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HINS_CH_SOL_05
Fabrication Summary and Test Results

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I. Fabrication Summary

HINS_CH_SOL_05 is the first pre-production solenoid without correctors. The main goal of making and testing this solenoid was to check how the design that employs G-10 coil bobbin works. The first prototype of the solenoid [1], that was built with copper bobbin, showed very fast training, but the bobbin was quite expensive, and making ground insulation to avoid coil shorts to ground was considered to be a problem, although quite solvable. The solenoid was built from Main Coil (MC) serial number PPT1-01, and Bucking Coils (BC) BC11 and BC12.

To wind the main coil of the solenoid, Oxford 0.8mm strand was used (spool 6056-2, coated diameter 0.846 mm). For the bucking coils, a new billet of Oxford 0.6 mm NbTi strand was used (billet 8538-1B spool 1797A, coated diameter 0.634 mm). Main design features of the solenoid (as built) are shown in Fig. 1 below.

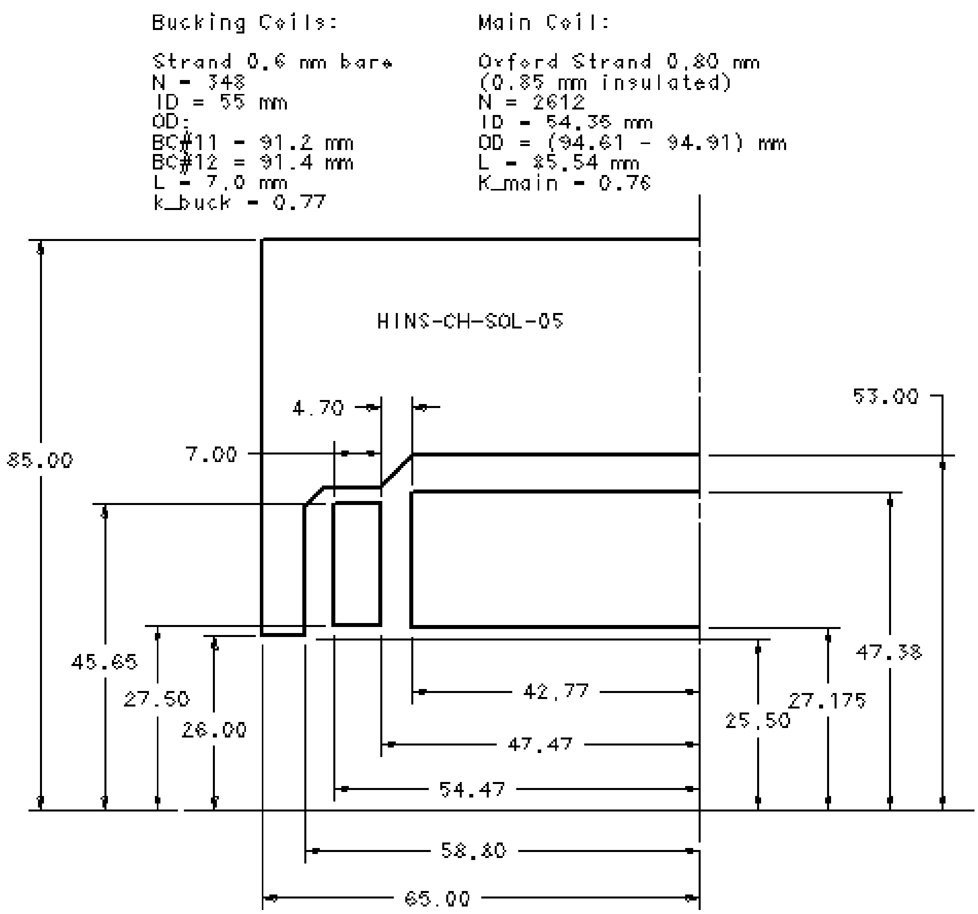

Fig. 1. HINS_CH-SOL-05 Type I pre-production solenoid design features (as-built).

The solenoid implementation was quite close to what was planned originally. The inner diameter of the bucking coil was a bit larger (55 mm vs. 54.2 mm), but the outer diameter was as expected because a better packing factor was achieved (0.77 vs. 0.74 planned). Also the main coil packing factor was slightly better than expected (0.76 vs. 0.75), resulting in a slightly smaller diameter for this coil. In both bucking coils, the number of turns was as expected, and there were no problems during winding. The bucking coils were positioned closer to the main coil than had been instructed by the design (a gap of 4.3 mm was made instead of the expected 7.25 mm): the reason was misreading of the assembly drawing. Nevertheless, it was shown by post-modeling that this did not result in a significant change of the expected field profile.

