R&D for Accelerator Magnets with React and Wind High Temperature Superconductors

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***Abstract*—High Temperature Superconductors (HTS) have the potential to change the design and operation of future particle accelerators beginning with the design of high performance interaction regions. HTS offers two distinct advantages over conventional Low Temperature Superconductors (LTS)—they retain a large fraction of their current carrying capacity a) at high fields and b) at elevated temperatures. The Superconducting Magnet Division at Brookhaven National Laboratory (BNL) has embarked on a new R&D program for developing technology needed for building accelerator magnets with HTS. We have adopted a "React & Wind" approach to deal with the challenges associated with the demanding requirements of the reaction process. We have developed several "conductor friendly" designs to deal with the challenges associated with the brittle nature of HTS. We have instituted a rapid turn around program to understand and to develop this new technology in an experimental fashion. Several R&D coils and magnets with HTS tapes and "Rutherford" cables have been built and tested. We have recently performed field quality measurements to investigate issues related to the persistent currents. In this paper, we report the results to date and plans and possibilities for the future.**

***Index Terms*—Accelerators, dipoles, high temperature superconductors, HTS and quadrupoles, interaction regions.**

I. INTRODUCTION

THE PERFORMANCE of High Temperature Superconductors has been continuously improving [1], [2]. At present, the critical current density of HTS in wires of reasonable length ($\sim$100 meter) exceeds that of LTS above about 12 T (Fig. 1). Therefore, it has become possible to design a short hybrid accelerator type R&D magnet where the inner HTS coils generate high fields and the outer LTS coils generate the background field [3]–[5]. This strategy gives us an opportunity to start a cost-effective magnet R&D program to develop the technology and to address the issues that are relevant to accelerator magnets. In coming years (5 years or so), while we learn and demonstrate this challenging technology, the engineering current densities of HTS should improve by about a factor of two, given the current rate of progress. At that stage, one could design accelerator magnets where HTS plays a major role, thanks to the development of high field HTS magnet technology carried out in the preceding years.

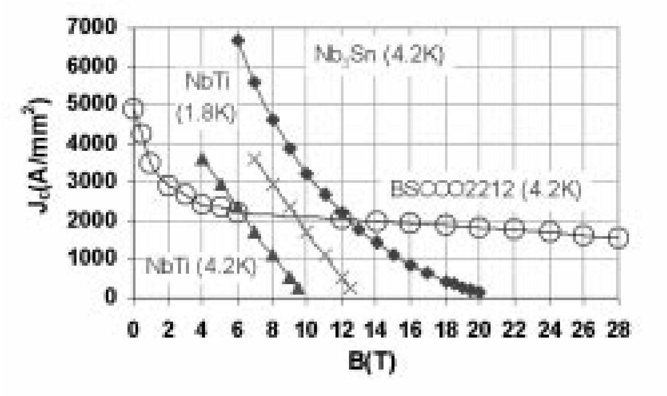

Fig. 1. The performance of conductor in year 2000.

The present major use of HTS in accelerators is the current leads [6] for LHC magnets [7] where they offer an overall better solution. Given the present high cost of the superconductor, HTS based accelerator magnets may find their first use in high performance interaction regions (IR), with a LHC luminosity upgrade being one such possibility. In such applications, performance rather than the material cost is the driver, since a few magnets would have a major impact on the overall performance of the machine. Apart from maintaining a significant critical current density at high fields, HTS magnets can operate at elevated temperatures without a large loss in performance. Moreover the operating temperature need not be controlled to the same level of uniformity as in conventional low temperature superconductors. These important benefits make HTS an ideal candidate for IR magnets as they are subjected to large energy deposition and must have a high pole-tip field for an efficient IR design [88].

II. HIGH TEMPERATURE SUPERCONDUCTORS

A. Conductor Choices

We have considered using BSCCO 2212, BSCCO 2223 and YBCO as possible candidates for HTS. Although MgB$_2$ (a higher temperature LTS) is making rapid progress in performance, it, like YBCO, is not yet available in sufficient length to make R&D coils. Therefore, all HTS R&D coils at BNL have been made with either BSCCO 2212 or BSCCO 2223. BSCCO 2212 looks more promising for accelerator magnet applications at present. This is because a) it is likely to be less expensive due to the manufacturing process involved, b) it already has equal or better critical current density than BSCCO

