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 Superconductor (HTS) operating at low temperature (~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 conventional Low Temperature Superconductor (LTS) to provide the remaining 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 will present a set of strategies to overcome some of those challenges.**

***Index Terms*— High Temperature Superconductors, HTS, High Field Magnets, 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 System and user facilities [4, 5]. 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 remaining by conventional LTS like NbTi and Nb_3Sn. Second generation (2G) HTS with a high strength substrate [6, 7] are key ingredients of this design. Initial demonstrations were carried out under a series of SBIR (Small Business Innovative Research) grants to Particle Beam Lasers, Inc. (PBL), with Brookhaven National Laboratory (BNL) being a research partner. Further R&D is now being primarily supported by the Muon Accelerator Program (MAP). BNL is working on a number of other HTS magnets [8] which provides a good synergy with this program. We first summarize the demonstrations, then discuss the challenges and the strategies to overcome them.

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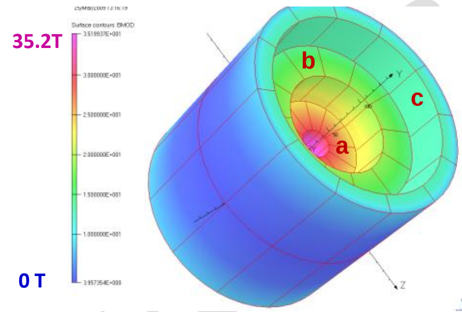

Fig. 1. Magnetic design (with field contours overlaid on the surface of the conductor) of a 35 T solenoid consisting of three coils: (a) HTS insert (b) HTS midsert and (c) LTS outsert.

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 ~25 mm. Each pancake is co-wound with ~4 mm ReBCO high strength 2G tape (from SuperPower) and Stainless Steel (SS) tape for insulation. SS tape also 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 far exceeded the original target of 12 T.

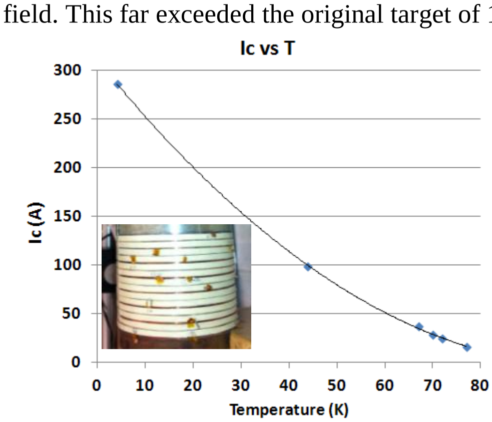

Fig. 2. Measured critical current as a function of temperature in 25 mm HTS insert consisting of 14 pancakes. A current of 285 A (achieved at 4 K) corresponds to 16.2 T peak field in the coil. The coil is shown in the inset.

B. 9 T Peak Field Half-length Midsert

The HTS midsert (coil (b) in Fig. 1) is made with 24 pancakes [1] having an inner diameter of 100 mm, each using ~100 meter 2G HTS tape from SuperPower [6]. Most of the design and construction techniques are similar to those used in the ~25 mm insert and have been described earlier [1,9]. Initially a half-length midsert (made with 12 pancakes) was built and tested. Fig. 3 shows the critical current (measured at a voltage gradient of 0.1 μV/cm) as a function of temperature. The coil successfully operated at 250 A 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 half-length midsert (which already exceeded the design value of 220 A in a full-length midsert) corresponds to a peak field of a 9.2 T and field at the center of 6.4 T.

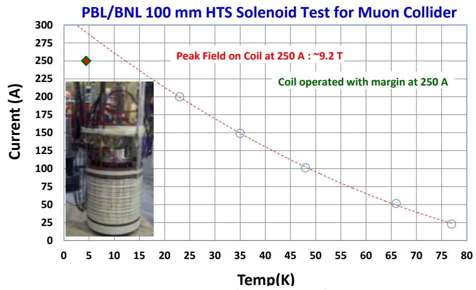

Fig. 3. Measured critical current as a function of temperature in 100 mm HTS midsert consisting of 12 pancakes. Inset shows the midsert with 24 pancakes.

C. *Test in Background Field*

A mini-insert coil made of four 25 mm pancakes (two co-wound with Kapton® (Kapton is a registered trademark of Dupont Corporation) and two with SS tape insulation) was tested in the background field of the 20 T resistive solenoid at 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.