Strand critical current parameters (10^{-14} Ω-m criterion) were measured by Daniele Turrioni and Emanuela Barzi and are shown in Table 1 (0.8 mm) and Table 2 (0.6 mm). The predicted load lines and quench currents for the Main and Bucking coils are shown in Fig. 2.

Table 1: Measured Performance of 0.8 mm Strand (Spool 6056-2)

B (T)	3	4	5	6	7	8	9
Ic (A)	842	711	592	477	356	230	107

Table 2: Measured Performance of 0.6 mm Strand (Spool 1797A)

B (T)	1	2	3	4	5	6	7
Ic (A)	749	559	462	392	330	270	210

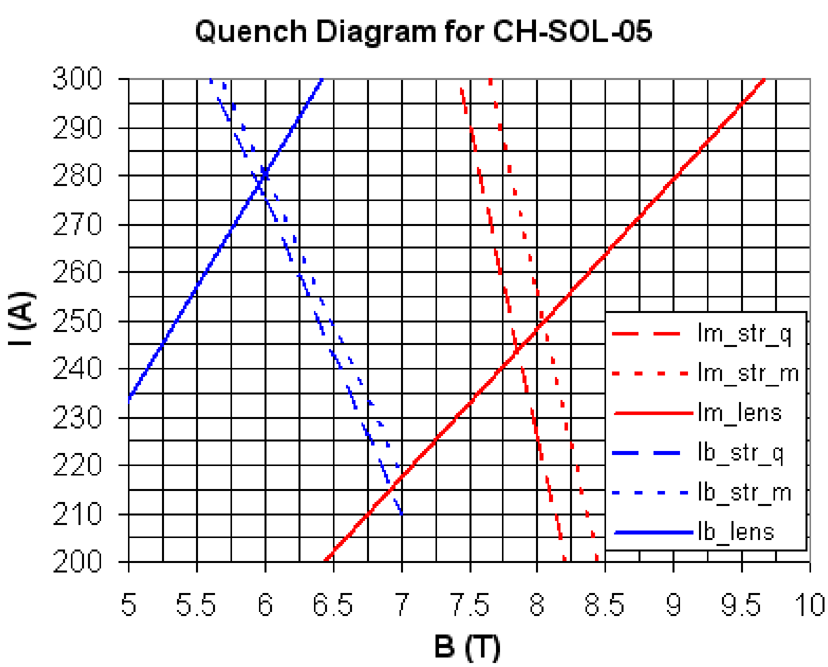

Fig. 2. Quench diagram showing load lines and critical surfaces for the as-built solenoid

In this diagram a maximum strand current is shown in dotted lines, so we can say that the quench in the solenoid is expected when the current is between 244 A and 250 A.

II. Test Overview

The first cool down took place on 9/26/07. Having three pairs of leads in the top flange of the Stand 3 dewar, we were able to use a separate pair of leads for each of the three coils in the solenoid, so all connections between coils were made outside of the dewar. Warm magnetic measurements were ***not*** made prior to cool down (as had usually been done in previous tests), and we later realized that this small step would have made the test much more efficient – unfortunately, after the first cold test we determined that (mis-labeling of leads caused) the field direction of bucking coil BC11 to be (incorrectly) aligned with the Main Coil, while BC12 field was opposed to the MC field (as it should be). Indeed, the trained quench current in the first test cycle was affected by this. Quench training was slow: it required more than 60 quenches to reach a plateau. A cold magnetic field profile was obtained on 9/28/07, and some stair-step measurements were taken to study the effects of iron saturation on the peak and fringe fields. Near the end of the first training cycle, problems arose with quenches in the superconducting leads, but they stopped and a plateau was reached.

