Performance of Coils Wound from Long Lengths of Surface-Coated, Reacted, BSCCO-2212 Conductor

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Abstract-- React-before-wind surface-coated BSCCO-2212 is being established as a relatively low cost HTS conductor for practical applications. Quality tape is presently being manufactured in lengths of 450 to 500m at a cost estimated to be 1/3 to 1/5 of the industry costs of BSCCO-2223 powder-in-tube tape. Robust, mechanically sound coils for applications ranging from NMR insert magnets to transformer windings are being made from this BSCCO-2212 tape. The coils have performed consistently through test and thermal cycling without degradation and as projected from short sample measurements. A hybrid approach, which uses mainly BSCCO-2212 augmented by BSCCO-2223 conductor in the high radial field end regions, is expected to halve magnet system costs.

I. Introduction

$Bi_2Sr_2Ca_1Cu_2O_x$ (BSCCO-2212) is attractive as a practical high temperature superconductor for magnet and energy applications because of high overall critical current densities and potential low cost of manufacture. One application of this conductor is for high field insert coils for magnets, utilizing the high current densities achieved at 4.2K in magnetic fields in excess of 20T [1-7]. Broader application may result from use at 20K, where reliable and efficient refrigeration is available from two-stage Gifford McMahon cryocoolers [8]. Critical current densities greater than 10^5 A/cm^2 in the oxide coatings of short 2212 samples have been measured at 20K in magnetic fields as high as 6T [9]. For lower field applications, such as for transformer windings which typically operate at 0.1 to 0.3 Tesla, sufficiently high current densities may be obtained for practical use at 35K to 40K [10]. Experiments have been performed using BSCCO-2212 in refrigerated liquid nitrogen at 64K to drive flux across air gaps in an iron yoked demonstrator for magnetic levitation applications [11].

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Coil construction is simplified and made more cost-effective if coil winding can be reliably performed in a conventional manner after all heat treatments and reactions have been applied to the superconductor. In this paper we report the development and performance of several coils which have been made for various applications from long lengths of a relatively low cost react-before-wind surface-coated BSCCO-2212 conductor. We also describe an approach for the construction of hybrid magnets which will utilize mainly this conductor, augmented by BSCCO-2223 powder in tube conductor in the end turn regions where radial fields are high.

II. BSCCO-2212 Conductor

Intermagnetics is presently manufacturing 2,000 meters per month of 6mm wide by approximately 0.1mm thick react-before-wind surface coated BSCCO-2212 tape in lengths of 450 to 500 meters. Figure 1 shows a reel of 485 m of reacted tape ready for winding into coils.

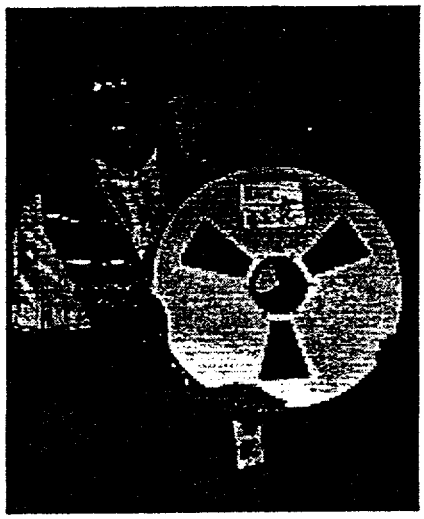

Fig. 1 - 485 meters, continuous length of high quality react-before-wind BSCCO-2212 surface-coated conductor.

We estimate that our costs for the manufacture of this conductor are approximately 1/3 to 1/5 of the present cost in the industry for powder-in-tube processed BSCCO-2223. The I_c's at 77K, 0T of short samples cut from optimally processed

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C. Minimum Bend Diameter

The minimum bend diameter for our surface-coated BSCCO-2212 tapes was established on a uniform 6 amp tape by winding short lengths as one turn coils over winding mandrels of various diameters and testing for I_c in self field in liquid nitrogen at 77K. The results, shown in Figure 5, indicate that this conductor can be safely wound on diameters as small as 50mm without significant degradation in I_c.

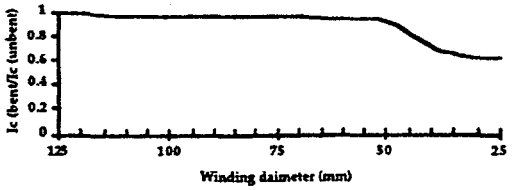

Fig. 5 - Ratio of Ic's of samples wound on mandrels to Ic's of unbent samples.