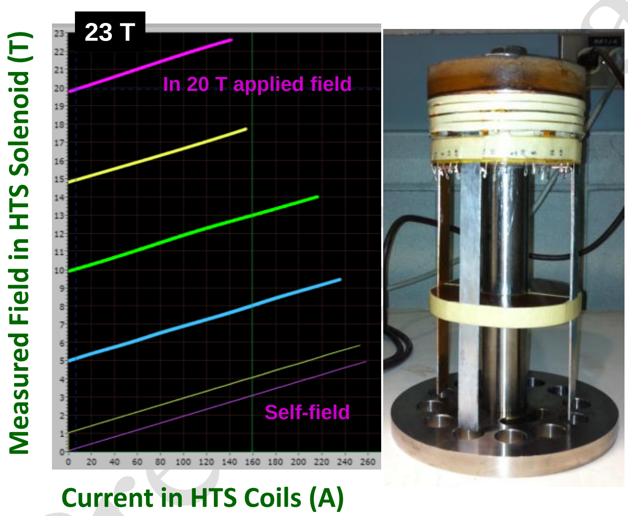

Fig. 4. Test results (left) of HTS mini-insert coil (right), consisting of two pancakes wound with SS tape insulation and two with Kapton®, in 20 T background field magnet at NHMFL.

D. *Extensive 77K 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 with a variety of conductors (Bi2212, Bi223 and YBCO/ReBCO) having different sizes and significant accumulated length (total length over 40 km when normalized to 4 mm tape). Even though for high field applications, HTS must be operated at low temperatures, 77 K measurements in liquid nitrogen provide an important Quality Assurance (QA) test. 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 meter of 2G HTS tape. The good performance of such a large volume of coils in this and other programs [11] shows that the technology has evolved enough that one can now consider HTS magnets for many applications.

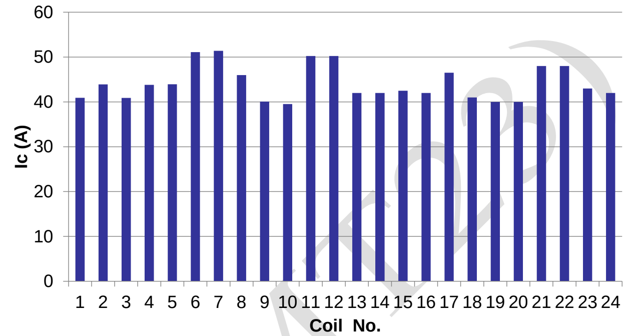

Fig. 5. Measured critical current at 77 K of twenty-four 100 mm diameter pancake coils, each made with 100 m of ~4 mm 2G HTS tape. The maximum computed field at 40 A is ~0.5 T (perpendicular component ~0.3 T).

III. Challenges and Strategies

A. *Quench Protection*

Quench protection in high field HTS magnets with large stored energy is a major challenge. A low quench propagation velocity (as small as a few mm/sec) means that the normal zone by itself would not spread and the energy deposited in a small section could raise the local temperature high enough to cause permanent damage. The challenge is to avoid this by either extracting energy quickly and/or by distributing it over a large section with quench heaters [12]. We use a multi-prong strategy to overcome this challenge.

Co-winding 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 section of coil and reduces the local increase in temperature. Finite Element Analysis (FEM) has shown that the reduction in hot spot temperature could be a factor of five or more and in some cases SS tape could eliminate a stagnant normal zone [13].

Detection of Pre-Quench Phase

To protect the coils from damage, we start extracting energy from the coil during the "*pre-quench*" phase where the coils are safe to operate. The "*pre-quench"* 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 "*pre-quench*" phase as the phase that corresponds to <1 mV. We have developed fast-acting high performance electronics and filtering software to isolate the onset of a small "*pre-quench"* resistive voltage in the presence of large noise and inductive voltages [14]. Fig. 6 shows the case where this "*pre-quench"* phase was identified even when the ramp rate (and hence inductive voltage) was changing (initial increase in individual coil voltages is due to accelerating ramp and final decrease towards the end due to decelerating). With this, we have been able to use a 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 below a limit where HTS coils can safely operate for a short period before sufficient energy is extracted.