During the warm up, careful study of the magnetic field revealed an asymmetry, and additional measurements uncovered the BC11 field error. Since this could be corrected by changing the external bus connections, we performed a second cold test without removing the assembly from stand 3 (to avoid additional checkout and to save time). The second cool down and test occurred on 10/04. Cold magnetic measurements were taken first, to confirm the field profile. In this new power configuration, the magnet trained very quickly to near the expected quench current (just over 240 A); however, quenches in the superconducting leads returned (following our attempts to lower the level of LHe to reduce its evaporation rate), with the current limited to about 180 A, and all attempts to prevent them (changing ramp rate; raising liquid level; waiting longer between ramps) failed. Voltage signals for both Sc Leads showed some “ringing”, suggesting the possibility of motion, but only the “negative” (BC) lead developed a quench. After the second warm up, a careful inspection of the assembly was made to try to discern the cause: all of the superconducting leads were mechanically unsupported between the solenoid and the stabilized superconducting power lead connection, so there could easily have been motion (although we believe the self-generated magnetic fields to be relatively small, and the leads to have been fully immersed in liquid helium, so lead quenches are still considered surprising.

Figures 1 and 2 show the time histories of current, liquid level, and helium temperature during the cold tests of this solenoid. In total, five 500 liter dewars of liquid helium were used to complete the test.

III. Quench Performance

Having learned in previous tests [1] that individual training of main and/or bucking coils does not result in faster training of the lens, we started training with all three coils connected in series. Training was conducted at a ramp rate of 1A/s, with a strictly enforced minimum of ten minutes between quenches. Figure 3 shows the training history: it was quite slow and started with a quench in the main coil at 117 A. The first 8 quenches (on 9/26) were made, intentionally, with no dump resistor: thus the solenoid survived full energy deposition up to 188 A. After ~ 60 training ramps a current of ~237 A was reached. Quenches were mostly in the Main Coil which trained upward more-or-less monotonically to ~ 220 A. The quench location then moved to BC11 which showed an erratic, but reproducible, high – then – low behavior; at the end however, the BC11 quenches did not fall back (in fact, there was more time between quenches), quenches returned to the MC and finally showed a training plateau. We suspect that in the high current BC11 quench, which is the worst case in terms of coil temperature rise, more time is needed between ramps to allow the coil to equilibrate to the bath temperature. We intend to study this conjecture with a thermal model, to estimate the time needed to return to the bath temperature after a high current BC quench.

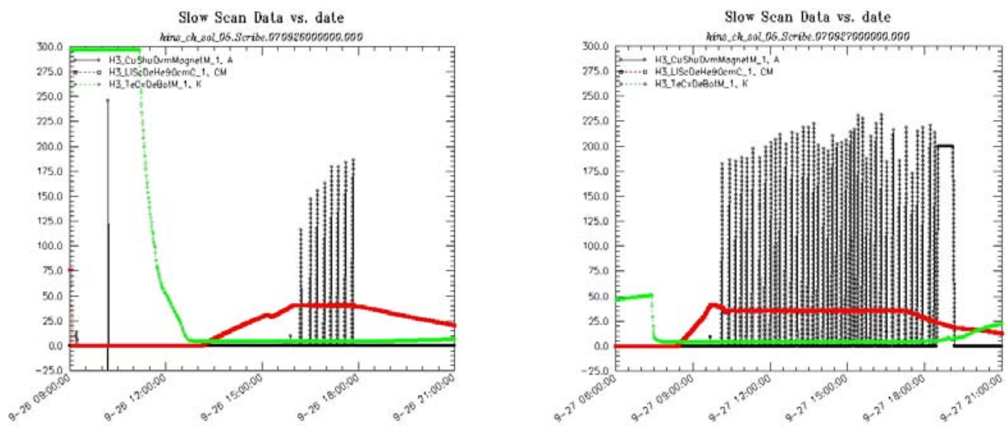

Figure 1. Test history from 9/26 and 9/27, showing MC+BC current (A), helium liquid level (cm) and temperature (K).

