HINS_SS1_Sol_03d: Pre-Production SS1 Focusing Lens Fabrication and Test Results

C. Hess, M. J. Kim, F. Lewis, D. Orris, M. Tartaglia, I. Terechkine, T. Wokas

I. Lens Design and Fabrication.

The design of a pre-production version of the SS1 section focusing lens was described in [1]. The main modification to the previously tested prototype lens [2] was to increase the solenoid length, to compensate for a lower current margin due to the slightly elevated temperature expected in the HINS cryogenic system at the Meson lab. The main design features of the solenoid are shown in Fig. 1.

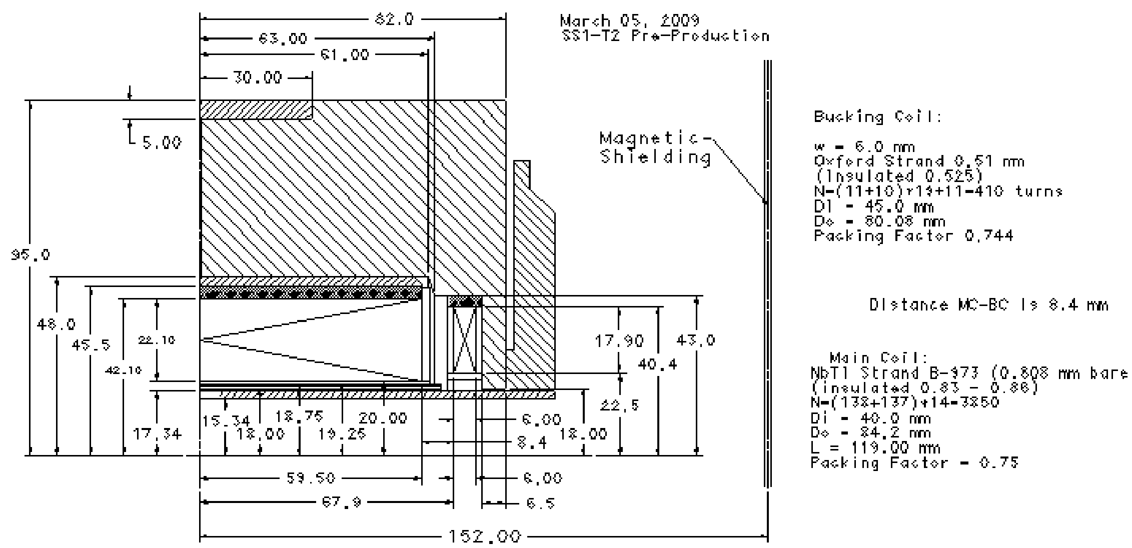

Fig. 1. Pre-production SS1 focusing solenoid design.

The Main Coil (MC) was wound using SSC-type strand from IGC, spool #B973-1-4-B. The bare strand diameter was 0.807 mm and insulated strand diameter was 0.843 mm. Fabrication data for the lens deviates slightly from the design. The inner diameter of the MC winding was 40 mm, as designed; the length L of the MC spool was 118.64 mm (vs. 119.00 mm). The outer diameter of the winding was between 84.83 and 85.34 mm, which average to ~85.1 mm (vs. 84.2 mm). The total number of turns in the main coil was 3877 (vs. 3850), resulting from 28 layers with 139 turns in each odd layer and 138 turns in each even layer. The total length of strand in the MC winding was 762 meters.

The bucking coils (BC) were wound using Oxford 0.5 mm NbTi strand (insulated diameter 0.53 mm), reel #54/50-1714. Each BC had 410 turns (39 layers with 11 turns in each odd layer and 10 turns in each even layer). The inner diameter of both windings was 44.5 mm (vs. 45.0 mm), and the lengths were each 6.0 mm. The outer diameter for the lead end Bucking Coil was 80.89 mm (vs. 80.08 mm); for the return end BC it was 81.22 mm. The total length of strand in each bucking coil was 82 m.

The gaps between BC and MC windings were about 0.2 mm more than the design value of 8.40 mm: 8.60 mm at the lead end and 8.58 mm at the return end. This gap increase was made to compensate for the changed coil outer diameters and MC length. It is important to note that even small changes in the coil dimensions and placement have implications for the fringe field. Fig. 2 shows how fringe field in the presence of the magnetic shield of the type described in [3] changes while bucking coil dimensions and position deviate from the design (marked in the figure as “Old BC”) values.

