High Field HTS Solenoid for a Muon Collider—Demonstrations, Challenges, and Strategies

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***Abstract*—The proposed muon collider requires very high field solenoids in the range of 30–50 T. The use of High Temperature Superconductors (HTS) operating at low temperature ($\sim$4 K) is essential for achieving such high fields in a superconducting magnet. As a part of this program, we have built and successfully tested a 25 mm aperture HTS insert generating $>$ 16 T peak field (the highest field ever achieved in an all-HTS magnet), a 100 mm aperture HTS midsert generating $>$ 9 T peak field, and designed an outsert with a conventional Low Temperature Superconductor (LTS) to provide additional field. In addition to presenting the test results and progress made in support technologies, we will also discuss a number of challenges associated with the high field HTS magnets. Finally, we present a set of strategies to overcome some of those challenges.**

***Index Terms*—High field magnets, high temperature superconductors (HTS), muon collider, solenoid.**

I. INTRODUCTION

HTS OFFERS a unique opportunity to build very high field superconducting magnets ($>$ 25 T). Such magnets [1] are required for ionization cooling [2] in the proposed muon collider [3] and could revolutionize several other applications such as Nuclear Magnetic Resonance, Superconducting Magnetic Energy Storage, and user facilities [4]–[6]. The overall goal of the program reported here is to develop and demonstrate the technology for a 30–50 T solenoid (Fig. 1) with the majority of the field created by HTS and the remainder by conventional LTS (NbTi and/or Nb_3Sn). Second generation (2G) HTS with a high strength substrate [7] is the key ingredient of this design. Initial demonstrations were carried out under a series of SBIR (Small Business Innovation Research) grants to Particle Beam Lasers, Inc. (PBL), with Brookhaven National Laboratory (BNL) as research partner. Further R&D is now being primarily supported by the Muon Accelerator Program (MAP). BNL is working on several other HTS magnets [8] which provide good synergy with this program. We first summarize the demonstrations, then discuss the challenges, and present the strategies to overcome them.

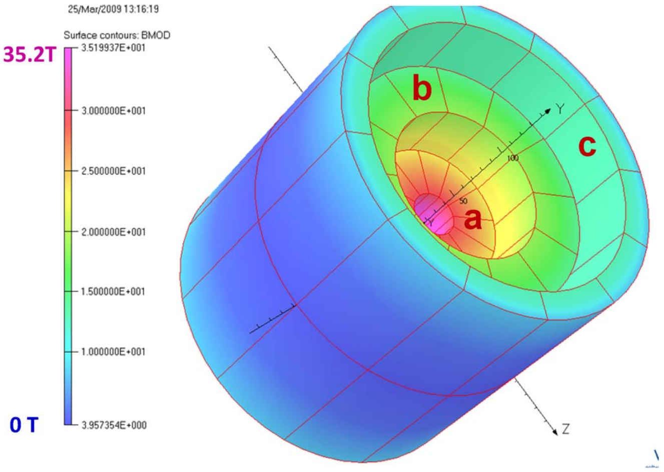

Fig. 1. Magnetic design (with field contours overlaid on the surface of the conductor) of a 35 T solenoid consisting of three coils: (a) HTS insert, (b) HTS midsert, and (c) LTS outsert.

II. DEMONSTRATIONS

A. 16 T Peak Field HTS Insert

The HTS insert (coil "a" in Fig. 1) is made with 14 pancakes having an inner diameter of $\sim$25 mm. Each pancake is cowound with $\sim$4 mm of ReBCO high strength 2G tape (from SuperPower) and Stainless Steel (SS) tape for insulation. The SS tape provides added strength and helps in quench protection. The design, construction, and test results have been described earlier [9]. Fig. 2 shows the measured critical current (for 0.1 μV/cm) as a function of temperature. The coil operated at 285 A current (overall current density in coil $>$ 500 A/mm^2) which corresponds to 16.2 T peak field and 15.8 T central field. This exceeded the original target of 12 T.

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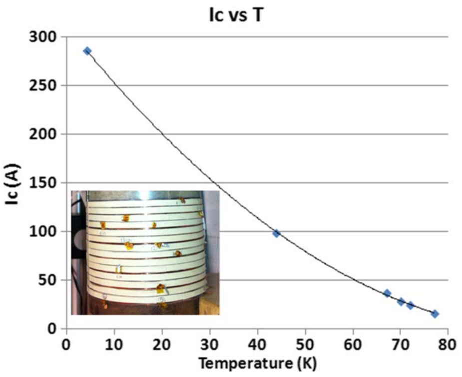

Fig. 2. Measured critical current as a function of temperature in 25 mm HTS insert consisting of 14 pancakes. A current of 285 A (achieved at 4 K) corresponds to 16.2 T peak field in the coil. The coil is shown in the inset.

