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MICE Spectrometer Magnet System Progress

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***Abstract*—The first magnets for the muon ionization cooling experiment will be the tracker solenoids that form the ends of the MICE cooling channel. The primary purpose of the tracker solenoids is to provide a uniform 4 T field (to better than ±0.3 percent over a volume that is 1 meter long and 0.3 meters in diameter) spectrometer magnet field for the scintillating fiber detectors that are used to analyze the muons in the channel before and after ionization cooling. A secondary purpose for the tracker magnet is the matching of the muon beam between the rest of the MICE cooling channel and the uniform field spectrometer magnet. The tracker solenoid is powered by three 300 amp power supplies. Additional tuning of the spectrometer is provided by a pair of 50 amp power supplies across the spectrometer magnet end coils. The tracker magnet will be cooled using a pair of 4 K pulse tube coolers that each provide 1.5 W of cooling at 4.2 K. Final design and construction of the tracker solenoids began during the summer of 2006. This report describes the progress made on the construction of the tracker solenoids.**

***Index Terms*—detectors, fabrication, ionization, solenoids, superconducting coils.**

I. INTRODUCTION

THE Muon Ionization Cooling Experiment (MICE) currently being constructed at the Rutherford Appleton Laboratory near Didcot, United Kingdom consists 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 tracker solenoid systems. The liquid hydrogen absorbers located within the AFC modules perform the muon ionization cooling [2]. The muons are re-accelerated by four 201 MHz RF cavities contained in each of the two RFCC modules [3]. Each of the tracker solenoids are comprised of five superconducting solenoid magnets that are used to couple the muon beam to the adjacent AFC modules and to measure the emittance of the muons as they enter and exit the cooling channel [4]. The tracker detectors located within the bore of the tracker solenoid modules are made up of five planes of scintillating fibers that measure the position of the particles within the magnet bore volume. An iron shield plate is used on the outer ends of the tracker solenoids to shield the photo multiplier tubes in an adjacent detector from the magnetic fields.

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II. TRACKER SOLENOID COIL GEOMETRY

Each of the tracker solenoid magnets consists of five superconducting coils wound on a common mandrel as shown by the 3-D CAD representation in Fig 1. Match Coil 1, Match Coil 2, and End Coil 1 operate as a quadrupole triplet to match the beam in the tracker solenoid with the beam in the adjacent AFC modules. The spectrometer solenoid portion of the tracker module consists of three coils: End Coil 1, the Center Coil, and End Coil 2. The spectrometer coils generate a 4 Tesla uniform field ($\Delta B/B < 3\times10^{-3}$) over a 1 meter long and 0.3 meter diameter volume. The two match coils combined with the first end coil match the β in the adjacent AFC module coils with the β in the uniform field region of the spectrometer coils.

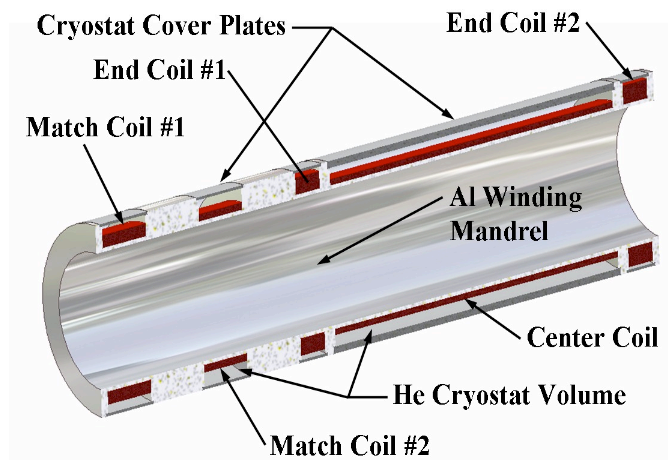

Fig. 1. CAD image of the tracker solenoid coils and cold mass assembly.