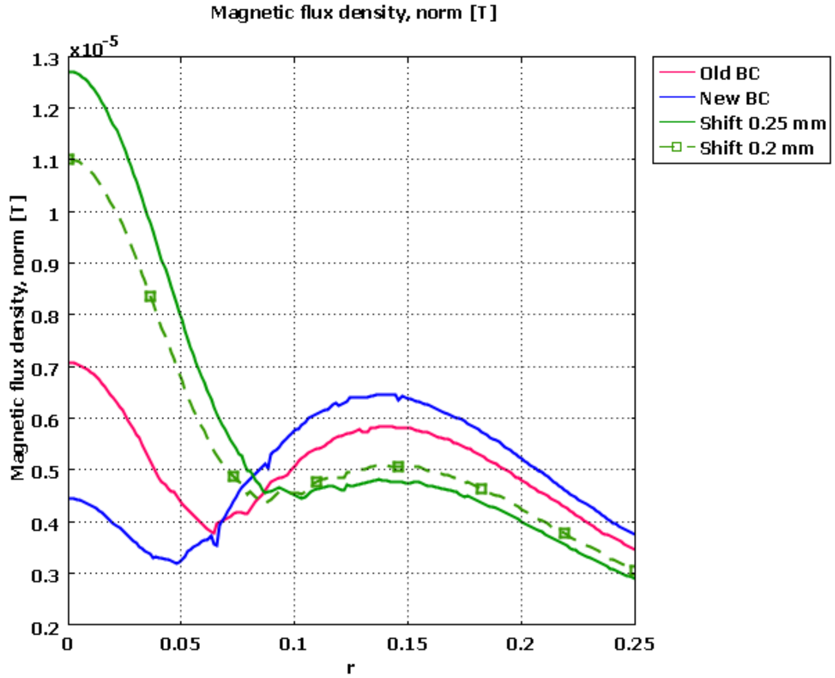

Fig. 2. Fringe magnetic field of the pre-production SS1 focusing lens (marked “New BC”) at Z = 225 mm for different distances between the BC-s and MC.

Fabrication of a second SS1 lens also provided an opportunity to make and study the dipole field shape and quench performance of another set of the single-layer dipole steering coils first described in [2]. The dipole correctors were wound using Supercon, Inc. 54S43 0.3 mm NbTi strand. Insulated diameter of the strand is 0.33 mm. The number of turns in each coil was 55, and the straight section length was 89.0 mm. The total length of strand in each coil was 14.5 m, and four coils total are used in the corrector assembly.

One of the primary leads of the horizontal corrector was broken in the vicinity of the coil during the final stage of fabrication; nevertheless it was possible to repair the damage by making a ~10 mm long splice. Subsequent test has shown that this length was quite adequate and did not affect the coil performance.

II. Test History.

The dipole corrector sub-assembly was completed during the summer, and was measured warm at low current using the DSP-1 measurement cart and a 25 mm diameter harmonic coil probe. The solenoid fabrication was completed late in October and delivered to MTF. Installation and warm magnetic measurements were made in the stand 3 test dewar on Nov. 13 and the first liquid helium cool down was made on Nov. 16. The FPGA-based power and test cart was changed for this test, from MQPS-1 to MQPS-2. This new cart, which had been previously used on stand 6, required a fair amount of setup and checkout before it was ready for use. Thus, the solenoid quench training program actually began on Nov. 20, after which solenoid magnetic measurements were made. Over the weekend a partial thermal cycle occurred as the solenoid warmed to 200 K, and was re-cooled on Nov. 23 for further testing. Solenoid re-training was studied, and then dipole quench training and magnetic measurements were completed. The dewar warmed to 300 K over the break for Thanksgiving, and a third thermal cycle of cold testing was completed on Dec. 2 with more study of the solenoid quench performance (which was somewhat erratic).

Quite a few issues arose during the first thermal cycle related to the new (MQSP-2) system. For the first time, this system used all three power supplies (PS#1 for solenoid, #2 for VD, #3 for HD, which is intended to be a standard configuration), so new current monitors had to be added to the slow scan system. The use of new modular isolation amplifiers in MQPS-2 led to an unexpected shortage of quench characterization channels: due to lack of space in the chassis, the system was one channel short of what was needed. As a result, the lead-end bucking coil (BCL) in the solenoid was initially not instrumented. One of the dipole voltage tap channels was re-configured to instrument BCL during the third thermal cycle for solenoid quench testing (although it was possible to infer which coil had quenched without this, the individual signals provide additional information about coil motion, which can produce visible “glitches” in the voltage trace or traces). In addition to hardware issues, there were also software problems: quench data saving into the Webdat database was not working, so data were manually archived; also, communication through the IFIX-DAQ gateway was intermittent as new IFIX servers were be brought online and tested.

A Lakeshore Cernox® RTD was embedded in the cold mass during construction, and the unix scan system was modified slightly to record the solenoid temperature, complementing the existing helium bath thermometry. This sensor will therefore be useful for measuring the solenoid temperature when it is operated in a future cryostat. Fig. 3 shows a comparison of the helium bath and solenoid temperatures during quench testing: the absolute agreement is good to ~10 mK at 4.4 K: bath temperature rises (off scale) following each quench, while the magnet temperature does not change much.

