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Hybrid High Field Cosine Theta Accelerator Magnet R&D with Second Generation HTS

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***Abstract*—Next generation particle accelerators, such as the proposed LHC energy upgrade (HE-LHC), will require very high field (>20T) superconducting magnets. This paper describes the progress towards this goal made to date as a part of collaborative work between Particle Beam Lasers (PBL), Inc. and Brookhaven National Laboratory (BNL). To reduce cost, high-temperature-superconductors (HTS) are used in a hybrid design with conventional low-temperature-superconductors (LTS) Nb_3Sn and NbTi. The focus of this paper is on using second generation (2G) ReBCO HTS tape in a cosine theta coil geometry. The complex ends of cosine theta geometry are particularly challenging for brittle HTS tape. We report the construction and 77 K test results, one with 4 mm and another with 12 mm ReBCO tape, neither showing measurable degradation. This paper also presents the first successful use of Kapton-CI insulation on HTS tape, which offers many advantages. Future plans include the construction and 4K testing of a full cosine theta HTS coil (first in a standalone mode and then in a hybrid structure with LTS coils), and modelling and measurements of magnetization. This work is a part of comprehensive R&D towards eventually building a high field accelerator quality dipole magnet.**

***Index Terms*—Dipoles, high temperature superconductor, HTS, high field magnets, superconducting magnets.**

I. Introduction

Use of High Temperature Superconductors (HTS), along with Low Temperature Superconductors (LTS), is envisioned in a hybrid coil structure for future very high field accelerator magnets such as those needed for the LHC energy upgrade[1-7]. As shown in Fig. 1, HTS provides higher current density in the high field region and LTS in the low field region. HTS coils have been successfully tested to provide field as high as 16 T in standalone configurations [8, 9]. Since the price of HTS is likely to remain high, a hybrid HTS/LTS design is attractive from a cost perspective.

As a part of a Small Business Technology Transfer (STTR) Phase I award, PBL and BNL collaborated to design, build and test at 77 K a cosine theta coil block using a 12 mm wide second generation (2G) Rare Earth Barium Copper Oxide (ReBCO) tape from SuperPower Corporation. A unique feature of that design was the use of Kapton CI insulation in an HTS coil. It may be pointed out that HTS conductor is brittle and is more prone to degradation in the ends of the complex cosine theta geometry than in the simpler racetrack coil geometry [3], [4], [10].

The PBL/BNL team was awarded a second Phase I STTR which is allows further progress. As a part of this program, we have built a cosine theta coil block made with ReBCO tape and tested it at 77 K. We are in the process of making a full coil to be tested at 4 K. Coils made with Nb_3Sn tape have been successfully made and tested at ~4 K in the past [11].

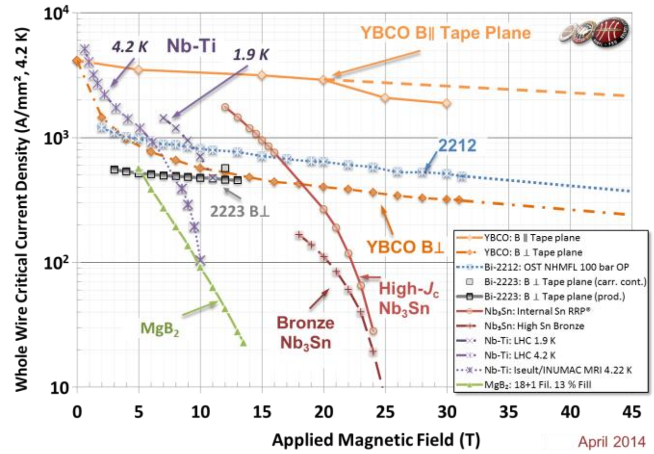

Fig.1. Engineering current density for YBCO tape and Bi-2212 wire compared to other high field superconductors, showing the advantages of YBCO and Bi-2212 at high fields. Data compiled by P. Lee, NHMFL.