End Coil 1 performs two functions in that it helps shape the field in the uniform field section of the module and it assists with the muon beam tuning process. The three spectrometer coils in each tracker module are connected to each other in series; a single 300 amp power supply is used to power both sets of spectrometer coils, connected in series to ensure equal currents. Four additional low current power supplies (up to ±60 amps) are used to independently adjust each of the end coils. The small current in End Coil 1, along with Match Coil 1 and Match Coil 2, helps tune the spectrometer solenoid with the MICE cooling channel. The small current in End Coil 2 serves to counteract the effects of the iron shield plate at the end of the tracker modules. Match Coil 1 from the upstream tracker solenoid will be connected in series to Match Coil 1 from the downstream module and powered with an additional 300 amp supply. The Match Coil 2's will be connected and powered in the same manner. Further details of the tracker solenoid design and operating parameters were presented previously [5].

The five coils in each of the tracker solenoid modules are all to be wound using the same superconducting wire. The superconductor properties are provided in Table I.

TABLE I SUPERCONDUCTOR PROPERTIES

Parameter	Quantity
Dimensions	1.00 mm × 1.65 mm
Critical Current	760 A at 5 T and 4.2 K
Cu to S/C Ratio	3.9 ± 0.4
Number of Filaments	222
Filament Diameter	41 μm
Conductor Twist Pitch	19 mm
Conductor Length	55 km/module

III. COLD MASS SUPPORTS

Fig. 2 provides an overall view of the 3-D CAD model showing the magnet cryostat and cold mass supports. The tracker solenoid uses a self-centering cold mass support system to ensure that the cold mass center remains unchanged as the magnet is cooled from room temperature to 4 K. 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 tracker solenoid cold mass support system has a large longitudinal spring constant (>200 MN/m) in order to prevent movement of more than 1.5 mm when the MICE magnets are powered. Tolerance requirements include the following: the axis of the solenoid must be co-axial with the warm bore axis to within ±0.3 mm; the maximum allowable tilt is ±0.001 radian.

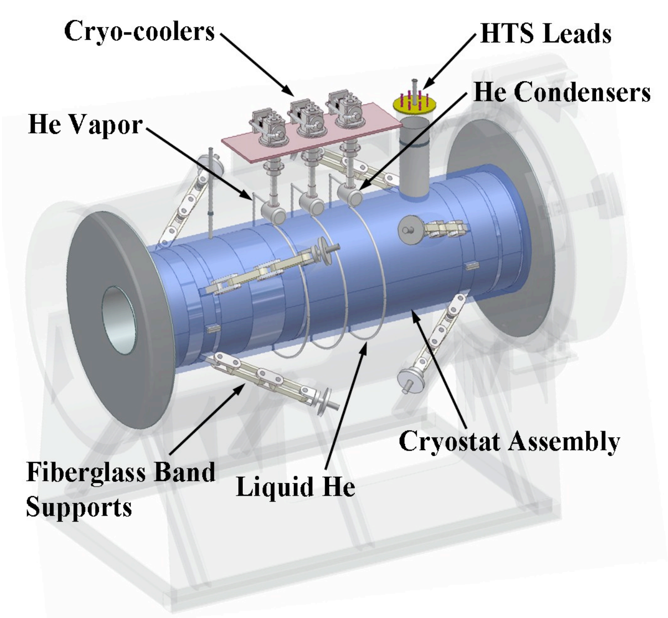

Fig. 2. CAD image of the tracker solenoid cold mass and cryostat.

IV. THERMAL PERFORMANCE

The heat leak into both the 50 K and 4 K regions of the magnet is dominated by the losses in the current leads. The second largest heat leak into the 4 K region occurs at the cold mass support fiberglass tension bands. The second largest heat leak at 50 K is due to thermal radiation through the multi-layer insulation (MLI). Based on the detailed calculation of the total heat leaks at 4 K and 50 K, it is expected that each tracker solenoid module can be cooled using two 1.5 W (at 4.2 K) pulsed-tube cryo-coolers. The magnets have been designed with the capability of installing a third cryo-cooler as a contingency.

