FOUR-COIL SUPERCONDUCTING HELICAL SOLENOID MODEL FOR MUON BEAM COOLING*

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Abstract

Novel configurations of superconducting magnets for helical muon beam cooling channels and demonstration experiments are being designed at Fermilab. The magnet system for helical cooling channels has to generate longitudinal solenoidal and transverse helical dipole and helical quadrupole fields. This paper discusses the Helical Solenoid model design and manufacturing of the 4-coil model with 0.6 m diameter aimed at verifying the design concept, fabrication technology, and the magnet system performance. Details of magnetic and mechanical designs, including the 3D analysis by TOSCA and ANSYS will be presented. The model quench performance and the test setup in the FNAL Vertical Magnet Test Facility cryostat will be discussed.

INTRODUCTION

The helical field concept for muon cooling was proposed and described in [1]. That concept was realized in the Helical Solenoid (HS) configuration [2], which generates the needed solenoidal, helical dipole, and helical quadrupole magnetic fields to achieve 6-dimensional muon beam cooling in the MANX cooling demonstration experiment [3,4]. The design of straight superconducting solenoids with ~5 T field is well known. However, the transverse displacements of the HS coils generate large transverse forces, which are zero in the straight geometry. These forces require technical solutions to protect the superconductor from large stresses and deformations. A short four-coil Helical Solenoid model has been designed at FNAL and the fabrication process has been started.

HELICAL SOLENOID MODEL

The Helical Solenoid model should demonstrate the magnet system performance and match the existing FNAL Vertical Magnet Test Facility (VMTF) equipment. The model outer diameter is limited by the 640 mm diameter cryostat bore. The stand has the required cryogenics, 30 kA power supply, quench detection, protection and control systems.

Magnetic Design

The four coil geometry with flux density distribution is shown in Fig. 1. The coils centers follow the helical beam orbit with 255 mm radius and 1.6 m helix period.

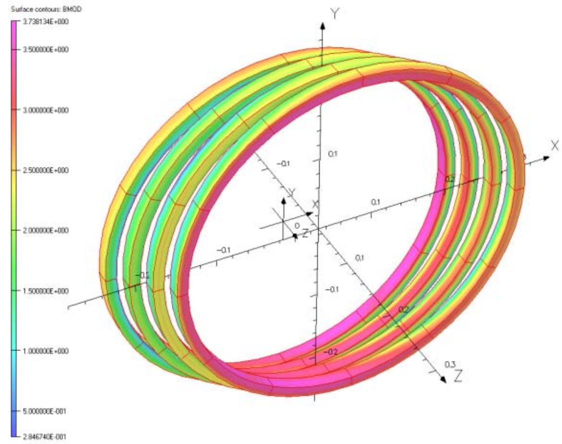

Figure 1: 4-Coil geometry and flux density.

Table 1: Solenoid Parameters

Parameter	**Units**	**Value**
Coil inner diameter	mm	426
Coil outer diameter	mm	455
NbTi superconducting cable	mm	12.34 x 1.46
Cable critical current at 7 T, 4.2 K	A	9660
Jc (non-Cu)	A/mm^2	1730
Copper to superconductor ratio		1.5:1
Strand diameter	mm	0.8
Helical orbit radius	mm	255
Number of turns per coil		10
Coil width	mm	20

The coil width of 20 mm was chosen to provide sufficiently smooth magnetic field distribution over the beam bore. The full length HS to be used for the MANX experiment is 3.2 m. The short 80 mm model should verify the design concept by reproducing the same level of fields, Lorentz forces, and corresponding stresses in the superconductor and support structures as in the long HS. Simulated magnetic design results are compared in Table 2 for the long HS design and the short HS design at two currents. Using the available margin in the cable current-carrying capacity to run the short model 46% above the nominal value, the Lorentz forces in the short model are seen to be comparable with those in the long HS.

*Work supported in part by DOE STTR Grant DE-FG02-06ER86282
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Table 2: Magnetic Design Parameters

Parameter	**Short HS Nominal**	**Short HS Max**	**Long HS**
Peak superconductor field, T	3.3	4.84	5.7
Current, kA	9.6	14	9.6
Coil inner diameter, mm	426	426	510
Number of turns/section	10	10	10
Fx force/section, kN	70	149	160
Fy force/section, kN	12	25	60
Fxy force/section, kN	71	151	171
Fz force/section, kN	157	337	299

Mechanical Design

The main goal of the mechanical design was to develop the mechanical concept which could be extrapolated to the long solenoids without changing the structure. From this point of view, the solenoid assembled from identical coils is the most promising approach.

