15+ T HTS SOLENOID FOR MUON ACCELERATOR PROGRAM*

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Abstract

This paper presents the construction and test results of an all-HTS solenoid which reached a central field >15 T, the highest field ever achieved in an HTS solenoid. This is a part of ~35 T solenoid being developed under a series of SBIR with Brookhaven National Laboratory (BNL) being a research partner with Particle Beam Lasers (PBL), Inc. The solenoid has an inner diameter of ~25 mm, outer diameter ~95 mm and a length ~70 mm. It consists of 14 single pancake coils made from ~4 mm wide 2nd Generation High Temperature Superconductor (2G HTS) from SuperPower Inc., co-wound with ~4 mm wide, 0.025mm thick stainless steel tape.

INTRODUCTION

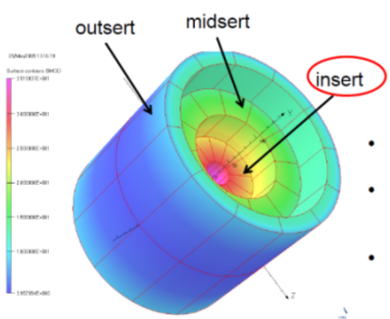

Figure 1: PBL High field solenoid consists of three solenoids. The insert and the midsert will be made with 2G HTS and outsert with LTS.

Very high field solenoids (30-40 T) are needed for the ionization cooling in the proposed Muon Collider [1]. A PBL/BNL team has proposed to build a proof-of-principle magnet with a series of concentric solenoids (insert, midsert and outsert) as shown in Fig. 1. Insert and midsert are made with HTS and outsert with conventional Low Temperature Superconductors (LTS) [2]. This paper focuses on the insert which produced over 15 T field on the axis. Construction and test results of individual coils in liquid nitrogen have been presented elsewhere earlier [3]. Both insert and midsert [4] are made from ~4 mm wide second generation (2G) HTS tape from SuperPower Inc. [5] and are expected to produce a combined field of ~22T.

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The overall approach, including the use of HTS and LTS, has many similarities to the ~32 T user solenoid, now under development at NHMFL [6].

CONSTRUCTION OF THE SOLENOID

The inner diameter of this solenoid is ~25 mm and the outer diameter is ~95 mm. There were 14 pancakes all together, each having over 270 turns and ~50 m of ~4 mm 2G HTS conductor. The height of the solenoid was ~64 mm. The solenoid was made with ~700 m of conductor.

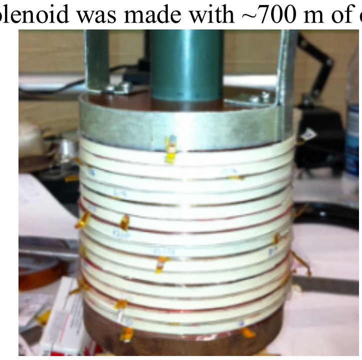

Figure 2: Photograph of the insert solenoid.

Fig. 2 shows the overall construction of the coil. Voltage taps are shown as yellowish pieces between coils. These are copper tapes insulated with Kapton tapes. Two current leads were copper backed 12 mm wide YBCO tape. A G-10 rod is at the center of solenoid. The solenoid is placed between 12.5 mm thick micarta plates.

MEASUREMENTS AT 77 K

The critical currents of seven double pancake coils were measured at 77 K with many voltage taps. Since no local defect was observed, these seven double pancakes were used in the construction of this solenoid. Fig. 3 shows the critical current of the conductor and the critical current of each coil at 77 K. The performance was likely to be limited by the perpendicular component of the field (highest in the coils at the two ends of the solenoid and the lowest in the middle), the coils were placed according to the measured coil I_c at 77 K. Therefore, the coils with the highest I_c were placed at the ends and the coils with the lowest coil I_c were placed at the center. Each coil was wound from 50 m of conductor. Inside splices were made with 60 mm long, 9 mm wide lap joints. The outside splices were made with 36 mm long and 9 mm wide lap joints. Voltage taps were also placed at each end of

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splices. Voltages on all fourteen coils and all splices were monitored individually.

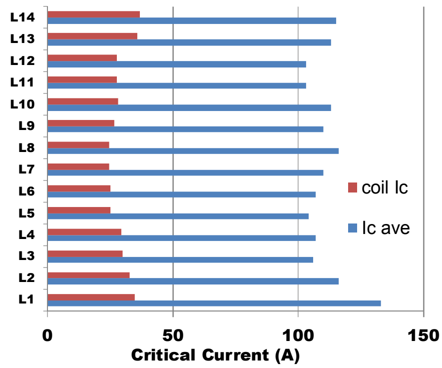

Figure 3: Critical current of 14 coils (measured at BNL) and critical current of conductor (measured at SuperPower) at 77 K used in the solenoid.