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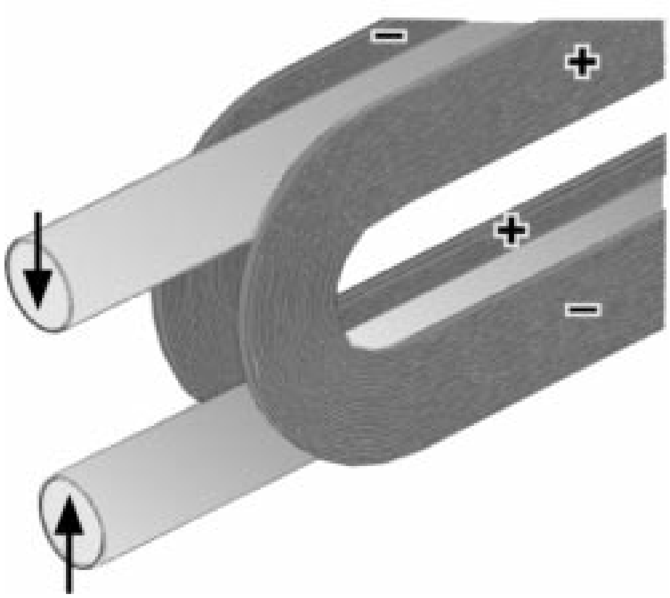

Fig. 2. The main coils of the "conductor friendly" common coil design concept.

2223 (which has been under development in industry for a long time) and performance improving more rapidly and c) it is readily available in both tape and wire forms.

B. Wire versus Tapes

For accelerator magnet applications, wire is preferred over tape. Apart from allowing higher current (lower inductance) for operating cable magnets made with a large number of wires, the Rutherford cable also provides better coupling between wires. Because of this and other reasons, the present magnet technology is based on Rutherford cables. At BNL, whereas BSCCO 2212 has been procured in both tape and wire forms, BSCCO 2223 has been procured in only tape form. We have made and tested coils made with both tapes and cables [9]. In addition to HTS coils, coils made with Nb_3Sn tapes and cables have also been made and tested [10]. An R&D saddle coil, using "Wind & React" technology, made by American Superconductor Corporation for a Cornell University project has also been tested [11].

Apart from making coils, we have also studied cable properties [1212]. Cables made with BSCCO 2212 strands, have already been reacted in ~70-meter lengths and efforts are underway to react them in longer lengths [2].

III. MAGNET DESIGNS

We are developing a number of alternate magnet designs for high field magnets that must use brittle superconductors, such as HTS and Nb_3Sn. The proposed designs are based on "conductor friendly" racetrack coil geometry with a "large bend radius." A large bend radius is critical to "React & Wind" magnets made with brittle materials. The proposed block-type designs for dipole and quadrupole magnets are also advantageous in containing the large Lorentz forces associated with high fields. These designs and their applications to various accelerators are briefly described here.

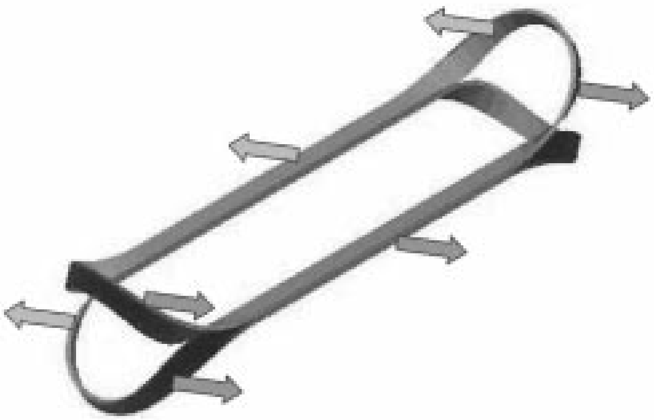

Fig. 3. Large horizontal Lorentz forces could move the coil, which would put strain in the magnet ends and may cause the magnet to quench.

A. Common Coil Design for Hadron Colliders

The 2-in-1 common coil dipole design [3] has been proposed for hadron colliders. In this geometry (Fig. 2), the main coils are two-dimensional (2-D) racetrack coils that are "common" to two apertures. Unlike conventional designs where the minimum bend radius of conductor is determined by the size of the aperture, in the common coil design it is determined by the separation between the two apertures. Since the separation between the two apertures is much larger than the size of the individual apertures, the geometry naturally offers a conductor friendly design with large bend radius.

