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ASSEMBLY AND TEST OF A MODIFIED SPECTROMETER SOLENOID FOR MICE *

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Abstract

The MICE superconducting spectrometer solenoids have been modified and rebuilt as a result of the testing done in 2008, 2009 and 2010. The number of two-stage cryocoolers was increased from three in 2009 to five in the modified magnet. The new radiation shield is fabricated primarily from 1100-O aluminum instead of 6061-T6 aluminum used in the former versions of the magnet. The thermal connection between the shield and the first-stage of the cold heads has been improved to reduce the temperature drop between the shield and the coolers. As a result of these changes, the first-stage temperatures for the coolers are below 45K, which resulted in an increase in the refrigeration generated by the cooler second stages. The quench protection system has been altered in order to provide additional protection to the magnet in the event of a lead failure between the magnet power supply and the magnet coils. The quality of the shield and cold mass MLI wrap has also been improved. Details of the modifications and final test and training results that demonstrate improved magnet performance are presented in this paper.

INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) [1] is sited at Rutherford Appleton Laboratory (RAL) in England and will demonstrate the principle of ionization cooling using a muon beam. The cooling channel portion of MICE will consist of two different types of modules. The three absorber-focus-coil (AFC) modules [2] will each contain two superconducting focusing coils and a liquid-hydrogen absorber to reduce the 3-D momentum of the muon beam. The two RF and coupling-coil (RFCC) modules [3] will each contain a central superconducting coupling coil and four 201-MHz normal-conducting RF cavities to re-accelerate the beam. The two identical spectrometer solenoid modules are located at either end of the MICE cooling channel. A CAD model of the layout of these modules is shown in Fig. 1. A photo of the first completed spectrometer solenoid magnet during training at the vendor is shown in Fig. 2.

The spectrometer solenoid modules each consist of five superconducting coils that are wound on a common 3-m-long aluminum mandrel (see Fig. 3). To measure the muon beam emittance as it enters and exits the cooling channel, a scintillating fiber tracking detector will be located in the bore of the three spectrometer coils, which generate a 4-T uniform field over a 1-m-long and 30-cm-

diameter volume. The two match coils operate as a focusing doublet to match the beam to the adjacent AFC modules. Additional details of the spectrometer solenoid design and operating parameters have been presented in a previous paper [4].

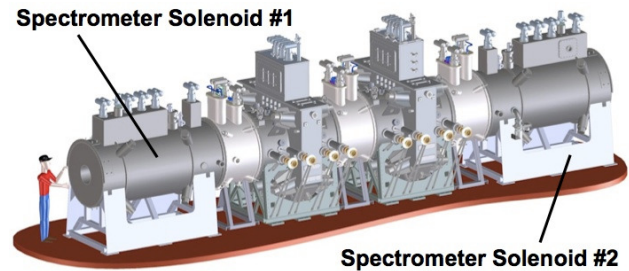


Figure 1: CAD model of MICE cooling channel layout.



Figure 2: First spectrometer solenoid during training.

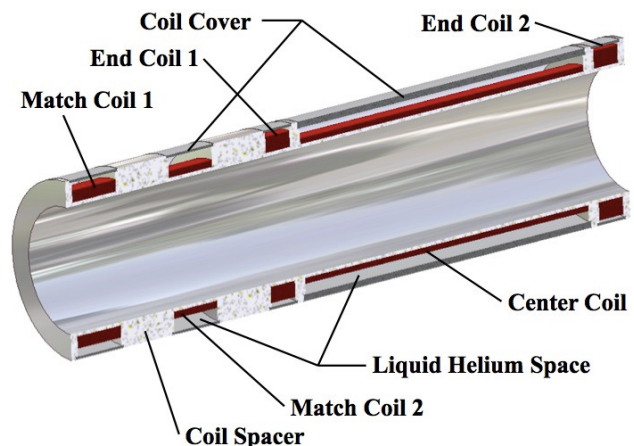


Figure 3: Spectrometer solenoid cold mass assembly.

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MAGNET DESIGN MODIFICATIONS

During the initial training of one of the spectrometer solenoids, several issues arose that resulted in the need to disassemble the magnet and carry out a series of repairs and design changes based on detailed analyses and review of the existing design [5,6]. The primary issues were the protection of the magnet leads during a quench and excessive heat leak to the magnet cold mass. A description the key design modifications that were implemented are presented here. Additional details and photos can be found in [7].

The magnets use cryocoolers to cool the cold mass and radiation shield. The initial cooling system design used three Cryomech PT-415 two-stage coolers to re-condense the liquid helium in the cold mass and to maintain the temperature of the 70K radiation shield. Each cooler nominally provides 40 W of cooling power at 45K and 1.5 W at 4K. An additional single-stage cooler (Cryomech AL-330) was used to provide 170 W of cooling at 50K in the area of the upper end of the HTS leads.

A series of design and assembly modifications have been implemented to address the issues with the original configuration of the magnets. The recent modifications include: improvement of the connection between the first stage of the cryocoolers and the radiation shield, increased thermal conductivity of the shield material, a new insulating vacuum pump and instrumentation system, and improvements to the design, manufacture and application of the multi-layer insulation (MLI) blankets. Through these and other enhancements, the total heat load on the cold mass of the reassembled magnet has been calculated to be just under 4 W. To provide a more comfortable margin, the total cooling power at 4K has been increased to 7.5 W by adding two additional pulse-tube cryocoolers.

