The Engineering Design of the 1.5 m Diameter Solenoid for the MICE RFCC Modules

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***Abstract*— The RF coupling coil (RFCC) module of MICE is where muons that have been cooled within the MICE absorber focus (AFC) modules are re-accelerated to their original longitudinal momentum. The RFCC module consists of four 201.25 MHz RF cavities in a 1.4 meter diameter vacuum vessel. The muons are kept within the RF cavities by the magnetic field generated by a superconducting coupling solenoid that goes around the RF cavities. The coupling solenoid will be cooled using a pair of 4 K pulse tube cooler that will generate 1.5 W of cooling at 4.2 K. The magnet will be powered using a 300 A two-quadrant power supply. This report describes the ICST engineering design of the coupling solenoid for MICE.**

***Index Terms*—Niobium Titanium, Passive Quench Protection, Superconducting Solenoid**

. Introduction

The muon ionization cooling experiment (MICE) will be located at the Rutherford Appleton Laboratory [1]. MICE consists of a proton target station, a pion collection system, a muon decay channel, and a muon cooling channel with spectrometers at each end. The muon cooling channel contains two spectrometer modules to analyze muons and other particles that enter and leave the MICE cooling channel [2], three absorber focus coil (AFC) modules that focus and ionization cool the muons in an absorber inside the focusing magnet [3], and two RF coupling coil (RFCC) modules that reaccelerate the muons back to their original momentum [4].

The RFCC module consists of a 1.9 m long vacuum vessel that contains four 201.25 MHz RF cavities that are bounded by thin beryllium windows [5]. Each of the cavities is separately powered through an RF coupler. The coupling magnet is located outside of the vacuum vessel that contains the RF cavities. The coupling magnet is a superconducting magnet that produces enough magnetic field (up to 2.2 T on the magnet centerline) to guide the muons and keep them within the iris of the thin RF-cavity windows. Fig. 1 shows an RFCC module of MICE. Shown in Fig. 1 are the RF cavity vacuum chamber, the RF cavities, and the coupling magnet.

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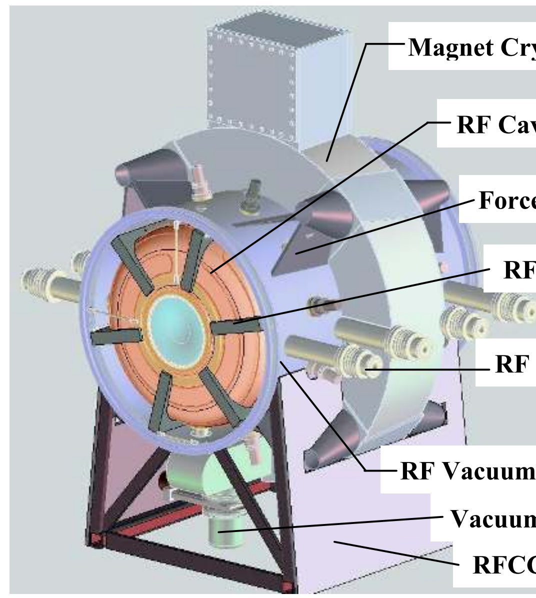

Fig. 1. The RFCC Module showing the RF Cavities, the RF Vacuum Vessel, the Vacuum Pump, The Couplers, a Cavity Tuners and the Coupling Magnet.

I. The MICE Coupling Magnet

The Institute of Cryogenics and Superconductive Technology at the Harbin Institute of Technology in partnership with the Lawrence Berkeley National Laboratory will build the coupling magnets for MICE and the MUCOOL experiment [6] at Fermilab. MICE requires two coupling coils; the 201 MHz RF cavity breakdown and dark current experiment at Fermilab requires a single coupling coil. The three magnets are identical except for the way the magnet cryostats are attached to the stand (see Fig. 1).

The coupling magnet consists of a single superconducting coil that carries up to 3.35 MA-turns [7]. The magnet cryostat is determined by the spacing between the RF couplers of the two center cavities within the RF cavity vacuum vessel. The vacuum pumping ports (see the vacuum pumps at the bottom of Fig. 1) for the RF cavities have the same spacing as the two center RF couplers. The left side of Fig. 2 shows a 3D view of the MICE coupling magnet cryostat. The right side of Fig. 2 shows a top view of the coupling magnet cryostat. The magnet coolers are shown in both views. The magnet cryostat is bounded by the center cavity couplers and vacuum ports. In order to maximize the coupling magnet coil length, the magnet vacuum vessel is designed to fit around the couplers and vacuum pump out ports.