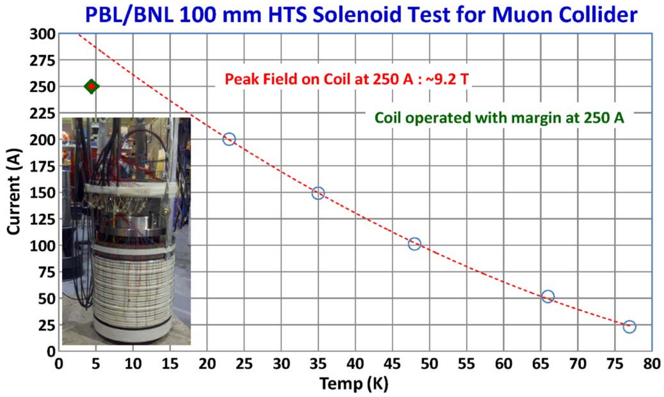

Fig. 3. Measured critical current as a function of temperature in 100 mm HTS midsert consisting of 12 pancakes. Inset shows the midsert with 24 pancakes.

B. 9 T Peak Field Half-Length Midsert

The HTS midsert (coil "*b*" in Fig. 1) is made with 24 pancakes having an inner diameter of 100 mm [1], each using ∼100 meters of 2G HTS tape from SuperPower [6]. Most of the design and construction techniques are similar to those used in the ∼25 mm insert [1], [9]. Initially a half-length midsert (made with 12 pancakes) was built and tested. Fig. 3 shows the critical current (measured at an electrical field or a voltage gradient criterion of 0.1 μV/cm) as a function of temperature. The coil successfully operated at 250 A (design current 220 A for full-length midsert) without showing any onset of resistive voltage. To protect the electronics (in the event of quench) the test was stopped at 250 A. A current of 250 A in the half-length midsert corresponds to a peak field of a 9.2 T and a central field of 6.4 T.

C. Test in Background Field

A mini-insert coil made of four 25 mm pancakes (two cowound with Dupont Kapton and two with SS tape insulation) was tested in the background field of the 20 T resistive solenoid at the NHMFL [10]. Test results and the coil in the test fixture are shown in Fig. 4. This test demonstrated the suitability and advantage of SS tape in high field solenoids.

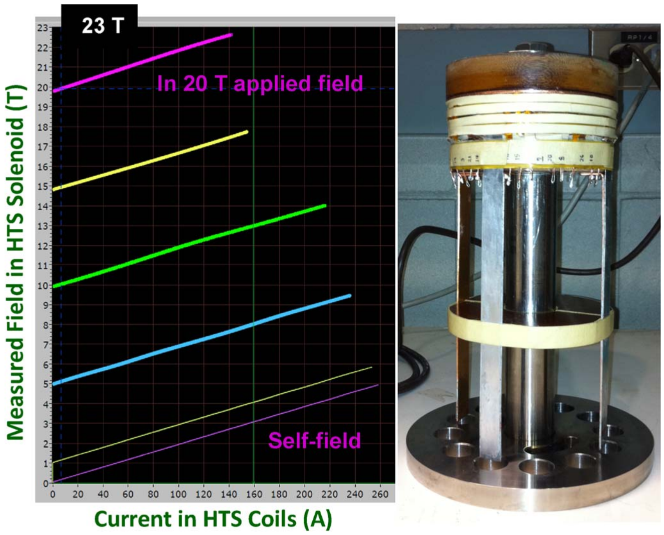

Fig. 4. (Left) Test results of (right) HTS mini-insert coil, consisting of two pancakes wound with SS tape insulation and two with Kapton, in 20 T background field magnet at NHMFL.

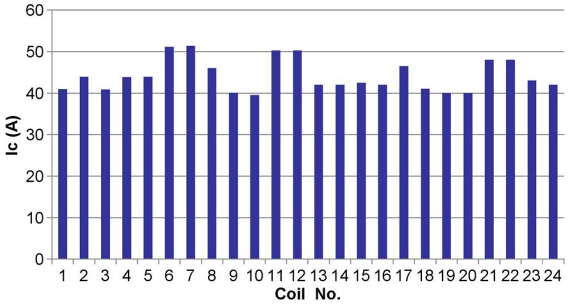

Fig. 5. Measured critical current at 77 K of twenty-four 100 mm diameter pancake coils, each made with 100 m of ∼4 mm 2G HTS tape. The maximum computed field at 40 A is ∼0.5 T (perpendicular component ∼0.3 T).

