4-COIL SUPERCONDUCTING HELICAL SOLENOID MODEL FOR MANX*

M.J. Lamm#, N. Andreev, V. S. Kashikhin,V. V. Kashikhin, A. Makarov, M. Tartaglia, K. Yonehara, M. Yu, A. Zlobin, Fermilab, Batavia, IL 60510, U.S.A.
R.P. Johnson, S.A. Kahn, Muons Inc., Batavia, IL 60510, U.S.A.

Abstract

Magnets for the proposed muon cooling demonstration experiment MANX (**M**uon collider **A**nd **N**eutrino factory e**X**periment) have to generate longitudinal solenoid and transverse helical dipole and helical quadrupole fields. This paper discusses the 0.4 M diameter 4-coil Helical Solenoid (HS) model design, manufacturing, and testing that has been done to verify the design concept, fabrication technology, and the magnet system performance. The model quench performance in the FNAL Vertical Magnet Test Facility (VMTF) will be discussed.

INTRODUCTION

Effective emittance cooling is a major challenge in utilizing muons in high energy lepton colliders. An efficient scheme utilizing a Helical Cooling Channel (HCC) has been proposed for 6-D beam cooling [1]. It requires a solenoid field with superimposed helical dipole and helical quadrupole fields, along with a low Z energy-loss media and RF cavities for momentum regeneration. A cooling experiment has been proposed (MANX) using the HCC without RF cavities to demonstrate the concept.

The Helical Solenoid (HS) is a novel approach for generating the required HCC fields by using thin solenoid rings, offset transversely in a helical pattern [2]. Further design considerations for this thin ring approach are discussed elsewhere [3,4]. This helical solenoid approach has an important advantage over a more conventional straight wide aperture solenoid with superimposed dipole and quadrupole windings. It requires much smaller coils resulting in smaller stored energy and less field on the conductor.

As part of a DOE sponsored STTR project, Muons Inc. and Fermilab have built and tested a "4 coil" demonstration magnet (HSM01) to validate the design concept and gain experience in this novel magnet technology. The design and construction are summarized here and reported in detail elsewhere [5]. This paper focuses on newly acquired test results.

MAGNET DESIGN AND CONSTRUCTION

The magnet demonstration goal was to reproduce, as much as possible, the field and mechanical forces expected in a full length magnet within facility constraints. The SC cable to be used for both MANX and this 4-coil magnet is SSC inner cable[2], insulated with Kapton over glass tape.

*Work supported in part by DOE STTR Grant De-FG02-06EER86282 and by FRA under DOE Contract DE-AC02-07CH11359
#lamm@fnal.gov

Table 1: Parameters for full scale vs. 4 coil HS.

Parameter	Long HS	4-Coil HS
Peak Field (T)	5.7	4.4
Operating Current (kA)	9.6	13.6
Coil ID (mm)	510	420
Number of turns/section	10	9 (see text)
Fx force/section (kN)	160	119
Fy force/section (kN)	60	21
Fxy force/section (kN)	171	121
Fz force/section (kN)	299	273

Table 1 shows the 4-coil and baseline MANX magnet design parameters. For the demonstration magnet, we chose the individual coil apertures so that a 4-coil helical magnet system would fit into the Fermilab VMTF Dewar of 600 mm diameter. The fields of this 4 coil system would be approximately half that of a full scale HS, however, the lower field on conductor makes it possible to operate at a much higher transport current. As shown in Table 1, the fields (generated from Tosca simulation) as well of as the forces (generated from ANSYS simulation) of the 4 coil model are comparable to the full scale magnet, with both magnets operating at 85 percent of the predicted short sample conductor limit.

Fig. 1 shows schematically the coil layout while Fig. 2 shows the coil winding near completion. Coils are wound on a horizontal winding table. The insulated cable is wound with a "hard way" bend around a G-10 insulated inner stainless steel (SS) support ring and supported axially with a bottom SS flange. There are nominally 9 turns/coil. As shown in Fig. 2, the spiral Kapton wrap is not overlapped. This was done to facilitate the epoxy impregnation into the coil. Once the coil is wound, a Kapton encapsulated quench protection heater is wound circumferentially on the 9 turn package. The coil with heater is held in place by an SS outer support ring. Once a coil is completed, the next inner support ring is mechanically locked in place with the correct helical geometry. The package is designed so that the leads from one coil transition smoothly into the next coil with adequate mechanical support. This pattern continues through the fourth coil, whose axial support is completed with a matching flange. The rings and flanges are welded together for structural support. Voltage taps are soldered onto the power leads as well as the transition region between coils. The coil volume is then vacuum-

impregnated to provide the necessary mechanical support of the conductor.

While the construction proceeded well, there were two significant fabrication issues. First, it was determined through resistance and inductance measurements that one of the four coils had an extra number of turns (10 vs. 9). This was later verified during the post-test magnet autopsy. This extra turn had a small effect on the predicted field and quench performance.

