

## THE Bi-2212 CONDUCTOR AND MAGNET PROGRAM AT THE NATIONAL HIGH MAGNETIC FIELD LABORATORY

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### Abstract

The NHMFL has had a long running program to develop  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$  (Bi2212) for high field magnets. The recent development of round wire Bi2212 (RW2212) has strengthened the effort to develop solenoid magnets with fields substantially greater than can be achieved with  $\text{Nb}_3\text{Sn}$ . The present paper briefly summarizes some of the results obtained at the NHMFL in the past 12 months. It summarizes the talk given by David Larbalestier at WAMSDO on May 24, 2008. Much of the work is ongoing and will be reported in the normal peer reviewed literature in late 2008.

### INTRODUCTION

This paper briefly summarizes the principal goals and recent achievements of the program at the National High Magnetic Field Laboratory which is aimed at utilizing  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$  (Bi2212) superconductors for constructing very high field solenoids. The principal driver for NSF support of this program at the NHMFL is that the lab presently spends ~\$6 million per year on electricity to enable world-wide users to access the suite of world record DC magnets at the NHMFL in Tallahassee. These 20 MW Florida Bitter magnets generate 35 T in a 32 mm warm bore, 31 T in a 50 mm bore and 20 T in a 200 mm bore. The highest DC field of 45 T is generated by the hybrid (11.5T superconducting outsert and 34 T 32 mm bore 25 MW insert). Unfortunately the price of electricity is rising significantly year by year as the recent strongly increasing cost of oil reminds us. At present costs, each hour of magnet use costs about \$1000. Together these facts make all-superconducting magnets that could break the barrier of 22 T, to which  $\text{Nb}_3\text{Sn}$  is limited, very attractive. Two recent test magnets show that >30T, all-superconducting magnet systems are foreseeable. In 2003 Weijers *et al.*<sup>1</sup> constructed a Bi2212 tape magnet which achieved 25T in the 20T background of the 20 cm large bore resistive magnet (LBRM). In 2007 a 10-pancake coil of YBCO coated conductor made by Hazelton *et al.*<sup>2</sup> of SuperPower was tested to 26.8T in the 19 T background of the LBRM at the NHMFL. The National Academy Panel COHMAG<sup>3</sup> also recommended construction of a 30T class HTS NMR magnet. These various considerations have incited a multi-group effort on HTS technology at the NHMFL. In this paper I briefly review recent work on round wire (RW) Bi-2212 since this is of greatest interest to the high energy physics

community because it enables Rutherford cables<sup>4</sup>.

### MAGNET GOALS

The immediate goal of the present NHMFL RW2212 program is to design and construct a 30 mm cold bore solenoid made in 4 sections using the wind-and-react (W&R) process which will yield 7 T when tested in the 20 T LBRM<sup>5</sup>. An overview of the design is shown in Fig. 1. To achieve this goal, which is an essential proof of principle for our program, we must be capable of reacting coils without leakage of the BSCCO core to any significant extent, be able to uniformly react thick multi-layer windings without concern for inhomogeneities of temperature, oxygen partial pressure or other significant process variable, and then energize the magnet without damage due to electromagnetic stress or to normal zone propagation. To our knowledge there is no demonstration of all these points in a magnet of the size and scale envisaged here, though some significant progress towards these goals was reported by Marken *et al.*<sup>6</sup> using RW2212 small coils that generated self fields up to ~2.3T.

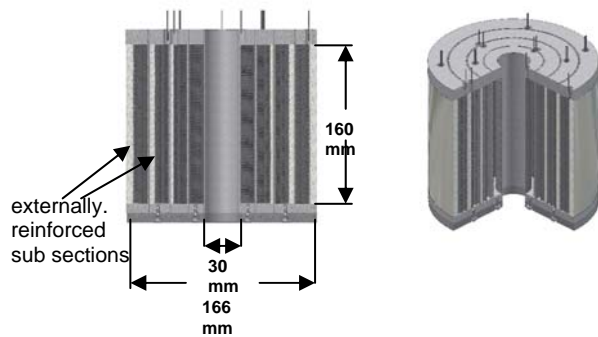


Figure 1: The NHMFL 7T insert solenoid design.

The conductor that is the heart of the coil is shown in Fig. 2. It is a double-stacked 85 x 7 design in which filaments are well separated before reaction but bridge extensively after reaction. As noted by Miao *et al.*<sup>7</sup>  $J_c$  falls off slowly from an engineering  $J_E$  ( $J_c$  referred to the whole wire cross-section, about 25% of which is Bi2212) of ~600 A/mm<sup>2</sup> at 5T, 4.2K to ~360 A/mm<sup>2</sup> at 30T. Such  $J_E$  values are high enough to make our coil feasible and probably not so high as either to cause self damage by Lorentz forces or under quench conditions. What is holding us back at present is the propensity of small coils containing 20-50 m of 1 mm diameter wire to leak Bi2212 in a small number of unpredictable places. We consider such leakage not acceptable for a robust coil technology.

This work was supported by NSF Division of Materials Research through DMR-0654118, the U.S. Department of Energy and the State of Florida.

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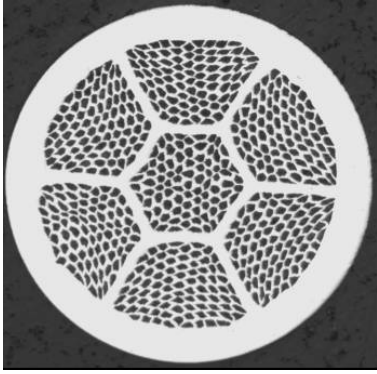


Figure 2: The OST Bi-2212 round wire conductor at a size of 1 mm diameter. The outer Ag web is alloyed with Mg while the remaining Ag is pure.