D. Extensive 77 K Testing of a Large Number of Coils

A large number of HTS coils (well over 100) having different geometries (racetrack, pancake, curved, saddle) have been made at BNL. They were made with a variety of HTS (Bi2212, Bi2223, and YBCO/ReBCO) with an accumulated length of over 40 km (when normalized to 4 mm tape). It has been found that 77 K measurements provide an important Quality Assurance (QA), as they can detect defects, if any, in an individual pancake. We install a large number of voltage-taps (typically after every 25 turns) in each pancake for extensive debugging.

Fig. 5 shows the performance of 24 pancakes for the midsert, each made with 100 meters of 2G HTS tape.

III. CHALLENGES AND STRATEGIES

A. Quench Protection

Quench protection in high field HTS magnets with large stored energy is a major challenge. The low quench propagation velocity (as small as a few mm/s) means that the normal zone may not spread adequately unless assisted, and the energy deposited in a small section could raise the local temperature high enough to cause permanent damage. The challenge is

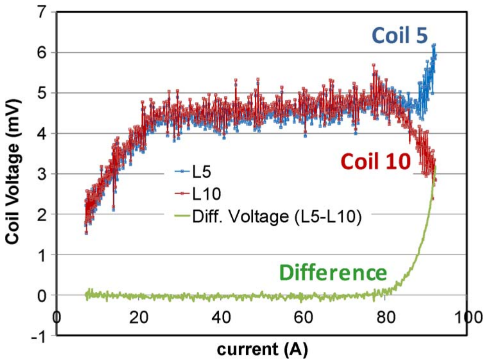

Fig. 6. Measured voltage in two pancake coils 5 (L5) and 10 (L10) along with the difference between the two to detect the prequench phase during a current ramp with changing rate (accelerating, constant, and decelerating).

to avoid this by either extracting energy quickly and/or by distributing it over a large volume with quench heaters [12]. We use a multi-prong strategy to overcome this challenge.

Cowinding of HTS Tape With Insulating SS Tape: We use Stainless Steel (SS) tape, rather than Kapton (or similar organic insulation), to provide turn-to-turn insulation and extra structure to coils [1]. SS tape, being a metal, distributes energy faster over a larger region of coil and reduces the local increase in temperature. Finite Element Analysis (FEM) has shown [13] that the reduction in hot spot temperature could be a factor of five or more and in some cases the SS tape could prevent a stagnant normal zone.

Detection of Prequench Phase: To protect the coils from damage, we start extracting energy from the coil during the "*prequench*" phase where the coils are safe to operate. The "*prequench*" phase, a semi-resistive phase with voltage one to two orders of magnitude below what is considered to be the quench voltage, occurs well before the onset quench or runaway. In LTS magnets, the quench detection threshold is typically well over 10 mV to even 100 mV. In HTS, the critical current is typically defined at 1 μV/cm, which becomes 100 mV for a coil made with 1 km of conductor. We define "*prequench*" phase as the phase that corresponds to $\sim$1 mV. We have developed fast-acting high-performance electronics and filtering software to isolate the onset of a small "*prequench*" resistive voltage in the presence of large noise and inductive voltages [14]. Fig. 6 shows the case where this "*prequench*" phase was identified at < 1 mV by using the difference voltage between two coils even when the ramp rate (and hence inductive voltage) was changing. We have been able to use a prequench detection threshold of a few hundred μV in a magnet made with several hundred meters to several kilometers of HTS tape. The goal is to keep this threshold to a regime where HTS coils can safely operate for a short period while energy is extracted.

Fast Energy Extraction Phase: Once the prequench threshold is reached at current "I," our strategy is to extract energy quickly (of the order of seconds). The extraction time constant is given by "L/R" and the voltage across the coil as "I^*R," where "L" is the inductance, "R" the external resistor. Such a fast energy extraction requires the quench protection circuitry for a larger magnet system to be able to handle high voltages. We have developed an electronic system that can handle isolation voltages of over a kV. Coils are also divided in sections to ensure that the inductance of a section (and hence the isolation voltage) is not too large.