HTS/LTS hybrid designs are possible with ReBCO (or BSCCO) HTS tape or Bi2212 HTS cable. Designs based on Bi2212 Rutherford cable offer the advantage of low magnetization and low inductance. However, Bi2212 is still not available in long lengths with high J_e and must be reacted in a controlled environment. Furthermore Bi2212 cable becomes significantly degraded when subjected to large stresses as are present in high field magnets. ReBCO, on the other hand, is already available from multiple vendors in much longer lengths and can withstand the large stresses present in high field magnets [12]. The disadvantage of ReBCO is that since it is available only in tape form, the designs based on it may have poor field quality because of conductor magnetization, unless reduced and/or compensated in the design. One of the purposes of this R&D program is to compare the designs based on the two conductors. However, in this paper, the discussion will be limited to work performed with only the ReBCO tape.

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II. High Field Hybrid Magnet Design Concept

We have carried out a series of conceptual magnetic designs of hybrid dipoles with apertures ranging from 25 mm to 40 mm and field from 20 T to 26 T. In all these designs inner coils (where the peak field is high) were made of HTS and outer coils (where the field is relatively lower, <12-15 T) were made of LTS. We also examined the case where the pole block in an individual coil could be made with HTS and the remaining blocks of the same coil could be made with LTS. One such design with a 40mm aperture and a central field of 23.4 T (peak field on the HTS coil being 24.1 T) is shown in Fig. 2. Overall current density in the coil ranges from 350 A/mm^2 in HTS to 600 A/mm^2 in LTS. It may be pointed out that a magnet with greater than 500 A/mm^2 overall current density in HTS has already been successfully tested with a peak field in the conductor of greater than 16 T [9].

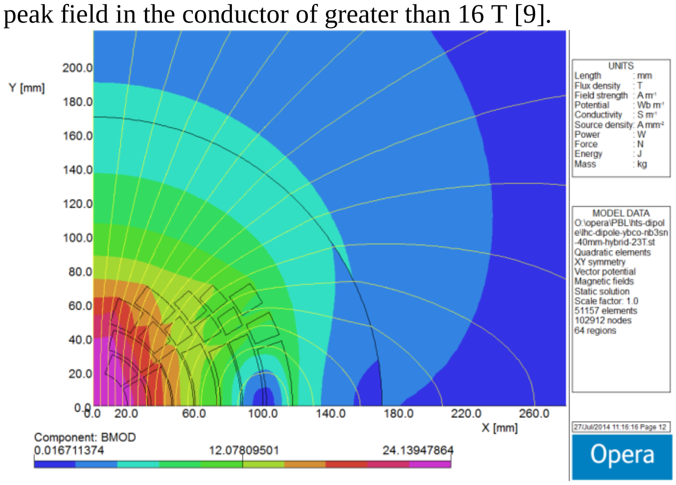

Fig.2. Conceptual magnetic design of a 23.4 T, 40 mm aperture hybrid dipole.

III. Coil with 12 mm Wide ReBCO Tape

In the first STTR (Grant Number DE-SC0011348), we designed, built, and tested a cosine theta coil block using 12 mm tape wrapped with Kapton CI insulation. In Phase I, the test was limited to 77 K.

A. Kapton CI Insulation in HTS Coil

The focus of this program was to investigate the feasibility of Kapton CI insulation on 12 mm YBCO tape [12] in cosine theta magnet geometry. Use of Kapton CI for protection and fabrication purposes is a promising approach for HTS coils. Kapton CI has been widely used in building cos θ coils for accelerator magnets, such as in RHIC dipole magnets [16]. In this program, it would protect the fragile YBCO tape from damage during coil fabrication and from delamination of the conducting layer on the tape when coated with filler epoxy in the ends. Mechanically securing the ends is a requirement for success in construction of cos θ coils. The "CI' polyimide adhesive layer on the 25 micron thick Kapton tape activates within 30 minutes upon heating to 225 °C, resulting in a coil in which all the turns are stuck together to form a package that can be handled and kept intact. In contrast to epoxy, the polyimide adhesive is quite radiation-resistant and thus can be used in high radiation environments without fear of degradation.