A more serious problem was from the insulation. 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. The exact location of the insulation failure was not determined, although a post mortem examination points to a likely coil-to -coil transition area insulation weakness. Because of the very small amount of stored energy in these coils, the magnet could be safely operated at full field. However, the ground current was closely monitored during the entire test. Furthermore, we decided to limit our quench protection heater studies to a few quenches, since these studies by their nature generate voltage imbalances in the coil.

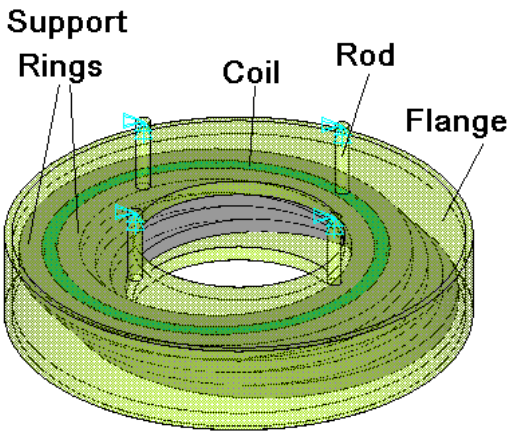

Figure 1: HSM01 Coil Layout

TEST PROGRAM

Tests were performed in the Fermilab VMTF. The Dewar can accommodate magnets up to 600 mm in diameter and 3.5 M in length, in temperatures in liquid helium from 1.7K to the nominal 4.5K. An anti-cryostat "warm finger" was inserted into the magnet for room temperature magnetic field probe measurements.

The test plan consisted of magnetic measurements at room temperature as well as in liquid helium, quench training, and quench protection studies. The strain gauges mounted on the magnet shell were monitored during the test. The results of these studies, summarized in the magnet test report [6], show that the strain changes during cool down or excitation are consistent with the ANSYS mechanical model predictions.

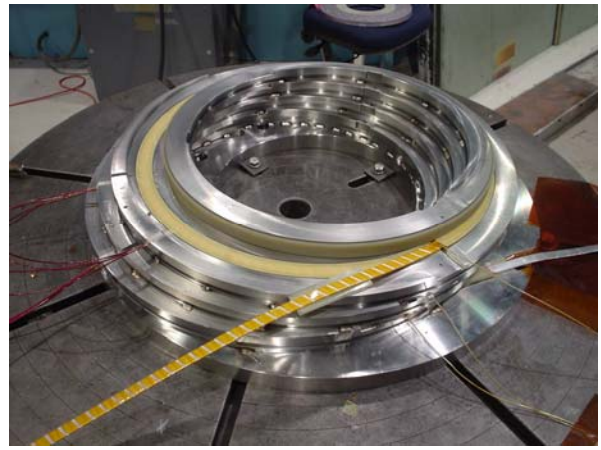

Figure 2: HSM01 During Assembly

Quench Performance

Fig. 3 is a summary of the HSM01 quench performance. The nominal ramp rate was 50 A/sec. After approximately 20 quenches, the magnet reached its quench plateau of approximately 13 kA which is approximately 85 percent of the predicted short sample. While training quenches are observed in all four coils, the quenches in the plateau were limited to coils Q1 and Q2. The exact location of the quench was not possible to determine due to lack of instrumentation. Quenches at lower temperature (3.0 K) were performed at ramp rates from 20 – 300 A/sec including nominal 50 A/sec with no significant changes in quench performance. We conclude that the mechanical support within each coil, provided primarily by the epoxy potting material, was probably not sufficient.

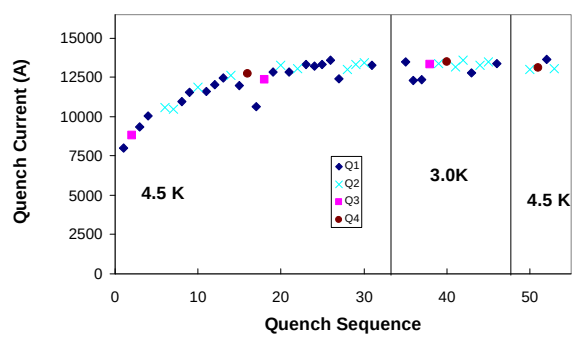

Figure 3: Quench Performance of HSM01. Coils are designation Q1-Q4 with Q1 closest to the positive lead.

Magnetic Field Measurements

Field measurements were taken with a 3-axis Hall probe at room temperature at ±10 A as well as in liquid helium at 2000 A. The field coordinate system was defined as follows: the "z" direction is normal to the lead end coil; "x and y" directions are in the plane of the lead

end coil; x=y=0 is the approximate geometric center of the 4-coil magnet system; and z=0 is on the lead end coil front face. At room temperature, scans were performed longitudinally along the z axis at approximately x=y=0. There were also parallel scans at large radius in 45 degree increments. Cold measurements were performed with a Hall probe at room temperature using the anti-cryostat "warm finger" placed in the x=y=0 location.

