FINAL ASSEMBLY AND TESTING OF THE MICE SUPERCONDUCTING SPECTROMETER SOLENOIDS*

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Abstract

The Muon Ionization Cooling Experiment (MICE) is an international effort to demonstrate the principle of ionization cooling in a segment of a realistic cooling channel using a muon beam. The experiment is sited at Rutherford Appleton Laboratory (RAL) in England. A pair of identical spectrometer solenoids will provide a 1-m-long, 4-T uniform field region at each end of the cooling channel. As the beam enters and exits the channel, the emittance will be measured within the upstream and downstream 40-cm-diameter magnet bores. Each magnet consists of a three-coil spectrometer group and a two-coil pair that matches the solenoid uniform field into the adjacent MICE cooling channel. An array of five two-stage cryocoolers and one single-stage cryocooler is used to maintain the temperature of the magnet cold mass, radiation shield and current leads. Previous coil training runs revealed several operational and design issues related to excessive heat leak, lead stabilization and quench protection that have since been corrected. Details of the magnet design modifications and the final assembly of the first magnet are presented here.

INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) [1], to be sited at Rutherford Appleton Laboratory (RAL) in England, will demonstrate the principle of ionization cooling using a muon beam. The cooling channel portion of MICE will consist of: three absorber-focus-coil (AFC) modules [2], each containing two superconducting focusing coils and a liquid-hydrogen absorber to reduce the 3-D momentum; two RF and coupling-coil (RFCC) modules [3], each of which contain a central superconducting solenoid and four 201-MHz normal-conducting RF cavities to re-accelerate the beam. The spectrometer solenoid modules are located at either end of the cooling channel.

Each spectrometer solenoid module consists of five superconducting coils wound on a common 3-m-long aluminum mandrel (see Fig. 1). A tracking detector consisting of five planes of scintillating fibers located in the bore of the three spectrometer coils of each spectrometer solenoid module measures the emittance of the muons as they enter and exit the cooling channel. Match Coil 1 and Match Coil 2 operate as a focusing doublet to match the beam in the spectrometer solenoid to the beam in the adjacent AFC modules. The spectrometer portion of the module, consisting of End Coil 1, the Center Coil and End Coil 2 will generate a 4-T uniform field over a 1-m-long and 30-cm-diameter volume. Additional details of the spectrometer solenoid design and operating parameters have been presented previously [4].

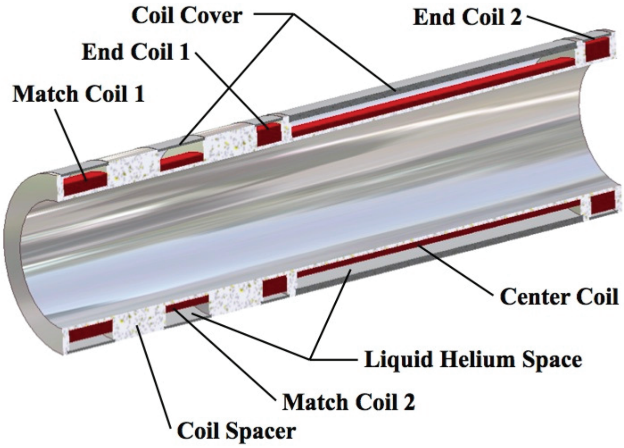

Figure 1: Spectrometer solenoid cold mass assembly.

MAGNET DESIGN MODIFICATIONS

During recent coil training of one of the spectrometer solenoids, several issues arose that resulted in the need to disassemble the magnet and to carry out detailed analyses and review of the existing design [5,6]. The primary areas needing attention were the protection of the magnet leads during a quench and excessive heat leak to the magnet cold mass. Details of some of the design modifications that were implemented are presented here.

The magnets use cryocoolers to cool the cold mass and radiation shield. The previous design of the magnet used three Cryomech PT-415 two-stage coolers to re-condense the LHe in the cold mass and to maintain the temperature of the 70K radiation shield. Each of these coolers provides 1.5 W of cooling power at 4K. An additional single-stage cooler (Cryomech AL-330) provided direct cooling in the area of the upper end of the HTS lead.

In order to address the issues with the original configuration of the magnets, a series of design and assembly modifications have been implemented. The modifications include: improvement of the connection between the first stage of the cryocoolers and the radiation shield, increased thermal conductivity of the shield, a new pumping and instrumentation system for the insulating vacuum, and improvements to the multi-layer insulation (MLI) blankets. Through these and other enhancements to the system, the total heat load on the cold mass has been calculated to be just under 4 W. Two additional pulse-tube cryocoolers have been added, increasing the total cooling power at 4K to 7.5 W.

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MAGNET REASSEMBLY

The first magnet has recently been modified and reassembled and is being prepared for cool down and coil training. The vacuum vessel and the cold mass have been successfully leak checked, and the cryostat is under vacuum and approaching the level necessary to initiate cool down. A new data acquisition and control system has been implemented as well as a reconfigured power supply rack. A series of photos are provided in this section showing some of the details of the design and the assembly process.

The MLI wrap on the magnet cold mass has been improved by incorporating a seris of custom cut blankets that were derived from a 3D CAD model. A series of brackets were also added to the exterior of the cold mass to provide a uniform MLI wrap surface and to prevent compression of the MLI layers. A photo of the completed cold mass is shown in Fig. 2. A similar MLI scheme was used for the radiation shield, which was remade using series 1100 aluminum rather than the previous 6061 aluminum in order to icrease its thermal conductivity. A photo of the cold mass/shield assembly being installed in the magnet cryostat is shown in Fig. 3.

