Title

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The Helium Cooling System and Cold Mass Support System for the MICE Coupling Solenoid

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Abstract—**The MICE cooling channel consists of alternating three absorber focus coil module (AFC) and two RF coupling coil module (RFCC) where the process of muon cooling and reacceleration occurs. The RFCC module comprises a superconducting coupling solenoid mounted around four conventional conducting 201.25 MHz closed RF cavities and producing up to 2.2T magnetic field on the centerline. The coupling coil magnetic field is to produce a low muon beam beta function in order to keep the beam within the RF cavities. The magnet is to be built using commercial niobium titanium MRI conductors and cooled by pulse tube coolers that produce 1.5 W of cooling capacity at 4.2 K each. A self-centering support system is applied for the coupling magnet cold mass support, which is designed to carry a longitudinal force up to 500 kN. This report will describe the updated design for the MICE coupling magnet. The cold mass support system and helium cooling system are discussed in detail.**

Index Terms—**Accelerator RF systems, magnetic devices, Superconducting magnet, cooling,**

I. INTRODUCTION

THE muon ionization cooling experiment (MICE) will be a demonstration of muon cooling in a configuration of superconducting solenoids and absorbers that may be useful for a neutrino factory [1]. The MICE cooling channel consists of alternating three absorber focus coil module (AFC) and two RF coupling coil module (RFCC) [2][3]. The RFCC module comprises a superconducting coupling solenoid magnet mounted around four conventional conducting 201.25 MHz closed RF cavities bounding by thin beryllium windows [4]. Ionization cooling occurs when there is a net loss of transverse muon momentum when the muons pass through the absorber material in the AFC module. The longitudinal momentum of muon beam is then recovered by accelerating the beam with the adjacent four cell 201.25 MHz RF cavity that is in a 2.2T magnetic field generated by the coupling magnet. The beam emittance before and after cooling will be measured in the tracker modules at each end of the channel [1]. A function of the coupling coil magnetic field is to produce a low muon beam
beta function in order to keep the beam from expanding beyond the edge of the RF cavity thin windows.

The engineering design of the MICE coupling magnet was carried out by the Institute of Cryogenics and Superconductivity Technology (ICST) in the Harbin Institute of Technology (HIT) in collaboration with the Lawrence Berkeley National Laboratory since December, 2006 [5]. ICST will fabricate the two coupling magnets for MICE and the third identical magnet for MUCOOL. MUCOOL is one program which is undertaken by the US Neutrino Factory and Muon Collider Collaboration to study the behavior of muon ionization cooling channel components [6]. The MUCOOL coil is necessary to pursue the R&D work on the performance of high gradient, large size RF cavities immersed in magnetic field. This is one of the main challenges in the practical realization of ionization cooling of muons, since no accelerator has ever worked with cavities operated under these conditions. The gradient that can be achieved under magnetic field is one of the important inputs in the optimisation of neutrino factory (and muon collider) design. This report will describe the updated design for the MICE coupling magnet.

II. THE MICE COUPLING MAGNET

The MICE coupling magnet consists of a single 285mm long superconducting solenoid coil. The coil is wounded on a 6061-T6-aluminum mandrel that is fit into a cryostat vacuum vessel [5]. The coil is made from a commercial copper matrix niobium titanium conductor originally used for MRI magnets. The inner radius of the coil is 750 mm and its thickness is 102.5 mm at room temperature. The coil assembly comprises the coil with electrical insulations and epoxy, and the coil case made of 6061-T6-Al including the mandrel, end plates, banding and cover plate, as shown in Fig.1. The bobbin, the end plates and the cover plate are respectively 13 mm, 19 mm and 15 mm thick. The length of the coil case is 330 mm.

As shown in Fig.2, the size and shape of the coupling magnet is determined by the RF cavities. The magnet cryostat is bounded by the center two cavity couplers and vacuum ports. In order to maximize the coil length, the magnet vacuum vessel has to be designed to fit around the RF cavity couplers, tuners and vacuum pump out ports [5] [7]. There are indentations at different locations on the vacuum vessel to fit in the 130 mm OD coupler tubes and the cavity vacuum pumping ports. The radius of the coupling magnet warm bore is about 694 mm, and the overall length of its vacuum vessel is 489 mm.