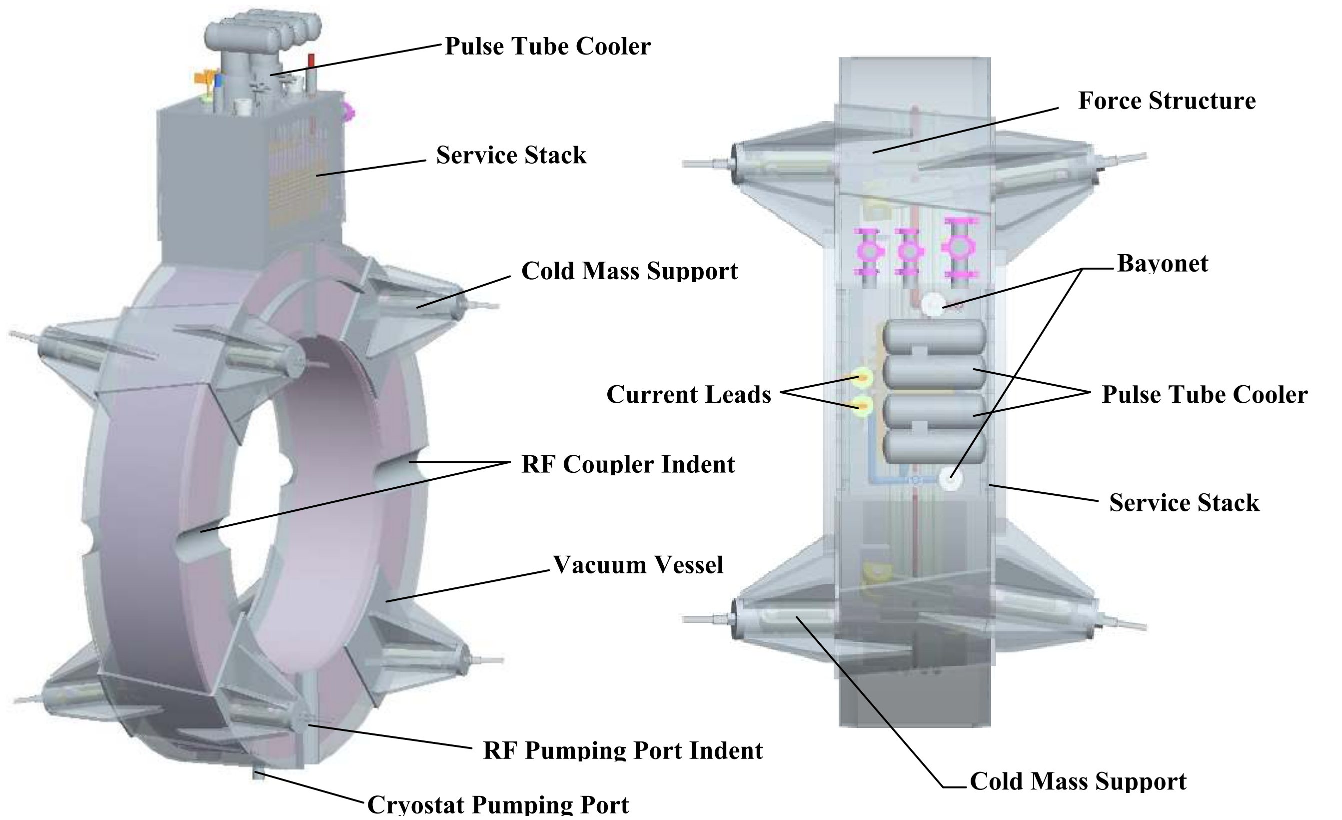

Fig 2. A View of the Coupling Magnet Cryostat. (The left side shows a 3 dimensional view of the magnet cryostat that shows the service stack and the two pulse tube coolers. The right view shows the magnet cryostat from the top. Note; the baseline magnet design is based on the use of two pulse tube coolers.)