The results are shown in Fig. 4 and Fig. 5. Due to a lack of accurately determined coil center positions, there was an uncertainty lining up the coordinates systems from the warm to cold as well as to the calculated fields. Thus in Fig. 4, the peaks of the measured warm and cold fields as well as the Tosca prediction are adjusted longitudinally to match. Because of the lack of magnetic material and the small thermal contraction in a larger aperture coil, it was expected and confirmed by measurement that the shape and normalization of the cold and warm room temperature transfer functions both agree well with the Tosca model calculation.

Fig. 5 shows a representative warm By distribution as compared to calculation. The discrepancy in the shape and normalization is likely related to the uncertainties in the accurately determining the coil center coordinates.

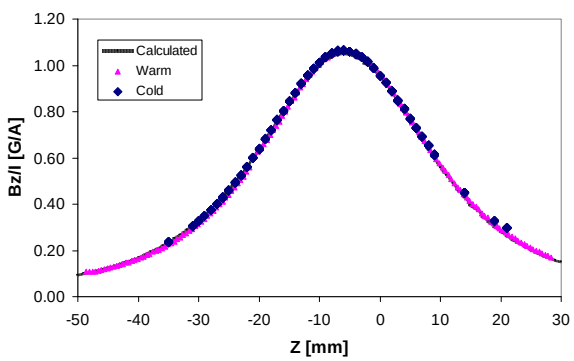

Figure 4: Longitudinal Field on axis vs. Calculation

Quench Protection

The quench heater studies were curtailed because of the 15 kΩ short to ground. Heaters in two coils were connected in series to a quench protection heater firing unit. Using the minimum unit setting of 50 V, and capacitor settings of 4.8 mF and 9.6 mF, the magnet was successfully quenched at 12 kA with a delay time of 150 ms and 120 ms respectively.

RRR measurements of the conductor were performed during the post test warmup. Values in the range of 140 were recorded.

RESULTS AND FUTURE PLANS

Our immediate goal is to build a nearly identical magnet with improved conductor insulation, potting procedure and mechanical support. There is evidence from the post mortem autopsy that there are voids in the epoxy impregnation which likely limited the quench performance. Finally the SS outer support ring will be replaced with aluminum to provide larger cold prestress.

Even if the coil reaches its full short sample limit, it is believed that these magnets will need a larger quench operating margin. A full scale HS would require over one hundred coils in series; thus quench stabilization needs to be considered. Both features call for a larger critical current density in the superconductor or a larger number of amp-turns. Thus we are looking into designs with wider conductor, "easy way" bend which would allow us to stack more amp turns, and Nb3Sn conductor.

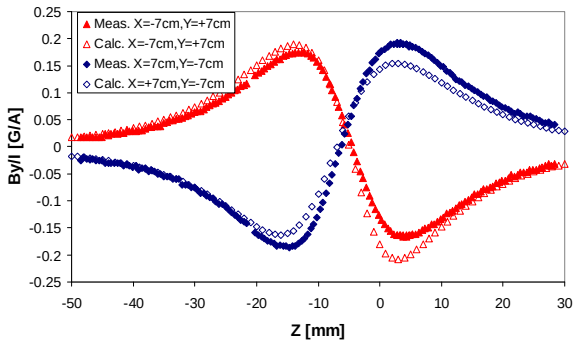

Figure 5: Representative Transverse Field/Current vs. Calculation

CONCLUSION

A 4-coil model of a Helical cooling channel solenoid has been successfully built and tested. The magnet reached 85 percent of short sample, the approximate level of design operation. It also reached a considerably higher current than the design current, albeit in a lower field. The field distributions agree well with predictions. Further care will be taken on subsequent magnets to fiducialize the coil geometry to facilitate field comparisons.

REFERENCES

[1] Y. Derbenev and R.P. Johnson, "Six-Dimensional Muon Cooling Using a Homogeneous Absorber", Phys. Rev. ST AB, 8, 041002 (2005)

[2] V.S. Kashikhin et al., "Magnets for the MANX 6-D Muon Cooling Demonstration Experiment" Proceeding of PAC07, Albuquerque, pp443-445.

[3] V.V. Kashikhin, et al., "Design studies of Magnet Systems for Muon Helical Cooling Channels" Proceeding of EPAC08, Genoa, Italy, pp2437-2439.

[4] M. Lopes et al, "Studies of the High-Field Section for a Muon Helical Cooling Channel", this conference.

[5] V.S. Kashikhin, et al., "Four-Coil Superconducting Helical Cooling Model for Muon Beam Cooling", Proceeding of EPAC08, Genoa, Italy, pp2431-2433.

[6] M. Tartaglia et al., "Test of Four Coil Helical Solenoid Magnet, HSM01" Fermilab TD Internal Note: TD-09-11.