Common coil geometry also offers the possibility of a simple and efficient mechanical structure because of the way Lorentz forces can be resolved into horizontal and vertical components. It is also interesting to compare how the large horizontal forces act in the ends of conventional and common coil designs. The net horizontal component of the Lorentz force puts a large strain on the conductor in the ends of conventional cosine theta or block designs (Fig. 3), especially if the coils are not contained with large pre-stress. In common coil designs, the horizontal forces move the coils (either on the left side or the right side of the bores, Fig. 2) as a whole. Because of this, there will be lower internal motion and strain on the conductor situated in the coil ends. This and a simple 2–D structure are expected to make more robust and better performing (quench) ends in common coil designs.

Several designs based on common coil geometry have been investigated [3]–[5], [9], [10], [14]–[23]. This includes the common coil magnet design for proposed VLHC-2 [22]. Computer calculations have shown that good field quality (body, ends and saturation) can be obtained in the common coil design [4]. Several R&D magnets based on this design have been built and tested in the last three years [4], [5], [9], [10], [17], [18]. A somewhat similar design was proposed by Danby in as early as 1983 [14].

B. Open Midplane Dipole Design for Muon Collider

Muon colliders and Neutrino Factories [25] offer a new way of doing high energy physics since muons are point like particles like electrons but lose much less power by synchrotron radiation due to their higher mass. However, they have short lifetimes and therefore produce a large number of decay particles that are primarily confined to the midplane. BNL is developing magnets with open midplane gaps to minimize the number of decay particles directly hitting the superconducting coils. As a first step to this technology, we are building R&D magnets [26] for a Neutrino Factory Storage Ring [25]. These magnets are also based on racetrack coils with large bend radius. HTS would be a natural candidate for "Muon Collider/Storage Ring" magnets because of the need for high field and the presence of large energy deposition on the coils.

C. Interaction Region Quadrupoles for VLHC-2

The interaction region (IR) magnets for the proposed very large hadron collider (VLHC) require high gradient quadrupoles for high luminosity performance. Moreover, in the case of doublet IR optics with flat beams [27], the design of the first 2-in-1 quadrupole defines the geometry and pole tip field in this and other IR magnets. A new design has been proposed that does not require any support between the two apertures and brings a large reduction in spacing (by about a factor of five) between the two apertures. Following the philosophy of the common coil program, the design is based on large bend radii that allow the use of "React & Wind" Nb_3Sn and HTS technology. The use of HTS is highly preferable in either VLHC or in a LHC luminosity upgrade program as IR magnets are subjected to a large amount of energy deposition and must have a large pole-tip field for an efficient IR design.

IV. BNL MAGNET PROGRAM OVERVIEW AND PHILOSOPHY

To develop the new HTS magnet technology in an experimental manner, a rapid turn around program has been instituted [4], [9]. The magnet structure has been designed to be simple and yet versatile enough to allow a variety of tests in various configurations. The first series of magnets has only 10 turns of cable in the coils and the straight section is only 30 cm long. All of these choices allow us to carry out cost effective magnet R&D, which is important because of the high cost of HTS and limited availability of resources. Moreover, this philosophy also encourages systematic and innovative magnet R&D since the cost of an individual coil/magnet in terms of time and resources is rather modest. Because of this philosophy we have been able to build ten coils (four HTS and six Nb_3Sn) in about two years despite limited resources. We have been developing "React & Wind" magnet and associated technologies with the help of a variety of tests that include completion of seven sets of magnet/coil tests at 4.2–4.7 K (liquid helium) and several at 55–77 K (liquid nitrogen) in just two years.

HTS cable and tape coils have been tested in a variety of configurations. We used the same design and same technology (React & Wind) with Nb_3Sn as used with HTS. Nb_3Sn has proved to be a good practice material for developing HTS "React & Wind" technology at a fraction of cost. Also, it allows R&D on high field magnets.

V. 10-TURN CABLE MAGNET DESIGN AND CONSTRUCTION

The details of 10-turn coil design have been presented earlier [4], [9]. All coils have a minimum bend radius of 70 mm and are made with pre-reacted HTS or Nb_3Sn cable using a wire $\sim$0.8 mm diameter.