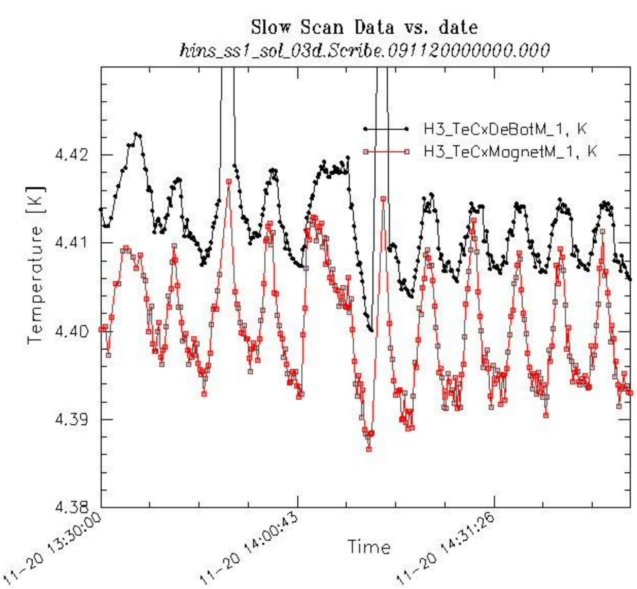

Fig. 3. Cold test temperatures of the helium bath (DeBot) and solenoid (Magnet).

III. Test Results.

A. Solenoid Quench Performance

The quench current in the MC of the solenoid is predicted to be 197 A at 4.41 K, as shown in Fig. 4 (bucking coil quench is expected above 230 A). However, during construction a lower than desired (by a factor of 2) tensioning force was applied on the beam tube during end flange welding, resulting in low pre-stress on the bucking coils. This condition could allow motion of the coils that might affect quench performance; thus quench training was especially interesting to study.

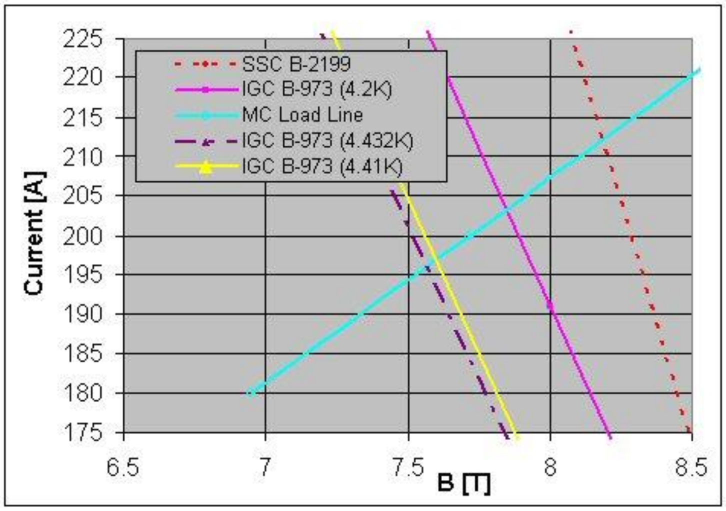

Fig. 4. Quench prediction for as-built solenoid at various temperatures.

Fig. 5 shows the solenoid training history during the three thermal cycles. The maximum current reached was 195.6 A, with numerous other quenches on a plateau of about 195 A, in the MC. This is consistent, within 1%, of the expected 197 A. However, as expected, the magnet quench performance was indeed erratic, with both bucking coils quenching well below the expected maximum current. Several events displayed voltage glitches at the start of the quench, indicating probable motion of a bucking coil: BCR showed glitches on quenches 1 and 4, and BCL showed a glitch in event 18 (no BCL signal was available until quench 12). Fig. 6 shows the voltage traces for events 1 and 18 around the time of quench initiation.

After the solenoid was removed from the test setup, it was found possible to increase the pre-load on the bucking coils. This was done by stretching the beam tube using hot water, then tightening the flux return iron yoke bolts, and inserting two brass shims (each half-circular for uniform loading) between the end flange and iron yoke on the lead end of the solenoid. Fig. 7 shows a photo of the shims in place. It is planned to re-test the solenoid to determine if this fixes the erratic quench behavior.