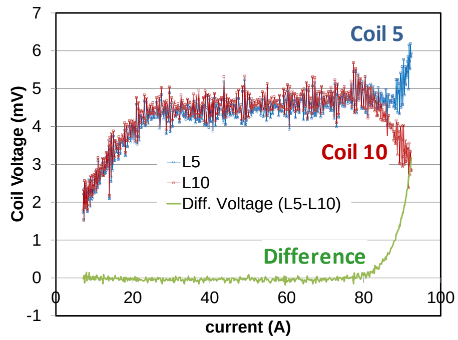

Fig. 6. Measured voltage in two pancakes (coils L5 and L10) along with the difference between the two to detect the pre-quench phase during a current ramp with changing rate (accelerating, constant and decelerating).

Fast Energy Extraction Phase

Once the pre-quench threshold is reached at current "*I*", our strategy is to extract energy quickly (of the order of seconds). This extraction time constant is given by "*L/R*", where "*L*" is the inductance and "*R"* the external resistor (R) and the voltage across the coil is "*I*R*". This requires that the quench protection circuitry for a larger magnet system, should be able to handle high voltages. We have developed an electronic system that can handle isolation voltage of over a kV. Coils are also divided in sections to avoid the inductance of a section (and hence need for the isolation voltage) becoming too large.

Copper Discs for Rapid Energy Extraction

Copper discs are used between the pairs of double-pancake to provide more uniform cooling across the coil. It has been found that a large amount of 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 field) and current in the coil in the case when the energy was extracted at 15.8 T at the center. This reduction in current occurs instantaneously and provides a crucial margin at a critical time.

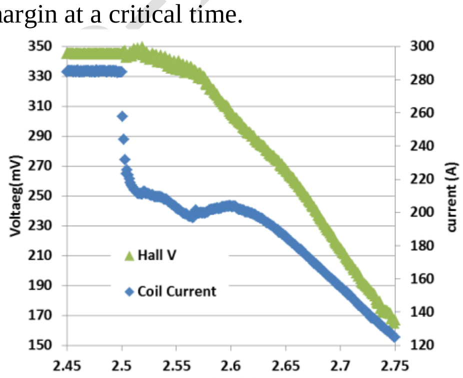

Fig. 7. Decay of field (as measured by Hall voltage) and current in coils embedded with copper discs. One can see a rapid drop of current in the coil which provides a crucial margin at a critical time.

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 in reducing the pre-quench detection threshold would reduce the chance of coils entering the "danger zone". Similarly advances in electronics in tolerating 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. The amount of copper and how it is placed on HTS tape would also help. The use of quench protection heaters [11] should further help in protection. There is a need for an extensive R&D program which includes making dedicated coils to study parameters and thresholds and to examine options.

B. Conductor

HTS makes high field superconducting magnet 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 a production conductor. Apart from the need to make conductor available in longer lengths, there is a need to attain more uniformity and reproducibility in properties of the conductor.

In-field Performance

HTS manufacturers typically provide electrical characteristic of conductor at 77 K, self field. The performance of the magnet, however, depends on the critical current at operating temperature and fields. Fig. 8 shows the measured scaling ratio of critical current between "*4K, 8 T*" and "*77 K, self-field*" in a series of production wires provided by SuperPower [16]. While a high value of scaling ratio is desirable, the large variation (>50%) is a cause of concern since a local weak section may limit the performance of the entire magnet.

Moreover, a weak correlation was found 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 discussed in last section (Fig. 5). This again points to the need for controlling production process and parameters that are critical for the in-field performance of the conductor.

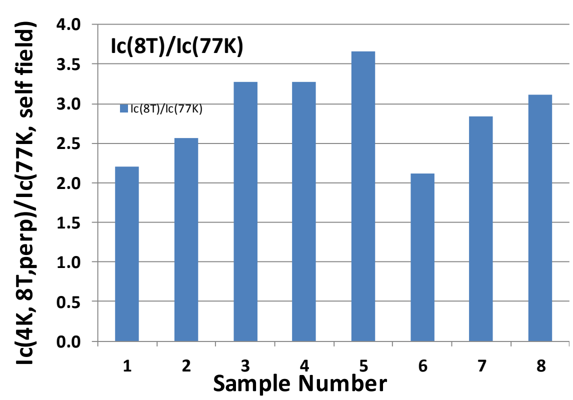

Fig. 8. Ratio of critical current measured at 4 K in 8 T background field (applied perpendicular to the wide face of tape) and at 77 K, self-field.

