

LBNL-59004  
SCMAG-855  
MICE-PUB-GEN-132

# **Power Supply and Quench Protection for the MICE Channel Magnets\***

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**September 2005**

**Presented at the 2005 European Applied Superconductivity Conference  
Vienna, Austria  
11 through 14 September 2005**

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\* This work was supported by the Oxford University Physics Department and the Particle Physics and Astronomy Research Council of the United Kingdom. This work was also performed at the Lawrence Berkeley National Laboratory with the support of the Office of High Energy Physics, United States Department of Energy under DOE contract DE-AC02-05CH11231. DOE funding for the US Neutrino Factory and Muon Collider Collaboration is gratefully acknowledged.

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# Power supply and quench protection for the MICE cooling channel magnets

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This report discusses the power supply and quench protection system selected for the MICE superconducting coupling and focusing magnets. First, the MICE focusing and coupling magnet parameters are presented. Second, the report describes passive quench protection systems for these focusing and coupling magnets. Thermal quench-back from the magnet mandrel, which is a key to the MICE magnet quench protection system, is also discussed. A system of diodes and resistors is used to control the voltage to ground as the magnet quenches. Third, the report presents the magnet power supply parameters for MICE magnets.

## 1. Introduction

The muon ionization cooling experiment (MICE) consists of a muon beam line, a pair of detectors and one cell of an ionization-cooling channel [1]. The full MICE ionization-cooling channel consists of a three-absorber-focus-coil modules (AFC modules) [2] and a pair of RF-coupling-coil modules (RFCC modules) [3] that are located between the AFC modules. At each end of the cooling channel is a tracker module. The tracker module consists of matching coils, a uniform-field detector solenoid, and a tracker that has five layers of scintillating fibers spaced over a distance of one meter. Figure 1 shows a three-dimensional view of the MICE cooling channel.

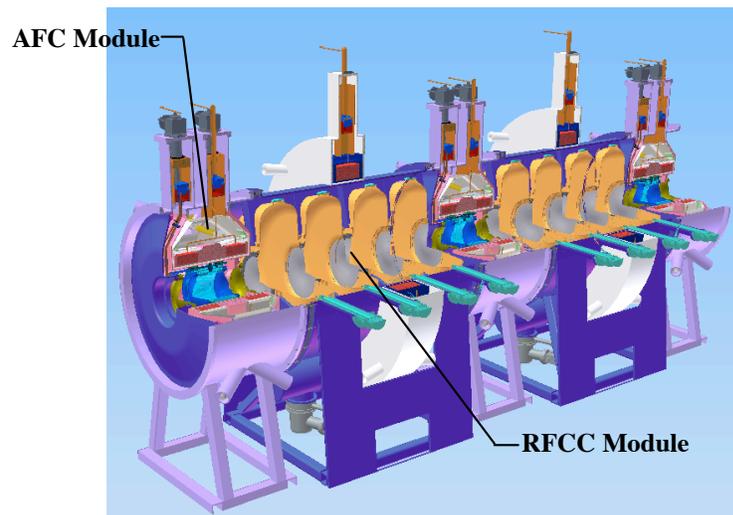


Figure 1. The full MICE cooling channel with two RFCC modules and three AFC modules.

Table 1. The parameters of the MICE focusing and coupling magnets [4] [5].

Parameter	Focusing Magnet		Coupling Magnet	
Number of coils	2		1	
Coil length (mm)	210		250	
Coil inner radius (mm)	263		725	
Coil thickness (mm)	84		116	
Coil Separation (mm)	200		Not applicable	
Number of turns per coil	9652		15704	
MICE operating mode	Flip	Non-flip	Flip	Non-flip
Coil current density* ( $A\ m^{-2}$ )	138	71.96	115.5	104.9
Magnet current* (A)	250.7	130.5	213.2	193.7
Magnet self inductance (H)	98.6	137.4	563	563
Peak induction in the coil (T)	7.67	5.04	7.81	7.10
Magnet stored energy* (MJ)	3.10	1.17	12.8	10.6
Matrix current density* ( $A\ mm^{-2}$ )	181	94.3	154.0	140.0

