PROGRESS ON THE COUPLING COIL FOR THE MICE CHANNEL

M. A. Green, D. Li and S. L Vorostek, Lawrence Berkeley Laboratory, Berkeley CA 94720, USA;
W. Lau, H. Witte, and S. Q. Yang, Oxford University Physics Department, Oxford OX1-3RH, UK;
and Y. Ivanyushenkov, CCLRC/RAL/ASTeC, Chilton, Didcot, OX11-0QX, UK

Abstract— This report describes the progress on the coupling magnet for the international Muon Ionization Cooling Experiment (MICE). MICE consists of two cells of a SFOFO cooling channel that is similar to that studied in the level 2 study of a neutrino factory [1]. The MICE RF coupling coil module (RFCC module) consists of a 1.56 m diameter superconducting solenoid, mounted around four cells of conventional 201.25 MHz closed RF cavities. This report discusses the progress that has been made on the superconducting coupling coil that is around the center of the RF coupling module. This report describes the process by which one would cool the coupling coil using a single small 4 K cooler. In addition, the coupling magnet power system and quench protections system is also described.

INTRODUCTION

The development of a muon collider or a neutrino factory requires that beams of low emittance muons be produced. A key to the production of low emittance muons is muon cooling. A demonstration of muon cooling is essential to the development of muon accelerators and storage rings [1]. The international Muon Ionization Cooling Experiment (MICE) will be a demonstration of muon cooling in a configuration of superconducting magnets [2] that may be useful for a neutrino factory.

Ionization cooling of muons means that muons have their momentum reduced in both the longitudinal direction and the transverse direction by passing them through a low Z absorber. RF cavities are used to re-accelerate the muons to their original longitudinal momentum. This report deals with the superconducting solenoid that is part of the RF coupling module (the RFCC module) [3].

MICE AND THE RFCC MODULE

The proposed MICE experiment will test cooling on a low intensity muon beam generated on a plunging target in the proton bem in the ISIS ring at the Rutherford Appleton Laboratory in the United Kingdom. Once the muons have been produced the beam is conditioned to produce muons with the proper emittance before.

In the first detector module muon emittance will be measured using four planes of scintillating fibers that are within a uniform solenoidal field (uniform to about 1 percent) that has an induction from 2.8 to 4 T [4].

Once the emittance of the muon beam entering the cooling section has been measured, the beam passes into the first absorber focus coil module (AFC module) [5]. The absorber cools the muon beam (reduces both the transverse and longitudinal momentum) by ionization cooling.

The muon beam is reaccelerated to provide longitudinal momentum to the muon. This reacceleration process occurs in the RFCC module. The acceleration process occurs in the RF cavities, which are in a 2.5 T solenoidal magnetic field that is generated by the coupling solenoid that is around the RF cavity. A three-dimensional view of an RFCC module for MICE is shown in Figure 1. The superconducting coupling magnet shown in Figure 1 surrounds a four cell 201.25 MHz RF cavity. In order to improve the acceleration gradient within the RF cavity, the end of the cavity thin beryllium windows terminate cells. The then beryllium windows on the cavity do not contribute significantly to muon scattering even though they have a higher z than the absorber material.

The MICE cooling channel consists of three AFC modules separated by two RFCC modules. At the end of the cooling channel, the longitudinal momentum of the muon is supposed to be the same as for those muons that entered the cooling channel from the first detector module. Since the acceleration and ionization cooling cannot be perfectly matched, the beam leaving the cooling channel may have a different longitudinal momentum from the beam entering the cooling channel.

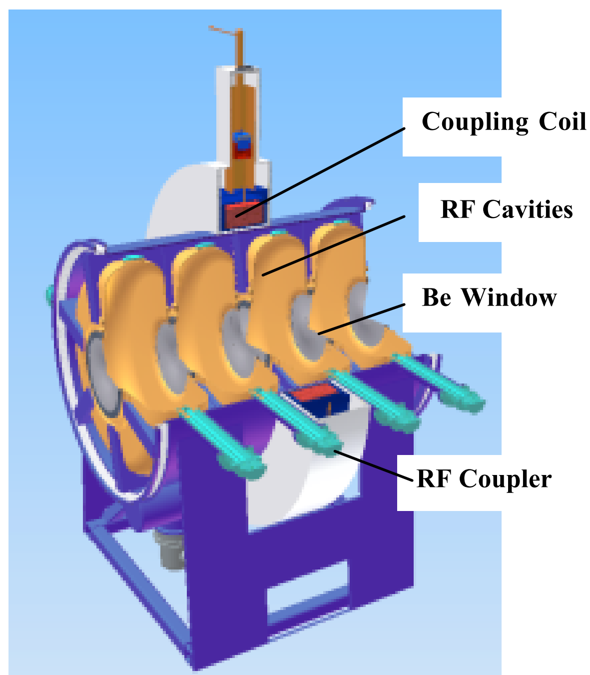

Figure. 1. A Three-dimensional View of the AFC Module

The second detector module measures the emittance of the muon beam after it has passed through the cooling channel. The cooling (or heating measured in MICE is a function of the emittance change measured by the two detector modules.