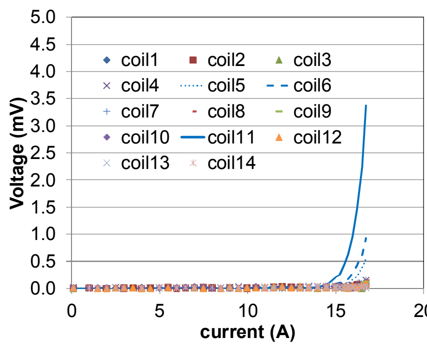

Figure 4: Measured voltage at 77 K across each of 14 coils when powered in series. Coil #11 becomes resistive first followed by #6 and #5.

Fig. 4 shows the voltage versus current for each coil in the solenoid at 77 K. Resistive voltage across coil #11 (4th from the end) is observed first, followed by coil #6 and #5. No resistive voltage was seen on the coils at or near the two ends, which was expected due to anisotropy of critical current vs. field angle in 2G HTS tape. This also implies that by placing the highest I_c coils at the ends of the solenoid, we have been able to gain in the overall critical current of the solenoid.

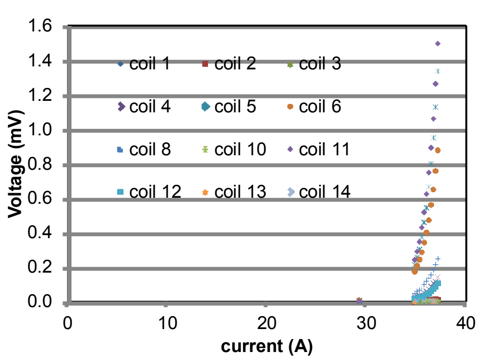

Figure 5: Coil #11 and #5 became resistive first followed by #6 at 67 K.

The solenoid was further cooled to 67 K by pumping the liquid nitrogen to allow higher current operation. As shown in Figure 5, at 67 K, coil #11, #5 and #6 showed resistive behavior first. Compared with 77 K I_c increased from 16 A to 38 A, however, the overall behavior is somewhat similar but coil #5 shows a more prominent and earlier resistive onset.

LOW TEMPERATURE MEASUREMENTS

To obtain highest field, the solenoid was cooled to 4.2 K in liquid Helium. In addition, the performance was also measured at an intermediate temperature of 44 K, which is achieved by controlling helium gas flow rate. For quench detection purpose, the coils with similar fields are paired: Coils #1 and #14, #2 and #13, #3 and #12, #4 and #11, #5 and #10, #6 and #9, #7 and #8 respectively. The quench detection threshold is kept at 2 mV relative difference between two coils in each pair. The overall coil voltage is also monitored.

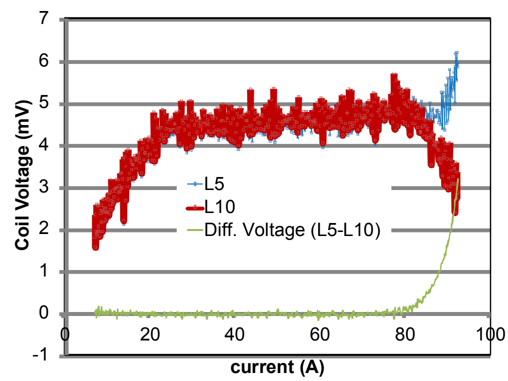

Figure 6: Coil #5 became resistive and voltage difference between #5 and #10 exceeded 2mV, so the power supply shut down at 92 A at 44 K.

Fig. 6 shows voltages at coil #5 and coil #10 at 44 K. First the coil current increases at a slow ramp rate before it reaches a constant ramp rate of 0.2 A/s. Since each coil inductance is ~20 mH, coil voltage due to inductance is ~4 mV. Then ramp rate decreases to zero. Voltage difference between these coils is also in the figure. The coil #10 does not show any voltage increase due to resistive behaviour of conductor. The coil #5 became clearly resistive and the voltage difference between coil #5 and #10 was detected by the quench detection system.

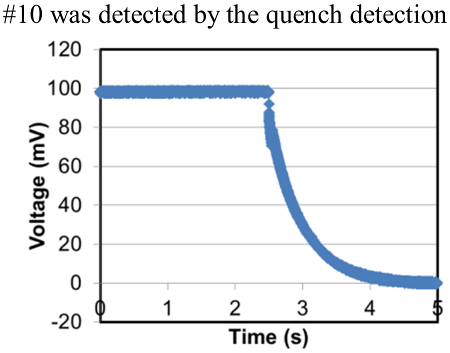

Figure 7: The coil current after the power supply shut off is plotted as a function of time.