Each coil is wound from Rutherford type superconducting cable on a stainless steel bobbin. Outer stainless steel collar rings provide the coil support and intercept the radial Lorentz forces. Since the coils are shifted in the transverse plane such that their centers follow the helical path, there are transition areas where the cable can smoothly be transferred between the coils. This technique allows continuous winding of the long HS without splices.

The short model consists of four superconducting coils with support structures and end flanges. The model reproduces a short section of the long helical solenoid. By operating at higher current, it is intended to reach the fields, forces, and stresses of the long HS to verify the design concept and fabrication technology.

There are two ways to protect coils from the transverse motion under Lorentz forces. The first is to weld inner and outer support rings to each other forming a solid mechanical structure. The second is to machine steps on both sides of the inner and outer support rings locking the coil motion in the transverse direction.

The 3D mechanical structure was modeled by the ANSYS code. Since the coils are to be epoxy impregnated, the analysis was made for a solid model with all the boundaries between different materials attached to each other. Fig. 2 shows the stress distribution in superconducting coils. The peak stress at 14 kA current is only 8.8 MPa which is well below the conductor degradation limit. The maximum stress in the support structure is ~23 MPa, as follows from Fig. 3, which is also acceptable. These relatively large margins in stresses will be beneficial in the long HS design, where the side flanges can be separated by a distance of 400 mm or even 800 mm.

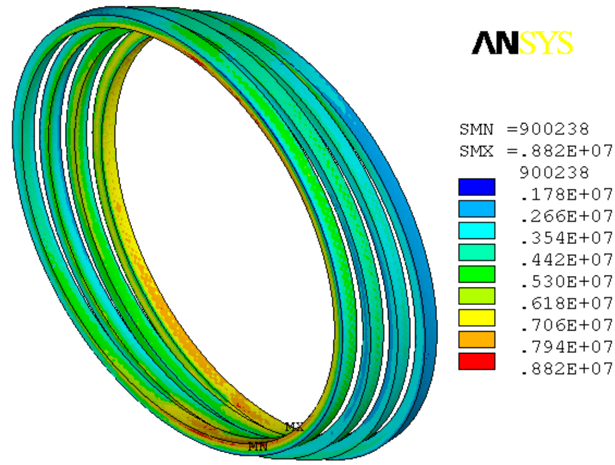

Figure 2: Coils stress at the peak current 14 kA.

The model will be attached to the cryostat by 4 rods as shown in Fig. 3.

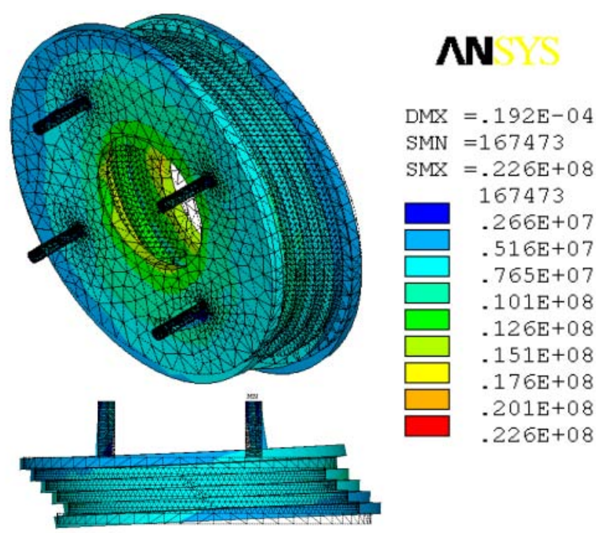

Figure 3: Stresses and deformations in the model.

The results of magnetic and mechanical modeling were verified by the 3D COMSOL code.

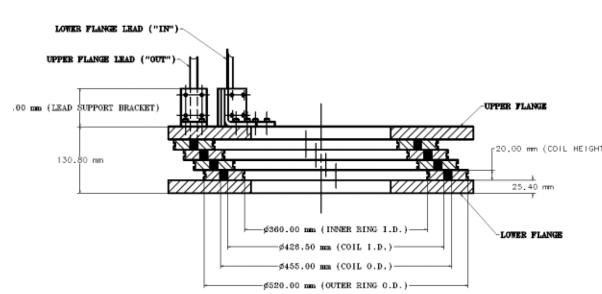

Figure 4: The model cross section.