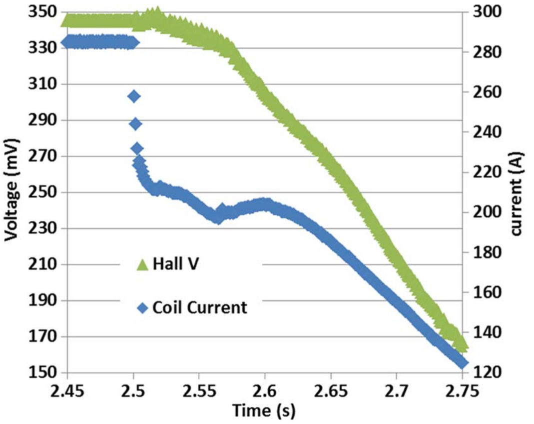

Fig. 7. Decay of field (as measured by Hall voltage) and current in coils embedded with copper discs. The rapid drop of current in the coil provides a crucial margin at a critical time.

Copper Discs for Rapid Energy Extraction: Copper discs are used between the pairs of double-pancakes to provide more uniform cooling across each coil. It has been found that a significant fraction of the current is inductively transferred from the HTS coils to the copper discs [15] in the beginning of the energy extraction process. Fig. 7 shows the Hall voltage (roughly proportional to the field) and current in the coil when the energy was extracted at a field of 15.8 T. This reduction in current occurs almost instantaneously and provides a crucial margin at a critical time.

Future Work and Strategies: Quench protection of large, high field, HTS magnets remains an area where more experimental data and demonstrations are needed. Further advances in electronics to reduce the prequench detection threshold would reduce the chance of coils entering the "danger zone." Similarly, advances in electronics to tolerate higher isolation voltage would allow energy to be extracted faster. One can also optimize the size, shape, and material of copper discs and can further investigate other coupling geometries. Optimization of the amount of copper and how it is placed on HTS tape would also help. The use of quench protection heaters [12] should further help in protection. Overall, there is a need for continuing an extensive R&D program, which includes making coils for this study.

B. Conductor

HTS make high field superconducting magnets possible. Several high field coils (such as those presented here) have clearly demonstrated its potential. However, further progress is needed before HTS can be considered as a production conductor. There is a need to make conductors available in longer lengths and attain more uniformity and reproducibility.

In-Field Performance: HTS manufacturers typically provide the electrical characteristics of conductor at 77 K, self field. The performance of superconducting magnet, however, depends on the critical current at operating temperature ($\sim$4 K in high field magnets) and field. Fig. 8 shows the measured scaling ratio of

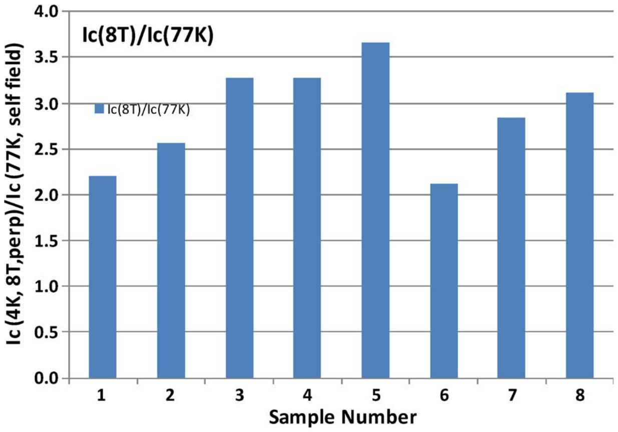

Fig. 8. Ratio of critical current measured at 4 K in 8 T background field (applied perpendicular to the wide face of tape) and at 77 K, self-field.

critical current between "4 K, 8 T," and "77 K, *self-field*" in a series of production wires provided by SuperPower [16]. The large variation (> 50%) is a cause of concern because a local weak section may limit the performance of the entire magnet.

Moreover, the correlation was week between the 77 K critical current data provided by the manufacturer and 77 K critical current measured in coils in the series of pancake coils (Fig. 5). This again points to the need for controlling production processes and parameters that are critical for the in-field performance of the conductor.

Mechanical Properties: Mechanical properties and robustness of the conductor are critical for high field magnets. Hastelloy substrate [7] or SS laminations [17] provide strength along the wide side of the 2G tape. Mechanical properties have also been measured along the narrow side [18]. In addition, the properties of the copper stabilizer and retention of its bonding to the substrate is important. In some cases the electro-plated copper and with it (or maybe without it) the superconductor coating gets detached from the substrate, causing a partial or full-width crack or discontinuity.

