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MECHANICAL ANALYSIS AND TEST RESULTS OF 4-COIL SUPERCONDUCTING HELICAL SOLENOID MODEL

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ABSTRACT

Novel configurations of helical superconducting magnets for muon beam 6D phase space cooling channels and demonstration experiments are being designed at Fermilab. Operating as needed for the beam cooling in a cryogenic environment, the helical solenoid generates longitudinal and transverse magnetic fields; meanwhile, large Lorentz forces are produced, so rigid coil support structures need to be designed. A short model of a helical solenoid (HS), consisting of four coils and supporting structures, was designed, built and tested at Fermilab. The magnetic and mechanical designs were analyzed using TOSCA and ANSYS. The supporting structures were fabricated and assembled using SSC NbTi cable. Strain gauges were utilized to monitor the deformation of the structures due to both thermal contraction and Lorentz forces. The superconducting coils were trained during the test. The model should prove the design concept, fabrication technology, and the magnet system performance.

KEYWORDS: Superconducting magnet, Muon beam cooling, Helical cooling channel, Four-coil helical solenoid.

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INTRODUCTION

The Large Hadron Collider (LHC) construction was finished at CERN and the first protons were fired around the entire tunnel circuit in September 2008. Soon LHC will be operated to study hadron-hadron collisions. Nowadays, physicists are carrying out complementary studies of lepton-lepton collisions, and one plan is to design a Muon Collider [1]. Muons are much heavier than electrons, so very high energy muon beams can be bent in beam lines and recirculated in an accelerator with much less energy loss. However muons are unstable particles with a very short lifetime and muon beams have large emittances. To meet the requirement of the Muon Collider, one of the extremely difficult challenges is to reduce the muon beam size in a very short time before muons decay away. For this purpose, the Helical Cooling Channel (HCC) concept for the six-dimensional muon beam cooling was suggested in [2]. The Helical Solenoid configuration [3] generates the needed solenoidal, helical dipole and helical quadrupole magnetic fields [4, 5] to realize the beam size reduction in a helical ionization cooling channel.

It is well known that hoop stress and axial compression are the dominant stress components for the straight solenoids. However, in a helical solenoid, much more complicated stress patterns are generated due to the magnetic field components and the structure configuration. It is important to develop the proper design and technology to protect the superconductor coils from large stresses and displacements during cool down and magnet excitation. A four-coil helical solenoid model, named HSM01, was designed, fabricated and tested at Fermi National Accelerator Laboratory (FNAL) to develop the manufacturing technology and demonstrate the magnet system performance. This paper will present the model design and the simulation results, and show the test results of magnet training, as well as strain gauge readings. The post-test model autopsy was finished to observe the inner mechanical structure, and the improvements for the next model were discussed.

DESIGN AND SIMULATION

To fit within the Vertical Magnet Test Facility (VMTF) at FNAL, HSM01 was designed with 640 mm outer diameter, limited by the cryostat bore diameter. The stand has all the cryogenics, 30 kA power supply, quench detection, protection and control systems. Simulations for both magnetic and mechanical design were executed to have a better understanding of the model performance before fabrication and test.

Magnetic Design and Simulation

HSM01 consists of four coils with the centers shifted along an arc corresponding to the helical orbit. The basic model parameters are listed in TABLE 1. Cable Ic(B) dependence and load lines for long HS and for HS 4-coil model are shown in FIGURE 1. For the long helical solenoid at 4.5 K, with cable current 9660 A, the peak superconductor magnetic flux density B reaches 5.7 T. To produce this same level of magnetic field and Lorentz force in the four-coil model, the cable current has to be raised up to 14 kA, and the peak magnetic flux density B in the superconductor is 4.84 T. Study and comparison of the magnetic field and forces between the four-coil model and the long helical solenoid model were made in [6]. The four-coil geometry and the simulated flux density distribution in ANSYS are shown in FIGURE 2.

TABLE 1. Solenoid Parameters.