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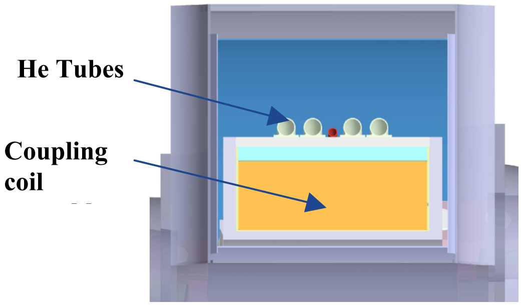

Fig. 1. Cross section of the coupling magnet cryostat

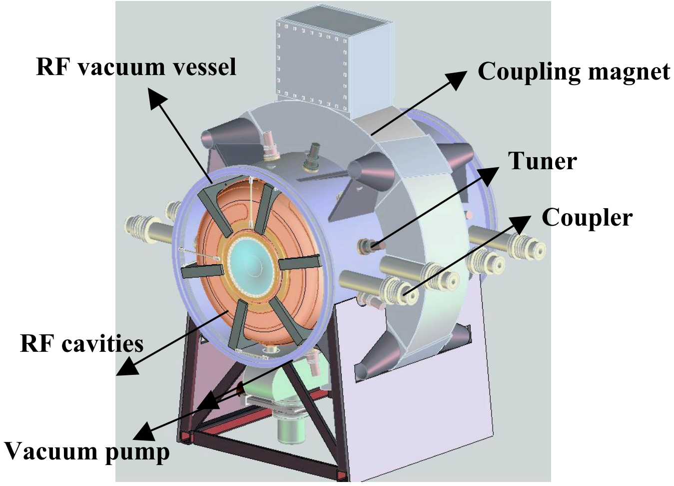

Fig. 2. The RFCC Module showing the RF Cavities, the RF Vacuum Vessel, the Vacuum Pump, the Couplers, Cavity Tuners and the Coupling Magnet

The coupling magnet is designed to operate in the MICE channel where the fields from other magnets can interact with it [8]. It will work in two modes due to the polarity change of two focusing coils in the AFC module. One is gradient mode (flip mode), and the other is solenoid mode (non-flip mode). The worst case is to operate the MICE in the flip mode at the 240 MeV/c average momentum of the muons traveling along the channel and the 420 mm beam beta at the center of the absorbers. The basic parameters for the coupling magnets at normal state of 200 MeV/c are shown in Table I. The performance of the coil conductor is presented in the paper [7]. Fig. 3 shows a 3D view of the MICE coupling magnet cryostat.

The coupling solenoid will be powered by using a single 300A/±10 V power supply that is connected to the magnet through a single pair of leads that are designed to carry a maximum current of 210A. A pair of binary current leads , composed of copper leads and high temperature superconducting (HTS) leads, are to be applied in order to reduce heat leakage around 4.2 K. The coupling magnet is to be passively protected by cold diodes and resistors across sections of coil and by quench back from the 6061 Al mandrel in order to lower the quench voltages and the hot spot temperature [9].

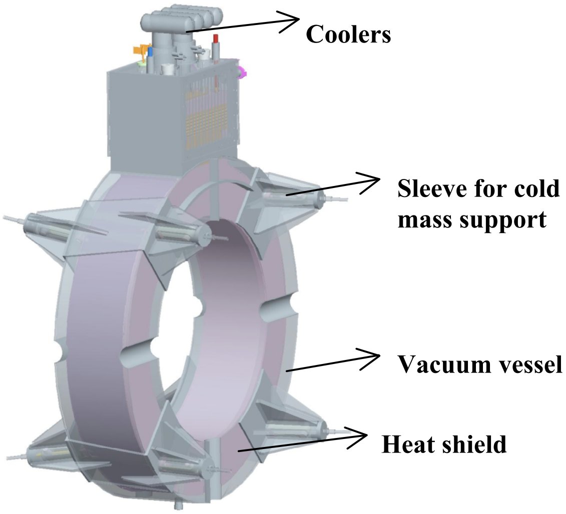

Fig. 3. The MICE coupling magnet cryostat

TABLE I COUPLING MAGNET SPECIFICATIONS

Parameter	Flip	Non-flip
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)	95.53	90.11
Magnet Current (A)	175.1	165.2
Magnet Stored Energy (MJ)	9.08	8.08
Peak Induction in Coil (T)	6.19	5.84
Coil Temperature Margin (K)	~1.69	~1.87
Coil Temperature Margin at worst case (K)	~0.79	~1.1

* based on $p = 200$ MeV/c and $\beta = 420$ mm

III. THE HELIUM COOLING SYSTEM

The coupling magnet is to be cooled by two-stage cryocoolers [10]. Because the temperature margin in the coupling magnet is relatively low (only 0.8K) at its full design current in the flip mode at p = 240 MeV/c and b = 420 mm, the key for the coil cooling is to minimize the temperature drop between the second stage cold head of cooler and the hot spot in the magnet. The coil cooling circuit must be arranged as a thermal siphon cooling system [10].