Fig. 2 shows the indentations in the coupling magnet cryostat that fit around the 130 mm OD couplers for the two center RF cavities. There is an indentation in the cryostat wall at the bottom of the magnet cryostat that fits around a 130 mm OD vacuum pumping post for the RF cavities and the vacuum space around the RF cavities. The depth of the indentations in the magnet cryostat wall is about 40 mm.

The cryostat shown in Fig. 2 has four cold-mass supports at each end. The 300 K ends of the cold-mass supports are at angles of 45, 135, 225 and 315 degrees with respect to the RF coupler ports. The cold mass supports carry a longitudinal force of 500 kN [8]. This force is transmitted to the ends of the magnet cryostat through a cone shaped structure around the support bands. There is an structure on the cryostat wall to carry the 135 kN longitudinal force between the cold mass supports, that are at the same angular orientation.

Pulse tube coolers will be used to cool the coupling magnet. The reason for selecting a pulse tube cooler is the magnetic field that is present at the magnet service neck [9]. The coolers shown in Fig. 2 have the rotary valve, its motor, and the ballast tanks attached to the cold head that goes down into the service neck for the magnet cryostat. The rotary valve motor for the cooler can be shielded with iron. Alternatively, the valve motor and ballast tanks can be moved p to 1-meter from the cooler cold head assembly. The pulse tube coolers shown in Fig.2 must be oriented vertically with the cold heads in the down position. The position of the magnet coolers and HTS leads is determined by the magnetic field generated by the coupling magnet and the rest of MICE [10, 11].

III. The Coupling Magnet Conductor

The magnet conductor selections depended on a number of factors. First, the maximum current in the coupling magnet is limited to 300 A. Having a larger magnet current is positive from a quench protection perspective. A larger magnet current means that the heat flow into the first stage of the cooler is increased. A larger first stage heat flow translates to a higher first stage temperature and a larger heat leak at 4 K. The quench analysis showed that the magnet will quench safely even at a lower current, so the conductor decision favored reducing the heat leak into both stages of the cooler. A lower current is also better for the HTS leads, which must operate in a magnetic field as high as 0.4 T. The same conductor as used for the tracker magnet was selected [2]. The conductor cross-section is shown in Fig. 3.

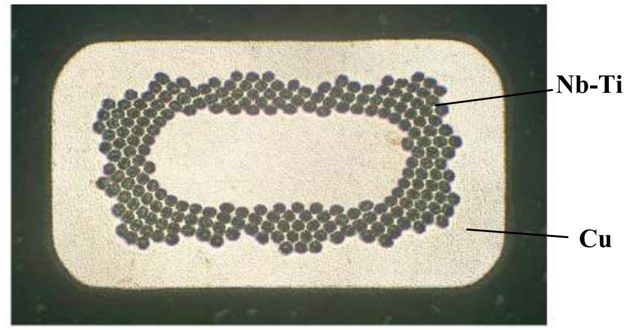

Fig. 3. Coupling Magnet Conductor Cross-section with 222 Nb-Ti Filaments in a Copper Matrix (I_c = 760 A @5 T & 4.2 K).