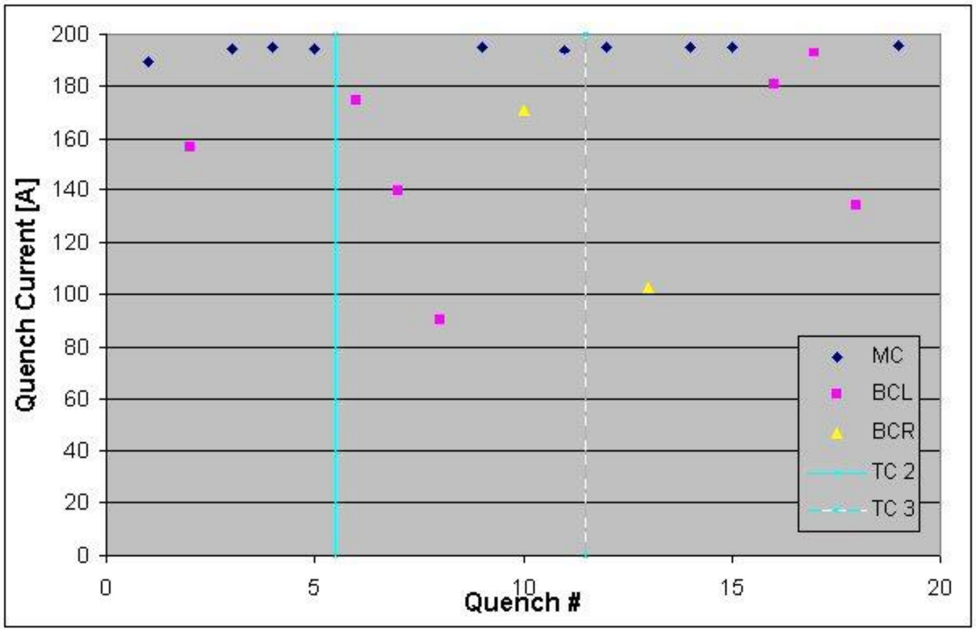

Fig. 5. Quench training history for pre-production solenoid SS1_SOL_03d.

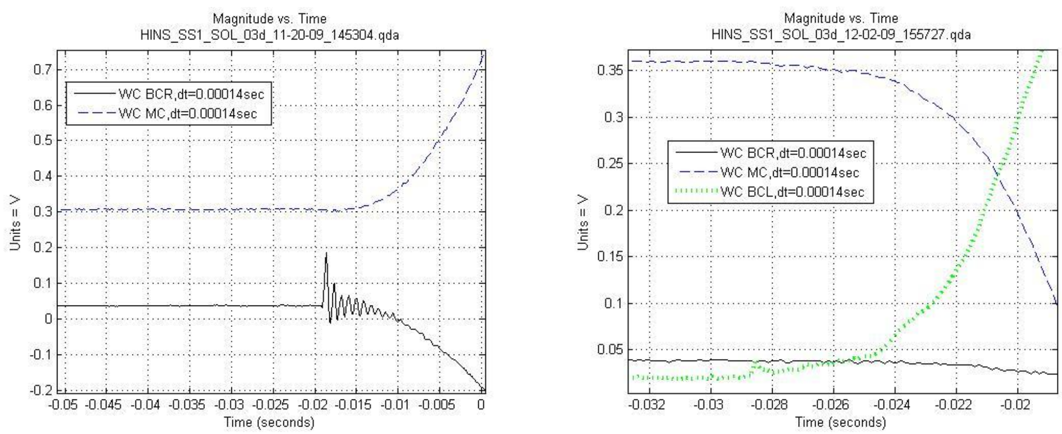

Fig. 6. Voltage signals for quench 1 (left) and quench 18 (right) showing glitches which suggest bucking coil motion preceding (and probably related to) quench initiation.