As a part of the collaboration, BNL provided Kapton CI tape to SuperPower to wrap it spirally with approximately 30% overlap on its 12 mm wide tape. BNL also provided other details on using Kapton CI insulation on HTS tape to SuperPower.

B. Coil Winding

An existing winding fixture was adapted for winding the 20-turn pole block of the coil (see Fig. 3). The bending radius of the conductor at all places including passing over several wheels was greater than the critical radius specified by the vendor.

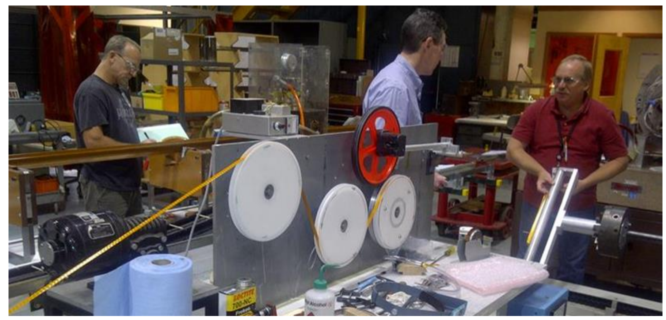

Fig.3. HTS coil being wound on the winding apparatus.

We designed and built tooling for a 300 mm long coil on a 50 mm radius mandrel at 70° angle to represent the pole block. The completed 20-turn winding of the pole block with 12 mm kapton insulated tape is shown in Fig. 4. It was placed in an oven for activating the polyimide adhesive at 225 °C. The winding was found to be in an excellent and robust shape after curing and it could be handled easily. The plan would be to fill any gaps between turns in the ends with a loaded epoxy, but this was not required in this small winding.

Fig.4. The 20-turn pole winding after fabrication. The 12 mm wide HTS tape conductor with its Kapton CI wrap is visible on the left.

C. Coil Testing

Preparation for testing required removal of the coil from its mandrel after curing for installing voltage taps and current leads. The coil was reinstalled on its mandrel, the restraining bars attached, and the entire structure wrapped with Kevlar cord under light tension. This step emulates the restraint that would be required in a true cos θ magnet and ensures that nothing will be loose during the test of the coil in liquid nitrogen. Fig. 5 shows the coil ready for a 77 K cryogenic test.

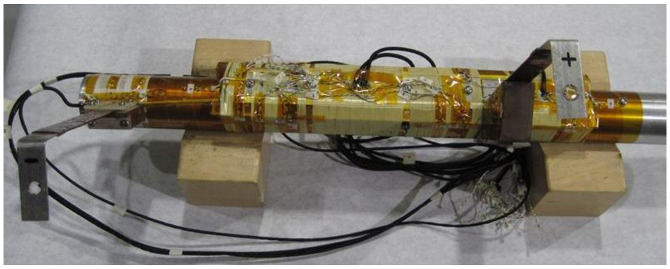

Fig.5. The coil ready for testing at 77 K in liquid nitrogen. The coil has been firmly secured to its mandrel, and current leads and voltage taps are in place.

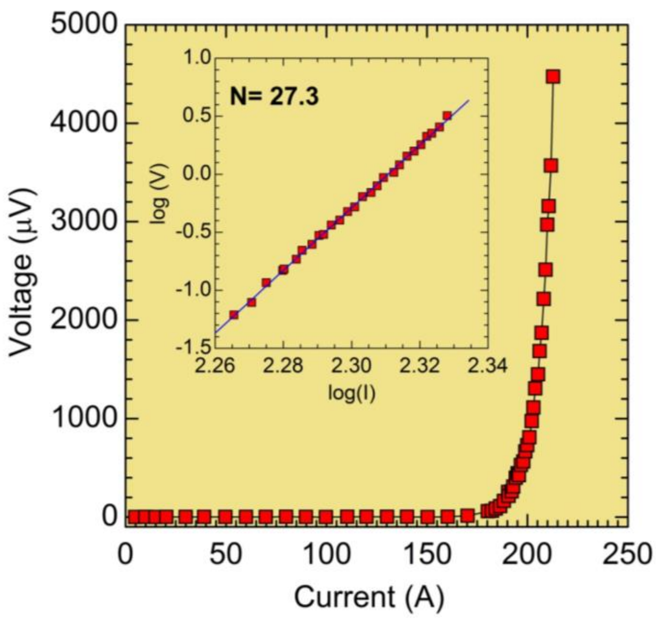

Fig.6. End-to-end coil voltage as a function of current when the 20-turn coil made with the 12 mm tape is tested at 77 K in liquid nitrogen. Insert shows a large n-value, indicating that there was little to no degradation in conductor performance.