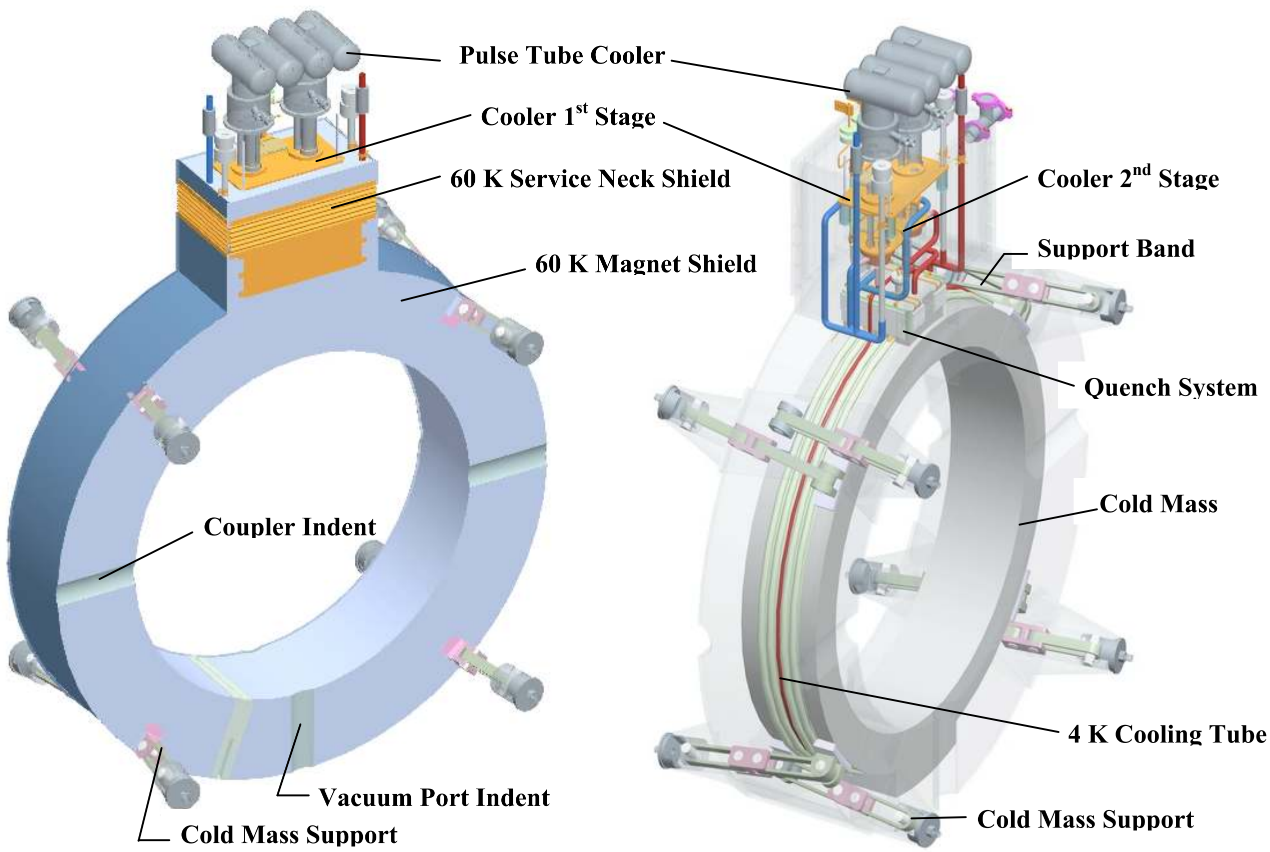

Fig. 4. A 3D View of the Coupling Magnet Cold Mass Assembly and the 60 K Shield Assembly (On the left side of the figure is the magnet cold mass with its Shield. On the right side of the figure is the magnet cold mass. Shown as part of the cold mass assembly are the coolers, the leads, and the cold mass supports.)

The superconductor in the coupling coil conductor is 47 wt percent titanium and niobium. The Nb-Ti has been processed and heat-treated for a $j_c > 2750$ A mm^{-2} at 5 T and 4.2 K. The conductor for the coupling magnet has insulated dimensions of 1.65 mm by 1.00 mm. (The bare dimensions are 1.60 mm by 0.95 mm.) The copper to superconductor ratio is about 4. The nominal RRR for the copper is 70; the conductor n value is greater than 35. The conductor has 222 filaments that are nominally 41 μm in diameter. The nominal twist pitch for the conductor is 19 mm. The I_c is >760 A at 5 T and 4.2 K. Using this conductor, the magnet margin is expected to be >0.8 K when the induction at the high field point is 7.44 T, the current is 210 A, and the cold mass temperature is 4.2 K

IV. The Coupling Magnet Design Parameters

The coupling magnet is the largest of the three types of magnets in MICE both in terms of diameter and stored magnetic energy at full current. The coupling magnet is also the largest magnet in the MUCOOL as well. The coupling magnet is designed to fit around the RF cavity vacuum vessel. The two halves of the RF cavity vacuum vessel will slide into the bore of the coupling magnet and they will be welded together. The force carrying gussets will connect the magnet cold mass supports to the RF cavity vacuum vessel, which in turn will connect to the rest of MICE. Table 1 shows the coupling magnet parameters.