MAGNET REASSEMBLY

The first magnet has been modified, reassembled, fully trained and tested, as described in the next section. In addition to the actual magnet improvements, a new data acquisition and control system and a reconfigured power supply rack have been implemented that more closely resembles the system that will be in operation at RAL. A new external quench detection system integrated with fast data acquisition capability has also been developed in order to enhance the protection of the coils and leads.

The cold mass MLI wrap was improved by procuring a series 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 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 increase its thermal conductivity. Also, the thermal conduction area between the first stage of the cryocoolers and the radiation shield was substantially increased by incorporating a series of flexible copper sheets that are welded to bi-metal strips on the shield body.

MAGNET TRAINING AND TESTING

From June of 2012 through February of 2013, the first spectrometer solenoid magnet was cooled down on three occasions, and three separate series of training runs were carried out. The first training series was discontinued and the magnet warmed up due to a failed HTS lead. It appears the failure was due to a poor solder connection to the warm lead. The failed lead and two other suspect leads were replaced using an improved soldering procedure, and the magnet was cooled down to resume training. During this second series, the coil currents reached ~97% of the target value when an ice blockage was discovered in the primary cold mass vent line. To prevent overpressurization and possible damage to the cold mass during a quench, the magnet was again warmed up. In order to prevent a recurrence of the problem, improvements were made to the cold mass heater control circuit and the pressure relief valve system. A gas bottle backup system was also incorporated in order to prevent the possibility of negative pressure in the cold mass.

During the third training run series, the center coil current reached the target value of 283 A, and the operational current was successfully held constant for a period of 24 hours, thus satisfying the acceptance criteria. The progression of training currents in the center coil is shown in Fig. 4 for the three runs. From the figure, it can be seen that retraining was always required after warming up the magnet. Also, the initial quench current for the training varied from a low of 135 A to a high of 185 A. The slope of the training curve was similar for all three series. The final training sequence went from 156 A to 283 A with 12 quenches in between. Our analysis of the fast coil voltage data indicates that these were all normal training quenches.

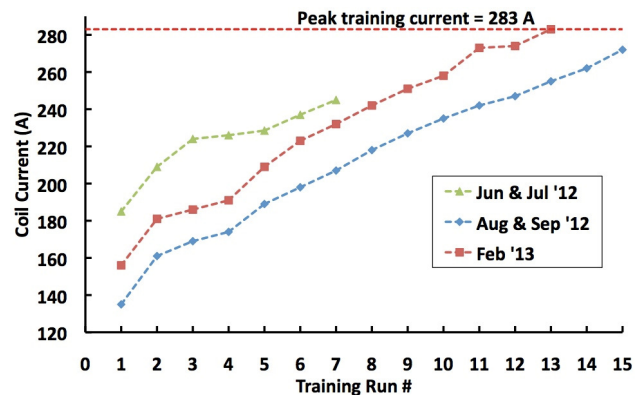


Figure 4: Center coil current during recent training runs.

During typical magnet operation, the five spectrometer solenoid coils will all operate at a different current. A rack containing three 300 A power supplies and two 60 A trim supplies for the end coils was used to power the system during training. Each supply is independently driven by the control system at a ramp rate that is directly proportional to each coil's target current. The progression of currents in each of the five spectrometer solenoid coils during the final training run series is shown in Fig. 5.

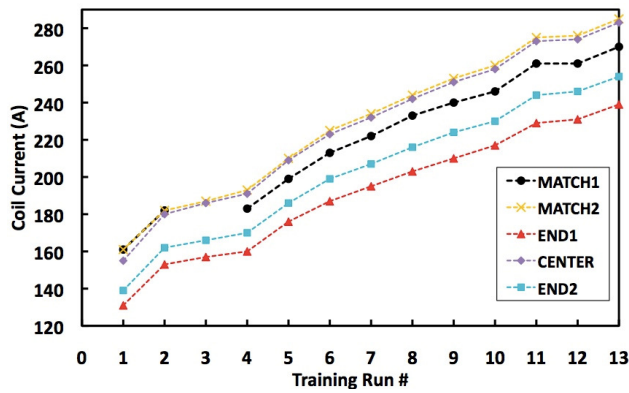


Figure 5: Final training series coil current progression.

In addition to achieving the coil design currents, a primary goal of the testing was to verify that the spectrometer solenoid could operate at full current while maintaining the liquid helium in the cold mass with no boil off. In order to reach this operational standard, the five 2-stage cryocoolers must provide more condensing power at 4K than the total heat leak into the cold mass. Based on our analysis of the test results, the excess cooling capacity at full current was approximately 3.5 W. During operation, an automatically controlled heater on the magnet cold mass was used to maintain a constant pressure of 1.05 bar in the helium circuit.

SECOND MAGNET PROGRESS

In parallel to the assembly and testing work carried out on the first magnet, a second spectrometer solenoid that has all of the same design enhancements is being assembled. At the time of this paper, the second magnet assembly is nearly complete. Remaining tasks include the installation of the HTS leads, final MLI wrapping in the cryocooler tower, final welding of the cryocooler tower side plates, and a vacuum leak check of the cryostat. An overall view of the second magnet is provided in Fig. 6.



Figure 6: Second spectrometer solenoid nearly completed.

SUMMARY

Early in 2012, design modifications were 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 has been trained to full operating current and passed all acceptance tests. The next step for the first magnet is a full 3D magnetic mapping at operating current before delivery to the MICE Hall at RAL later this year. A second, identical magnet is being assembled in parallel and is expected to be ready for cooldown and training in June 2013.

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