PROGRESS ON THE FOCUS COIL FOR THE MICE CHANNEL

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Abstract— This report describes the progress on the magnet part of the absorber focus coil module 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 absorber focus coil module consists of a pair of superconducting solenoids, mounted on an aluminum mandrel. The coil package that is in its own vacuum vessel is around an absorber. The absorber is within a separate vacuum vessel that is within the warm bore of the focusing magnet. The superconducting focus coils may either be run in the solenoid mode (with the two coils at the same polarity) or in the gradient mode (with the coil at opposite polarity causing the field direction to flip within the magnet bore). The coils will be cooled using a pair of small 4 K coolers. This report discusses the progress on the MICE focusing magnets, the magnet current supply system, and the quench protection system.

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. If the scattering in the absorbing medium is not too large, the reaccelerated muon beam will have a lower emittance than the original beam. In order to reduce the multiple scattering of the muon beam in the absorber, the muon beam beta must be low in the absorber and the absorber must have a low Z. The candidate absorbers include H_2, LiH, Li, or Be. The absorber in MICE is located within the absorber focus coil module where the beam has the lowest beta (is well focused).

MICE AND THE AFC MODULE

The proposed MICE experiment will test cooling on a low intensity muon beam from the ISIS ring at the Rutherford Appleton Laboratory in the United Kingdom. Once the pions have decayed into muons, the muon beam is conditioned to produce muons with the proper emittance before entering the first detector module.

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 [3].

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). The absorber cools the muon beam (reduces both the transverse and longitudinal momentum) by ionization cooling. This report describes the progress that has been made on the two-coil focusing solenoid that surrounds the absorber in the AFC module [4]. The focusing magnet is designed to produce either a relatively uniform field or a cusp shaped field (a solenoidal quadruple field) that changes polarity as one goes along the axis. When the focusing magnet operates in the gradient mode (with both coils at opposite polarity) the field is zero at the magnet center and the center of the absorber. A three-dimensional view of an AFC module for MICE is shown in Figure 1. A cross-section view of the AFC module is shown in Figure 2. The cross-section shows the superconducting coils that surround a liquid cryogen absorber. In MICE a solid absorber can replace the liquid absorber.

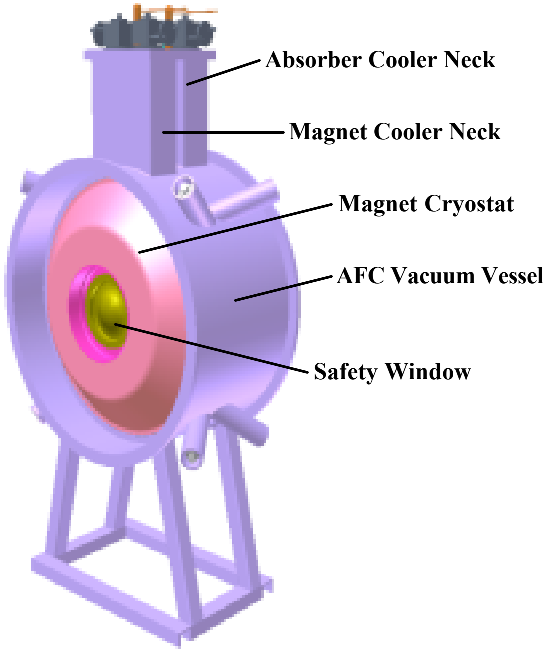

Figure. 1. A Three-dimensional View of the AFC Module

The muon beam longitudinal momentum is recovered by accelerating the beam within the RF coupling coil module (RFCC module) [5]. A four cell 201.25 MHz RF cavity that is in a 2.5T magnetic field accelerates the beam. The MICE cooling channel will consist of three AFC modules that are separated by two RFCC modules