There are two approaches to cool the coupling coil [5]. One is directly immersing the coil in liquid helium contained in a helium vessel made of the mandrel and the cover plate. The other is indirectly cooling the coil by liquid helium flowing in extruded cooling tubes attached to the outer surface of the coil case. The two cooling schemes were numerically compared for the coupling coil by using FEA method [5]. The analyses show that the peak stress in the coil case is about 160 MPa, which is dominated by thermal stress during cool down.

The coil case can not be used as a pressure vessel because the peak stress is higher than allowable stress (e.g. for 6061 T6 aluminum >80 MPa). Therefore, ICST proposes to cool the coupling coil using extruded tubes attached to the magnet case. The calculated peak stress in the coil case should be acceptable since the magnet case isn't used as a pressure vessel.

The coupling coil cooling system is shown in Fig. 4, which consists of cryocoolers and helium re-condensers, piping system for cool down and normal operation, liquid helium buffer tanks and safety device.

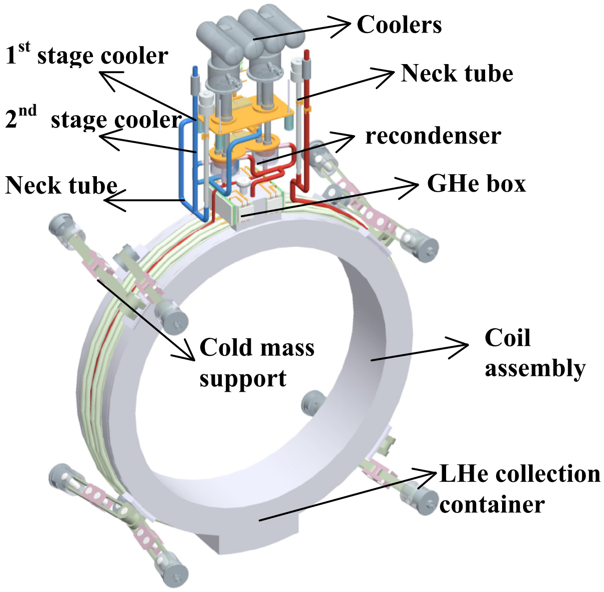

Fig. 4. The MICE coupling coil cooling system

For each coupling solenoid, two 1.5W/4.2K pulse tube cryocoolers are proposed by ICST to provide the refrigeration in terms of possible heat loads in the magnet. The first stages of the coolers will provide the cooling for radiation shields, warm ends of HTS leads, cold ends of copper leads and thermal intercepts for cold mass supports, neck tubes and instrumentation wires. The second stages of the coolers will be connected to condensers that re-liquefy the helium in the magnet cryostat after the cooling circuit has been filled with liquid helium. The cold ends of HTS leads are also flexibly connected to the second stages.

As shown in Fig.4, the liquid helium from the bottom of a re-condenser enters a LHe collection container at the bottom of the cold mass along a supply pipe with 12 mm ID, and then is delivered into four extruded tubes at each side with 24 mm ID welded on the outside of the coil case. The liquid helium in tubing is heated and boils off along the cooling path by conduction. The boil off helium gas is then gathered into a box at the top of the cold mass, and then fed back to the condenser through a separated pipe.

For cool down and off normal operations, there are two neck tubes with thermal intercepts connected to the first stage of the cooler. The entrance pipe for cryogens is connected to the magnet at the bottom and at one end of the magnet. The vent pipe is connected to the upper side of the helium condenser, and then goes to the first-stage cold head where it is coiled and attached to the cold head or thermal shields close to the warm end of HTS leads [5]. The two neck tubes are connected to the outside of the cryostat by two bayonets, respectively. The neck tubes serve as quench vent lines as well.

The temperature drop between the hot spot in the magnet and the cooling tube inner surface was studied using FEA for steady operating state and unsteady states such as charging and rapid discharging process [5]. Table II and III list the calculated temperature drops and AC losses induced by the coil and the coil case as a function of time for a coil charge time of 13860 second (based on a charge at the full voltage delivered by the power supply) and a rapid discharge with a time constant of 3600 seconds (based on a peak voltage across the coil of 33.6 V when a resistance of 0.16 ohms is put across the coil at the power supply). Table 4 shows the estimated heat loads for the magnet at normal operation [5].

