PROGRESS ON THE FABRICATION AND TESTING OF THE MICE SPECTROMETER SOLENOIDS *

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Abstract

The Muon Ionization Cooling Experiment (MICE) is an international collaboration that will demonstrate ionization cooling in a section of a realistic cooling channel using a muon beam at Rutherford Appleton Laboratory (RAL) in the UK. At each end of the cooling channel a spectrometer solenoid magnet consisting of five superconducting coils will provide a 4 tesla uniform field region. The scintillating fiber tracker within the magnet bore will measure the muon beam emittance as it enters and exits the cooling channel. The 400 mm diameter warm bore, 3 meter long magnets incorporate a cold mass consisting of two coil sections wound on a single aluminum mandrel: a three-coil spectrometer magnet and a two-coil section that matches the solenoid uniform field into the MICE cooling channel. The fabrication of the first of two spectrometer solenoids has been completed, and preliminary testing of the magnet is nearly complete. The key design features of the spectrometer solenoid magnets are presented along with a summary of the progress on the training and testing of the first magnet.

INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) will consist of a cooling channel [1] which is made up of three absorber focus-coil modules (AFC modules) and two RF and coupling-coil modules (RFCC modules). Located at either end of the cooling channel are the two spectrometer solenoid modules.

The liquid hydrogen absorbers located within the AFC modules perform the muon ionization cooling [2], and the muons are re-accelerated by four 201 MHz RF cavities contained in each of the two RFCC modules [3]. Each spectrometer solenoid consists of five superconducting coils. The total length of the spectrometer solenoid module is 2923 mm. Two of the coils match the muon beam to the adjacent AFC modules. The tracker detectors located in the bore of the other three coils are made up of five planes of scintillating fibers that measure the emittance of the muons as they enter and exit the cooling channel [4].

A 188 mm long space at the AFC module end of the magnet allows for installation of a radiation shutter. The shutter shields the tracker's scintillating fiber detectors from the electrons and gamma radiation that comes from the RF cavities during conditioning. An iron disk on the outer ends of the solenoids shields the photomultiplier tubes in an adjacent detector from the magnetic fields. A CAD image of the magnet is provided in Fig. 1.

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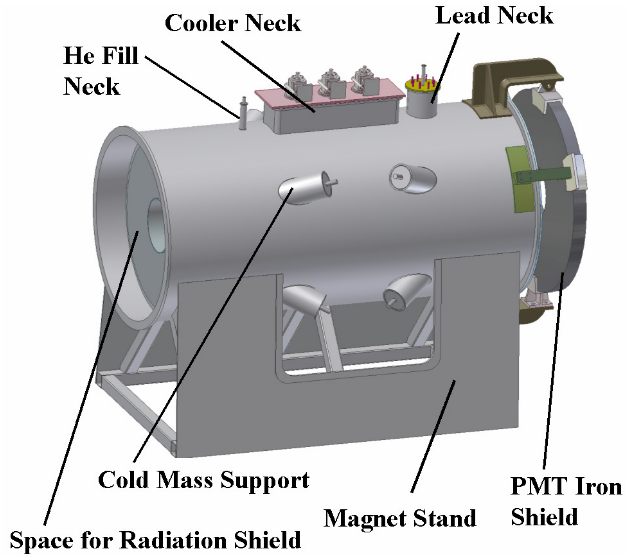

Figure 1: Spectrometer solenoid module 3D CAD image.

COIL CONFIGURATION

Each of the spectrometer solenoid magnets consists of five superconducting coils wound on a common aluminum mandrel. Match Coil 1 and Match Coil 2 operate as a focusing doublet to match the beam in the spectrometer solenoid with the beam in the adjacent AFC modules. The spectrometer solenoid portion of the module consists of: End Coil 1, the Center Coil, and End Coil 2 which generate a 4 Tesla uniform field ($\Delta B/B < 3\times10^{-3}$) over a 1 meter long and 0.3 meter diameter volume. A CAD image of the coil assembly is provided in Fig. 2.