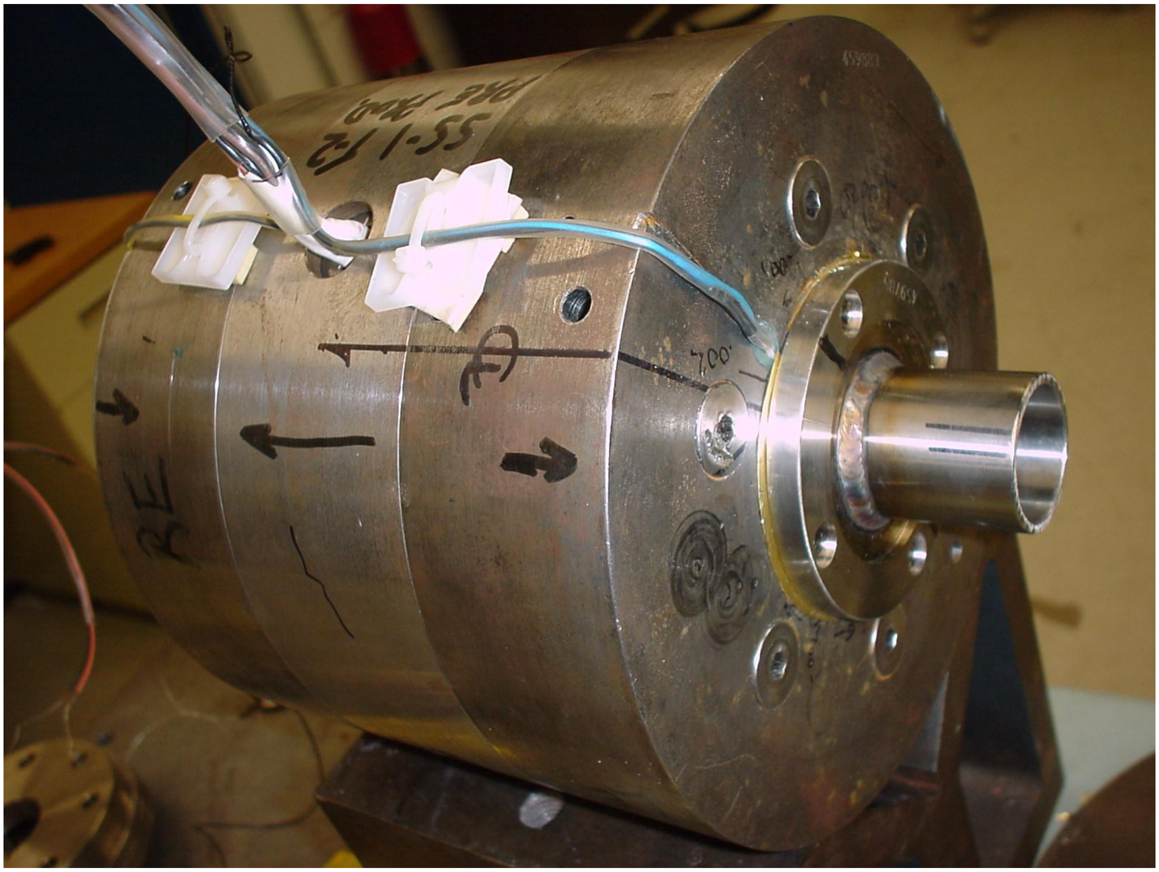

Fig. 7. Photo of brass shims installed between end flange and iron yoke to increase BC pre-load.

B. Dipole Quench Performance

The dipole quench prediction is shown in Fig. 8 for the dipoles operating in the solenoid field at 180 A, the approximate operating current for the pre-production solenoid. Temperature dependence is also shown, to illustrate the typical range of operating conditions in stand 3 tests. The prediction is for the solenoid peak field at radius 18.5 mm, which is the outer radius of the inner dipole (VD).

Figure 9 shows the dipole quench history. In the prototype model magnet, HINS_SS1_SOL_02d [3], we investigated dipole quench performance in the solenoid operating field. For the pre-production magnet, an additional quench test was done first: each dipole was by itself ramped to quench, to see how it performed in its self-field. A single ramp to quench was made for the vertical dipole, and two ramps to quench were made for the horizontal dipole. Then the solenoid was powered at 180 A and each dipole was ramped to quench. Both quenched at or above 45 A in the solenoid operating field, somewhat higher than the predicted current of 41 A. Absent the solenoid background field, the horizontal dipole went to twice this current (and did not improve in the second attempt), while the vertical dipole performed even better, and reached 152 A. So, this gives some feeling for the capability of this (wind on a flat substrate) technology for stand-alone correction coils.

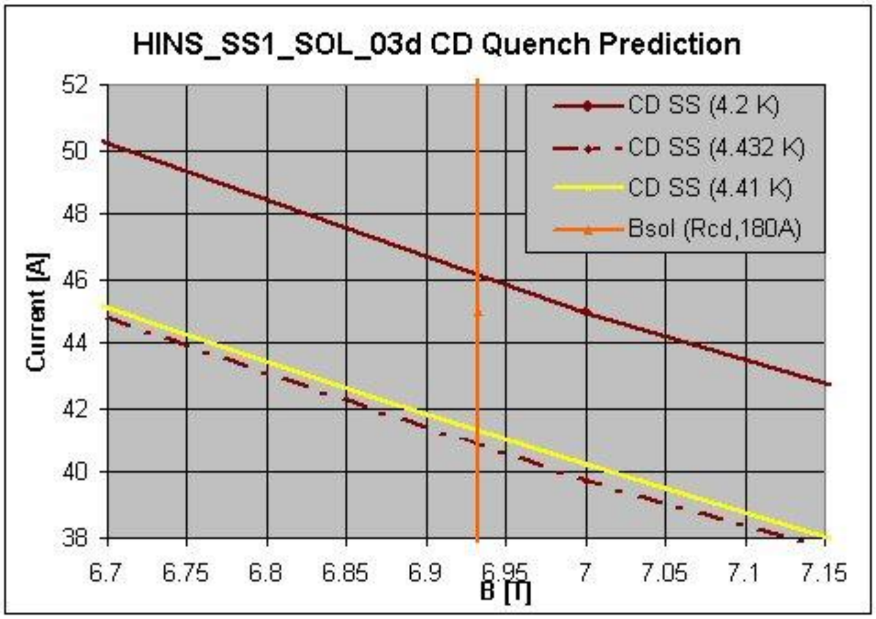

Fig. 8. Steering dipole quench prediction for as-built solenoid operating at 180 A.