D. Practical Large Bore High Field NMR Insert Coil [13]

Practical NMR coils will need a substantial clear bore to allow for dewar walls and adequate room temperature space for samples. A 6 amp tape, similar in quality to that used for the bend test described above, was used to construct a 63mm I.D. x 138mm O.D. x 77mm long (winding region), 50mm clear bore insert coil, shown in Figure 6. This coil was layer-wound using three 270m lengths of conductor. It produced a 1.08 Tesla central field at 4.2K in the largest (5.5 Tesla) background field conveniently available. The self field thus produced is 90% of the self field generated by the same coil in zero background field, confirming that the coil performance up to 5.5T is limited mainly by the radial component of the self field of the insert coil. Arrangements are being made to test this coil in higher background fields.

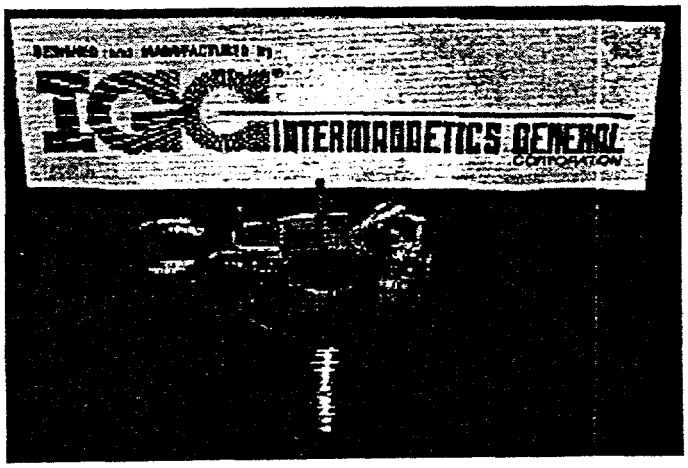

Fig. 6 - Insert coil for high field NMR coil made from surface-coated react-before-wind BSCCO-2212.

E. Small Coils Simulating Transformer Windings: To Test for 60Hz AC Losses [10]

Two pairs of coils were constructed to test for ac losses in simulations of the operation of transformer primary and secondary windings. Each coil set was approximately 125mm in diameter and 100mm long. Losses were measured calorimetrically for each coil set by controlling coil temperature in helium gas in the range of 15K to 40K, applying 60 Hz ac for several seconds, measuring the temperature rise produced, and calibrating the rise against pulses of similar duration from heaters. One pair of coils was made of 6 amp tape and the other of 8 amp tape. Each coil set reached critical currents projected from measurements on short samples for the fields and temperatures of coil operation.

F. 1-MVA HTS Demonstration Transformer [10]

React-before-wind, surface-coated BSCCO-2212 conductor was wound to make the first coil for a 1-MVA HTS Demonstration Transformer. The approximately 2/3 m diameter x 4/3 m long winding former for the coil is shown at winding start in Figure 7. The I_c of this coil measured in preliminary tests in liquid nitrogen at 77K is as projected for the fields produced in the coil for the 10 ampere conductor tape that was used. Primary and secondary coils will soon be assembled into the transformer for cryo-cooled operation in the range of 20 to 35K.

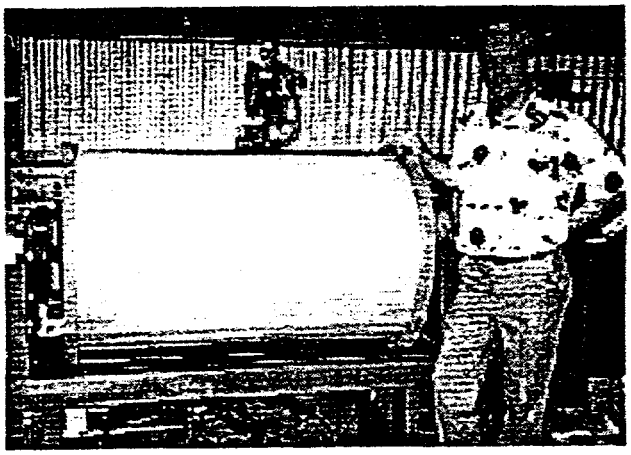

Fig. 7 - Former for first of the 1MVA transformer coils mounted on the winder at winding start.