Parameter	Units	Value
Coil inner diameter	mm	426
Coil outer diameter	mm	455
NbTi cable dimensions	mm	12.34 x 1.46
Cable critical current at 5.3 T, 4.5 K	kA	16.4
Strand diameter	mm	0.8
Helical orbit radius	mm	255
Helix period	mm	1600
Number of turns per coil		10
Coil height	mm	20

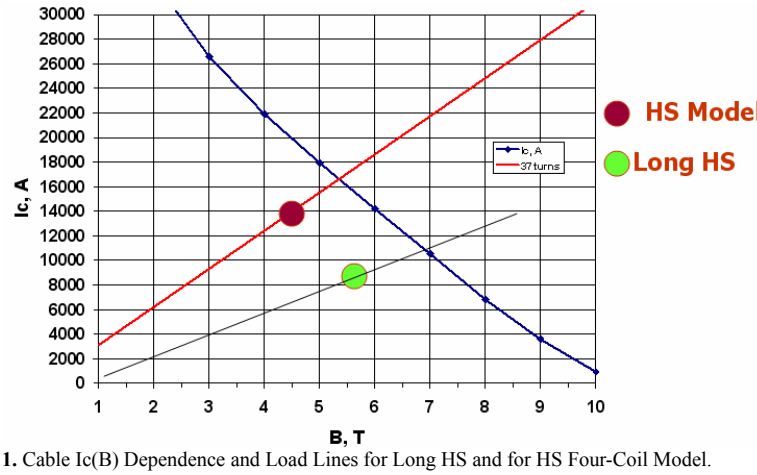


FIGURE 1. Cable Ic(B) Dependence and Load Lines for Long HS and for HS Four-Coil Model.

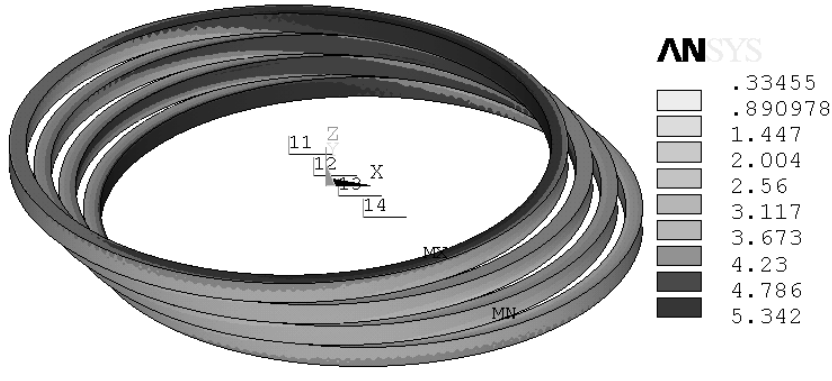


FIGURE 2. Four-Coil Geometry and Magnetic Flux Density Distribution (Values in T) at 14 kA.

Mechanical Design and Simulation

The helical solenoid generates solenoidal, helical dipole and helical quadrupole magnetic fields; meanwhile, it produces large radial and longitudinal forces, as well as bending, so solid mechanical structures are needed to intercept the forces and support the coils [6]. FIGURE 3 shows the design sketch in cross section view. The material is stainless steel for the supporting structures, including inner rings, outer rings, and end flanges, etc. Steps are machined on both sides of the inner and outer rings to lock the coil from moving in the transverse direction. The inner rings, as well as the outer rings, are welded together with the end flanges to strengthen the whole structure. Due to the magnetic forces and the helical structure configuration, complex stress patterns exist, including hoop stress, radial compression, axial compression, and shear stress.

The 3D mechanical model is built in ANSYS, shown in FIGURE 4. Since the model is simplified (for instance, there are no steps modeled in the support rings), for the boundary conditions all the structure components are glued to each other, and the model is attached to VMTF by 4 rods for the test.

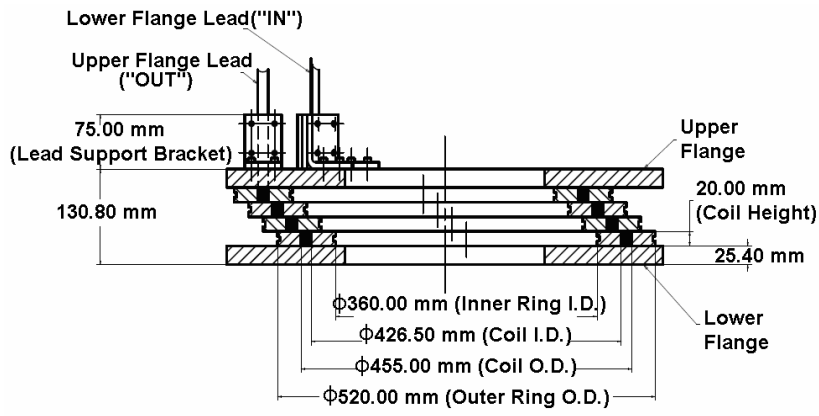


FIGURE 3. The Model Design Sketch in Cross Section View.