THE COUPLING MAGNET DESIGN

The MICE coupling magnet is a single 250-mm long coil wound on a 6061-T6-aluminum mandrel [6]. The length of the coupling magnet is determined by the space between the RF couplers for the four RF cells (See Fig 1). As a result, the length of the coil cryostat must be less than 400mm. The total length of the cold mass package (while warm) is 290 mm. The cold mass inner radius is 712 mm, and the cold mass outer radius is about 875mm. The 6061 aluminum mandrel its aluminum cover, and the superconducting coil carry the magnetic forces when the magnet operates over a range of currents. The worst-case net force on the cold mass support can be as large as 500 kN (50 metric tons) in the longitudinal direction. A cross-section view of half of the coupling magnet is shown in Figure 2. Figure 2 shows the basic dimensions of the magnet.

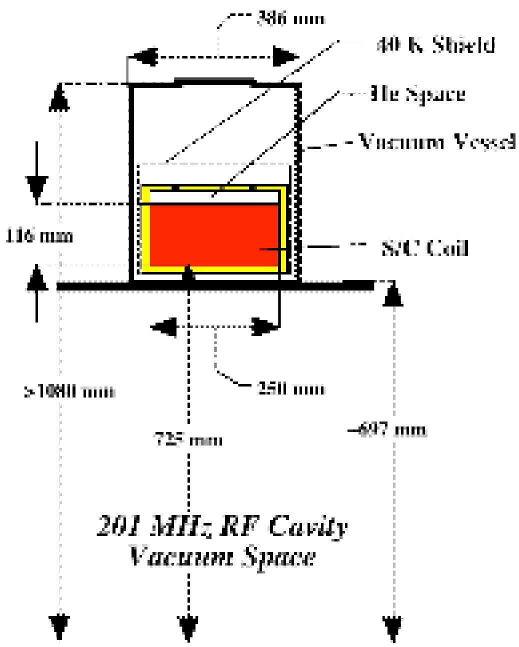

Figure 2. A Cross-section View of One Half of the Coupling Magnet Showing the Magnet Dimensions

Table 1. Design Parameters for the Coupling Magnet

Parameter	
Coil Length (mm)	250
Coil Inner Radius (mm)	725
Coil Thickness (mm)	116
Number of Layers	104
No. Turns per Layer	151
Magnet J (A mm^{-2})*	115.5
Magnet Current (A)*	213.2
Magnet Self Inductance (H)	563
Peak Induction in Coil (T)*	7.81
Magnet Stored Energy (MJ)*	12.8
4.2 K Temp. Margin (K)*	~0.6

* Design based on p = 240 MeV/c and beta = 420 mm

Figure 3 compares the magnet load lines for the focusing magnet and the coupling magnet in the flip mode. Table 1 shows the basic parameters of the MICE coupling magnet operating at the highest current and field case for the MICE. Despite having very different load lines, the temperature margin for the coupling magnet is nearly the same as for the focusing magnet at 4.2 K [5].

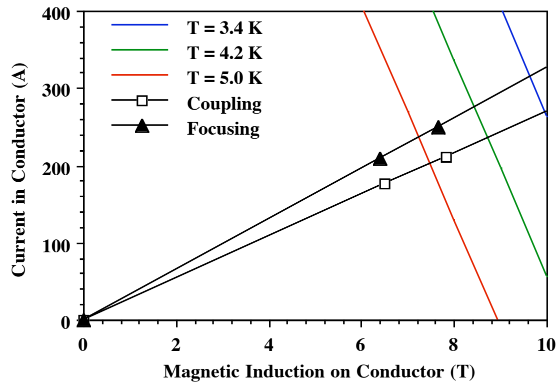

Figure 3. Load Lines for the MICE Focusing and Coupling Magnets in the Flip Mode. (The higher current points apply to p = 240 MeV/c. The lower current points are for 200 MeV/c.)

The coupling magnet uses the same conductor as the focusing magnet [5]. The coupling magnet stored energy is quite high for a magnet that uses this conductor [6]. Because the coupling magnet has a high stored energy, the magnet must operate at a lower current than the focusing magnet. The coupling magnet will be protected by cold diodes across sections of coil and by quench back from the 6061 aluminum mandrel. Because of the quench protection system used, the two coupling magnets may be hooked up in series. We shall see later in this report that this may not be advisable.

COOLING THE MAGNET WITH A COOLER

The MICE coupling magnets will be cooled using a single (1 to 1.5 W) 4.2 K cooler [7]. The dominant heat load in the cooler first stage is the two 300 A copper current leads. About forty percent of the heat leak into the 4.2 K region from the first stage temperature is down the two HTS leads that are connected to the room temperature current leads. The HTS leads are an enabling technology that permits 4.2 K magnets to be continuously powered.