To protect the coil, the current was decreased to ~0 A within 0.5 s as shown in Fig. 7. Again the coil at the end (#1 or #14) does not show any sign of resistive behaviour. The coil in the middle (#5) shows resistive behaviour first. Although at 77 K coil #11 showed the resistive behaviour first, at 44 K, coil #5 became resistive first.

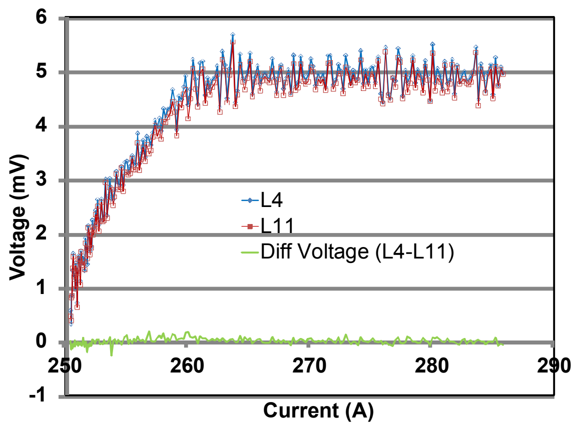

Figure 8: There is no noticeable voltage difference between the pairs #4 and #11 at 4.2K.

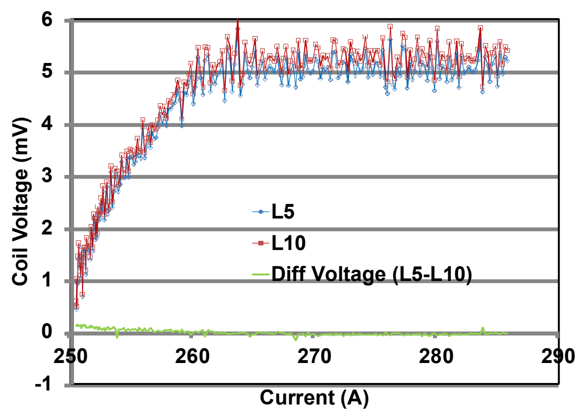

Figure 9: There is no noticeable voltage difference between coil#5 and #10 at 4.2K.

The 4.2 K measurement for coil #4 and coil #11 is shown in Fig. 8. The measurement for coil #5 and coil #10 is shown in Fig. 9. There is no noticeable voltage difference between these pairs. All coil voltages are due to coil inductance. None of coil voltages appeared to become resistive between 250 A and 285 A. Therefore, the real critical current of the solenoid should be higher than 285 A. We deliberately stopped ramping the magnet at 285 A because a critical voltage tap was lost and we wanted to protect the coil for future use.

DISCUSSION

The critical current I_c of the solenoid as a function of temperature is shown in Fig. 10. The critical current of this solenoid was only 16 A at 77 K, but was more than 285 A at 4.2 K. The corresponding central field was over

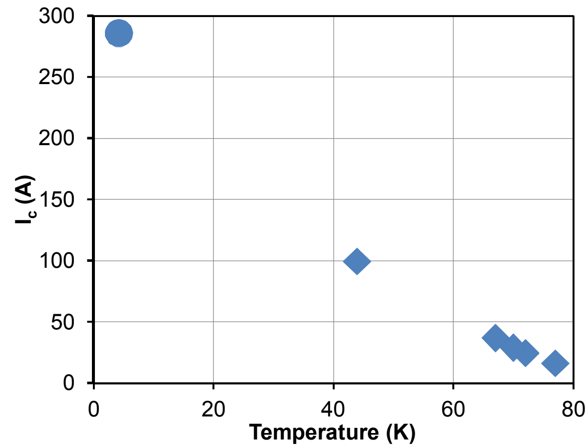

Figure: 10: The critical current is plotted as a function of temperature. Although critical current is only 16A at 77K, it could be above 285A at 4.2K (shown as a circle).

15 T and the peak field on conductor was over 16 T. This is a major advancement in technology, as we have improved the previous best record of HTS solenoid. The previous record was 10.4 Tesla at 4.2 K which was achieved by SuperPower and NHMFL in 2009 [5]. The field collapses within 0.5 s at 44 K. After the helium test, the solenoid was tested at 77K again and V-I curves at various coils were the same as the first nitrogen test. This shows that no damage was introduced by various high field tests in helium.

ACKNOWLEDGMENTS

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