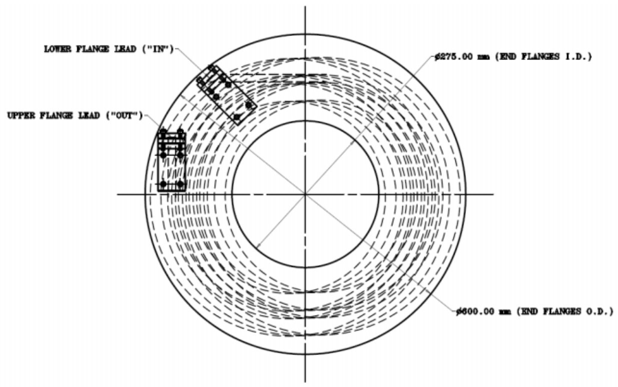

Figure 5: The model top view.

As it seen in Fig. 5, the coils have easy transition areas near the vertical axis. The transition turns will be placed in these areas during the coil winding.

Fabrication

FNAL has about 40 km of good NbTi superconducting cable left after the SSC project. It is more than enough to build the muon cooling channel demonstration experiment. The model will be wound using the FNAL horizontal winding rotational table system as shown in Fig. 6.

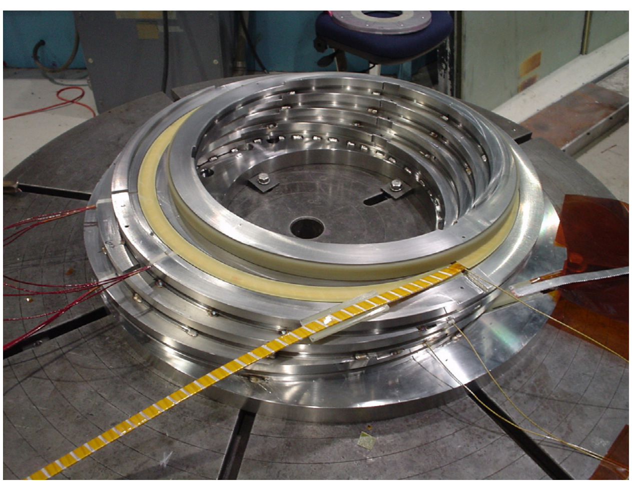

Figure 6: The model assembly view before the 4-th coil winding.

Since the available superconducting cable is keystoned, it was necessary to confirm the possibility of smooth coil winding without the loss of mechanical stability and strand separations by a winding experiment. The manufactured tooling will provide smooth continuous coil winding without splices.

The winding and magnet assembly procedure will have the following steps:

- the side flange attached to the rotating table;
- the first coil inner ring locked and fixed to the flange;
- all outer rings stocked in the space between winding table and superconductor bobbin with the cable passing through all ring bores;
- first coil lead end fixed and coil wound;
- outer ring for the first coil installed;
- inner ring for the second coil installed;
- the second coil wound;
- the outer ring for the second coil installed;

So, this process is repeated until all coils are wound. After that the upper side flange and outer support rings will be installed. All rings and flanges are fixed to each other by skip welds. Their angular position is controlled by pins. The whole assembly will be vacuum impregnated with epoxy to provide the necessary structural integrity.

Preparation for Test

The HS model will be tested in the VMTF at Fermilab. The cryostat has 640 mm inner bore diameter. The model will be attached to the top plate by 4 rods. The walls of the cryostat and surrounding space are non-magnetic, thus there will be no unbalanced forces applied to the model.

The model will be instrumented with the strip heaters, voltage taps, and strain gages. All instrumentation will be connected to the VMTF control system which will detect the quenches, measure voltages and currents, strains, etc. During a quench some part of the stored energy will be transferred from the magnet to an external dump resistor. The solenoid will be trained to the maximum current. The quench history will show the magnet system mechanical and magnetic stability

The magnetic field in the model center will be measured by a rotational coil field measurement system and a Hall probe system.

CONCLUSION

- The 4-Coil Helical Solenoid model has been designed.
- The model is capable of reproducing the same level of stresses in superconductor and support structure as in long solenoids.
- The Helical Solenoid fabrication is now in progress.
- The model test is planned for the summer of 2008.

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