V. VACUUM VESSEL AND EXTERIOR INTERFACES

An overall view of a 3-D CAD model of the tracker solenoid module is provided in Fig. 3. The total length of the spectrometer solenoid module is 2923 mm; the length of the magnet vacuum vessel is 2735 mm. A 188 mm long space at the AFC module end of the tracker solenoid module is provided for installation of a radiation shutter. The shutter will be used to shield the tracker's scintillating fiber detectors in the magnet bore from the electrons and gamma radiation that comes from the RF cavities during conditioning. The total thickness of the radiation shutter is equivalent to 50 mm of lead. The AFC end of the tracker solenoid module connects to the adjacent AFC module by means of a large diameter bellows which is spanned by load carrying studs. In order to provide a helium atmosphere for operation of the scintillating fiber tracker, a thin aluminum window will isolate the tracker solenoid bore from the vacuum at the AFC end of the magnet.

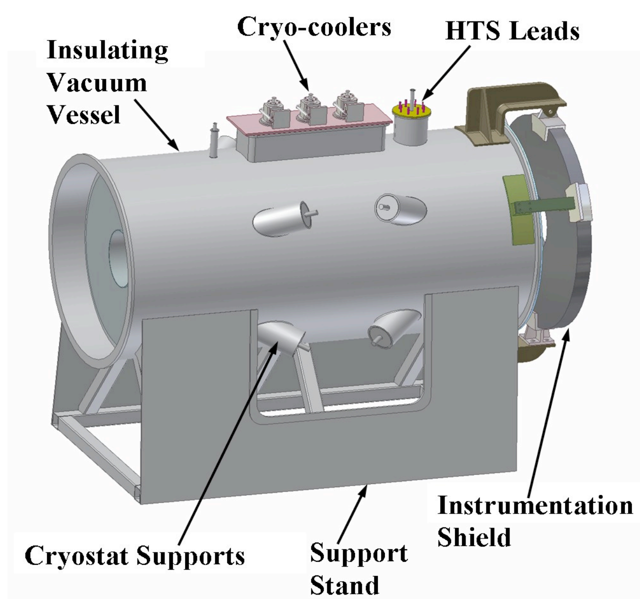

Fig. 3. CAD image showing the exterior of the complete tracker solenoid.

The support stand shown in Fig. 3 is designed to carry the magnetic forces acting on the coils of up to 500 kN in the longitudinal direction to the floor of the experiment hall. The support structures for the AFC modules adjacent to the tracker solenoids are not capable of carrying the magnetic forces on those modules to the floor. Since the tracker solenoid module vacuum vessel is the same diameter as the AFC module vacuum vessel, the forces carried by the AFC module coils can easily be transmitted to the tracker vessel and its stand by means of studs in the flanges that span the bellows joint.

An iron plate is used to shield the photo multiplier tubes (PMT's) from the magnetic field generated by the spectrometer magnet (Fig. 3). In the approximately 250 mm of space between the iron shield and the end of the magnet cryostat is a patch panel that carries the light fibers from the scintillating fiber detector to the readout device. The upstream tracker solenoid contains a diffuser system that produces a muon beam with the desired input emittance.

The two tracker solenoids have been designed and are currently 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 tracker 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 both on responsiveness to the specification and on price. The superconducting wire, cryo-coolers and power supplies were included in the tracker solenoid specification and are being provided to the vendor by the MICE Project.

The vendor that was awarded the tracker solenoid 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 is now complete for the first magnet. The coils were wound with a wet winding process using Stycast epoxy. Upon completion of the coil winding process, aluminum banding was wound around the outside diameter of the coils for support. A photo showing the current progress of the fabrication of the first magnet is provided in Fig. 4. The first tracker solenoid magnet is nearing completion and is expected to be finished and tested under power before the end of CY 2007.

A passive quench protection system consisting of a series of diodes and resistors will be located within the helium cryostat. Fabrication of the quench system is complete and installation is under way, as shown in the photo in Fig. 5. Upcoming fabrication steps include welding of cover plates to the coil forming mandrel to create the helium vessel and installation of reinforcement bands to allow connection of the cold mass supports.

