PROGRESS ON THE COUPLING COIL FOR THE MICE CHANNEL

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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. 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 protection system are also described.

INTRODUCTION

The proposed MICE experiment will test cooling on a low intensity muon beam generated from a target in the proton beam in the ISIS ring at the Rutherford Appleton Laboratory in the United Kingdom [1], [2]. MICE consists three sections: two spectrometer sections and the cooling channel that is between them. The MICE cooling channel consists of the three absorber focus coil (AFC) modules separated by two RF coupling coil (RFCC) modules, as shown in Figure 1.

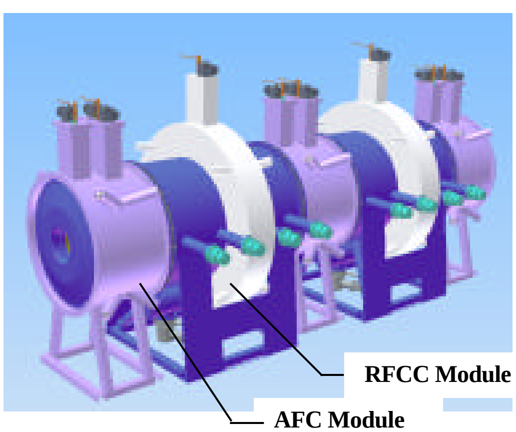

Figure 1. The MICE cooling channel.

The RFCC module consists of four RF cavities that are surrounded by a vacuum vessel and a superconducting coupling solenoid [3]. This report describes the operating and quench parameters of the RFCC coupling solenoid, which is around the two center cavities.

THE RFCC MODULE

The RFCC module consists of four 201.25 MHz RF cavities that are in a 2.5 T solenoidal magnetic field that is generated by the coupling magnet [3]. A three-dimensional view of the RFCC module for MICE is shown in Figure 2. In order to increase the acceleration gradient within the cavity for a given input power to the cavity, the cavity irises have been terminated by thin beryllium windows. 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 420-mm diameter thin windows.

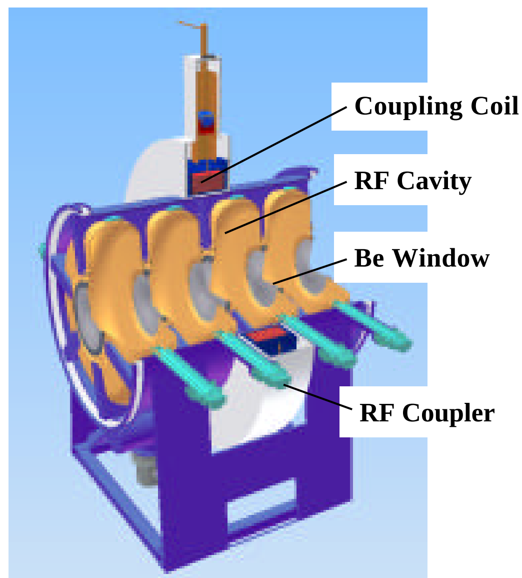

Figure. 2. A 3-dimensional view of the RFCC module.

The RF cavities are evacuated to prevent electrical breakdown at the high acceleration gradients. The cavity vacuum and the MICE vacuum outside of the cavity are interconnected to prevent a differential pressure across the RF windows. The MICE vacuum is separated from the magnet vacuum, in order to prevent contamination of the RF vacuum by volatile components from the magnet insulation.

THE COUPLING MAGNET DESIGN

The MICE coupling magnet is a single 250-mm long coil wound on a 6061-T6-aluminum mandrel [4]. The length of the coupling magnet cryostat is determined by the space between the RF couplers for the center two RF cavities (See Figure 2). As a result, the length of the magnet must be less than 400mm. The length of the cold mass package was set at 290 mm. The cold mass inner radius is 712 mm, and the cold mass outer radius is about 875mm. The 6061-aluminum mandrel, the mandrel cover, and the coil carry the magnetic forces when the magnet operates. The worst-case net force on the cold mass support can be 500 kN (50 metric tons) in the longitudinal direction.

A cross-section view of half of the coupling magnet is shown in Figure 3. Table 1 presents the basic parameters of the coupling magnet while it is operating at its highest possible current in the flip mode [4].

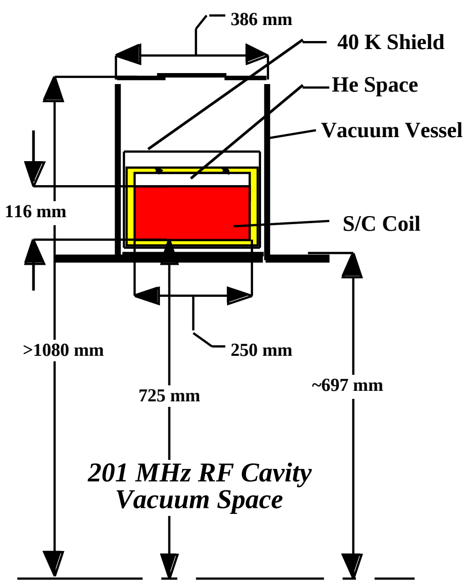

Figure 3. A cross-sectional view of one half of the coupling magnet.