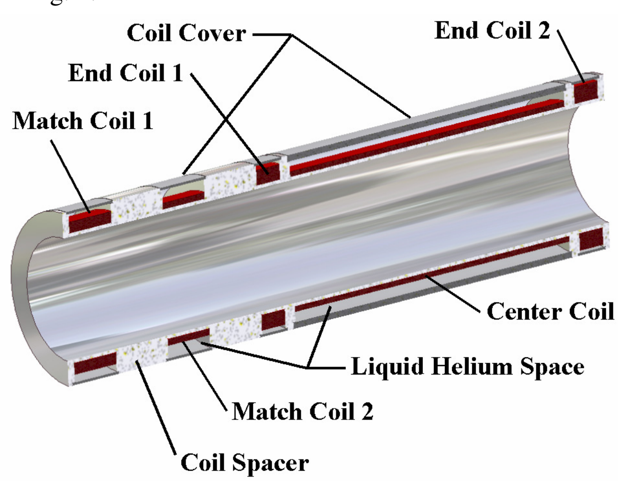

Figure 2: Spectrometer solenoid cold mass assembly.

The three spectrometer coils in each magnet are wired in series to a single 300 A power supply. To ensure equal currents, the same supply feeds both sets of spectrometer coils in series. Four additional low current power supplies (±60 A max) independently adjust each of the end coils. Match Coil 1 from the upstream magnet will be connected in series to Match Coil 1 from the downstream magnet and powered with an additional 300 amp supply. The Match Coils 2 will be connected and powered in the same manner. Additional details of the spectrometer solenoid design and operating parameters were presented previously [5].

The five coils in each magnet were wound using the same 1.00 mm by 1.65 mm superconducting wire with a copper-to-superconductor ratio of 3.9 and a twist pitch of 19 mm. The wire contains 222 Nb-Ti filaments of 41 μm diameter. Each magnet was wound using a total of 55 km of conductor.

COLD MASS SUPPORTS & HEAT LEAK

The spectrometer solenoid uses a self-centering cold mass support system to ensure that the coil centers remain unchanged as the magnet is cooled to 4K. The fiberglass tension band support system is designed to carry a total load of 500 kN (50 tons) in either longitudinal direction and 50 kN (5 tons) in the radial direction. The large longitudinal spring constant (>200 MN/m) of the cold mass support system restricts movement to <1.5 mm when the MICE magnets are powered. Specified tolerances require that the axis of the solenoid be co-axial with the warm bore axis to within ±0.3 mm with a maximum allowable tilt or yaw of ±0.001 radian.

The heat leaks into both the 50K and 4K regions of the magnet are dominated by losses in the current leads. The next largest heat leak into the 4K region is due to the fiberglass cold mass support bands. The second largest heat leak at 50K is due to thermal radiation through the multi-layer insulation (MLI). Based on the calculation of total heat leaks at 4K and 50K and testing of the cryo-coolers, it is expected that each magnet can be cooled using three 1.5 W (at 4.2K) pulsed-tube cryo-coolers.

MAGNET FABRICATION

The two spectrometer solenoids have been designed and are being fabricated by a qualified vendor under a build-to-spec agreement. Physicists and engineers working on the MICE Project developed a preliminary concept for the spectrometer solenoids and produced a detailed specification that includes all interfaces, requirements and system parameters.

A pre-qualified group of superconducting magnet manufacturers was solicited for bids which were assessed based on responsiveness to the specification and on price. The superconducting wire, cryo-coolers and power supplies were provided to the vendor by the MICE Project. The vendor that was awarded the contract developed a detailed design based on the requirements and guidelines set forth by the specification. The design was subsequently reviewed and approved by a panel consisting of members of the MICE collaboration.

The winding of the 5-coil assembly on a one-piece, forged aluminum mandrel has been completed for both magnets. The coils were wet wound using Stycast epoxy. Upon completion of the coil winding, aluminum banding was wound around the outside diameter of the coils for support. Cover plates were welded to the coil forming mandrel to create the helium vessel, and reinforcement bands were installed to allow connection of the cold mass supports. A passive quench protection system consisting of a series of diodes and resistors is located within the helium cryostat. Fig. 3 shows a photo of the magnet cold mass prior to installation into the radiation shield and subsequent installation in the magnet vacuum vessel. Fig. 4 shows a photograph of the magnet cold mass suspended within the vacuum vessel.