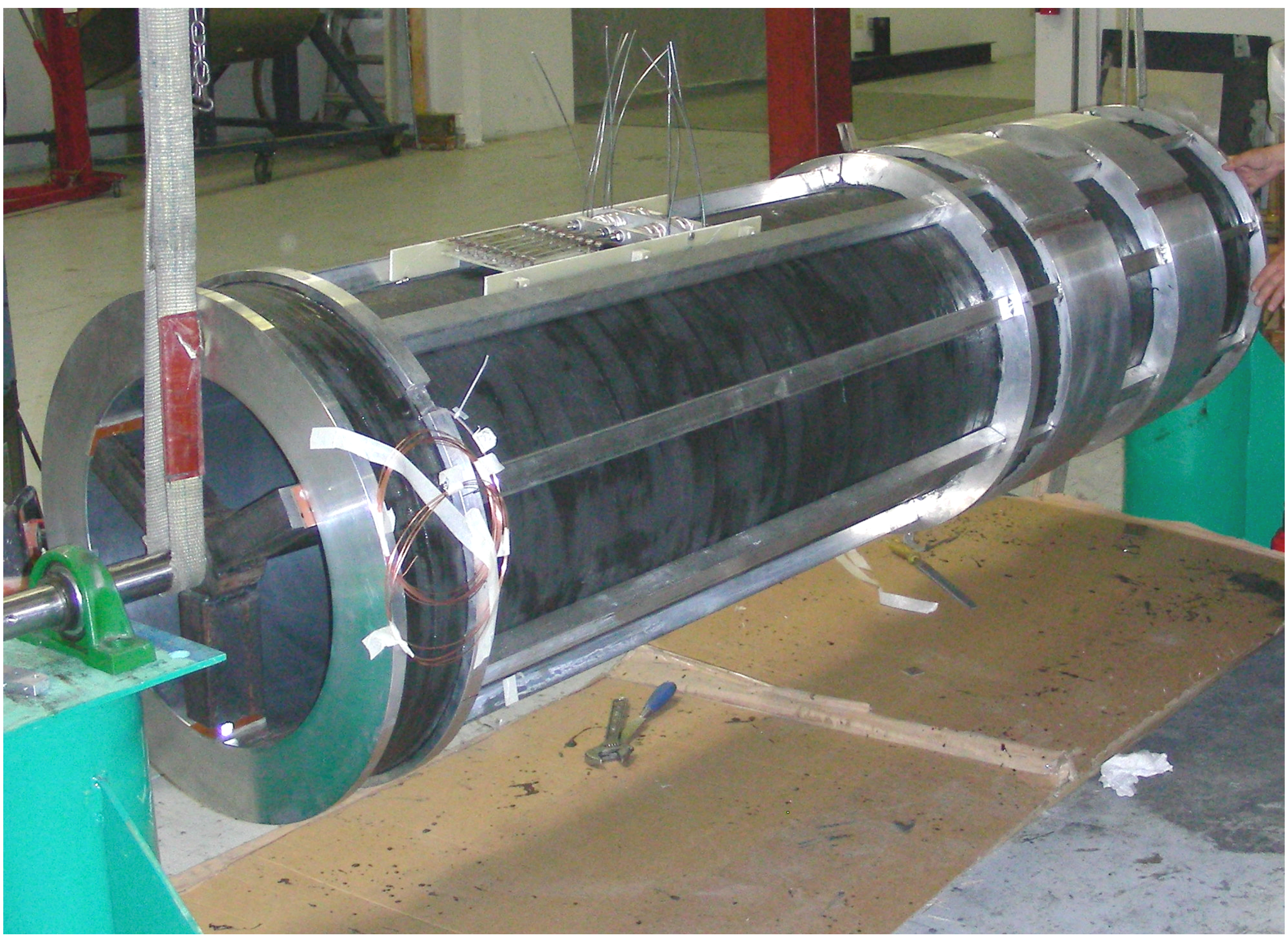

Fig. 4. Photo showing the current progress on the fabrication of the first of the two MICE tracker solenoids.