The insulation is provided by a fiberglass and epoxy matrix. A productive partnership has been formed with several industries [28]–[30] to reduce the insulation thickness. Several fiberglass insulation schemes were tested on the cable samples and on the superconducting coils. The tests performed so far have passed the rigorous insulation requirements at cryogenic temperatures and have resulted in reducing the insulation thickness from $\sim$0.4 mm to $\sim$0.2 mm and effective insulated cable thickness from $\sim$1.85 mm to $\sim$1.65 mm.

The coil is wound on a bobbin. We have tested experimental coils made with different bobbin materials, namely, aluminum, low carbon steel, stainless steel and bronze. So far, the material of the bobbin has not played a deterministic role in the quench performance of the coils.

The coils are vacuum impregnated in a fixture. After impregnation the side plates of the fixture are removed to leave a thin insulated coil cassette/module which has only the central bobbin in addition to coil and insulation. In future designs, the bobbin will also be removed. Two versatile support structures have been designed and built to allow modular assembly and testing of one to six coils (modules) in various configurations. These coils can be powered by multiple power supplies to facilitate testing of HTS coils in the background field generated by outer Nb_3Sn coils. The inner splice of the coil is made in the middle of the bobbin, which is also a low field region, an advantage of the common coil design.

VI. HTS TAPE MAGNET DESIGN AND CONSTRUCTION

In addition to the HTS cable magnet program described in the previous section, there is an ongoing HTS (BSCCO 2212 and BSCCO 2223) tape magnet program at BNL. This program was started about four years ago and after making coils with Nb_3Sn tape, six 1-meter long HTS coils have been built and tested. A common coil NbTi cable magnet has also been commissioned to provide a background field to test these HTS tape coils. This program also relies on a simple structure and has also demonstrated rapid turn around with minimum resources. The minimum bend radius of the tape coils is only 28.5 mm as compared to 70 mm for cable coils. This lower bend radius is acceptable because the thickness of the HTS tape is $\sim$0.3 mm whereas the diameter of the HTS wire in the cable is $\sim$0.8 mm. Design, construction and test results of the HTS tape magnet program has been reported earlier [5], [10].

VII. MAGNET TEST RESULTS WITH HTS CABLE COILS

So far two sets of two 10-turn coils (total four) have been made with 18-strand cable. The magnets were assembled so that the two coils could be powered alone or with the relative polarity

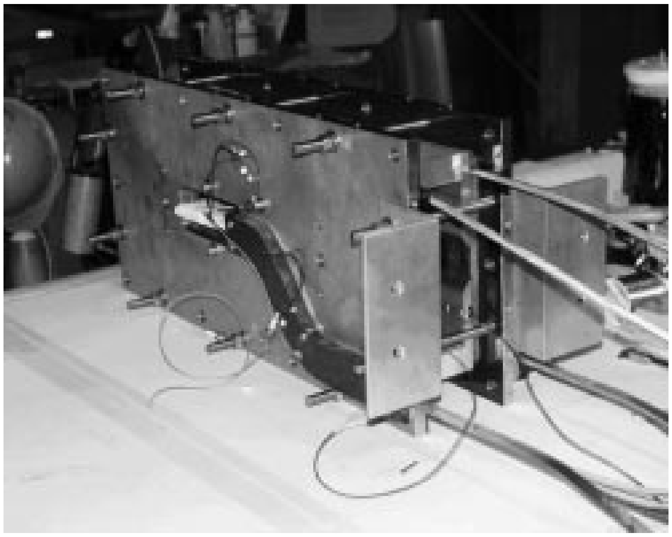

Fig. 4. The common coil magnet DCC006 made with HTS coils. It has an aperture of 74 mm to allow field quality measurements with rotating coil.

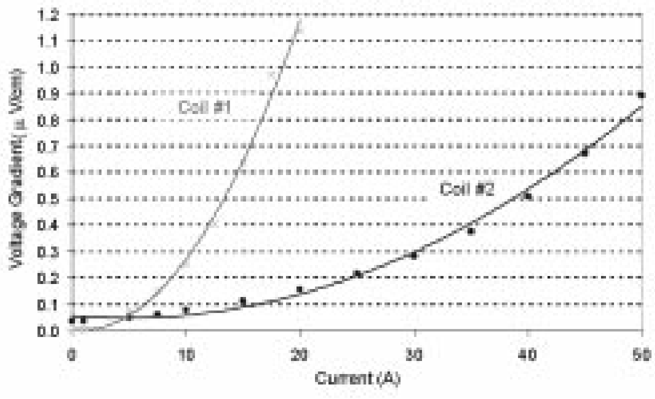

Fig. 5. Measured performance of Coil #1 and Coil #2 in HTS magnet DCC004 at ∼70 K.

being same or opposite. This allows tests in the following configurations:

- A common coil 2-in-1 dipole configuration (the field in the middle of two apertures actually has a quadrupole symmetry).
- A muon collider single aperture dipole configuration where the field in the middle has a dipole symmetry.
- A single coil test configuration where only one of the two coils is powered.