Figure 3: Cold mass ready for installation.

Figure 4: Magnet vacuum vessel and support stand with cold mass and radiation shield in place.

Each of the eight sets of cold mass supports consists of two pairs of wound fiber/epoxy, racetrack shaped bands capable of carrying the required load while minimizing the heat leak. The support band pairs are arranged in parallel to maximize the strength of the assembly. The two pairs of parallel bands are used such that one end of the supports is maintained at 4K (at the cold mass), an intermediate point is at about 70K (at the thermal shield) and the other end is at 300K (the room temperature end on the vacuum vessel).

DESIGN MODIFICATIONS

During the middle of CY2008, the first spectrometer solenoid magnet was completed and ready for testing. The magnet was cooled down to liquid helium temperature, and training of the coils began. However, it was found that the recondenser system used to maintain the cold mass at 4K was not functioning as designed. The system consisted of condenser blocks attached to the second stage of the cold heads. Helium vapor was recondensed by the cold heads and returned to the bottom of the cold mass through small diameter liquid return lines. It is likely that frozen nitrogen trapped in the liquid return lines prevented the condensing circuit from operating; this condition prevented the cold mass from maintaining its superconducting temperature.

In order to prevent this problem from reoccurring, the vendor developed a modified design whereby the helium vapor and liquid are carried to and from the condenser through a direct, large diameter connection at the top of the cold mass. Since the second magnet had not yet been assembled, the design change was implemented on that unit first so that disassembly of the first unit would not further impact the schedule.

The vendor also took this opportunity to apply several other design enhancements to the spectrometer solenoids. The connection between the first stage of the cryo-coolers and the radiation shield was enlarged to improve the heat transfer path to the cold head and allow the shield to reach lower temperatures. An additional vent line and upgraded pressure relief valve were added to the cold mass to reduce the peak pressure during a quench. Also, a liquid nitrogen reservoir was added to the radiation shield. The reservoir provides a means of cooling down the shield directly using liquid nitrogen and also serves as a thermal mass to protect the high temperature superconductor (HTS) leads in the event of a power failure.

MAGNET TESTING

The second unit of the MICE spectrometer solenoids is now complete. The magnet is being cooled down (Fig. 5), in preparation for magnet testing and coil training. During training, each of the coils will be run at its design current (ranging from 223 A to 271 A) or higher. During the original training of the first unit, all five coils had reached a current of 196 A before training was halted due to the condenser circuit issue. Upon completion of qualification and training at the vendor, the magnets will be shipped to Fermilab for magnetic field mapping before being moved to RAL for insertion in the MICE beamline.

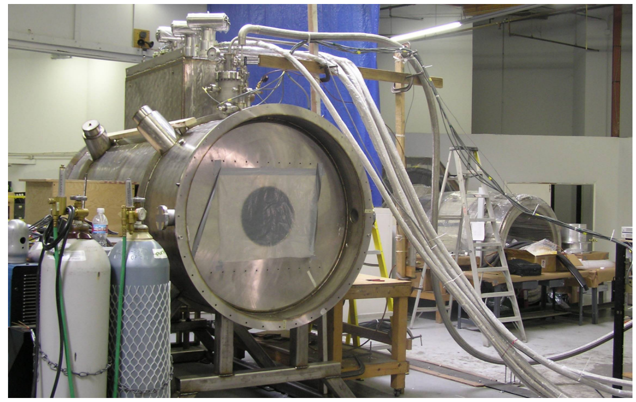

Figure 5: Cool down of a completed magnet.

CONCLUSION

The fabrication of the second unit of the MICE spectrometer solenoids is now complete and is undergoing testing. This magnet incorporates several design improvements over the previously completed first unit. The original first unit has been disassembled, and the same design modifications are currently being applied. Completion of this unit is expected in approximately three months.

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