FABRICATION, TESTING AND MODELING OF THE MICE SUPERCONDUCTING SPECTROMETER SOLENOIDS *

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Abstract

The Muon Ionization Cooling Experiment (MICE), an international collaboration sited at Rutherford Appleton Laboratory in the UK, will demonstrate ionization cooling in a section of realistic cooling channel using a muon beam. A five-coil superconducting spectrometer solenoid magnet will provide a 4 tesla uniform field region at each end of the cooling channel. Scintillating fiber trackers within the 400 mm diameter magnet bore tubes measure the emittance of the beam as it enters and exits the cooling channel. Each of the identical 3-meter long magnets incorporates a three-coil spectrometer magnet section and a two-coil section to match the solenoid uniform field into the other magnets of the MICE cooling channel. The cold mass, radiation shield and leads are currently kept cold by means of three two-stage cryocoolers and one single-stage cryocooler. Liquid helium within the cold mass is maintained by means of a re-condensation technique. After incorporating several design changes to improve the magnet cooling and reliability, the fabrication and acceptance testing of the spectrometer solenoids have proceeded. The key features of the spectrometer solenoid magnets, the development of a thermal model, the results of the recently completed tests, and the current status of the project are presented.

INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) will consist of a cooling channel [1] which is made up of three absorber focus-coil (AFC) modules [2], each containing a liquid hydrogen absorber and two focusing coils, along with two RF and coupling-coil (RFCC) modules [3], each of which contain four 201 MHz accelerating RF cavities centered on a superconducting solenoid. Located at either end of the cooling channel are the spectrometer solenoid modules (Fig. 1).

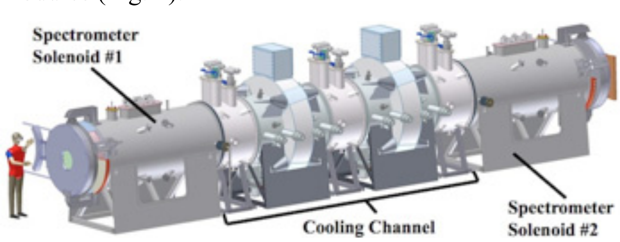

Figure 1: MICE cooling channel 3D CAD image.

The absorbers perform muon ionization cooling to reduce the beam emittance while the RF cavities re-accelerate the beam. Each spectrometer solenoid consists of five superconducting coils wound on a common 2923 mm long aluminum mandrel. A CAD image of the coil assembly is provided in Fig. 2. 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. The tracker detectors, which are made up of five planes of scintillating fibers, are located in the bore of these three coils and are used to measure the emittance of the muons as they enter and exit the cooling channel. Additional details of the spectrometer solenoid design and operating parameters were presented previously [4,5].

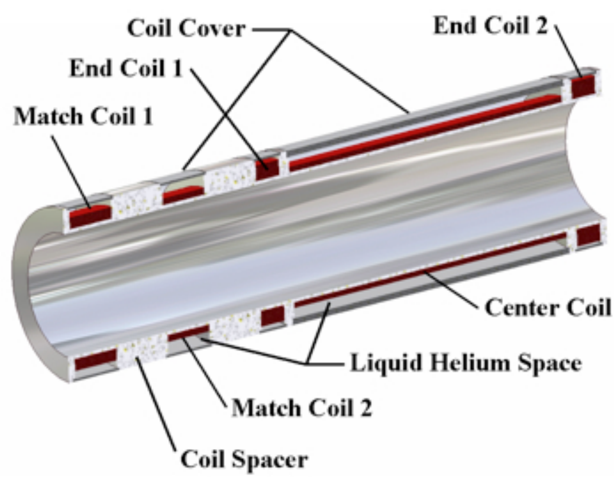

Figure 2: Spectrometer solenoid cold mass assembly.

MAGNET THERMAL MODELING

A 3D finite element model of the first stage cooling for the MICE spectrometer solenoid has been recently developed. The model has been used to perform a parametric study of the magnet cooling system under load. The model was been written using Cast3M software [6] that is based on an object-oriented language, Gibiane, which has been specifically developed for finite element analysis. The solver uses the concept of Lagrangian multipliers to enforce the first law of thermodynamics.

A number of assumptions have been made in the analysis as follows:

- steady state conditions
- idealized geometry (perfect thermal connections)
- temperature dependent material properties
- linear interpolation of the cryocooler thermal performance map
- approximation of the superinsulation cooling as an equivalent heat transfer coefficient

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The model has been simplified in the sense that some of the geometries are not detailed. To take into account the discrepancies between the model and the actual geometry, the material properties are multiplied by correction factors to ensure a proper heat distribution even though the temperature profile across the sub-geometries may not be accurate.

The first stage thermal model geometry as displayed by Cast3M is shown Fig. 3, and the resulting temperature distribution is shown in Fig. 4.

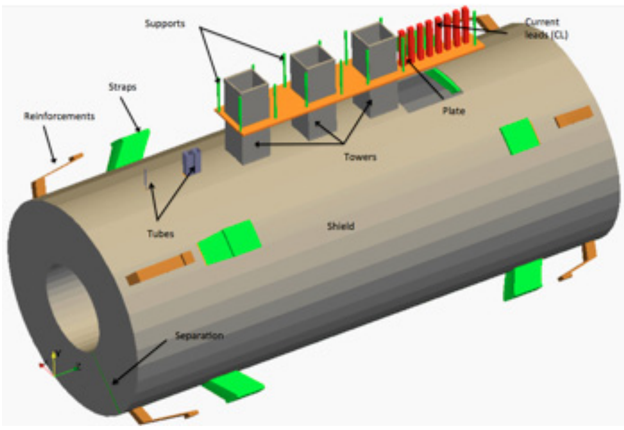

Figure 3: Overall view of the first stage thermal model.