The maximum field on the conductor depends on a particular configuration. In common coil geometry the computed maximum field at 1000 Ampere is ∼0.5 Tesla.

The first set (magnet DCC004) was made from wire that was made about a year ago; since then, the wire performance has improved by over a factor of three. The second set (magnet DCC006) was made with better wire but the cable has only 2 strands of HTS (the remaining 16 are made of silver). To allow field quality measurements in DCC006 (Fig. 4), the separation between two coils was increased to ∼74 mm instead of the ∼2 mm used in DCC004.

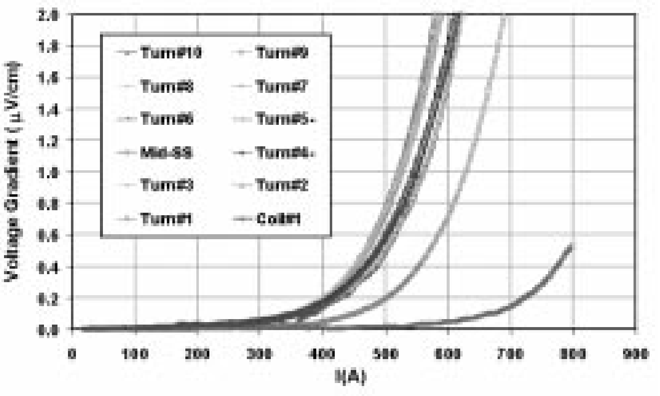

Fig. 6. Performance of each of 10 turns of Coil #1 in common coil configuration of HTS magnet DCC004, measured at ∼4.2 K.

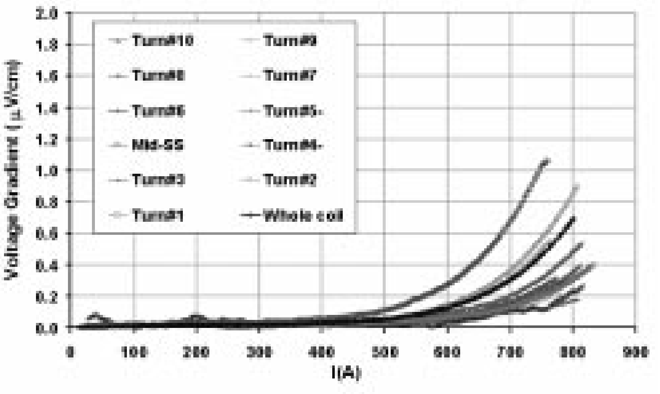

Fig. 7. Performance of each of 10 turns in Coil #2 in common coil configuration of HTS magnet DCC004, measured at ∼4.2 K.

A. Quench Performance Test

1) Test Results of DCC004: The two coils of DCC004 were made with two early batches of cable received from IGC/Showa. The cable was tested at BNL in liquid nitrogen and in liquid helium [1212]. The quench test of two coils (Fig. 5) in liquid nitrogen (∼70 K) clearly shows that the cable used in the second coil is much superior to the one in the first coil.

The performance of coil #1 and coil #2 in common coil configuration is shown in Figs. 6 and 7. The lower temperature (liquid helium) measurements show a smaller difference in coil performance than the higher temperature measurements (liquid nitrogen). Twelve voltage-taps are put on each coil to investigate performance of each of the ten turns individually. One can observe a large variation in the performance of the turns, presumably associated with a variation in cable I_c along the length. Incidentally, the inner turns of both coils have higher I_c than the outer, indicating that the major source of variation in I_c is not the bend radius.