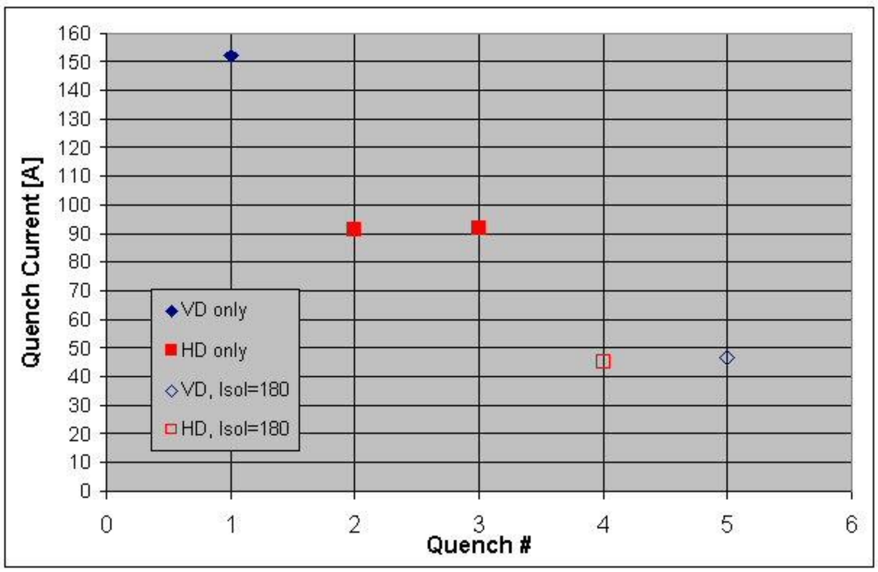

Fig. 9. Quench history for steering dipoles. Each dipole was separately ramped to quench with solenoid not powered, then with solenoid at nominal operating current of 180 A.

C. Solenoid Magnetic Measurements

Magnetic measurements were taken using a Cryomagnetics, Inc. cryogenic axial Hall probe (HSP-A ser. No. 602, with 300 K calibrated sensitivity of 21.41 mV/T), digitized with a Cryomagnetics GM-700 tesla-meter (ser. No. 3739). A scan of the axial field profile was made at 180 A (which was partially repeated in the positive Z lead end region). After ramping down to 0 A another scan of the field profile was made to measure the superconductor magnetization field.

Figure 10 shows the profile around the magnet peak field, which agrees nicely with the as-built model prediction. The measured peak transfer function is 376.2 G/A, which is 0.6% below the predicted 378.6 G/A.

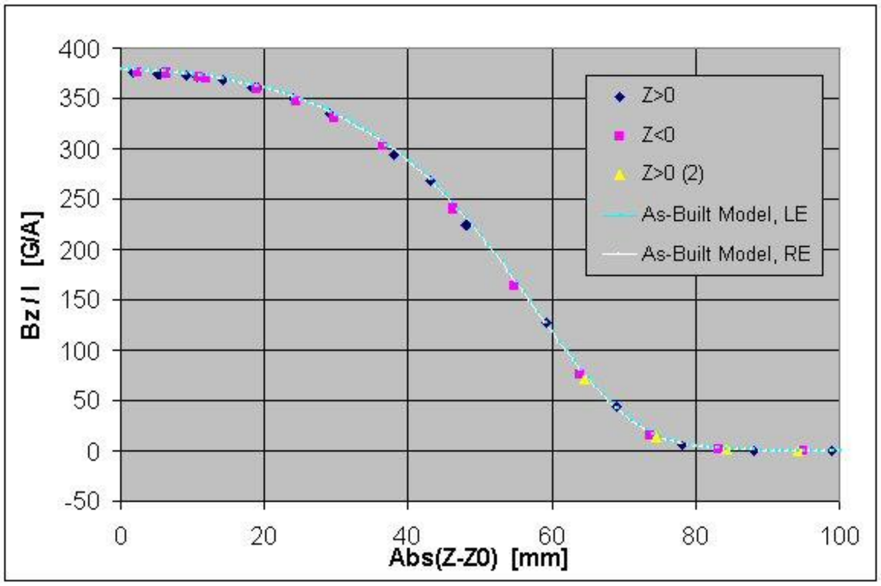

Fig. 10. Solenoid axial field profile around the peak field position at 180 A.

The fringe field is shown in Fig. 11, showing that measurements are in reasonable agreement with the as-built model. The slight shift between the measured and predicted positions of the dip, and of the asymptotic Bz strength at large Z, suggest the BC locations are not exactly as intended. It will be interesting to make a re-measurement of this with the added end shims (Fig. 7), to see if this change is reflected in the fringe field.

Magnetization of the superconductor after ramping up and down is shown in Fig. 12. Note that the direction (sign) of this field is the same as that of the powered solenoid.

