The Mechanical and Thermal Design for the MICE Coupling Solenoid Magnet*

M. A. Green, S. Q. Yang, U. Bravar, W. Lau, D. Li, B. P. Strauss, S. P. Vorostek, A. E. White, and H. Witte

***Abstract*— The MICE coupling solenoids surround the RF cavities that are used to increase the longitudinal momentum of the muon beam that is being cooled within MICE. The coupling solenoids will have a warm-bore diameter of 1394 mm. This is the warm bore that is around the 200 MHz RF cavities. The coupling solenoid is a single superconducting coil fabricated from a copper matrix Nb-Ti conductor originally designed for MRI magnets. A single coupling magnet is designed so that it can be cooled with a single 1.5 W (at 4.2 K) cooler. The MICE cooling channel has two of these solenoids, which will be hooked together in series, for a magnet circuit with a total stored-energy of the order of 12.8 MJ. Quench protection for the coupling coils is discussed. This report also presents the mechanical and thermal design parameters for this magnet, including the results of finite element calculations of mechanical forces and heat flow in the magnet cold mass.**

***Index Terms*—Superconducting Solenoids, and Muon Cooling**

I. 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], [2]. The international Muon Ionization Cooling Experiment (MICE) will be a demonstration of muon cooling in a configuration of superconducting magnets [3] that may be useful for a neutrino factory. One must reduce the emittance of the beam to a level that can be accepted by the acceleration section that must follow a cooling channel.

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 momentum. If the scattering in the absorbing medium is not too large, the reaccelerated muon beam will have a lower emittance than the muon beam that entered the absorbers. 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 hydrogen (either as liquid or gas), lithium hydride, lithium metal or beryllium metal.

Manuscript received 5 October 2004. M. A. Green (email: MAGreen@lbl.gov), S. Q. Yang (email: s.yang@physics.ox.ac.uk), U. Bravar, W. Lau, and H. Witte are from the Oxford University Physics Department, Oxford OX1-3RH. D. Li and S. T. Vorostek are from the Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA, B. P Strauss is from the Office of Science DOE Germantown MD USA, *This work was supported by the Oxford University Physics Department and the Particle Physics and Astronomy Research Council of the United Kingdom.

II. The Proposed MICE Experiment

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. The pions that decay into muons are produced by dipping a metal target into the ISIS proton beam. The Pions will decay into a well-defined muon beam. The muons will be collected and then they will be carried to an experimental hall containing the MICE cooling channel and two identical detectors..

The beam enters the experiment by passing through a foil that will scatter the muons to produce a beam of desired emittance. The initial muon beam emittance will be measured by four planes of scintillating fibers that are in a uniform solenoidal magnetic field [4] from 2.8 to 4 T that is generated by the detector magnet. Fig. 1 shows a schematic cross-section view of MICE.

Once the emittance of the muon beam entering the cooling section has been measured, the beam passes through an absorber that cools the muon beam by ionization cooling. The absorber is in a high magnetic field region where the field either goes through zero to a field of opposite polarity or a region where the field is reasonably uniform (Which field configuration depends on the cooling mode that is being tested). In either case, the beam beta is supposed to be minimized. The MICE test absorbers may be liquid hydrogen, liquid helium, beryllium, or plastic. The preferred cooling absorber material is hydrogen, because it has the lowest multiple scattering of any of the absorber materials for a given energy absorption and beam beta. The absorber is surrounded by a two-coil solenoid that produces a uniform field or a cusp field that flips as one goes along the axis.

The muon beam momentum is recovered by accelerating the beam with a four cell 201.25 MHz RF cavity that is in a 2.5T magnetic field produced by the coupling magnet [5]. The field from the coupling magnet keeps the muon beam tuned over a wide range of momenta. A second role for the coupling magnet is to tune the cooling channel so that a range of beam betas can be developed within the absorber, without changing the length of the cooling channel. After the muon beam has been re-accelerated, it passes through a second absorber in a second low beta region. The process of re-acceleration is repeated in a second set of RF cavities; then the beam passes through the final absorber. At this point, the beam should be cooled enough, so that the cooling can be clearly measured.

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.