2) Test Results of DCC006: The entire 30-meter length of cable used in DCC006 was tested nondestructively in 3-meter long sections before it was used in magnet [1212]. The test results of this 18 strand (2 HTS and 16 silver) cable at 4.2 K are shown in Fig. 8, where each point represents the average I_c of a 3 meter long section. I_c is defined here as the current corresponding to a voltage gradient of 1 μV/cm over the length of

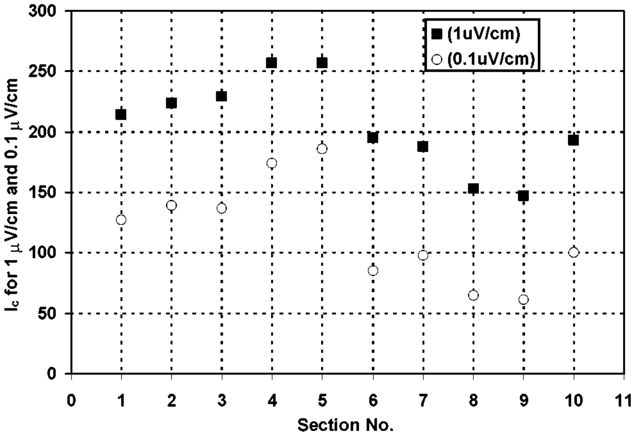

Fig. 8. The performance of 30 meter long cable at 4.2 K, measured using nondestructive techniques in ten 3 meter long sections each.

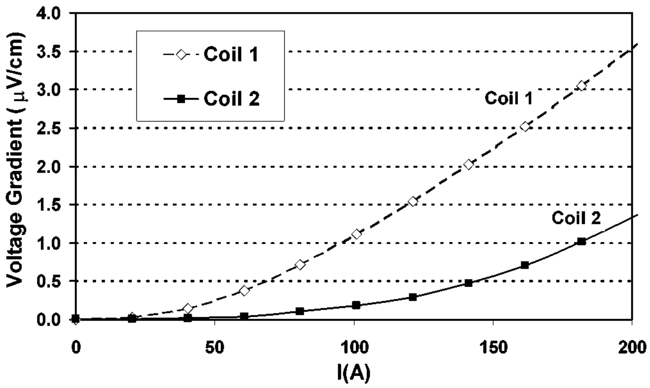

Fig. 9. Performance of Coil #1 and Coil #2 in HTS magnet DCC006 measured at a temperature of ~5.2 K (1 degree higher than the nominal 4.2 K).

the cable chosen. The total length of the cable was 30 meters of which 11 meters each were used in each of two coils. Coil no. 1 was made with the worse part of cable and coil no. 2 was made with mostly better part of the cable.

The test results of the critical current (I_c) measurements in the coils are shown in Fig. 9. Since the coil was tested at ~1 degree higher temperature than at which the cable was tested (Fig. 8), the expected critical current is reduced by a small amount (~5 A). I_c of the first coil is ~100 A and I_c of the second coil is ~180 A. This shows that despite the fact that the coils were made by adapting most techniques that are used in making coils with ductile NbTi, they did not suffer major damage. There is a degradation of ~40 A which, interestingly, is independent of the cable I_c. The source of this degradation (which is small given the beginning of program) will be the subject of future investigations. It may either be due to the bend radius chosen in the design, or sintering of the cable during reaction, or one of the several manufacturing steps. Since the coil has a voltage tap at every turn, we can observe the performance of each turn individually. In Fig. 10, we plot the voltage gradient across each turn. Turns no. 1 through turn no. 7 were apparently made with the better part of the cable and have an I_c of ~210 A with a small spread.

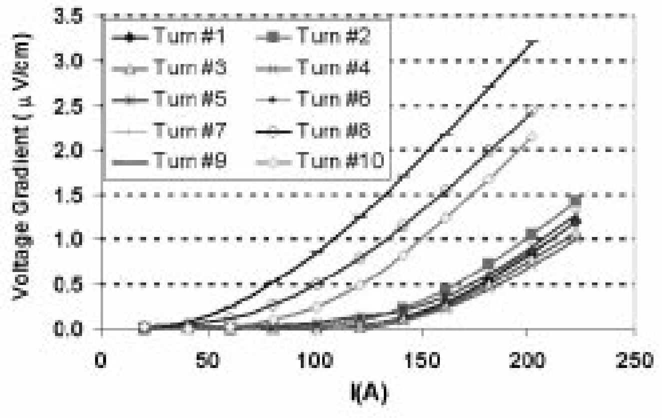

Fig. 10. Performance of each of the 10 turns in Coil #2 in single aperture dipole configuration of HTS magnet DCC006, measured at ~5.2 K.

