4-COIL SUPERCONDUCTING HELICAL SOLENOID MODEL FOR MANX

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Abstract
Magnets for the proposed muon cooling demonstration experiment MANX (Muon collider And Neutrino factory eXperiment) 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.

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 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.

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

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

Table 1 shows the 4-coil baseline MANX 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 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.

**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.

**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.
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 show a representative warm \(B_y\) 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.

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