Progress on the Design and Fabrication of the MICE Focusing Magnets

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***Abstract*— The Muon Ionization Cooling Experiment (MICE) focusing solenoid magnets focus the muon beam within the MICE cooling channel on a liquid or solid absorber that is within the warm bore of solenoid. The focusing magnet has a warm bore of 470 mm. This magnet consists of two coils 210-mm long that is separated by an aluminum mandrel that is 200 mm long. Each of the coils has its own leads. The coils may be operated in either the non-flip mode (solenoid mode with both coils at the same polarity) or the flip mode (quadrupole focusing mode where both coils are at opposite polarity). This report describes the focusing solenoid magnet design that will be built by the vendor. The progress on the construction of the first of the focusing magnets will also be discussed in this report. Ultimately three of these magnets will be built. These magnets will be cooled using a pair 1.5 W (at 4.2 K) pulse tube coolers.**

***Index Terms*—Superconducting Focusing Magnet**

. INTRODUCTION

The MICE focusing magnet is the magnetic element of the absorber focus coil (AFC) module [1-3]. The AFC module is where muon ionization cooling occurs within the experiment. At the center of the AFC module is absorber that reduces the momentum of the muons in both the longitudinal and transverse direction. The muons are re-accelerated in the longitudinal direction using RF cavities that are within the RF coupling coil (RFCC) module. If after reacceleration there is a net reduction transverse momentum, then there is net cooling. While the absorber is reducing the transverse momentum, scattering of the muons occurs as they interact with the absorber material. The absorber at the center of the AFC module may be either a liquid absorber or a solid absorber. The best absorber material (the material that produces the least amount of scattering) that can be used at the center of the AFC module is liquid hydrogen. Thus the AFC module is designed as a superconducting magnet with a liquid hydrogen absorber at its center.

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The overall outside diameter of the AFC module (not including the turret for superconducting magnet and absorber services) is 1404 mm. The overall length of the AFC module is limited by the space occupied by the RF cavities in adjacent RFCC modules. When one allows for getting the modules in and out of the experiment, the length of the AFC module is 782 mm. The magnet cold mass, the magnet shields, the magnet insulation, and the liquid hydrogen absorber system is bounded by a cylindrical volume that is 1404 mm in diameter by 782 mm in length. The turret above the cylindrical volume contains the coolers, the shield connections, the magnet leads, and the liquid hydrogen absorber liquefaction and cooling system. The position of the coolers and HTS leads within the turret is determined by the stray magnetic field from the magnet when it is operated at its maximum current [4].

The warm bore of the focusing magnet cryostat was set at 470 mm. Within the magnet warm bore is the solid or liquid absorber. The absorber minimum diameter is 350 mm. For a solid absorber this is the minimum diameter of the solid disc. For a liquid hydrogen absorber, the diameter of both types of thin windows was set 350 mm. The liquid hydrogen absorber that is designed to fit into the warm bore of the magnet has an outer diameter of about 400 mm [5]. This allows for a radial space of 35 mm, which will contain the liquid hydrogen service pipes, a support system and the absorber multilayer insulation. The placement of the absorber within the absorber is shown in Fig 1.

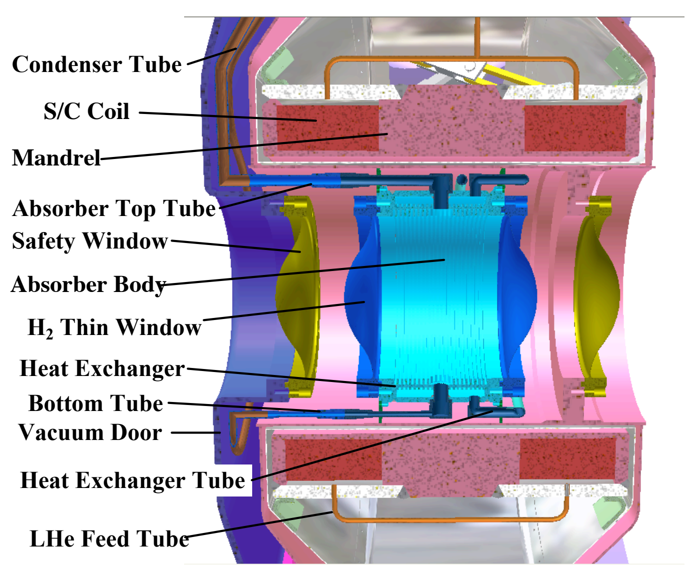

Fig. 1. A three dimensional cross-section of the MICE liquid absorber, its thin windows, the liquid hydrogen feed tubes, and the focusing magnet.