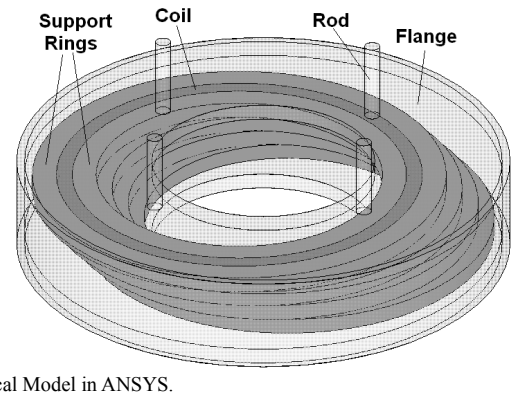


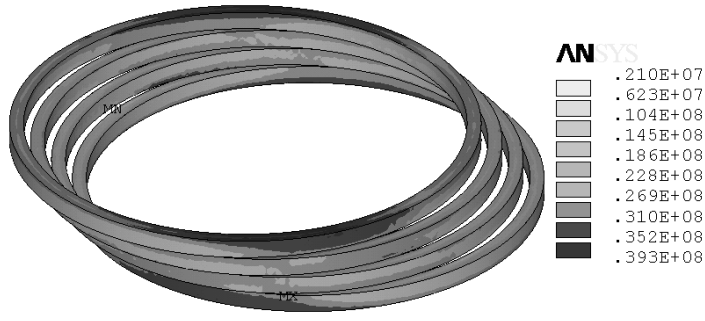
FIGURE 4. 3D Mechanical Model in ANSYS.

The magnetic forces are calculated based on the Lorentz Force Law on a current-carrying wire, and the results are consistent with the results from TOSCA. The forces are then applied on the nodes of each coil. The accumulated force for each coil is considerably large, for instance, in the top coil, the accumulated radial force is about 150 KN and the accumulated axial force is about 320 KN. The forces are trying to straighten the helical coils, and compress the superconductors in both radial and axial direction, so the support rings not only have to provide the coil support, but also have to prevent coil motions. Besides the magnetic forces, thermal contractions of the helical structure during cool down, from room temperature to 4.5 K, also causes big stresses in the superconducting coils, especially in the axial direction.

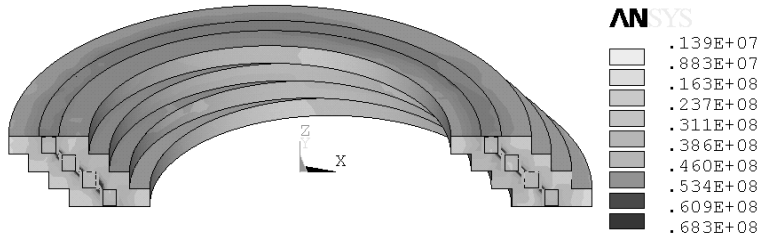
The stress distributions in the coils and the support rings are shown in FIGURE 5 (a) and (b). The maximum stress is 39.3 MPa in the coils and 68.3 MPa in the support rings, which is well below the conductor degradation limit stress 150 MPa and the stainless steel yield stress 550 MPa. The relatively large margins in stress will be beneficial for the long HS design.

FABRICATION AND TEST

HSM01 was fabricated and tested at FNAL. Heaters were installed in the gap outside of the outer coil radius to provide quench protection. Strain gauges were glued in the outer surface of the support rings to monitor the deformation of the structure.



(a). Stress in Coils.



(b). Stress in Coils and Support Rings from Cross Section View.

FIGURE 5. Stress Distribution (Value in Pascal) at the Peak Current 14 kA.

Fabrication

The horizontal winding rotational table system was used to wind NbTi cable, shown in FIGURE 6. The side flange was attached to the table, and then the first coil inner support ring was locked and welded to the flange. The cable, passing through all the outer support rings, was wound around the first inner ring, and the first outer support ring was locked. The other three coils were wound and assembled with the similar procedure. Welding was made at certain spots on the support rings and the other side flange. Since the coil centers are shifted, the hard-bend winding way was adopted to provide continuous winding without any splices; however from coil to coil, the transition turns shown in FIGURE 7 should be well insulated and arranged. Extra pieces of G-10 insulation were used, and pressure was applied to make the transition turns fit inside the support rings. The long solenoid can also be wound and assembled in the same way as the short model.

