparing the performance of coil sections. The data shows the critical current to be 43 A when measuring the coil from end to end. The critical current increased to 46 A with the outer and inner turn excluded from the voltage measurement. An improvement in the transition also resulted from excluding the outer and inner turn. The index value increased from 7 to 9. The improvement appears to be the result of handling losses in the outer turn on the return end of the coil. The handling associated with terminating the windings is the likely source of increased voltage on that turn, which is approximately equal to the difference in the two coil measurements. Also, the outer turn on the lead end shows considerably less voltage. The voltage measured on the inner turn at both ends of the coil, as well as both straight elements, is negligible relative to the coil voltage. However, the outer turn of the straight element shows higher voltage than the inner turn, again suggesting handling losses on the outer turn.

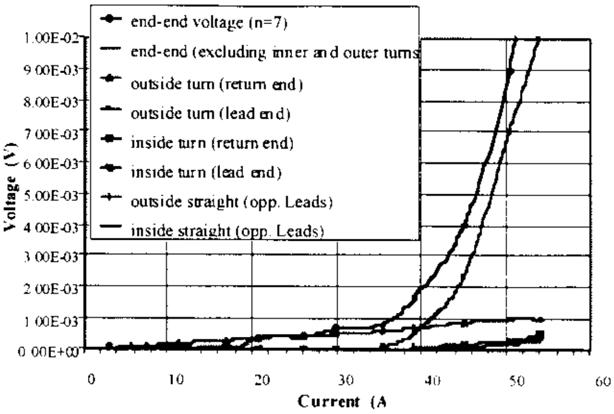

Fig. 5
77 K performance of the HTS saddle coil.

The performance of the coil relative to the conductor characteristics is shown in Fig. 6. Six short conductor samples were cut from each strand, three from the start and three from the finish of the windings. The short samples were measured across 1 cm, resulting in an average critical current of 53 A at 77 K, 1μV/cm, and self field. The critical current of the saddle coil shows the conductor performance after handling, bend strain, and field effects. Handling losses are seen in the measurement of the outer turn in figure 5. Bend strain was characterized in two independent experiments designed to quantify losses associated with the end turns. The results of both experiments were consistent, suggesting a 15% loss in performance due to bend strain. The effect of magnetic field on HTS performance is well known [7]. The field component perpendicular to the wide face of the conductor will dominate the critical current retention of the coil.

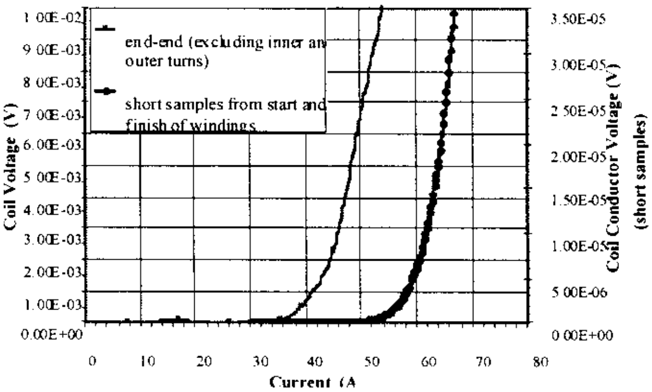

Fig. 6
77 K Coil performance relative to coil conductor taken from the start and finish of windings.

Figures 7 and 8 show the coil performance at 4.2 K and the coil mounted on the test probe, respectively. The data shows similar characteristics in the same coil sections as seen at 77 K. The critical current of the coil is 230 A with an index value of 7. The increase in critical current due to excluding the inner and outer turn is less than was seen in the 77 K measurements. The index value shows no appreciable difference.

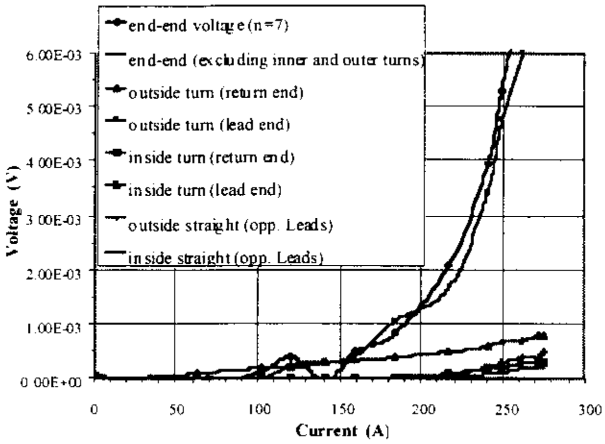

Fig. 7
4.2 K performance of the HTS Saddle Coil

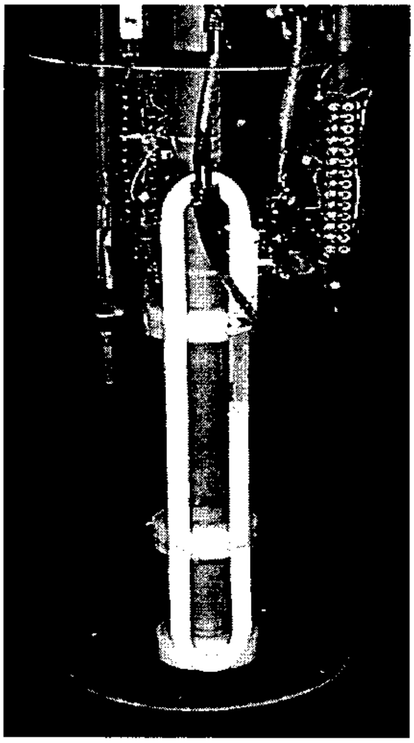

Fig. 8
HTS Saddle Coil Mounted on Test Probe

V. CONCLUSIONS

Design and fabrication techniques for small quadrupole saddle coils using HTS tape conductor have been successfully developed. A small saddle coil, designed for use in a compact dual-bore superconducting quadrupole magnet, has been fabricated from BSCCO-2223 tape conductor. The critical current performance of the coil at liquid nitrogen and liquid helium temperatures has been measured.

The critical current measurements at 4.2 K show a scale factor of 5.3 improvement over the 77 K performance. The equivalent improvement factor for 30 K operation is expected to be 4. Using this scale factor, we estimate the coil's critical current at 30 K, 1μV/cm, (self field) to be 172 A. This current is sufficient to meet the 5500 A-turn requirement mentioned in the introduction, which will produce the required field gradient. When operated at 172 A at 30° K, the power dissipation in each coil would be about 0.4 W, leading to a total power dissipation of about 3.2 W at 30° K for an 8-coil dual bore quadrupole magnet.

The successful implementation of a quadrupole magnet for high energy physics applications also requires meeting demanding field quality specifications. To determine whether this requirement can be met, a complete prototype quadrupole magnet, using four saddle coils, must be assembled and field mapped.

ACKNOWLEDGEMENTS

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