I. The Focusing Magnet Design Parameters

The superconductor for the focusing magnet is somewhat smaller than the conductor proposed for the original focusing magnet design. This conductor selected by the vendor is slightly smaller than the conductor used for the original spectrometer solenoid magnet design. (The original conductor comes from a different vendor.) The focusing magnet un-insulated conductor dimensions are 0.95 mm by 1.52 mm. The insulated dimensions are 1.00 mm by 1.57 mm. Like the conductor proposed in the original design, the conductor that will be used has a copper to superconductor ratio of 4, number of filaments 220, filament diameter ~41 μm, and a twist pitch of about 19 mm. The j_c of the superconductor is greater than 3000 A mm^{-2} at 5 T and 4.22 K. The measured critical current for the conductor is >800 A at 5 T and 4.2 K. The piece lengths for the conductor are on the short side. As a result, the vendor coil design calls for splices within the coils. The maximum allowable splice resistance is set at 10 nΩ [6].

Since the conductor critical current is higher than for the original design, there will be small changes in the coil design that will result in a larger temperature margin for the magnet. The magnet quench characteristics will change slightly. The propagation velocities in all directions will be increased about six percent [7]. The hot spot temperature will increase, but the conductor will probably decrease the quench-back time for the coils, once the normal region has been formed [8], [9]. Table I shows the basic design parameters for focusing magnet as the magnet vendor design dictates.

Table I. The Basic Parameters of the MICE Focusing Magnet in the Flip and Non-flip Modes

Parameter	Non-flip	Flip
Warm Bore Radius (mm)	235	
Outer Cryostat Radius (mm)	702	
AFC Module Length (mm)	844	
Magnet Cryostat Length (mm)	745	
Cold Mass Length (mm)	690	
Number of Coils in the magnet	2	
Magnet Coil Length (mm)	210	
Coil Separation Distance (mm)	200	
Coil Inner Radius (mm)	263	
Coil Thickness (mm)	84	
Coil End to End Distance (mm)	620	
Number of Conductor Layers	76	
Number of Turns per Layer	132	
Magnet J (A mm^{-2})*	69.8	135.4
Magnet Current (A)*	123.1	236.1
Magnet Self Inductance (H)	148.4	106.5
Peak Induction in Coil (T)*	4.94	7.52
Magnet Stored Energy (MJ)*	1.12	2.98
4.2 K Temp. Margin (K)*	~2.1	~0.7
External B at R = 0.7 m (T)*	0.12	~0.65
Direction of Field Lines	Axial	Radial
Inter-coil Z Force (MN)*	-0.54	3.39

* Worst case currents based on p = 240 MeV/c and β = 420 mm

The focusing cold mass support system is designed to carry magnetic forces in the longitudinal direction (along the magnet axis) of 900 kN. There has been a change of scope as far as the experiment is concerned. The focusing magnet will have a self-centering support system [3] as does the MICE spectrometer solenoid [10] and as is proposed for the MICE and MuCOOL coupling magnets [11].

The support system proposed by the focusing magnet vendor is a single-band support system. The spectrometer solenoid and coupling magnet use or will use a double-band support system. Fig. 2. illustrates the concept behind the proposed single-band focusing magnet cold mass support system. The focusing magnet vendor proposes to stress the cold mass support bands at a higher stress levels than the support bands for the spectrometer and coupling magnets.

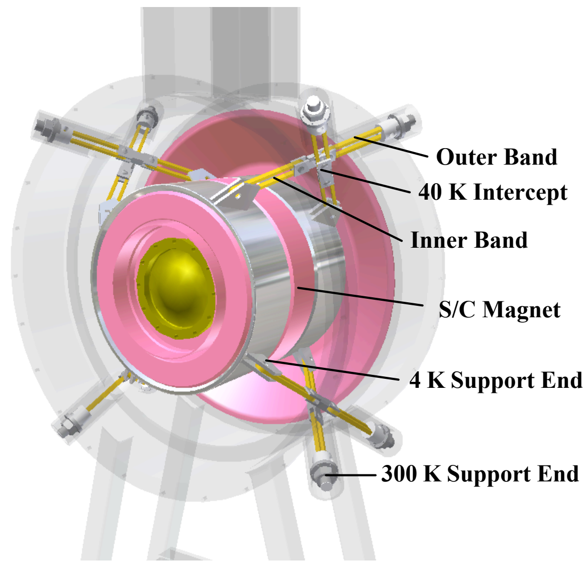

Fig. 2. A Schematic representation of the single-band cold mass support system that is proposed for the MICE focusing magnet.