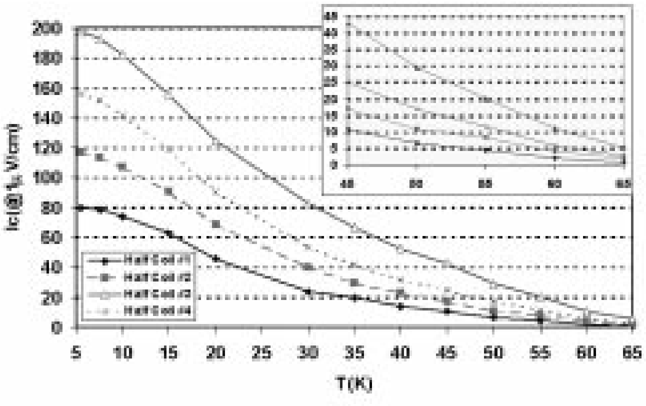

Fig. 11. Critical current measurements of HTS (BSCCO 2212) cable coil as a function of temperature. For these measurements, the voltage taps are selected so that the two coils are divided in two halves each (total four halves).

B. Field Quality Test

The field quality issues related to HTS (in particular related to conductor magnetization) should be known before they can be seriously considered for accelerator magnet applications. To carry out such a study DCC006 was assembled with a bore of 74 mm. In this paper, we discuss the field quality measurements made when it was tested in single aperture dipole mode. The 10-turn coil block (~9 mm wide and ~17 mm high) starts at $x = 70$ mm and $y = 37$ mm. The measurements were made from $I = 0$ A to $I = 200$ A. The maximum field on the conductor at 200 A is ~550 G (~0.055 T). Magnetization measurements on a similar cable show that the maximum magnetization was at ~1 T.

The magnetic measurements were made with a 1-meter long measuring coil, which is longer than the magnet, which has a straight section of 0.3 meter. Measurements of B_3 (sextupole integral over the whole magnet in Tesla-meter not normalized by central field) at 25 mm reference radius during up and down ramp are shown in Fig. 12. At these low fields the absolute measurement errors become important. Practically no difference is observed between up (boxes) and down (crosses) ramp values of this or any other harmonic harmonics. Therefore, one can

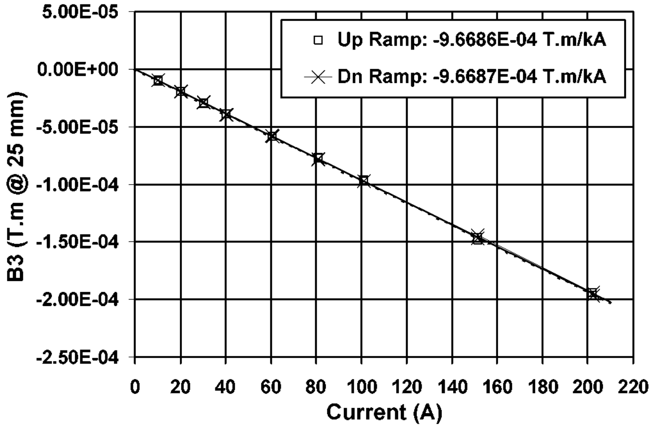

Fig. 12. Measurements of B_3 harmonic (sextupole in Tesla-meter) in HTS magnet DCC006.

conclude that the magnetization effects are less than the measurement errors.

VIII. SUMMARY AND FUTURE PLANS

HTS-based magnets offer significant advantages for the future accelerators since they can operate at elevated temperature and can generate high fields. BNL has started a magnet R&D program to address technical issues associated with this challenging conductor. We have made several R&D coils with HTS cables and HTS tapes. Apart from developing magnet designs and technologies appropriate for HTS, we are experimentally investigating issues related to field quality and quench performance/degradation. Though much work still needs to be done, no showstoppers have been encountered so far and the results to-date have been encouraging. Since the performance of present HTS is close to what is required (within a factor of two), the results of this program with somewhat increased R&D in the coming years (∼5 years) would allow the community to make a more informed decision about the future potential of HTS in accelerator magnets. The first application appears to be high performance IR magnets where the requirements on field and the energy deposition on coil are large. The next step of the R&D program at BNL is to build a 12 T background field magnet where ∼40 turn HTS coils can be tested in a hybrid design. That would address the issues related to high field HTS magnets.

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