There were two significant fabrication issues. First, due to the limited winding space, one of the four coils has 10 turns, while the other three coils have only 9 turns, but it did not have a big effect on the magnet performance. Second, during the room temperature insulation hipot tests, the magnet could withstand no more than 250 V to ground without a discharge. In liquid helium, a 15 kΩ short to ground developed [7]. A post-test inspection points to a likely coil-to -coil transition area insulation weakness which was probably caused by the insulation bending under the pressure to fit the transition turns.

Test

HSM01 was suspended in the VMTF cryostat, with an insulated warm bore tube passing through the aperture to measure the magnetic field components near the center. Because there are only 9 turns in three coils, an update model was built and simulated in TOSCA. The model

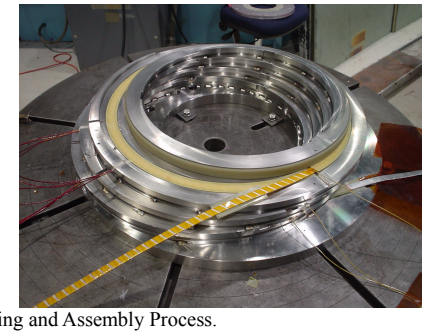


FIGURE 6. The Model Winding and Assembly Process.

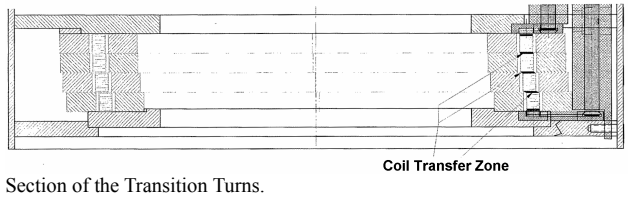


FIGURE 7. Cross Section of the Transition Turns.

predicts shapes and strengths that are very similar to the measured ones [7]. Quench performance and temperature dependence were also studied, and the results are shown in FIGURE 8. The magnet reached quench plateau of about 13 kA, 85% of the predicted maximum current at 4.5 K, and lack of improvement at lower temperature indicated that it was mechanically limited.

From the readings on compensation gauges shown in FIGURE 9(a), as the magnetic field increases, the magnetic field effect on the strain gauges increases in a very small range. The readings on active gauges changed slightly with maximum around 0.003% shown in FIGURE 9(b), while the simulation gives about 0.007%. Compared to the 0.2~0.3 % strain from cool down, the Lorentz force strains are relatively small and very consistent with prediction. The radial thickness of the inner and outer support rings were designed far beyond the safety requirement for this magnet with around 70% safety margin. For the future model with higher magnetic field obtained by using different superconductors such as Nb_3Sn, the thickness of the rings is still sufficient with an estimated safety margin 30%.

The model was cut after the test to find out if there is any mechanical defect around the coil, which may help to better understand the quench performance, etc. From the photos taken on the cutting surfaces, shown in FIGURE 10, there are some imperfections, such as the voids and thick epoxy which may easily cause epoxy to break at low temperature. G10 bending may

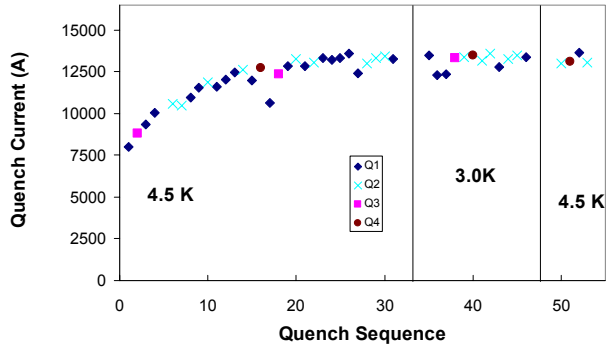
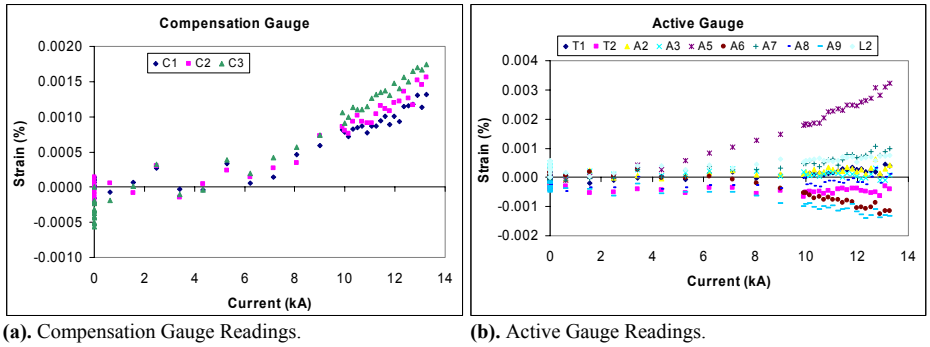