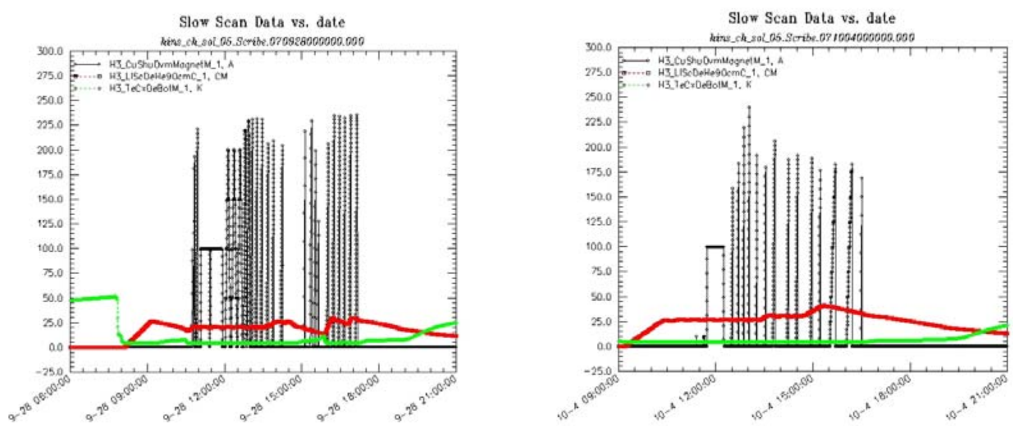

Figure 2. Test history from 9/28 and 10/04, showing MC+BC current (A), helium liquid level (cm) and temperature (K).

At the end of testing on 9/27, after when the liquid helium supply was exhausted, a test was made to power the solenoid at 200 A while the liquid level dropped to a rather low level, 18 cm instead of the usual 35 cm, without a quench (see Figure 1). This gave us some confidence that we could operate with lower liquid level, and thus lower heat load and boil-off rate. Starting with the current ~235 A, operating with quite a low level of LHe (7.8”), transitions in superconducting (Sc) leads became a frequent reason for the system trips. Although 237 A current was somewhat lower than the predicted quench current, we accepted this current level as the limit we could reach.

Careful analysis of the magnetic field data was made at this point, and reversed field polarity of BC12 was revealed: that resulted in a very asymmetric field distribution, with higher than predicted central field, and thus lower than expected quench current. Magnetic measurements between thermal cycles demonstrated that the lens was oriented with BC11 on the bottom, and BC12 above the MC. The MC field was pointing up when positive terminal of the power supply (PS) was connected to positive MC lead. The polarity correction was easily made with the external bus connections and a new cold test cycle was begun on 10/4.

After capturing (and checking) magnetic measurements at 100A, re-training started in the main coil with a quench at 160 A and quickly (four ramps) reached 242 A, where a superconducting lead quench occurred. Subsequent ramps never reached this level again, and in fact the Sc lead quench current degraded to about 180 A. Voltage taps of each lead segment were available and were added to the QC system (though only two could be captured at a time, labeled K and L): these indicated the Sc leads of BC11, mostly the positive lead, was quenching; all events had a characteristic sharp spike within the voltage trace, followed by monotonic rise to the 50mV threshold. After numerous attempts without success to prevent Sc lead quenches, the test was terminated. As discussed above, post-test examination of the tower did not show any explicit signs of strand or splice damage, but the superconducting lead strands dangled loosely around the solenoid suggesting that strand motion during excitation was easily possible. One section of the BC11 Sc Leads were secured near the top of the solenoid, at a level which would have been above the liquid helium when problems first occurred on 9/28.