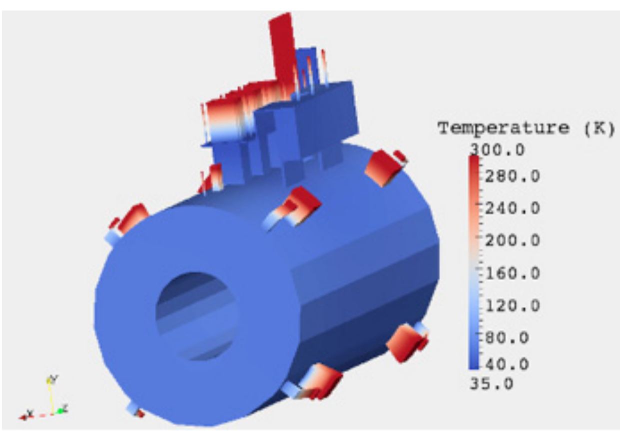

Figure 4: Model temperature distribution at full current.

Based on the results obtained from the thermal model, several conclusions and recommendations have been developed. At least one additional cryocooler besides the three 2-stage coolers originally used will be required to ensure that the HTS current leads are adequately cooled. The cooler must be located at the far end of the HTS leads and can be a single-stage cooler (recently installed and tested) or a 2-stage cooler to gain additional cooling power at 4K. The magnet currently uses an internal liquid nitrogen tank to speed the cooldown of the shield. The tank should be removed since it adds extra heat load to the first stage of the coolers and does not have an appreciable effect on the rate of cooling of the shield. It is also recommended that additional temperature sensors be incorporated in order to better characterize the heat leaks to the magnet cold mass.

OFFLINE LEAD AND COOLER TESTS

A series of offline tests have been carried out in order to verify the performance of the Cryomech PT-415 cryocoolers, to characterize the heat leak and resistive heating of the warm leads, and to confirm proper operation of the HTS leads. The test system vacuum chamber and the internal components are shown in Fig. 5.

Figure 5: External and internal view of the test apparatus.

The test setup is designed to approximate the configuration of the actual magnet first stage copper plate, the cryocooler connection, the lead thermal intercepts and the vacuum-to-cold-mass power feedthroughs. The 2-stage cryocoolers operate in a drop-in configuration where no internal bolted connections are used. The first stage connection is made by means of a circular tapered joint, and the cooler helium space is kept separate from the magnet insulating vacuum by a pair of thin stainless steel sleeves. During testing of the cryocoolers, it was determined that their effective cooling capacity at 4K is reduced from 1.5 watts to 1.3 watts due to the extra heat leak through the sleeves.

All of the actual magnet warm and HTS leads are also tested under full current and measured by means of a series of voltage taps. During recent testing, it was determined that the warm leads were not optimum and that the resistive heating was considerably higher than that predicted by the design calculations. The conductor used for the warm leads was increased in diameter and slightly shortened in order to provided a better balance between the heat leak and the resistive heating; the new lead design was confirmed through subsequent tests.

RECENT DESIGN MODIFICATIONS

During the middle of CY2009, the second iteration of the spectrometer solenoid magnet was completed and was in the process of being trained. After multiple successful training runs, an open circuit in the leads connecting to the Center coil was noted after a 238 A training quench. Subsequent removal of an access panel on the magnet vacuum vessel revealed a burned out HTS lead (Fig.6).

Figure 6: Burned out HTS lead (right side).

It was determined that the lead failed due to excessive temperature at its upper end. The configuration of the first stage copper plate is such that the leads extend away from the nearest cryocooler. A thermocouple adjacent to the leads on the copper plate was reading temperatures in excess of 90K with current in the magnet. At this temperature, the HTS leads cease to remain superconducting and will eventually go normal and burn out, as observed.

To remedy the situation, the vendor developed a design whereby a single stage cryocooler capable of removing 170 W of heat at 55K was added to the first stage copper plate at the far side of the leads. The added cooler had the desired effect in that the temperature at the upper end of the HTS leads was reduced by ~35K during operation. A secondary benefit was that the thermal shield temperature was also reduced by about 20K.

MAGNET TRAINING

The modified magnet was successfully cooled down in March 2010 in preparation for the completion of training (Fig. 7 shows the magnet during a quench). During training, the coils are connected in series and run with a single power supply. While the coils have operating currents ranging from 223 to 271 amps, the intention is to train all of them up to at least 275 amps.

Figure 7: Quench during spectrometer solenoid training.

During the recent training, all five coils reached a current of 258 amps. At this point, it was discovered that one of the leads connecting to the Match 2 coil was open circuit. Subsequent investigation using the voltage taps indicated that the failure was between the lower end of the HTS lead and at a voltage tap inside the cold mass near the vacuum/helium feedthrough. While the magnet remained cold, training continued on the undamaged Center and two End coils. Training runs reaching currents of 271 amps and 252 amps were completed. The reason for the lower current in the second run has not been determined. Also, it was noted during these tests that the three 2-stage coolers were not sufficient to maintain the liquid helium in the cold mass without boil-off occurring.

CURRENT STATUS

An evaluation of the magnet is under way to fully assess the cold mass heat leak issue. It is likely that the solution to the problem will involve further measures to reduce the heat leak as well as adding either one or two 2-stage cryocoolers to the system. The magnet has recently been partially disassembled in order to investigate the lead failure. Inspection of the accessible areas has indicated that the failure is internal to the cold mass. Further disassembly is under way in order to pinpoint the location and cause of the open circuit lead.

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