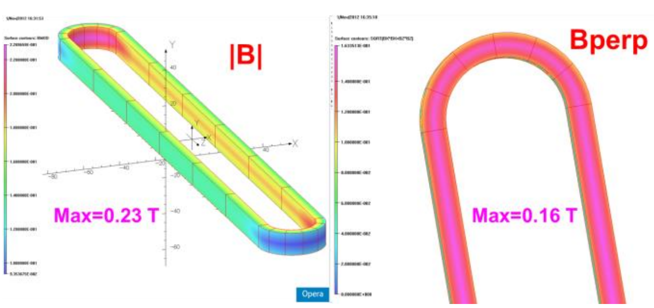

Fig.7. Computed magnitude of the field at 200 A, superimposed on the 20-turn coil on the left and perpendicular component superimposed on the right.

Since voltage taps were installed after curing the coil, they could only be placed on the inner most and outer most turns. Fourteen such voltage taps were placed at strategic locations to help identify significant degradation in the conductor performance, particularly in the end region where the conductor is likely to experience the maximum strain and the maximum field. End-to-end coil voltage, measured as a function of current at ~77 K in liquid nitrogen, is shown in Fig. 6. The measured critical current of the 20-turn coil is 187.8 A based on a 0.1 μV/cm criterion and 204 A based on a 1 μV/cm criterion.

The self-field critical current of the tape at ~77 K was about 480 A. The computed peak field in the coil at 200 A is 0.23 T and the maximum field perpendicular to the wide face of conductor is 0.16 T (see Fig. 7). Given the fact that a significant variation in the ratio of self-field and in-field performance has been found between various samples, the measured critical current in the coil is consistent with the expected performance. As expected, the minimum critical current was found to be in the pole region, with detailed measurements across 14 voltage taps indicating no significant degradation. A high n-value of 27.3 further indicates that the conductor did not go through any significant degradation in performance during the whole process.

IV. Coil with 4 mm Wide ReBCO Tape

In the second Phase I STTR (Grant Number DE-SC0007738), to allow high current testing at lower temperature (4 K) with the existing leads, we chose to wind coils with 4 mm tape [12]. A coil made with 4 mm tape would have a lower current, which goes against the desire of developing a magnet design with higher operating current. However, this is only a test convenience related to the limited funding in Phase I. In fact, the coils in Phase II would be made with a cable made with several 12 mm tapes to facilitate a design with higher operating current (several thousand amperes).

Fig. 8 shows the 45-turn coil made with 4 mm ReBCO tape co-wound with ~38 micron kapton tape. It has a straight section of 300 mm and is wound on a 50 mm radius mandrel at 70° angle to represent the pole block. The inner lead and several voltage taps were installed during the winding of the coil.

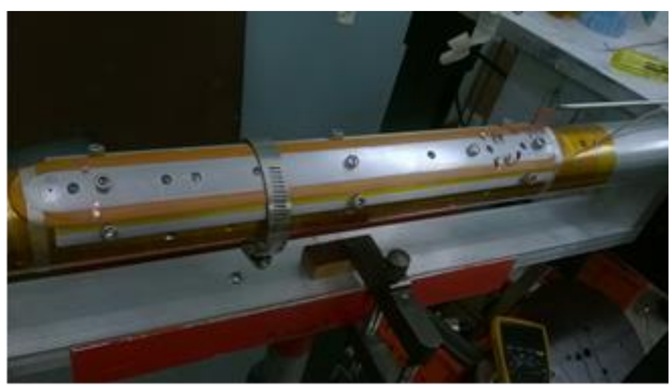

Fig.8. A 45-turn coil wound with ReBCO tape co-wound with Kapton tape.