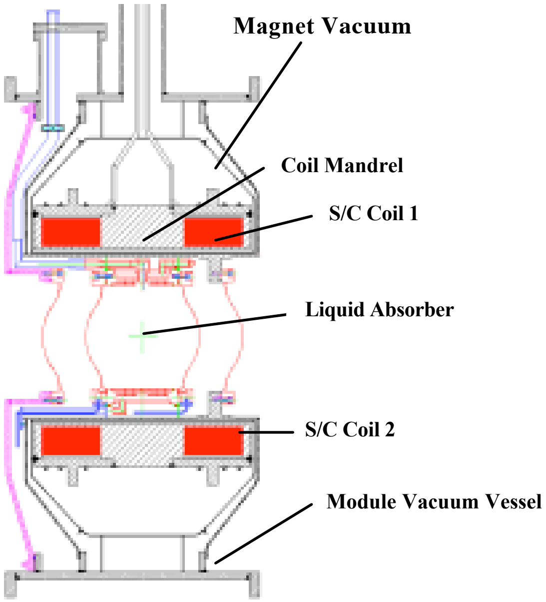

Figure 2. A Cross-section of the AFC Module

Once the beam has passed through the ionization cooling section, it enters the second detector section. The second detector section is identical to the first detector, except for the time of flight detectors at the end of the experiment. If there is cooling the second detector module will measure a lower beam emittance than the first detector module.

THE FOCUSING MAGNET DESIGN

The MICE focusing magnet has two 210 mm long coils wound on a 6061-T6-aluminum mandrel [4]. The mandrel forms the 200-mm long spacer between the coils. The mandrel end flanges are 20 mm thick, so that the total length of the cold mass package (while warm) is 660 mm. The inner bore radius of the cold mass is about 251 mm (at 300 K). The 6061 aluminum mandrel and its covers carry the magnetic forces when the magnet operates in either the solenoid mode or the gradient mode. In the gradient mode, the force can be as large as 3.53 MN (360 metric tons) pushing the two coils apart. The focusing solenoid warm bore radius is 235 mm. The length of the outside of the magnet cryostat vacuum vessel is 720 mm.

The focusing magnet Nb-Ti conductor is a conductor that is designed for use in MRI magnets. The bare dimensions of the conductor are 0.955 mm by 1.60 mm, with rounded ends to prevent cracking of the Formvar insulation. The insulated dimensions of the conductor are 1.00 mm by 1.65 mm. The conductor consists of four parts RRR > 75 copper and one part Nb-Ti. The superconductor is subdivided into 55 filaments, which are about 78 microns in diameter. The conductor twist pitch is about 12.7 mm. The focusing magnet layer thickness shown in Table 1 is about 1.1 mm.

Table 1 shows the basic parameters of the MICE focusing magnet. The magnet parameters are shown for both of the MICE magnet operating modes (where the magnetic field flips as one moves along the solenoid axis and where the field doesn't flip as one moves along the magnet axis). In both cases, the average momentum of the muons traveling along the MICE cooling channel is 240 MeV/c and the beam beta at the center of the absorbers is 420 mm.

Table 1. The Basic Parameters of the Focusing Magnet in the Non -flip and the Flip Mode

Parameter	Non-flip	Flip
Coil Inner Radius (mm)	263	
Coil Thickness (mm)	84	
Number of Layers	76	
No. Turns per Layer	127	
Magnet J (A mm^{-2})*	71.96	138.2
Magnet Current (A)*	130.5	250.7
Magnet Self Inductance (H)	137.4	98.6
Peak Induction in Coil (T)*	5.04	7.67
Magnet Stored Energy (MJ)*	1.17	3.10
4.2 K Temp. Margin (K)*	~2.0	~0.6
Inter-coil Z Force (MN)*	0.56	3.40

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

The focusing magnet cold mass support is a self-centering support system consisting of eight tension bands [6]. (The magnet center does not change as the magnet is cooled down.) The support system is designed to carry a sustained longitudinal force up to 500 kN (50 tons) and transient forces up to 1000 kN (100 tons). The maximum longitudinal force applied to the focusing magnet is less than 500 kN.

MAGNET COOLING WITH SMALL COOLERS

The MICE focusing magnets are designed to be cooled using a pair of small (1 to 1.5 W) 4.2 K coolers [7]. The second cooler is needed because the dominant heat load in the cooler first stage are four 300 A copper current leads. About half the heat leak into the 4.2 K region from the first stage temperature is down the four high temperature superconductor (HTS) leads that are connected to the room temperature current leads. The HTS leads are an enabling technology that permits magnets at 4.2 K to be continuously powered from a current source at room temperature.