Mechanical Properties

Mechanical properties and robustness of the conductor are critical for high field magnets. Hastelloy substrate [6,7] 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 copper stabilizer and retention of its bonding to the substrate is the important. It has been seen that, in some cases, the electro-plated copper and with it (or maybe without it) superconductor coating gets detached from the substrate, causing a partial or full width crack or discontinuity. This is a major issue that needs to be solved in manufacturing or one needs to develop other robust alternatives.

Conductor Configurations

2G conductor comes in the form a HTS tape with thin micron-size coating. The challenge is to first detect and then eliminate those small size (mm long) 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 value of the total current which also helps in quench protection.

C. HTS Coils and High Field Magnets

HTS coils have been demonstrated to have the capability of generating very high fields. However, many groups 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 a particular batch of conductor can tolerate.

Degradation during Thermal Cycle

There have been several reported instances [21] 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, were degraded. During one 77 K test of the midsert solenoid (consisting of 24 pancakes, each wound with ~100 meter tape), several pancakes were degraded at different levels (see Fig. 9). This occurred despite the fact that these pancakes were tested before several times (both individually and in a group with other pancakes) and showed no change in performance. Interestingly none showed any further deterioration later during several more test cycles.

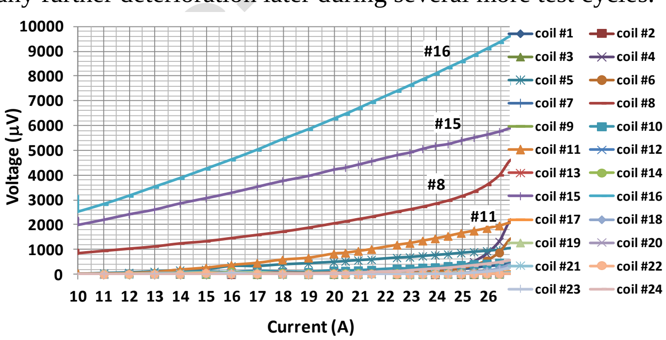

Fig. 9. Early onset of voltages in several pancakes during this 77 K test indicates a variable level of degradation in them. These pancakes were earlier tested several times and showed no change in performance before this test.

Close examination revealed two critical points: (a) there was a significant thermal gradient within the pancake during the cool down and (b) in some pancakes, copper became delaminated from the conductor – this was visible in the inner-most turns and outer-most turns. However, the damage is not always visible.

We removed the first turn from each of twenty four pancakes by carefully peeling it off. This resulted in repairing many (about half) of the pancakes. The repaired pancakes behaved normally and will be used in the magnet. One such case of repair is shown in Fig. 10 where the performance of a pancake is shown before and after the repair.

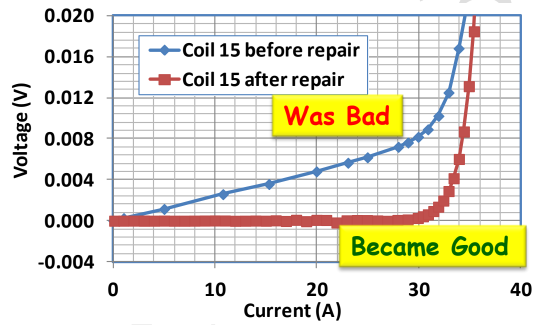

Fig. 10. Measured performance of the coil before and after the repair during two 77 K tests.

Mechanical Structure

In high field magnets, Lorentz forces become very large. Using stainless steel tape as insulation plays a significant role in reducing build-up of forces. However, in very high field solenoids, mechanical structure still needs to segment the coil with intermediate structure, both in radial [1] and in axial direction [20] to ensure that the conductor limits of hoop and axial strains 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 [22] that avoided copper delamination. Copper discs, used in our design to reduce thermal gradients, may be further optimized. One can further reduce the rate of cooling and/or use an alternative to testing with liquid nitrogen. 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 and elsewhere show the potential of HTS in accomplishing very high field (30-50 T) superconducting magnets. We also summarized several remaining challenges and a possible way forward, including the benefits of a more robust conductor.

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