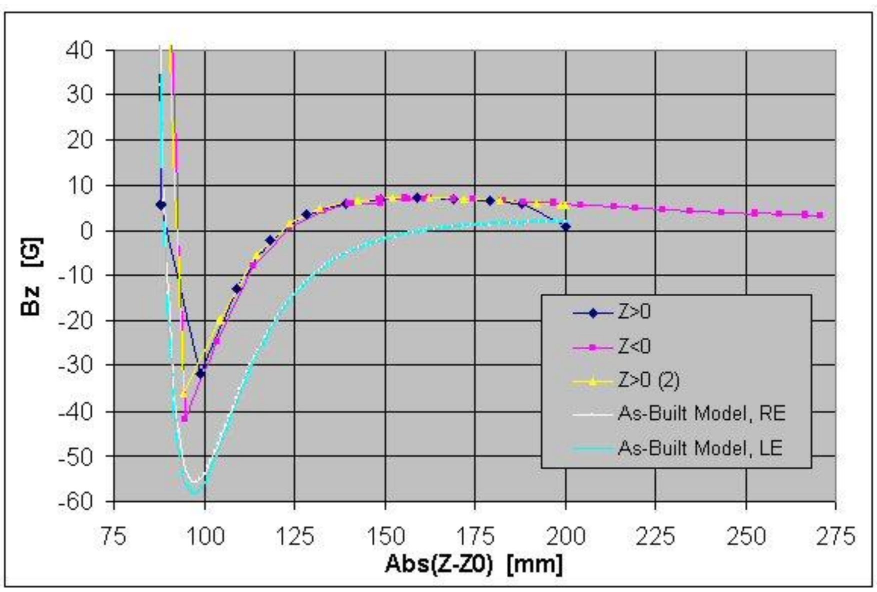

Fig. 11. Solenoid axial field profile in the fringe region at 180 A.

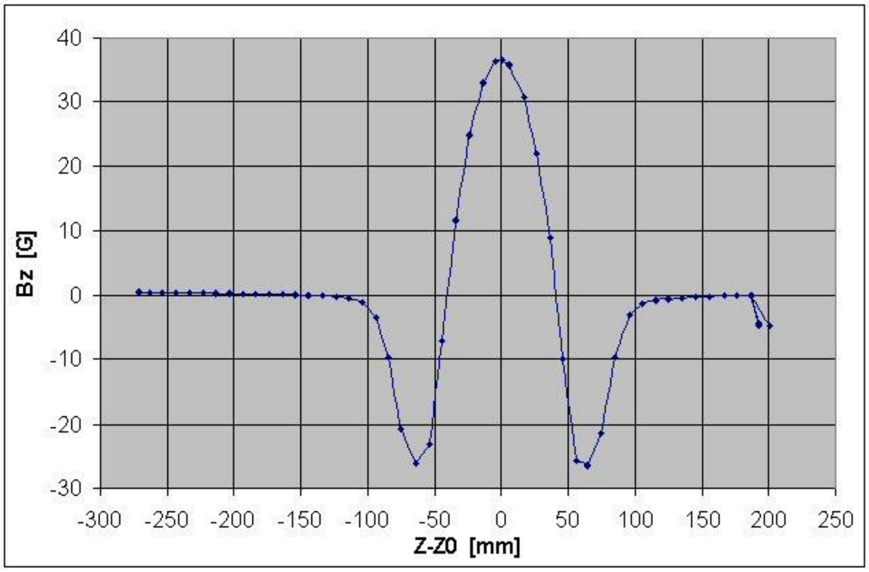

Fig. 11. Magnetization field of the superconductor after solenoid ramp up to 180 A and down again to 0 A.

D. Dipole Magnetic Measurements

Dipole magnetic measurements were taken during the cold test using a Cryomagnetics, Inc. cryogenic transverse Hall probe (HSP-T serial number 598, with 300 K calibrated sensitivity of 36.60 mV/T), digitized with the same Cryomagnetics GM-700 tesla-meter. Scans of the axial field profile were made at 50 A for each dipole, after first orienting the probe to align it with the field at the dipole center. Fig. 12 shows the overlaid profiles of HD and VD transverse fields. These are quite consistent with those measured (warm) in the prototype SS1 solenoid [3] in peak strength (20 G/A pre-production, vs. 23 G/A prototype) and integral strength (210 G-cm/A, vs. 213 G-cm/A).

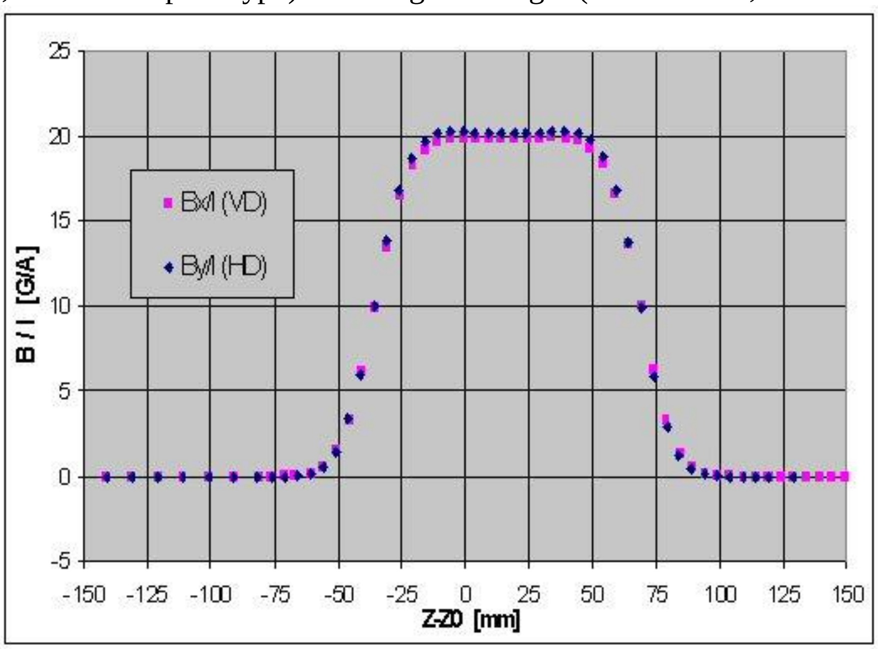

Fig. 12. Transverse field profiles of Horizontal and Vertical Dipoles at 50 A.