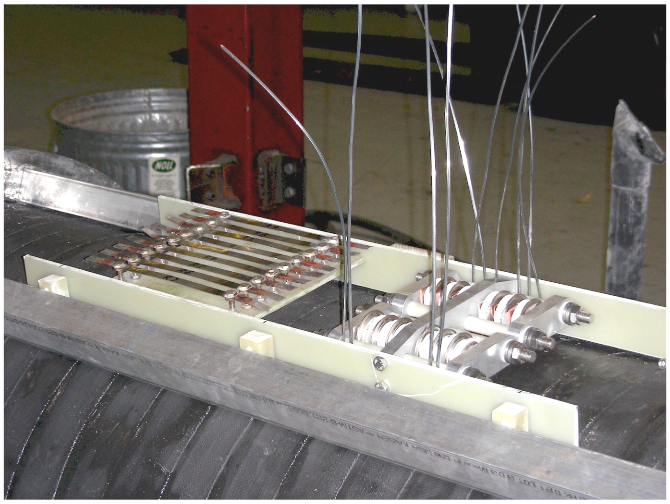

Fig. 5. Preliminary installation of the magnet quench protection system.

The fabrication of the magnet cold mass supports is also complete. Each of the eight sets of supports will consist 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 4 K (at the cold mass), an intermediate point is at 50 K (at the thermal shield) and the other end is at 300 K (the room temperature end). A photo of a single completed cold mass support assembly is provided in Fig. 6.

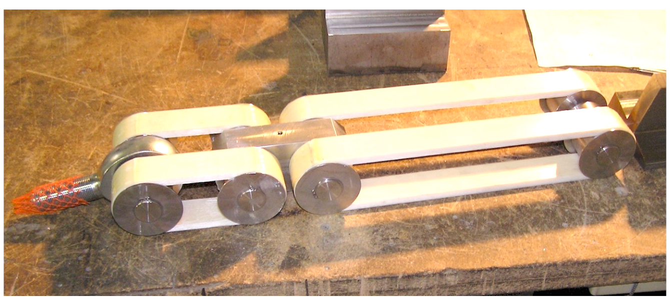

Fig. 6. Preliminary installation of the magnet quench protection system.

The magnets will be cooled using either two or three Cryomech PT-415 pulsed-tube cryo-coolers. The system has been designed to allow the coolers to be installed by means of a drop-in type configuration. With this set-up, the coolers can be installed and removed without breaking the cryostat insulating vacuum. The condenser is connected directly to the second stage of the cold head prior to installation, as shown in Fig. 7. A tapered adapter mounted at the cryo-cooler's first stage makes thermal contact with a mating adapter connected to the magnet's thermal shield.

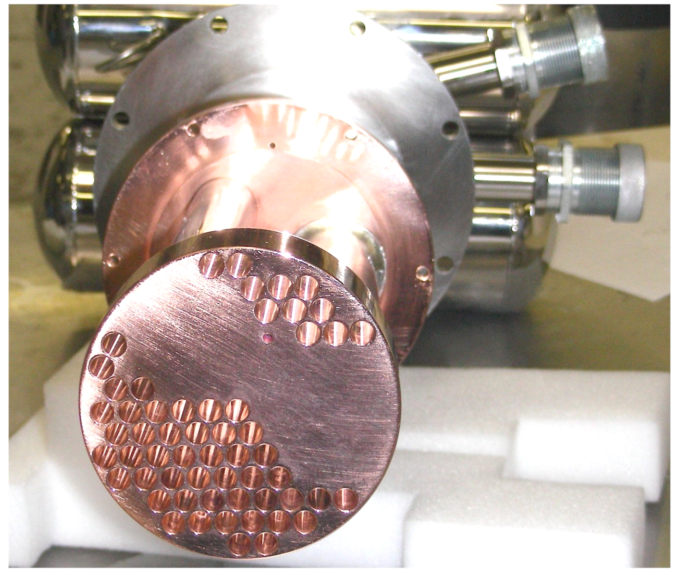

Fig. 7. Cryocooler cold head with condenser attached.

VI. Conclusion

The first magnets for the MICE cooling channel, the superconducting tracker solenoids, have been designed and are currently being fabricated by a US vendor. The first of the two identical 4 T uniform field magnets will be complete before the end of 2007. The second magnet is expected to be ready in early 2008.

Acknowledgment

The authors would like to acknowledge the design and fabrication efforts of our subcontracted vendor on this project, Wang NMR, Inc. of Livermore, CA. The development of the initial design concepts by Wing Lau and Stephanie Yang of the Mechanical Group in the Department of Physics at Oxford University is acknowledged as well.

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