Fig. 9 shows the measured voltage of this coil as a function of current at ~77 K in liquid nitrogen. In addition to end-to-end coil voltage, Fig. 9 also shows the measured voltage in the inner and outer turn. The measured critical current of the 45-turn coil block is 60 A based on a 0.1 μV/cm criterion and 67 A (by slight extrapolation) based on a 1 μV/cm criterion. The computed peak field in the winding at 65 A is 0.24 T and the maximum field perpendicular to the wide face of conductor is 0.17 T. These are similar to those shown in Fig. 7. The critical current values in this 45-turn coil wound with ~4 mm tape are about 1/3 of those for the coil wound with ~12 mm tape discussed in the previous section. Examination of the detailed performance and a high n-value of 28.5 indicates that this conductor also did not go through any significant degradation during winding.

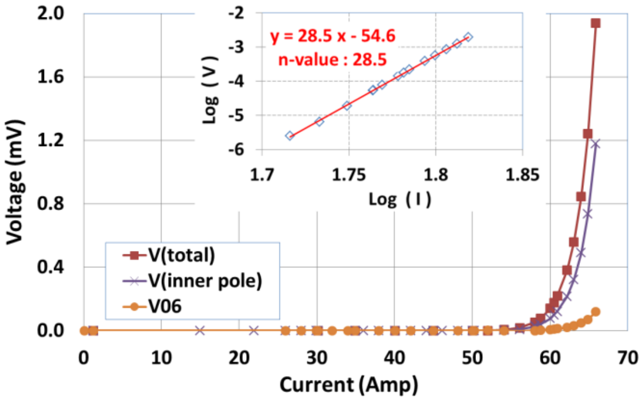

Fig.9. Measured voltage in end-to-end and individual sections as a function of current when the 45-turn coil block made with the 4 mm tape is tested at 77 K in liquid nitrogen. Insert shows a large n-value, indicating that there was little to no degradation in conductor performance.

V. Future Program

Following the successful winding and testing of these pole turn coils, the next step in the Phase I program will be to wind and test a full cross section dipole coil which includes pole and midplane turns. 4 mm wide ReBCO tape will be used so that the coil can be tested at 77 K as well as 4 K with the existing power leads in the test setup.

In preparation for the construction of a higher current, higher field coil in a subsequent Phase II SBIR program, samples of clad tape (two single layer tapes soldered together) will be tested with respect to bending and current transfer properties. CERN has provided [14] a sample of such conductor which is developing HTS dipole under EuCARD2 program. We are also in discussion of obtaining a variation of that directly from SuperPower. The best performing clad tape will be selected for model coils to be constructed and tested in Phase II.

Persistent current induced harmonics due to higher conductor magnetization is a major issue in magnets made with HTS tape. As a part of this program (particularly in Phase II), we will compute and develop ways to minimize these magnetization induced harmonics. The full coil to be built and tested at 4 K in Phase I will be used in the initial part of Phase II to measure field harmonics and compare them with the models.

Quench detection and protection is another major area of interest in developing high field magnet technology. We will implement and further enhance our advanced quench detection system and philosophy used in other HTS magnet programs [9], [10], [13].

VI. Conclusion

HTS has the potential to produce very high field (>20 T) magnets. Hybrid magnet designs with HTS used in inner coils and LTS used in outer coils are more attractive from cost perspective. In this paper, we described the work on a cosine theta design, which is more complex to build with brittle conductor than the simpler racetrack coil designs. Two model dipole coils (pole turns only) have been wound using REBCO tapes of 4 mm and 12 mm widths and insulated with Kapton. These two model coils have been tested at 77 K and the current/voltage measurements show that the coils were wound without damaging the conductors. These initial positive results will be followed with winding a complete dipole cross section. This coil will be tested at 4K, and is expected to generate a significant field. Future work includes modelling and measurements of field harmonics, particularly due to conductor magnetization, and design, construction and test of an accelerator quality high field hybrid dipole magnet.

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