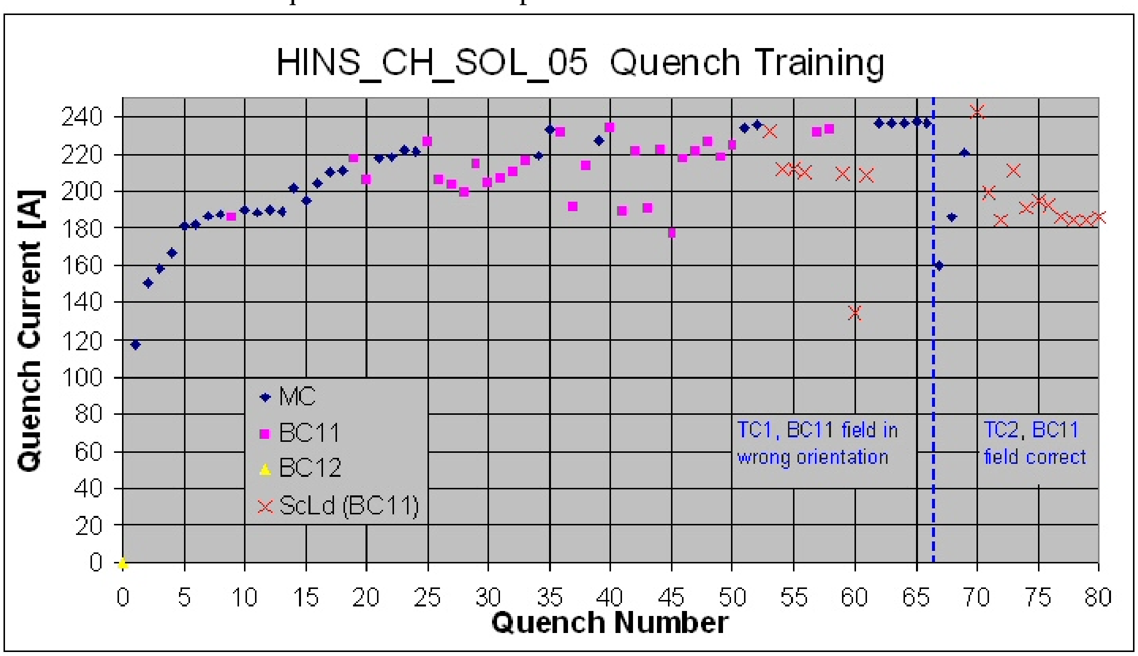

Fig. 3. Quench history of MC+BC

The history of this test tells us how important it is to prepare and conduct the test in a well defined sequence:

- paying close attention to all details, carefully examine the test assembly to make sure everything has been correctly positioned or oriented, properly insulated and connected, with Sc leads secured.
- make warm magnetic measurements before starting to fill the dewar with LHe
- ensure that a plentiful LHe supply is available for test flexibility and contingency.

IV. Magnetic Performance

Fig. 5 shows the solenoid magnetic field map at the expected quench current (244 A)

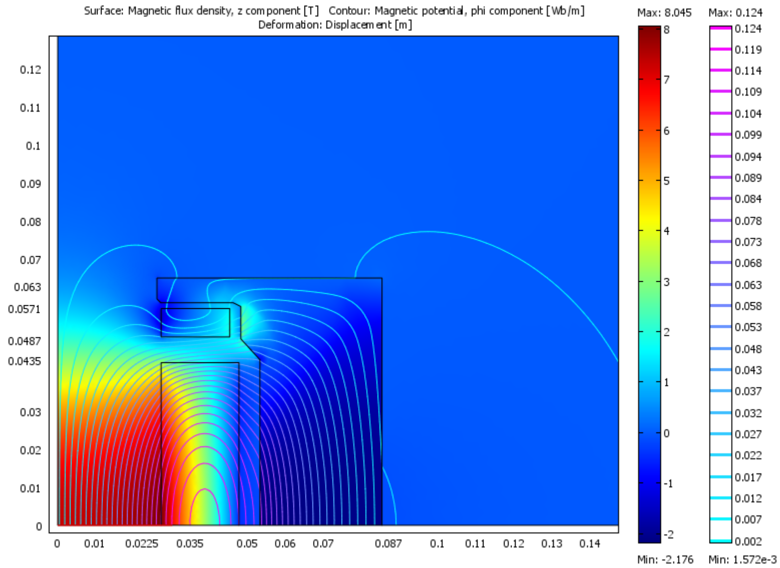

Fig. 5: HINS-CH-SOL-05 magnetic field map

Throughout this test, magnetic measurements were made using the “new” Senis 3D Hall probe (ser. No 54-06) positioned “on-axis” in the G-10 probe support, as described and shown in Figure 10 of [2]. The probe readout utilized the same Keithley 2700 multiplexing DMM as for previous tests with this probe, but with improved shield grounding to reduce noise levels. Offset voltage levels were recorded as part of each measurement and subtracted in performing the analysis (especially important for fringe field measurements). The RMS noise levels were less than 1.5 Gauss for each of the three elements.

Measurements made at different current levels demonstrated that the predicted solenoid parameters are quite close to the observed ones. Fig. 6 compares the predicted and measured magnetic field near the median plane of the solenoid at 100 A.

The solenoid transfer function shows some nonlinear behavior as a function of current that slightly affects its central field and, to a greater extent, its fringe field. Fig. 7 shows the model prediction of transfer function in the center of the solenoid for different currents. (The initial measurements taken to study this effect cannot be compared directly to these model predictions, because the field distributions differ greatly due to the bucking coil polarity reversal. However, those data do show clearly non-linear behavior in both the central peak and fringe field regions).