G. Next: Relatively Low Cost Hybrid HTS Magnet Systems

The I_c of BSCCO-2212 surface coated tape is limited primarily by radial components of magnetic fields, which are strongest in the end-turn regions of solenoidal magnets. This relatively low cost conductor can be made much more effective by sandwiching it between BSCCO-2223 coils. The latter coils are more expensive, but need only comprise 20% of the winding and are less affected by the radial fields. We

tapes consistently fall within an 8 to 10 ampere range. Typical I_c data for these samples (at a resistive onset of one microvolt per cm) in field and at this and lower temperatures are shown in Figure 2 for fields parallel and perpendicular to the wide face of the tape.

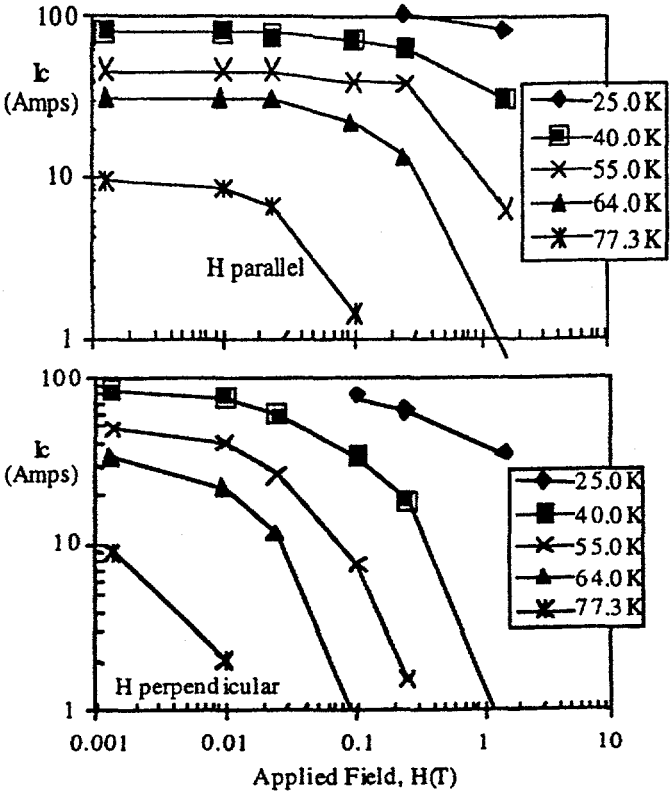

Fig. 2 - I_c performance of short samples of surface-coated BSCCO-2212 conductor vs. applied field at five different temperatures

Our development of coils began with earlier tapes ranging in I_c from 3 to 6 amperes at 77K, 0T. More recent coils have used the better production tapes described above, with I_c's at 77K, 0T as high as 10 amperes. Unless specifically stated otherwise, tape currents in the rest of this paper are the I_c's of short samples from the ends of long lengths and measured in liquid nitrogen at 77K, 0T using a 1 microvolt per cm voltage onset criterion.

III. Coil Technology

A. *Coil Construction*

Although the surface-coated BSCCO-2212 conductor is relatively fragile, we have developed handling and construction procedures which result in robust, mechanically sound coils which perform without degradation and as projected from short sample I_c data for the temperature and field of operation. These procedures were established at first using uniform tapes in the 3 to 4 amp range. Approximately twenty meter lengths of these tapes were wound into thin bifilar single pancake or double-pancake ring coils having diameters ranging from 140mm to 190mm. One such coil, fully instrumented for testing, is shown in Figure 3. No change in performance was observed in tests before and after impregnation of the coils with epoxy resin and before and after thermal cycling from room temperature to 77K.

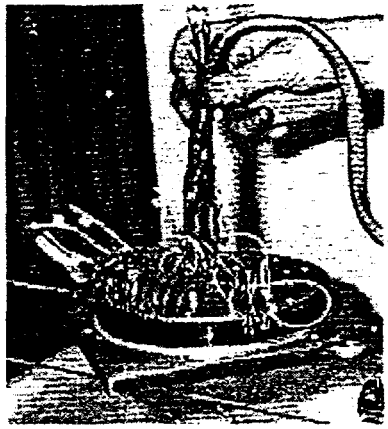

Fig. 3 - Bifilar coil of surface-coated react-before-wind BSCCO-2212 for epoxy and joint tests, wired for testing at 77K.