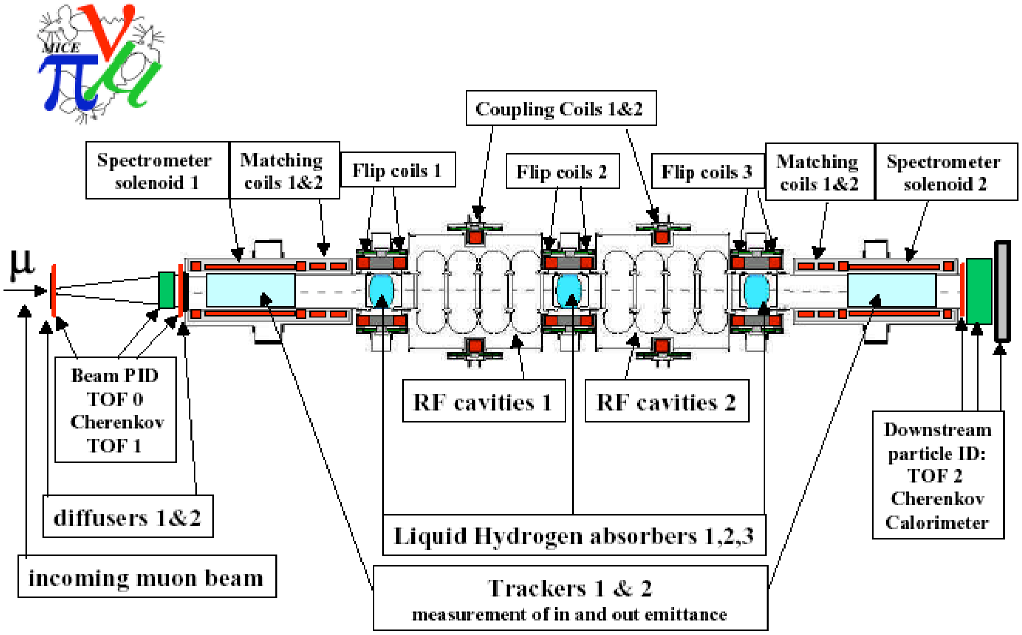

Fig. 1. A Schematic Representation of the MICE Experiment and its magnets shown in Cross-section. The RF and coupling module consists of a four cell 201.25 MHz RF cavity surrounded by the coupling magnet (called the coupling coil in the figure).

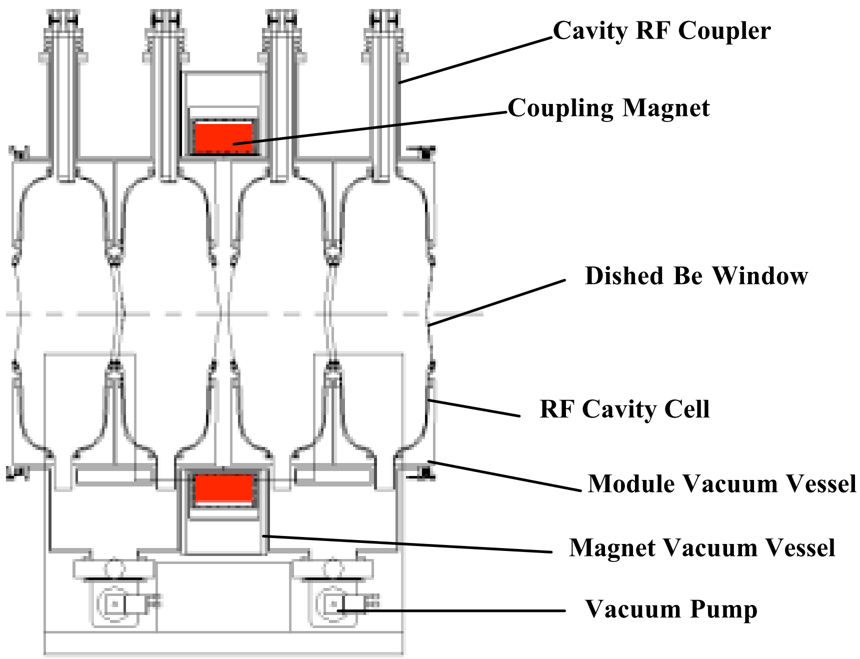

Fig. 2. A Schematic Cross-section of the MICE Coupling and RF Module. The cross-section shows the coupling magnet, the coupling magnet vacuum vessel, the coupling module vacuum chamber and a four-cell 201.25 MHz water-cooled RF cavity within the module.

III. THE MICE COUPLING AND RF MODULE

The MICE coupling and RF module is shown in Fig. 2. The module includes the RF module vacuum vessel that is 1906 mm long. The RF module shares a common vacuum with the adjacent absorber focus coil modules. Within the vacuum vessel is a four-cell 201.25 MHz RF cavity. Each cavity section has a pair dished beryllium windows that allow the cavity to be excited to very high gradients without breakdown. Each cavity cell must have a very good vacuum ($<10^{-7}$ torr) within it. The cell windows are dished to prevent the cavity from becoming detuned as it warms up due to RF heating. Shown in Fig 2. are the couplers that connect the cavity cells to their power amplifiers. Between the two center couplers is coupling magnet. The shape of the coupling solenoid is determined by the space between the RF couplers entering the two central RF cavity cells. In addition to the RF coupler are RF tuners that are not shown in Fig 2.

IV. The Coupling Magnet Design

The MICE coupling magnet has a single 250 mm long coils wound on a 6061-T6-aluminum mandrel. The mandrel end flanges are 20 mm thick, so that the total length of the cold mass package (while warm) is 290 mm. The inner bore radius of the cold mass is about 712 mm (at 300 K). The 6061 aluminum mandrel its aluminum cover, and the superconducting coil carry the magnetic forces when the magnet operates at its design current. The cold mass support system is connected to the magnet coil and mandrel through the coil covers. This worst case net force on the cold mass support can be as large as 500 kN (50 metric tons) in the longitudinal direction (parallel to the magnet axis). The coupling solenoid warm bore radius is 707 mm. The length of the outside of the magnet cryostat vacuum vessel is about 386 mm.