The focusing magnet will be indirectly cooled using a pair of Cryomech PT415 pulse tube coolers that generate 1.5 W of cooling at 4.2 K on the second-stage while generating 50 W of cooling on the first stage, at a temperature of 55 K. Table II shows the projected heat leaks into the magnet cryostat at 4 K and 55 K. These heat loads could be low given the experience on other magnets that have been cooled using two-stage coolers. The key is keeping the first stage temperature low.

Fig. 3. shows an exploded view of the AFC module. Included are the magnets components, the absorber, the absorber piping and the absorber cooling components.

Table II. The Estimated Focusing Magnet Heat Loads at 55 K and 4.2 K

Component	Heat Leak (W)	
	@ 55 K	@ 4 K
Cold Mass Supports	~13	~0.62
Radiation through MLI	~10	~0.60
Necks and Instrumentation	~9	~0.43
Current Leads	~50	~0.20
Total Estimated Heat Leak	~82	~1.75

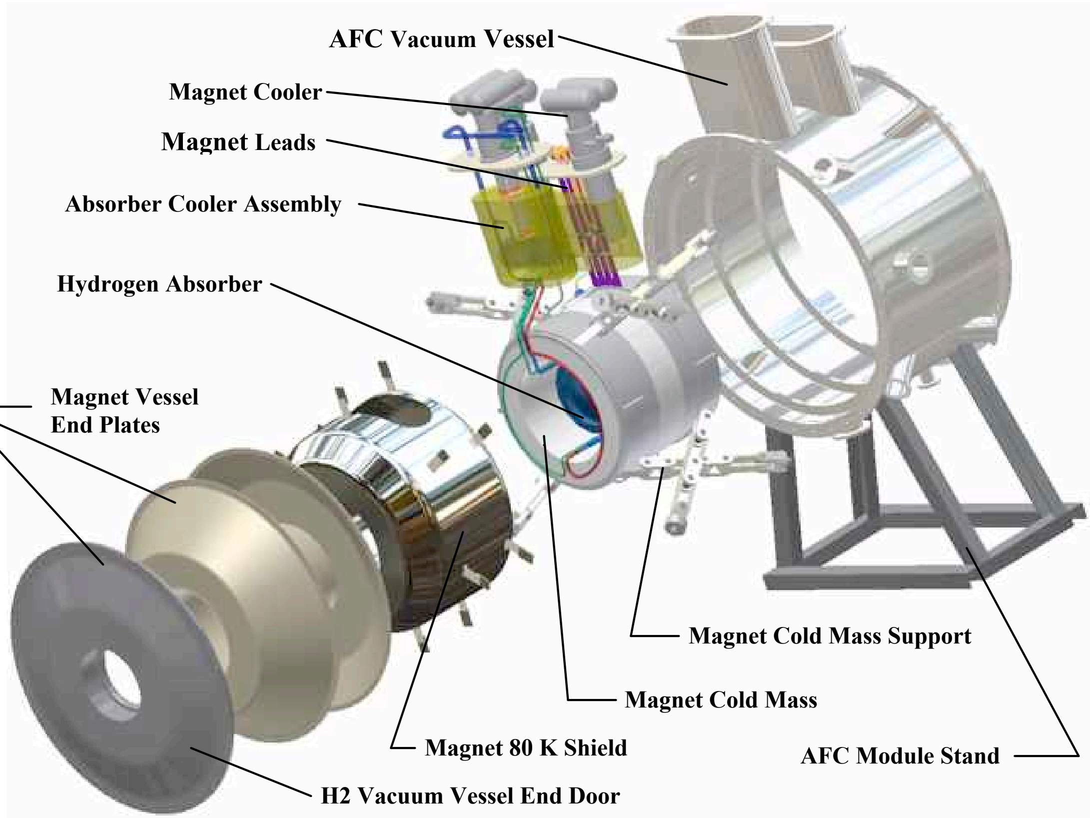

Fig. 3. A schematic exploded view of the AFC module showing the magnet, the magnet coolers, the absorber, and the absorber cooler.

When one looks at Table II one sees that the projected first stage heat load on each cooler is about 41 W. If the first stage heat leaks were 41 W, the stage temperature would be <50 K. The heat load calculations suggest that the copper leads are the dominant. This heat leak from 293 K down the copper leads is well understood [12], [13]. While the copper leads represent over sixty percent of the heat load into the first stage, the other heal loads must not be ignored. It is extremely important that the top of the HTS leads be kept below 60 K. Failure to keep the tops of the HTS cold can cause the leads to fail [14].