Because the temperature margin in the focusing magnet is quite low at its maximum design current, it is important to minimize the temperature rise from the cooler second stage cold head and the hot spot in the magnet. (In the focusing magnet the hot spot in the magnet is very close to the high field point in the magnet winding.) First one must reduce the temperature rise within the magnet by applying the cooling evenly over the outside surface of the magnet. 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. One can apply cooling to the outside surface of the coils by immersing them in liquid helium. The same liquid helium is an integral part of the gravity feed heat pipe that delivers the heat from the helium in the magnet to the cold head. Unlike conducting heat in a copper strap, the temperature drop along the heat pipe is independent of the distance between the cooler cold head and the surface of the magnet [7]. If the heat pipe is correctly designed, the temperature drop from the magnet hot spot to the 2nd stage cold head of the coolers can be less than 0.2 K.

POWER SUPPY AND QUENCH PROTECTION

It has been proposed that the three focusing magnets be powered in series. Since the MICE focusing magnet is almost identical to the Lab G solenoid at Fermilab, it was known that a single magnet would quench safely in both operating modes. The question was whether three magnets in series quench differently than a single magnet. Figure 3 compare the calculated quench for a single focusing magnet and three focusing magnets in series [8]. Table 2 shows the quench characteristics of the MICE focusing magnet.

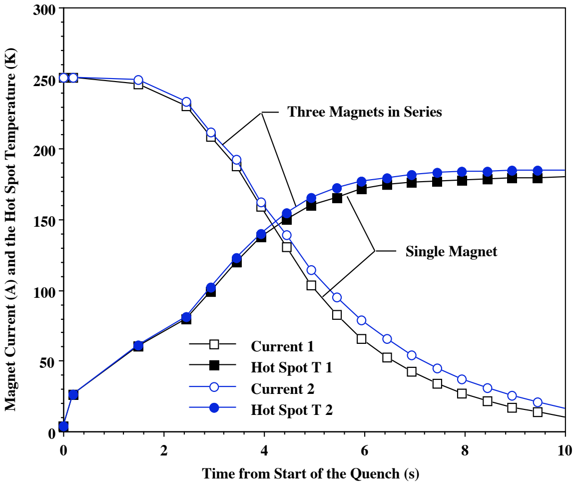

Figure 3. The Focusing Magnet Current and Hot Spot Temperature as a Function of the Time from the Quench Start for the Magnet Coils Hooked together in the Flip Mode.

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

Parameter	
Maximum Current (A)	250.7
Conductor Current Density (A mm^{-2})*	181.7
Magnet Self Inductance (H)	98.6
Magnet Stored Energy (MJ)*	3.10
E J^2 at Maximum Current (J A^2 mm^{-4})*	1.02×10^{23}
Quench Velocity along Wire (m s^{-1})	5.2
Coil Average Radius (mm)	305
Coil Thickness (mm)	84
Coil Length (mm)	210
Time Constant for a Safe Quench (s)	7.33
Nominal Quench Back Time (s)	1.07

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

Three focus magnets appear to quench as a single magnet, because quench back occurs quickly in all magnets. The stored energy of the second and third magnets is not available to go into the hot spot in the magnet that quenches. As a result, it is clear that the three MICE focusing magnets can be hook-up in series as shown in Figure 4. The quench studies also show that a focusing magnet is unlikely to quench the coupling magnets [8].

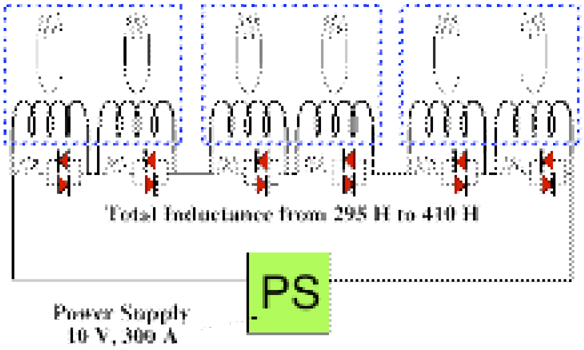

Figure 4. Circuit Diagram for Three Focus Magnets in Series

CONCLUDING COMMENTS

The focusing magnets for MICE can be built using commercial niobium titanium MRI conductors. The MICE focusing magnet are designed to be operated either as a split pair solenoid or as a gradient solenoid. The successful operation of the magnet in the either mode require that the magnet be kept near 4.2 K. Magnet operation in the gradient mode defines the design of the magnet.

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

The focusing magnet is designed so that it can be operated in the MICE cooling channel where the fields from other magnets interact with the focusing magnet. The focusing magnet quench characteristics permit the three magnets to be operated in series.

ACKNOWLEDGEMENT

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