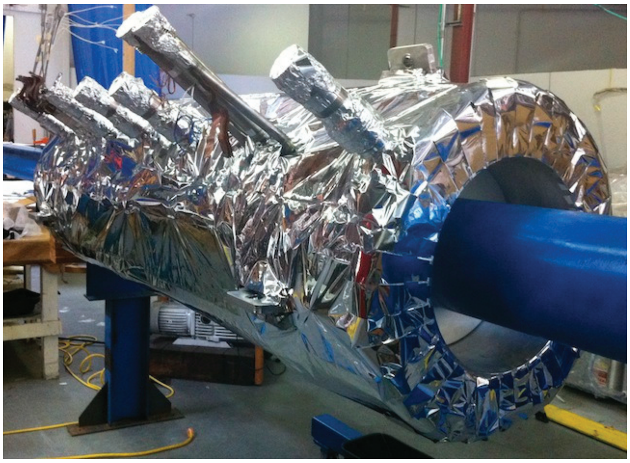

Figure 2: Cold mass after MLI wrapping.

Figure 3: Assembly of shield/cold mass into cryostat.

Another improvement to the magnet design was the enhancement of the thermal connection between the first stage of the cryocooler heads and the radiation shield. The original design used a series of aluminum straps to make the connection. The new design uses an array of flexible copper sheets to provide a larger cross sectional area and a more thermally conductive material (see Fig. 4).

Figure 4: Improved shield connection to cryocoolers.

In order to accommodate the addition of two cryocoolers, a new main cooler tower was fabricated, and a second tower containing one cooler was added as well. The main tower now houses four of the two-stage coolers, the single-stage cooler and all of the power feedthroughs for the coil leads. A photo of the completed main cryocooler tower is shown in Fig. 5. A new port was also added to the main tower that incorporates a series of vacuum gauges and a residual gas analyzer (RGA) head. The improved vacuum and instrumentation system will allow for better MLI performance by ensuring that a sufficient amount of moisture is removed from the system prior to cool down.

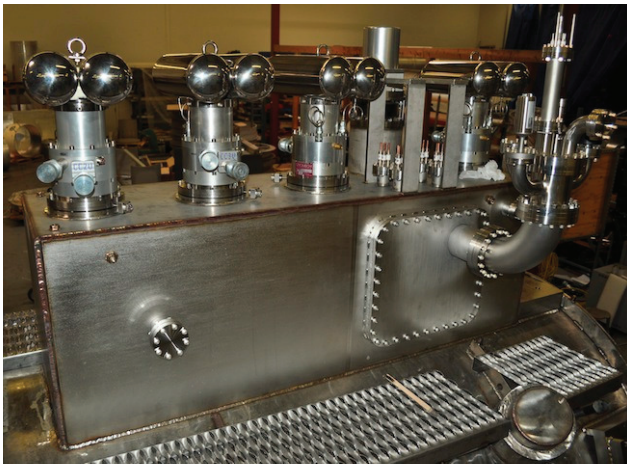

Figure 5: Completed main cryocooler tower.

At the time of this paper, the first magnet has been fully assembled and is being prepared for coil training. Preliminary work includes: testing of all instrumentation channels and the control system, vacuum leak checking of the cold mass and cryostat vessel, vacuum pumping and warm nitrogen purging of the cryostat to remove water vapor, and test running of the cryocoolers to verify proper operation and functionality of the temperature sensors. An overall view of the first completed magnet is provided in Fig. 6.

Figure 6: Completed reassembly of first magnet.

MAGNET ANALYSES

The spectrometer solenoid uses a series of diodes and resistors within the cold mass as a passive quench protection system. The suitability of this scheme has been reviewed and analyzed to verify to what degree the design can safely protect the system under reasonable fault scenarios. The final analyses have been carried out using the Opera-3D modeler with the QUENCH module [7]. Under normal operating conditions, the magnet protection system was found to function correctly. When a quench initiates in any one coil, a sequence of quenches is passively triggered in the remaining coils. The majority of the stored magnetic energy is safely and evenly dissipated in the coil conductor by means of resistive heating. Furthermore, the internal voltages are acceptable, with adequate turn, layer, and ground insulation in the coil.

A series of analyses of the new radiation shield was carried out in order to determine the magnitude of eddy currents, forces, displacements and stresses during a quench. The results of the analyses were used to establish the locations of electrical breaks in the shield body.

An ANSYS model of the shield was also developed in order to predict the shield stresses and displacements due to shipping. The same ANSYS model was also used to predict the steady-state temperature distribution in the shield subject to the estimated heat loads.

Additional details of these and other analyses were presented in a previous paper [8].

SUMMARY

A series of design modifications have been carried out in order to improve the performance and reliability of the MICE spectrometer solenoid superconducting magnets. At the time of this writing, the first magnet is fully assembled and being prepared for coil training. A second, identical magnet is being assembled in parallel and is expected to be complete approximately two months later. During coil training at the vendor, a series of magnetic measurements will be carried out for performance verification. More detailed magnetic mapping will be conducted once the magnets are delivered to the MICE Hall at RAL later this year.

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