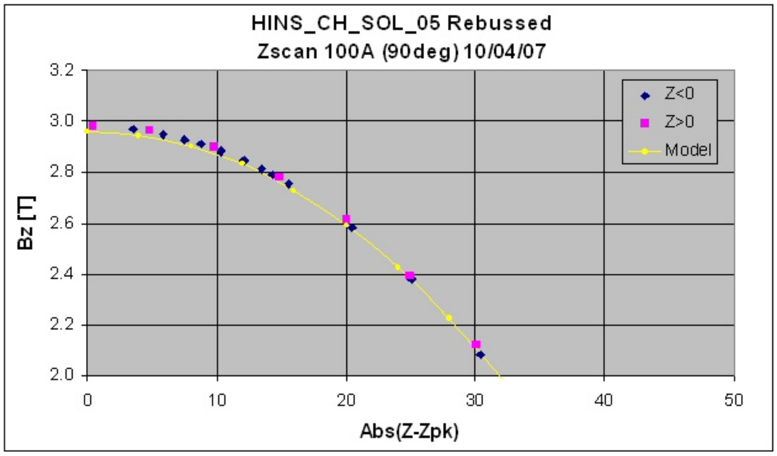

Fig. 6: Comparison of predicted and measured axial magnetic field at 100A: actual field is 0.8% higher than predicted.

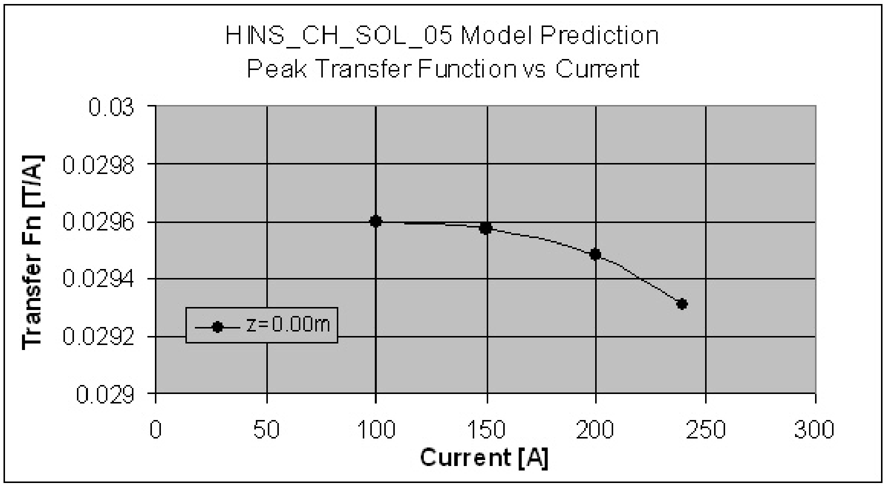

Fig. 7. Transfer function versus current at the solenoid center (model prediction)

Similar curves for several peripheral points along the axis are shown in Fig. 8. One can see that the relative importance of this saturation effect is much larger in the peripheral (fringe field) region. At low current, the modeling gives results quite close to those measured. Fig. 9 shows the magnetic strength profile at 100 A at several peripheral positions: the agreement is very good here, although the measured field is about 50% above the prediction. Fig. 10 shows that the measured current dependence of the transfer function in the fringe region remains constant below 180A, while the prediction suggests some rise is expected. Both results can arise from the uncertainty in our knowledge of the flux return magnetic properties, which may differ in detail from those used in the model. Unfortunately, due to problems with the Sc leads, we were unable to further explore this behavior at currents above 175A.

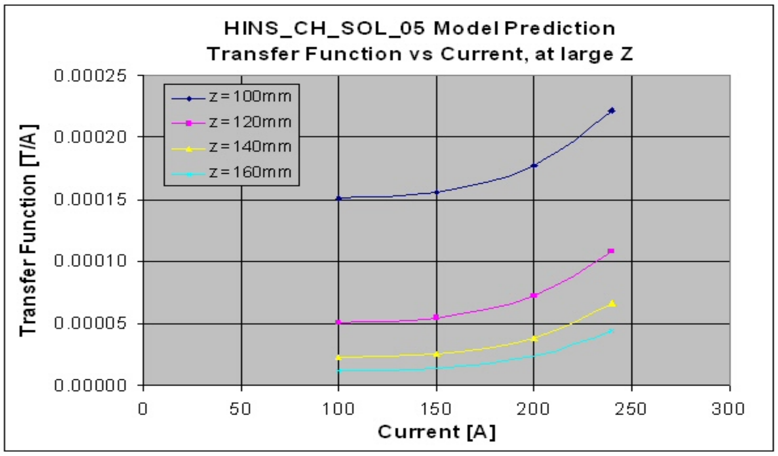

Fig. 8: Model predictions for current dependence of the solenoid transfer function in the peripheral region, at different distances from the center of the solenoid.