The FEA analyses show the temperature difference of 0.082K is acceptable for normal operation. The hot spot in the magnet is at the high field point in the coil winding

From the tables, it can be concluded that the coupling coil can be charged at the full voltage of the power supply, if there are two coolers used or if 5 to 6 liters of liquid helium is boiled away during the coil charging process. The coil can be rapidly discharged in an hour using a variable resistor that puts about 34 V across the coil. About 8 liters of liquid helium will boil away in the process. The sensible heat from the boiled helium can be used to ensure that the top of the HTS leads is kept cold enough to prevent them from going normal. Another approach is to add cold sink mass for preventing the HTS leads from burning out in case of any failure modes [10].

TABLE II TEMPERATURE DROP AND AC LOSS WITH TIME DURING CHARGING PROCESS

Time (s)	AC loss (W)	ΔT(K)
1733	1.698	0.225
5198	1.001	0.14
8663	0.678	0.1
12127	0.528	0.082

TABLE III TEMPERATURE DROP AND AC LOSS WITH TIME DURING RAPID DISCHARGING PROCESS

Time (s)	AC loss (W)	ΔT(K)
450	2.80	0.221
1350	3.39	0.292
2250	4.64	0.438
3150	7.34	0.739

The only part that is sensitive to the magnetic field for the pulse tube cooler is the rotary slide valve drive motor. The field in the motors is between 0.16 T and 0.20 T, perpendicular to the axis of the motor. The motor can be locally shielded for operation in the field up to 0.5 T. If not shielded, it can also be moved to a location up to 1 meter from the rest of the cold head assembly, but the cooler capacity is reduced about 10 percent [11]. The field in the space of 1 meter distance away from the cold head assembly is lower than 0.05T, which is acceptable for the motor.

TABLE IV 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	8.54	0.71
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)	38.84	1.31
Stage Temperature (K)	~40	~4.05

IV. THE COLD MASS SUPPORT SYSTEM

The coupling magnet cold mass support is a self-centering support system so that the magnet center does not change as the magnet is cooled down from 300K to 4.2K [12].

The support system for the MICE coupling magnet must withstand the forces put on the magnet during a quench or a fault as well as when the MICE channel is normally operated besides its weight. The forces imposed on the coupling coils were analyzed by using FEA method [5]. According to the calculations, the peak longitudinal load on the coupling magnets happens when one coupling coil's leads reverses in the flip mode at 240MeV/c, and the peak value is 416.4 kN, towards the channel center. The support system is designed to carry a longitudinal force up to 500 kN (50 tons) in either direction, and the radial force of 58.5 kN. Its spring constant is 4.8x 10^7 N/m, and the resonance frequency is larger than 20 Hz.

The self-centering cold mass support system consists of eight support strap assemblies, four at each end of the magnet. Each support strap assembly consists of two oriented fiberglass epoxy support bands with attachment hardware at each end and an intermediate temperature intercept between the two bands. The nominal length for the warm and the cold tension bands are respectively about 220 mm and 289 mm. Each band has a width of 40 mm and a thickness of 7.5mm. The intermediate temperature intercept is tied to the first stages of the coolers. The tension force along one support strap assembly is about 127 kN. The interception temperature is expected to be between 50 K and 60 K. The warm ends of the cold mass supports will be near the vacuum vessel ends at azimuthal angles of 45, 135, 225, and 315 degrees. The cold ends will be at the same angles but off by plus or minus several degrees toward the mid-plane.

The 3-D view of the cold mass support system is shown in Fig. 4. The cold mass support clevis will be fabricated from 6061-T6-aluminum and welded to the outside of the cold mass. The thermal intercept section between the support bands will be fabricated from 304 or 316 stainless steel. The room temperature end of the support system will be mounted on the vacuum vessel through a stainless steel sleeve enforced by ribs.

The calculated heat leak for one cold mass support is 0.022 W from 60 K to 4.2 K, and 0.354 W from 300K to 60K. Therefore, the total heat leak down the eight cold mass supports is about 0.176 W from 60 K to 4.2 K, and 2.832 W from 300K to 60K.

V. CONCLUDING COMMENTS

The engineering design of the MICE coupling magnet was carried out by the Institute of Cryogenics and Superconductivity Technology (ICST) in the Harbin Institute of Technology (HIT) in collaboration with the Lawrence Berkeley National Laboratory. The coupling magnet was proposed to be cooled through extruded tubes attached to the coil assembly by two 1.5W/4.2K coolers in terms of analyses on the heat loads and temperature margin, and considering effect of stray magnetic field on the cooler performance. The self-centering cold mass support system was applied and designed for the coupling magnet, which is capable of carrying a longitudinal force up to 500 kN.

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