Prior to the solenoid assembly, warm magnetic measurements were made of the completed dipole corrector package, primarily to get another look at the field quality of the correctors. A 12.3 mm radius, 25 cm long tangential coil probe was used to capture integral strength and harmonic field measurements. Probe rotation was controlled using the VMTF vertical tower, and signals were recorded with the DSP-1 EMS magnetic measurement cart. Data for VD were taken at currents of ±0.1 and ±0.25 A.

Analysis of the harmonics leads to the contour plots shown in Fig. 13 of the errors in Bx and By, normalized to the vertical dipole field (B1). These appear to be very similar to those measured for the prototype, which are shown in Fig. 26 of [3]. Some slight asymmetry is evident.

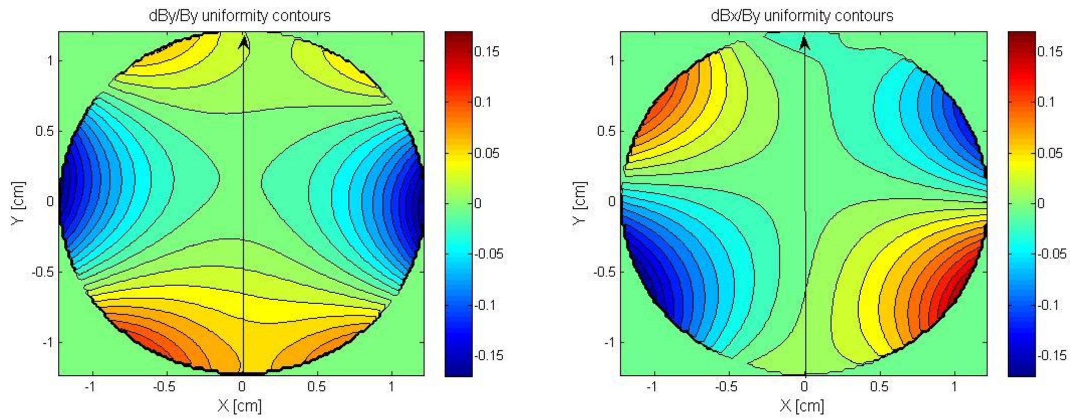

Fig. 13. Field uniformity maps within probe radius of 1.22 cm for vertical dipole, showing dBy/B1 (left) and dBx/B1 (right). Arrows indicate dipole field direction.

IV. Conclusions.

Following prototype magnet test results, which showed a need for greater margin to operate the solenoid at higher temperature expected in the Meson lab, a revised design of this solenoid for the SS1 section of HINS was made. The construction and test of this "pre-production" solenoid were described in this note.

The solenoid fabrication suffered from one small but important defect: axial pre-stress during the assembly was only about half of the design value. As a result, it was expected that motion of the bucking coils might lead to anomalous quench performance. In fact, this was the case: although the solenoid did reach the maximum current many times, it quenched at rather low current after one thermal cycle, and showed erratic behavior even after the quench plateau was achieved. Although it can work, this behavior would introduce operational inefficiency. After the test, a method for increasing the axial pre-stress was found and implemented, without disassembly of the device. Another test of this solenoid is planned to determine to what extent this repair improves the quench performance.

The solenoid magnetic field was mapped and found to be in quite good agreement with the predicted strength and shape. The fringe field agreement is good but slightly off, which may be an artifact of the bucking coil positions not being exactly as expected, or perhaps from a difference of assumed and actual cold iron material properties.

The corrector dipole coils – the second set of this design to be built and tested – worked as predicted in the solenoid operating field. The dipole spontaneous quench currents with solenoid off were also explored, to get a sense of how well they can work independently. The dipole peak and integral magnetic strengths were measured and found to be very consistent with the prototype version of the dipole corrector package. Warm harmonic coil measurements of this package indicate the map of field uniformity is very consistent with the prototype, as well as with the 3D model prediction.

V. References.

1. G. Davis, et al., "Pre-Production Solenoid for SS1 Section of HINS Linac", FNAL TD note TD-09-010, March 2009.
2. G. Davis, et al., "HINS Linac SS-1 Section Prototype Focusing Solenoid Design", TD-08-010, FNAL, March 2008.
3. G. Chlachidze, et al., "HINS_SS1_SOL_02d Fabrication Summary and Test Results," FNAL TD note TD-09-001, January 2009