TABLE 1. Coupling Magnet Specifications

Parameter	Flip	Non-flip
Cryostat Length (mm)	489	
Cryostat Inner Radius (mm)	694.4	
Cryostat Thickness (mm)	~390	
Coil Length (mm)	285	
Coil Inner Radius (mm)	750	
Coil Thickness (mm)	102.5	
Number of Layers	96	
No. Turns per Layer	166	
Magnet Self Inductance (H)	592.5	
Magnet J (A mm^{-2})*	114.6	108.1
Magnet Current (A)*	210.1	198.2
Magnet Stored Energy (MJ)*	13.1	11.6
Peak Induction in Coil (T)	~7.40	~7.12
Coil Temperature Margin (K)	~0.8	~1.0

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

Each coupling magnet will be powered using a single two-quadrant power supply with a controlled voltage ±10 V and a controlled current from 0 to 300 A. At the full design voltage of the power supply, the magnet will charge to 210.1 A in about 13140 s (at an average voltage of 9 V). In a rapid discharge mode, the magnet will discharge in about 5400 s.

V. Magnet Quench Protection, Cold Mass Supports, Current Leads, and Cooling

The coupling magnet will be passively quench protected by sub-dividing the coil into eight parts. Each coil sub-division will have a diode and resistor across it. The quench protection diodes will permit the coil to be charged and discharged with as much as 22 V across the coil. The resistors and diodes limit the voltages to ground to <2000 V and the layer-to-layer voltages to within the coil to <320 V. Quench back in combination with coil sub-division ensures that the hot spot temperature in the coil will be <120 K. The coupling magnet quench protection system details are described in [12].

The coupling magnet will use an oriented tension band support system similar to the support bands used in helium cryostats used for MRI magnets and in long life helium tanks used in space. The use of tension bands ensures that the heat flow into the coil cold mass will be minimized. The cold mass supports for the coupling magnet are described in [13].

The current into the coupling magnet will enter the magnet through a pair of 220 A leads. The lower part of the leads will be HTS leads. The upper leads will be conduction cooled copper leads. The heat flow down these leads is carried to the first stage of the magnet coolers. The performance of the HTS leads is affected by the magnetic field in the region between the first and second stages of the magnet coolers [10]. The leads and the connection of the leads to the magnet cooling system are described in [13].

Figures 2 and 4 show a pair of pulse tube coolers on the magnet service neck. It is assumed that the coolers will be Cryomech PT415 pulse tube coolers that generate 1.5 W at 4.2 K and 40 W at 40 K. It is expected that the magnet can operate while fully charged on a single cooler. The second cooler will be needed to cool the magnet while charging. The use of two PT410 (1.0 W at 4.2 K with 40 W at 40 K) is also an option. The coolers will be connected to the magnet using a thermal-siphon loop [14]. The details of the coupling magnet cooling system are described in [13]. Table 2 shows the expected temperature and heat loads when the magnet is operated on two PT415 coolers.

TABLE II. PROJECTED COUPLING MAGNET HEAT LOADS

Source of the Heat Load	**Heat Load (W)**	
	1st Stage	**2nd Stage**
Cold Mass Support	3.0	0.2
MLI Radiation Heat Load	~8.5	~0.7
Pipes and Necks	6.0	0.14
Instrumentation Wires	1.0	0.12
Heat Shield Supports	1.0	----
Current Leads	19.3	0.13
Superconducting Joints	----	0.01
Total Stage Heat Load (W)	38.8	1.30
Stage Temperature (K)	~40	~4.05

VI. Concluding Comments

The MICE and MUCOOL coupling solenoid magnets have a maximum stored energy of 13.1 MJ. These magnets will operate at currents at or below 210.1 A, so the magnet self-inductance is high. The design of the passive quench protection system is dictated by the magnet self-inductance and stored energy.

The magnets will be cooled using 4.2 K pulse tube coolers. This choice of cooler is dictated by the magnetic field outside of the solenoid. Because the magnets will be cooled using small 4.2 K coolers, they must be engineered so that the heat leak into both stages of the cooler is minimized.

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