Because the temperature margin in the coupling magnet is quite low, it is important to minimize the temperature rise from the cooler second stage cold head and the hot spot in the magnet. First one must reduce the temperature rise within the magnet by applying the cooling evenly over the outside surface of the magnet [6]. Second, one must reduce the temperature drop from the point where the cooling is applied to the magnet surface and the cooler second stage cold head. The best approach is to apply cooling to the outside surface of the coupling coil by immersing it in a bath of liquid helium. The same liquid helium can also be an integral part of the gravity feed heat pipe that delivers the heat from the helium around the magnet to the cold head. Unlike conducting heat in a copper strap, the temperature drop along the heat pipe is low (<0.2 K) and independent of the distance between the cooler cold head and the magnet [7].

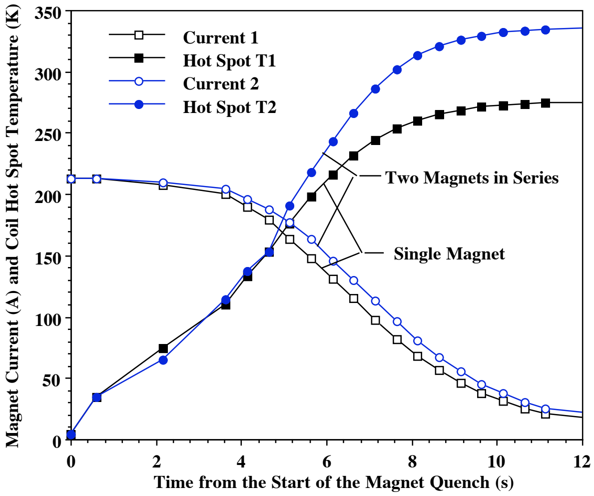

Figure 4. The coupling Magnet Current and Hot Spot Temperature as a Function of Time from Quench Start for a Single Magnet and Two Magnets in Series in the Flip Mode

Table 2. The Basic Quench Characteristics of the Focusing Magnet Operating at Peak Current in the Flip Mode

Parameter	
Maximum Current (A)	213.2
Conductor Current Density (A mm^{-2})*	154.5
Magnet Self Inductance (H)	563
Magnet Stored Energy (MJ)*	12.8
E J^2 at Maximum Current (J A^2 mm^{-4})*	3.06x10^{23}
Quench Velocity along Wire (m s^{-1})	4.0
Coil Average Radius (mm)	783
Coil Thickness (mm)	116
Coil Length (mm)	250
Time Constant for a Safe Quench (s)	10.09
Nominal Quench Back Time (s)	2.17

* Design based on p = 240 MeV/c and beta = 420 mm

POWER SUPPY AND QUENCH PROTECTION

It has been proposed that the two coupling magnets be powered in series. There are two questions that must be asked: 1) Can the coupling magnet be quench safely using only passive quench protection? 2) Can both coupling magnet be connected in series on a single power supply. From Figure 4, one can conclude that the answer is yeas to both questions, however because of the high stored energy and long quench back time, two magnets in series will result in a larger hot spot temperature at the point of the quench [8].

Sub –division of the coupling magnet using cold diodes and resistors will result in lower quench voltages and a lower hot spot temperature even when the magnets are in series. The concept of sub-dividing the magnet with cold diodes and resistors is illustrated in Figure 5. The sub-division method shown in Figure 5 has been applied in large stored energy MRI magnets. The primary argument for not connecting the coupling magnets in series is the long time needed to charge the magnet pair using a single 10 V power supply.

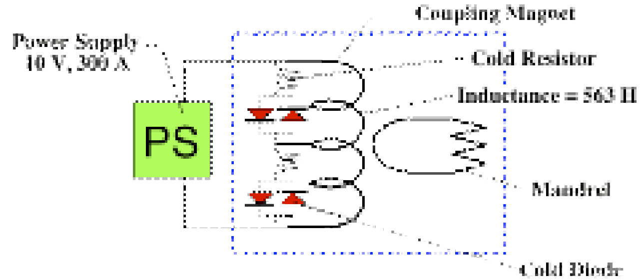

Figure 5. The Circuit Diagram for a Single Coupling Magnet

CONCLUDING COMMENTS

The coupling magnets for MICE can be built using commercial niobium titanium MRI conductors. The size diameter of the coupling magnet is determined by the diameter of the 201.25 MHz RF cavities and the vacuum vessel that must go around the cavities. The length of the coupling magnet is determined by the space between the cavity RF couplers and the cavity tuners.

The coupling magnet is designed to be cooled using a single of two-stage cooler that produce up to 1.5 W at 4.2 K. The connection of the cooler to the magnet is designed to maximize the coupling magnet operating temperature margin.

The coupling magnet will quench safely without quench protection. The two coupling magnets can be connected in series, but separate power supplies for each magnet will result in a shorter charging time for the coupling magnets.

ACKNOWLEDGEMENT

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