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 β = 420 mm

Figure 4 compares the magnet load lines for the focusing magnet and the coupling magnet in the flip mode. 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].

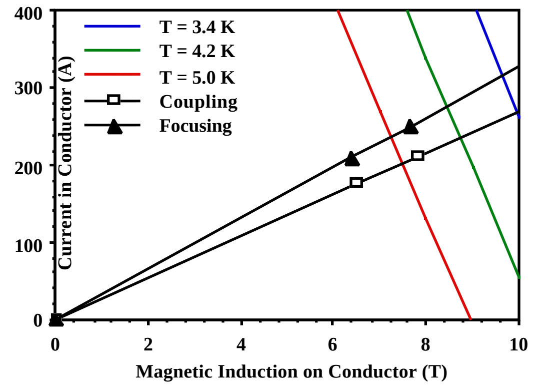

Figure 4. The MICE focusing and coupling magnets load lines in the flip mode. (The higher current points are p = 240 MeV/c; the lower current points are for 200 MeV/c.)

It is anticipated that the coupling magnet will use the same conductor as the focusing magnet [5]. Because the coupling magnet has a high stored energy, the magnet must operate at a lower peak design current than the focusing magnet. The coupling magnet will be protected by cold diodes across sections of coil and by quench back from the 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.

THE MAGNET COOLER

The MICE coupling magnets will be cooled using a single (1 to 1.5 W) 4.2 K cooler [6]. The dominant heat load to 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 cooler first stage 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 while operating on a cooler.

Because the temperature margin in the coupling magnet can be quite low, it is important to minimize the temperature rise between the cooler 2^{nd} stage cold head and the hot spot in the magnet. First one must reduce the temperature rise within the magnet by immersing it in a bath of liquid helium. [6]. Second, one must reduce the temperature drop from the magnet to the cooler 2^{nd} stage cold head. The liquid helium around the magnet can be a part of the gravity feed heat pipe that delivers the heat from the magnet to the cold head. Unlike conducting heat from the magnet to the cooler through 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 [6].

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 magnets be connected in series on a single magnet power supply? From Figure 5 and Table 2, the answer to both questions is yes. Because of the high stored energy and a long quench back time, two magnets in series will have a higher hot spot temperature.

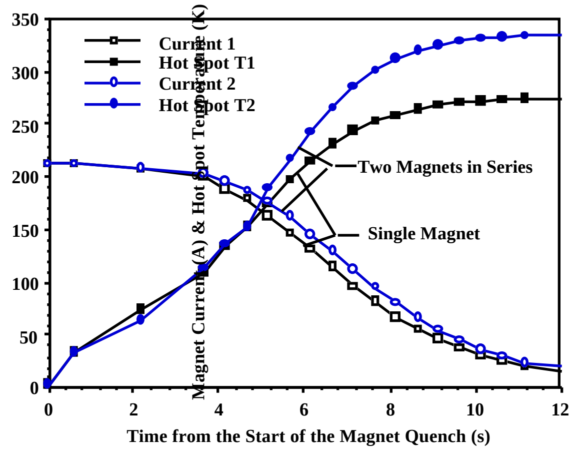

Figure 5. The coupling magnet current and hot spot temperature as a function of the time from the quench start for a single magnet and two magnets in series.

Table 2. Basic Quench Characteristics of the Coupling 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 m^{-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 β = 420 mm

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 6.

The sub-division method shown in Figure 6 has been applied in large stored energy MRI magnets with good results. Even when the magnets are in series with a total circuit stored energy of 25.6 MJ, the magnets will quench safely. The primary argument for not connecting the coupling magnets in series is the long magnet charge time using a single 10 V power supply.

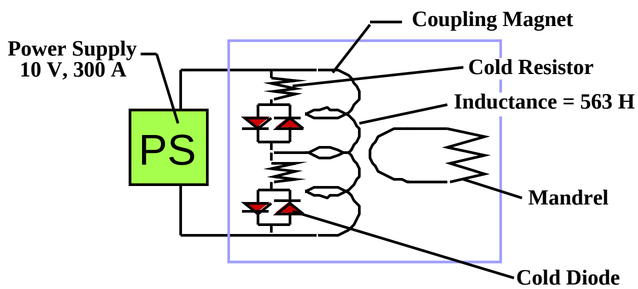

Figure 6. Circuit diagram for a single coupling magnet.

CONCLUDING COMMENTS

The coupling magnets for MICE can be built using commercial niobium titanium MRI conductors. The size and shape of the coupling magnet is determined by the RF cavities.

The coupling magnet is designed to be cooled using a single two-stage 1.0 to 1.5 W 4.2 K cooler. The connection of the cooler to the magnet is designed to maximize the 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 magnets.

ACKNOWLEDGMENT

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