In fact of the 12 small coils that we made in 2007, 11 exhibited leakage. Most leakage was intermittent of the sort shown in Fig. 3, sometimes with greater and sometimes with lesser frequency. On occasions the leakage produced a rupture defect which was quite clear in the cross-section of the wire<sup>8</sup>, where evident reactions with the mullite wire insulation were also seen<sup>9</sup>. As noted earlier by Wesolowski *et al.*<sup>10</sup> the presence of many materials in proximity to RW2212 leads to wicking of the 2212 core through the silver sheath. We occasionally find that leakage occurs at obviously damaged sections of the wire, but this is not invariably true. Research to understand this leakage better is ongoing<sup>8</sup>.

A second challenge to be faced is that the behavior of the test coils was highly variable, the coils achieving  $I_c$  values varying from 60 to 281A in a background of 5T at 4.2K<sup>5</sup>. What is noteworthy about these  $I_c$  values is that they correspond to  $J_E$  values ranging from  $\sim 75$  to 350 A/mm<sup>2</sup>, well below the champion values of 600 A/mm<sup>2</sup> quoted above. While part of the discrepancy is to be associated with the higher electric field of Miao's report (5 $\mu$ V/cm) and part with their wire being at a smaller and more favorable size (0.8 mm), a common feature of long versus short samples is that significant  $J_c$  is easily lost for reasons that remain unclear.

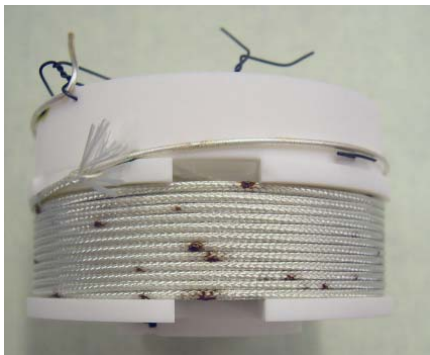


Figure 3: Intermittent leakage on the surface of the mullite-braid-insulated wire after reaction of test coil 3.

One set of experiments carried out in recent months to try to understand whether the  $J_c$  variation seen in our

standard reactions can be attributed to variations of vortex pinning or of connectivity or of some unknown mixture of the two is shown in Fig. 4. An extensive series of variable temperature magnetization curves<sup>9</sup> have been performed, two of which are shown in Fig. 4, where the highest  $J_c$  smaller diameter wire (0.8 mm) is contrasted with a typical 1 mm dia. sample cut from a deconstructed test coil. What is true of these two is true of all. Even though  $J_c$  is varying by more than a factor of 4, the irreversibility field defined by the linear extrapolation of the Kramer pinning function remains constant for standard reactions. It thus appears that  $J_c$  is independent of vortex pinning and controlled by connectivity.

A reconsideration of the reaction conditions for wires is also underway<sup>11</sup> following extensive consideration of the reaction studies of Rikel *et al.*<sup>12</sup> These studies are indeed showing that there is much to improve in the processing of wires to higher  $J_c$ , as will be forthcoming soon.

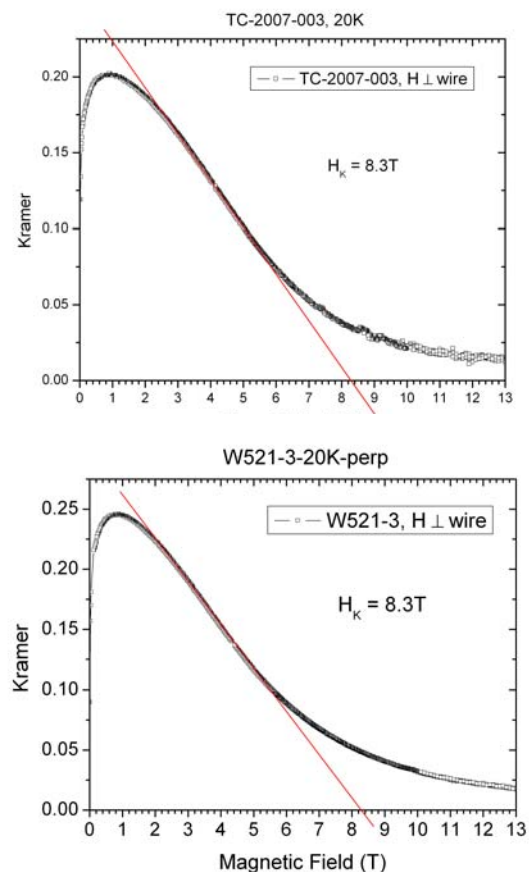


Figure 4: Hysteretic magnetization, reduced to Kramer function units, of two samples of RW2212 with very different  $J_c$  values. Both have almost identical Kramer fields equivalent to  $H_{irr}$  of 8.3T at 20K, even though test coil 3 sample (1 mm dia.) had  $J_E(5T, 4.2K) = 270$  A/mm<sup>2</sup>, while the optimum-sized (0.8 mm dia.) wire W521 had  $J_E = 700$  A/mm<sup>2</sup>.  $J_c$  appears to be controlled by connectivity rather than vortex pinning changes.

These recent experiments to test the capabilities of RW2212 are soon likely to be expanded by a more

extensive collaboration between groups at BNL, FNAL, LANL, LBNL, NHMFL, NIST and Texas A&M, with interest and expertise in Bi-2212. We hope that the essential tests of this very attractive conductor technology will be greatly advanced by this joint effort.

### ACKNOWLEDGEMENTS

We are grateful to Dr Seung Hong and his colleagues at Oxford Superconducting Technology for their long term collaborations and to Mark Rikel for many stimulating discussions about the processing of Bi2212. Dr Denis Markiewicz of the NHMFL is also thanked for many helpful discussions.

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