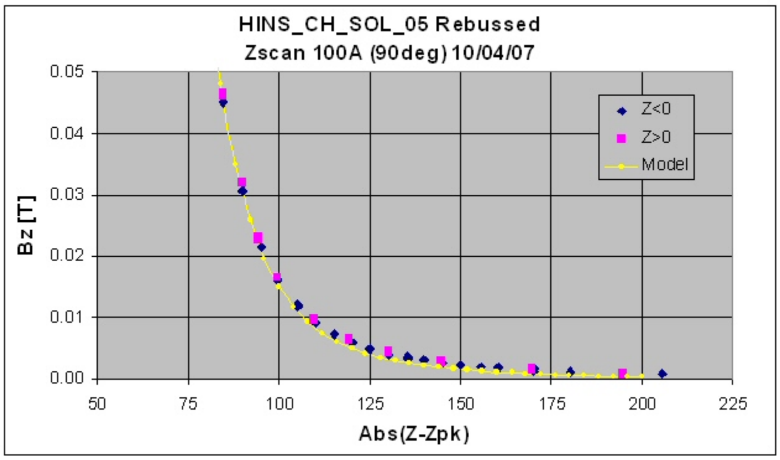

Fig. 9: Modeled and measured axial magnetic strength profiles at 100A in the fringe field region.

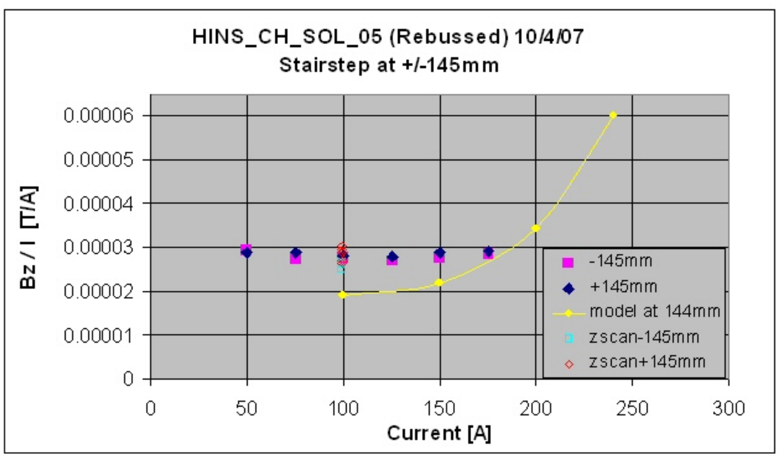

Fig. 10: Comparison of model and data, current dependence of axial field transfer function profiles at 145 mm from the solenoid center.

V. Conclusions

In quench performance testing the solenoid essentially reached the predicted current level with quenches in the main coil; however, superconducting lead quenches – most likely due to inadequate mechanical support outside of the magnet - prevented us from reaching the ultimate quench current plateau. The initial quench training (with incorrect BC11 field configuration) was relatively slow, but re-training was very quick when the correct configuration was then established. What appears to have been erratic and slow bucking coil training, is hypothesized to be the result of coil heating followed by inadequate time to equilibrate with the helium bath before the next current ramp – modeling of this situation is needed for better understanding of the time dependence of coil temperatures.

Magnetic measurements were made to explore, in greater detail than previous tests [1], the current-dependent effects due to iron saturation. Model predictions and measurements of the transfer function profile are in good agreement at low current, though superconducting lead quenches limited the ability to extend the measurements to higher current. The effect of saturation becomes relatively important in the fringe field region at, or just above, the solenoid nominal operating current.

References

[1] E. Barzi, G. Davis, C. Hess, F. Lewis, D. Orris, M. Tartaglia, I. Terechkine, D. Turrioni, T. Wokas, "HINS_CH_SOL_04d Expected Performance and Test Results", FNAL TD Note, TD-07-027, FNAL, 30 Oct 2007.

[2] C. Hess, F. Lewis, D. Orris, M. Tartaglia, I. Terechkine, T. Wokas, "Focusing Solenoid HINS_CH_SOL_02 Fabrication Notes and Test Results", FNAL, TD-07-008, May 09, 2007.