FIGURE 8. Magnet Quench Performance.



(a). Compensation Gauge Readings. **(b).** Active Gauge Readings.

FIGURE 9. Strain Gauge Monitor during Magnet Excitation.

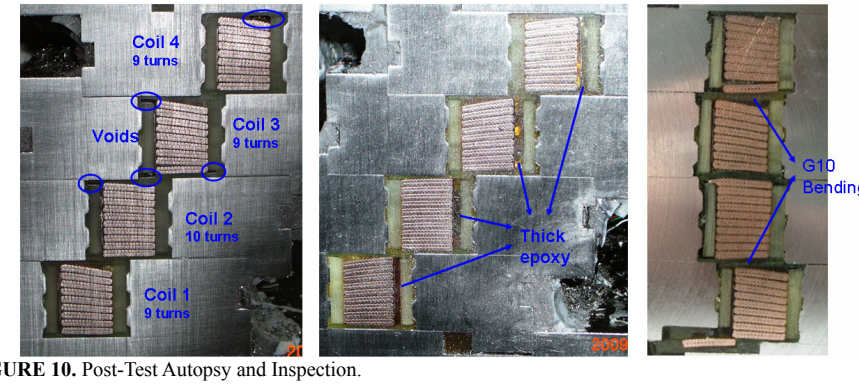


FIGURE 10. Post-Test Autopsy and Inspection.

cause the weakness of the insulation and make coil short to ground in the liquid helium. Some design improvements for the next model are: (a). The support rings will be 2 mm more in axial thickness to increase the thickness of G-10 spacers covering the coils; (b). Additional slots will be made in G-10 layers to fill the epoxy evenly; (c). The outer support rings will be furnished with a copper cooling tube to check the efficiency of the solenoid indirect cooling system.

CONCLUSION

HSM01 has been successfully fabricated and tested. Both the magnetic field measurement and strain gauge readings were consistent with the simulation predictions. The magnet reached 85% of the maximum current. The outer structures can provide sufficient support to the coils. The fabrication technology of building such a helical-configuration model was developed and the imperfections of the model will be improved for the next model which will be fabricated and tested in late 2009.

REFERENCES

1. Neuffer, D., "Multi-TeV Muon Colliders," in *AIP Conference Proceeding Vol.* 156, 1987, pp. 201-208.
2. Derbenev, Y. and Johnson, R.P., *Phys. Rev. STAB* 8, 2005, pp. 041002.
3. Kashikhin, V.S., et al., "Superconducting Magnet System for Muon Beam Cooling," in *Proceedings of Applied Superconductivity conference, IEEE Transactions on Applied Superconductivity, Volume* 17, Issue 2, June 2007, pp. 1055-1058.
4. Kashikhin, V.S., et al., "Magnets for the MANX 6-D Cooling Demonstration Experiment," in *Particle Accelerator Conference*, Albuquerque, 2007, pp. 461-463.
5. Yonehara, K., et al., "The MANX Muon Cooling Demonstration Experiment," in *Particle Accelerator Conference*, Albuquerque, 2007, pp. 2969-2971.
6. Kashikhin, V.S., et al., "Four-Coil Superconducting Helical Solenoid Model for Muon Beam Cooling," in *European Particle Accelerator Conference*, Genoa, Italy, 2008, pp. 2431-2433.
7. Lamn, M.J., et al., "4-Coil Superconducting Helical Solenoid Model for MANX," in *Particle Accelerator Conference*, Vancouver, Canada, 2009, to be published.