B. *U.S. NAVY Homopolar Motor/Generator Coils [12]*

Figure 4 shows a pair of 194mm I.D. x 245mm O.D. BSCCO-2212 ring coils that were constructed for the Navy. Each coil contains two double-pancake sections. Six to eight Amp tape was used in each of these coils to produce at 4.2K current densities in the conductor (oxide and substrate cross section) of 1.7×10^4 A/cm^2 and self-fields on the winding of 1.08T. This is the best performance of all of the BSCCO-2223 and BSCCO-2212 coils that have been tested by the Navy to date.

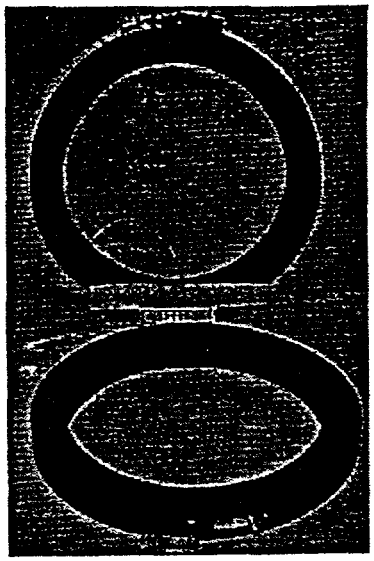

Fig. 4 - Coils of surface-coated react-before-wind BSCCO-2212 for NRL homopolar motor.

estimate that by using both BSCCO conductors the cost of HTS magnet systems may be lowered by a factor of two or more. Figure 8 shows the layer-wound insert coil of Figure 6 sandwiched between pancake-wound BSCCO-2223 coils. (The BSCCO-2223 coils, tested together as a short magnet at 4.2K, have already produced 4.2T. To our knowledge this is a world record self field for any HTS magnet [14].) Extension of the region of the hybrid occupied by BSCCO-2212 conductor (both radially to the same diameter as the end pancakes and axially to produce a longer section between them) will produce a hybrid magnet that is expected to generate at 4.2K a long, uniform central field of approximately 5T in a 36mm diameter clear bore.

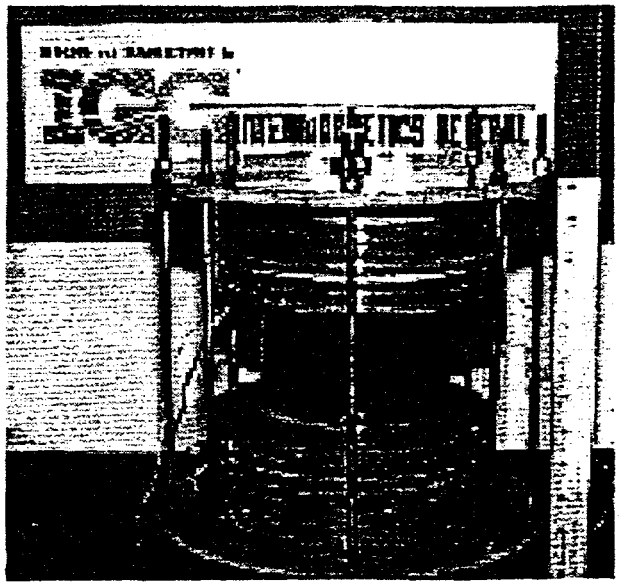

Fig. 8 - Hybrid magnet with react-before-wind BSCCO-2212 center section between BSCCO-2223 ends.

IV. Conclusions

React-before-wind surface-coated BSCCO-2212 is being established as a relatively low cost HTS conductor for practical applications. Quality tape is presently being manufactured in lengths of 450 to 500m at a cost estimated to be 1/3 to 1/5 of the industry costs of BSCCO-2223 powder-in-tube tape. Robust, mechanically sound coils for applications ranging from NMR insert magnets to transformer windings are being made from this BSCCO-2212 tape. The coils have performed consistently through test and thermal cycling without degradation and as projected from short sample measurements. A hybrid approach, which uses mainly BSCCO-2212 augmented by BSCCO-2223 conductor in the high radial field end regions, is expected to halve magnet system costs.

Acknowledgements

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