The coupling magnet Nb-Ti conductor is a conductor that is designed for use in MRI magnets. The bare conductor is 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 about 78 microns in diameter. The conductor twist pitch is about 12.7 mm. The magnet has a layer of glass fiber epoxy 0.1 mm thick between each layer of conductor. The thickness for each of the layers referred to in Table 1 is about 1.1 mm.

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

Table 1 shows the basic parameters of the MICE coupling magnet. Fig. 3 depicts a cross-section for half of the coupling magnet. The magnet parameters are shown for MICE operating in the flip mode 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. When the coupling magnet is operated while the MICE channel in the non-flip mode, the current in the magnet is a few percent lower than the current shown in Table 1. The operating case shown in Table 1 represents the highest current and highest field case for the MICE coupling magnet. The 4.2 K temperature margin for the coupling magnet is nearly the same as for the focusing magnet [5].

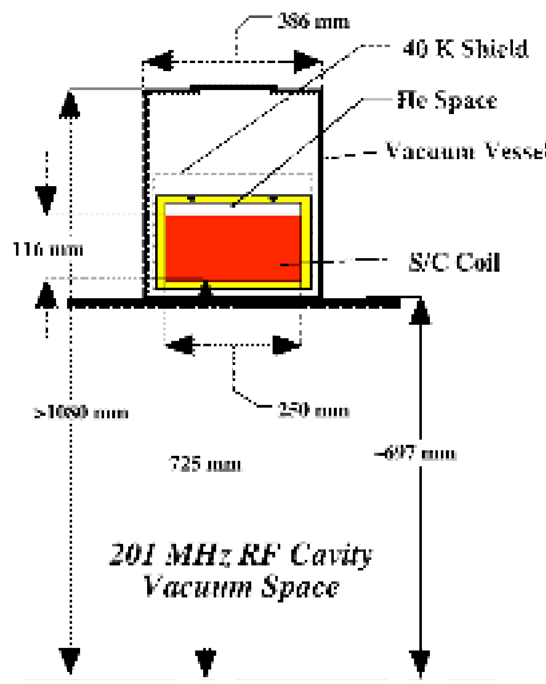

Fig 3. A Cross-section View of Half of the Coupling Magnet Showing the Basic Magnet Dimensions

The coupling magnet stored energy is quite high for a magnet that uses the same conductor as the MICE focusing magnet. Because the coupling magnet has a high stored energy, the magnet operates 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 the coupling magnet is subdivided with each section protected by a cold diode and resistor, the two coupling magnets can be hooked up in series so that they all quench together.

The stress and deflection in the coupling magnet was analyzed using FEA methods. The largest stresses and deflections of the coupling magnet occur during the magnet cool down from 300 K to 4.2 K [6]. The aluminum mandrel and support structure is put into tension in both the longitudinal and the hoop directions during the cool down. The coupling coil is put into compression during the cool down. Powering the coil adds to the tensile stress in the aluminum. The FEA model shows the highest von Mises stress (about 200 MPa) is found in the corners between the mandrel and the end plates. This stress is very highly localized and it will have little effect on the rest of magnet.

The coupling magnet cold mass support is a self-centering support system consisting of eight tension bands [7]. (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).

V. Cooling the Magnet with Small Coolers

The MICE coupling magnets are designed to be cooled using a single (1 to 1.5 W) 4.2 K cooler [8]. The dominant heat load in the cooler first stage is the two 300 A copper current leads. About half the heat leak into the 4.2 K region from the first stage temperature is down the two 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.

Because the temperature margin in the coupling 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 coupling magnet the hot spot in the magnet is at 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 [9]. 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.

Even though the coupling coil can be connected directly to the second stage cold head, the cooling should not be applied to a single point on the outer surface of the coil. If one cools the coupling coil at a single point, the temperature drop from the magnet hot spot to the cooler cold head can be of the order of 1 K, which is unacceptable for a magnet with a temperature margin as low as 0.5 K. 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 volume of this bath need only be large enough to ensure that the coupling magnet can be shut down during a power failure without quenching. The same liquid helium can also be 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 [8]. If the heat pipe is correctly designed, the temperature drop from the magnet hot spot to the second stage cold head of the coolers can be less than 0.2 K.

It is possible to cool down the coupling magnet with the cooler, provided one uses a large enough copper strap to carry the heat from the magnet to the cooler during the cool down. Since using the cooler to cool down the magnet takes a long time (over 2 weeks), the coupling magnet is designed to be cooled using liquid nitrogen until the magnet is at 90 K and liquid helium from 90 K to 4.2 K. Once the magnet has liquid helium in contact with the cryostat, one has to wait for as long as two days until the heat that is stored in the insulation soaks into the magnet. Once this soaking process is finished the cooler will keep the magnet cold. It may take a week for the magnet to reach its equilibrium temperature.

VI. 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 needed for the cavity RF couplers and the cavity tuners.

The coupling magnet is designed to operate in a channel where the fields from other magnets that can interact with the magnet. The stress levels within the magnet are reasonable, even at the highest design currents.

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.

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