Heat flow into the 4 K region is directly affected by the temperature of the cold mass support intercepts, the pipe and instrumentation wire intercepts and the top of the HTS leads. If one looks at these three terms in Table II, one sees that sixty-five percent of the 4 K heat loads comes from these sources. Conduction heat loads are proportional to the temperature squared [13]. If the 55 K temperature in Table II is increased to 70 K, the total heat load at 4 K goes up from 1.75 W to 2.46 W w/o considering the extra radiation heating.

The magnet cold mass must be insulated with multilayer insulation (MLI). The MLI protects the cold mass from thermal radiation shine that might occur because of the many holes that will be in the shield. In addition MLI between the shield and the cold mass greatly reduces free-molecular conduction through gas in the vacuum space.

The original magnet design called for the coils to be surrounded by liquid helium. When one combines the magnet with a helium vessel, the pressure vessel code comes into play. As a result, the focusing magnet will be indirectly cooled using helium in tubes attached to the magnet coil cover plates.

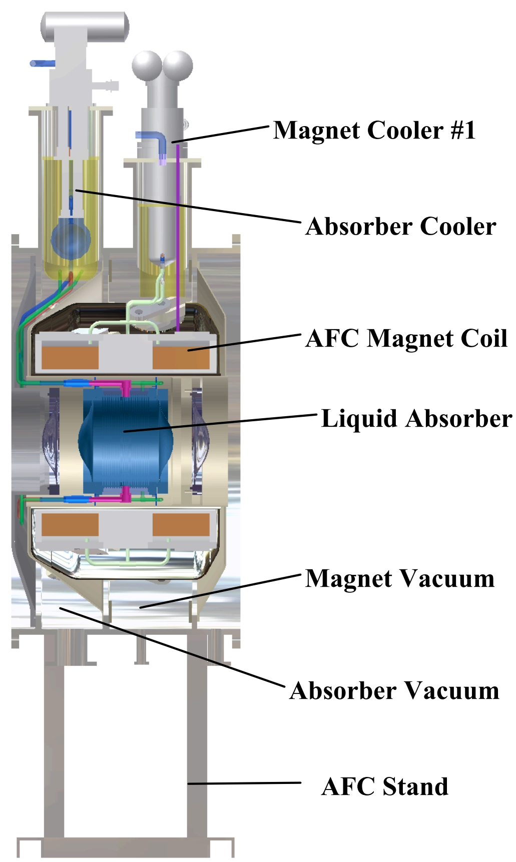

Fig. 4. A cross-section view of the MICE AFC module showing the magnet coils, the liquid absorber, the cryostat vacuum vessel and the coolers.

Fig. 4. is a cross-section of the magnet through the coils, the magnet turret with its coolers and leads. Fig. 4. shows the magnet cryostat vacuum vessel, the absorber vacuum vessel with its safety windows, and the magnet thermal shield. The absorber cooler, its condenser tank, and the absorber piping are also shown in Fig. 4. The magnet as shown in Fig. 1. and Fig. 4. shows bath-cooled coils. The helium bath in Fig. 4. will be replaced by cooled aluminum closure rings indirectly cooled with liquid helium in tubes.

III. Progress on the Focusing Magnets

Construction of the first focusing magnet cold mass has started. The mandrel was fabricated out of a 6061-T6-aluminum forging. The cover plates that cover the coils and contain the magnet cooling are also fabricated out of 6061-T6-aluminum forgings. Fig. 5. shows the machined mandrel for the first focusing magnet. One end of the mandrel is thicker than the other end. The thicker end of the mandrel will be machined to match the other end of the mandrel after the magnet coils are wound and banded. The machined closure rings will be welded to finished coil assembly. The helium cooling tubes that connect the top and bottom helium tanks are welded to the closure. A separate cool down tube will also be attached to the finished cold mass assembly.

Fig. 5. The machined mandrel for the first focusing magnet.

Fig. 6. Focusing magnet closure ring forging.

IV. Conclusion

Tesla Engineering Limited in the UK was selected as vendor for the AFC module in 2007. After a year of detailed engineering by the vendor, fabrication of the focusing magnets has started. The magnet design is based on a conductor with insulated dimensions of 1.0 x 1.57 mm. The number of turns in the focusing magnet changed along with other magnet parameters. The magnet will be indirectly cooled with helium in tubes. The focusing magnet will use a passive quench protection system based on diodes and resistors across the coil. Quench-back from the 6061-T6 aluminum mandrel will cause both coils in the focusing magnet to quench.

The AFC module may be a challenge for cooling with small coolers. There are two pairs of leads designed to carry 250 A in a radial magnetic field that approaches 0.3 T at the top of the HTS leads that are at the highest temperature. Keeping the temperature of the top of the leads at 60 K or lower will be a challenge given the 50 W heat load that will come down the copper leads from room temperature.

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