Conductor Configurations: 2G conductor comes in the form of tape with a thin layer of HTS (about a micron thick). The challenge is to first detect and then eliminate those small size (of the order of mm) weak-links that could limit the electrical and mechanical performance of the conductor at high fields and high stresses. A conductor design based on multiple tapes could relax this requirement. Some of the options are several layers of tapes, Roebel [19] or CORC [20] cable. Such configurations also increase the total current, which helps in quench protection.

C. HTS Coils and High Field Magnets

HTS coils have demonstrated the capability to generate very high fields. However, many institutions have reported observing a change in performance during the 77 K testing with liquid nitrogen. This could be due to thermal and/or mechanical strains in excess of what the conductor can tolerate.

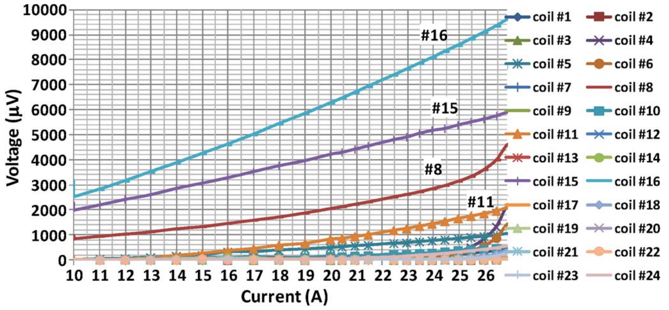

Fig. 9. Performance of individual pancakes during a test where several of them got degraded (as seen by the onset of voltage well before 25 A). These pancakes have been tested several times before and showed no such behavior.

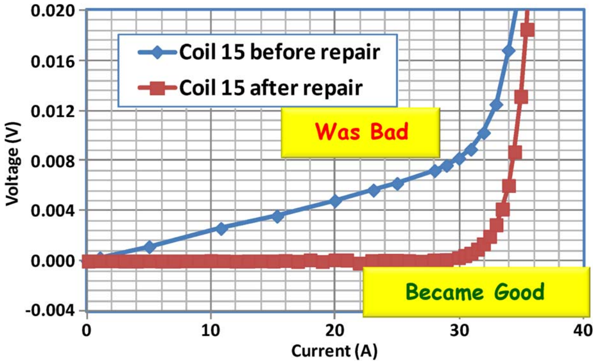

Fig. 10. Measured performance of the coil before and after the repair during two 77 K tests.

Degradation During Thermal Cycle: There have been several reported instances [6], [21], [22] of epoxy-impregnated 2G HTS coils becoming degraded during the 77 K testing with liquid nitrogen. In some instances even the coils that were not epoxy-impregnated, got degraded. During one of many 77 K tests of the midsert solenoid [1] consisted of 24 pancakes (each wound with ~100 meters of tape), several pancakes were found to be degraded to various extents (see Fig. 9), as seen by the early onset of voltage (well before ~25 A). Interestingly, these pancakes have been tested many times before where they did not show such behavior. Moreover, these pancakes showed any further deterioration in performance during the subsequent 77 K tests either.

Close examination revealed two critical points: (a) there was a significant thermal gradient within the pancake during the cooldown and (b) in some pancakes, copper became delaminated from the conductor. In some cases, the delamination was visible in the innermost turns and outermost turns.

We were able to repair many pancakes by carefully peeling off the innermost turn. The repaired pancakes will be used in the magnet. One such case is shown in Fig. 10, where the performance of a pancake is shown before and after the repair.

Mechanical Structure: In high field magnets, Lorentz forces become very large. Stainless steel tape (used as insulation) also contributes to the support structure in reducing the maximum accumulated stress. However, in very high field solenoids, mechanical structure still needs to be segmented [1], both radially and axially to ensure that the conductor limits of hoop and axial strains [18] are not exceeded.

Future Work and Strategies: Although, eventually, the conductor has to become more robust to become viable for large-scale applications, one can use some intermediate strategies.

The NHMFL group has tested a thin polyester film surrounding the tape [23] that avoided copper delamination. Copper discs, used in BNL's design to reduce thermal gradients, may be further optimized. To reduce the maximum transient thermal strain, one can reduce the rate of cooling. For the time being extensive 77 K testing, as mentioned in previous section, plays a key role in detecting weak-spots. However, this extensive testing is expected to be reduced as the conductor and coil technology become more streamlined and robust.

IV. SUMMARY

The demonstrations and technology described here show the potential of HTS in accomplishing very high field superconducting magnets. We also have summarized several remaining challenges and a path forward, including the benefits of more robust conductors.

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