\* MICE channel operation at an average muon momentum  $p = 240\ MeV/c$  and a beam  $\sigma = 420\ mm$

## 2. The MICE focusing and coupling magnet parameters

The AFC module consists of a pair of superconducting coils surrounding an absorber. The role of the magnet is to create a low beam  $\sigma$  region at the center of the AFC module. The absorber cools the muons through ionization cooling. (Liquid hydrogen is the most effective cooling medium.) The superconducting magnets are low-current magnets because they are cooled using a pair of 1.5 W (at 4.2 K) coolers. The AFC magnets may be operated with the two coils operating at the same polarity (the solenoid or non-flip mode), or the two coils may be operated at opposite polarity (the gradient or flip mode). The maximum operating current for the focusing magnet, in any of its operating modes, is less than 265 A.

The RFCC module consists of four RF cavities that restore the longitudinal momentum lost in the absorbers. If multiples scattering does not produce more transverse momentum than that lost as the beam goes through the absorber, there will be net beam cooling. The RFCC module also has a single superconducting coil that maintains the muon beam within the confines of the RF cavities. Beam blow up would cause the muon beam to be lost as it strikes the RF cavity iris. The coupling magnet is cooled using a single 1.5 W (at 4.2 K) cooler. Because leads represent a major heat load for a magnet system cooled by a small cooler, the magnet current in the coupling magnet is limited to 225 A.

Table 1 shows the basic parameters for the focusing magnet operating in both the flip and non-flip modes. Table 1 also shows the basic parameters for the coupling magnet operating in the MICE cooling channel with the AFC magnet operating in both modes. The cases shown in Table 1 represent the worst-case operating parameters for both types of magnets.

## 3. The quench characteristics of the MICE focusing and coupling magnets

Since the current density in the MICE conductor is well above the limit for cryogenic stability, quench protection of both types of magnets is an issue [6]. The primary mode of quench protection for both the focusing magnet and coupling magnet is through quench-back from the mandrel that the coils are wound upon. When the magnet coils go normal, a current is induced in the magnet mandrel. The mandrel current heats the superconducting coil causing it to go fully normal faster than it would through quench propagation in the coil alone. Figure 2 shows the current in the coil and the hot-spot temperature in the focusing magnet with just passive quench protection using quench-back [7].

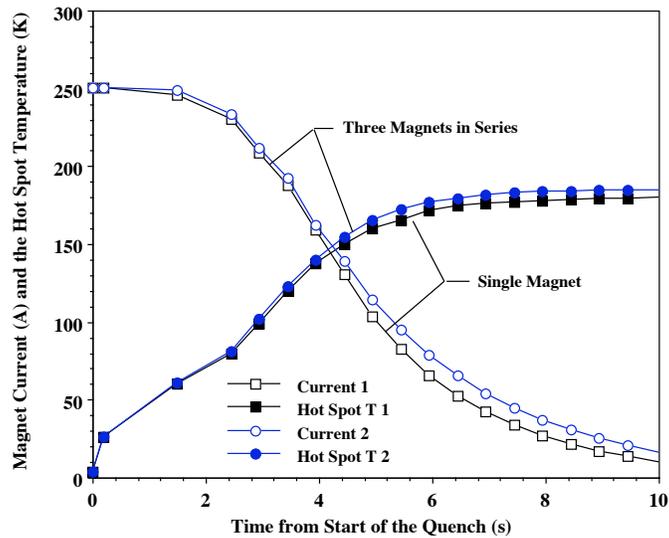


Figure 2. The magnet current and hot-spot temperature as a function of the time from the start of the quench for a single focusing magnet and three focusing magnets in series. All use passive protection.

Similar calculations were done for the coupling magnet [8]. It was found that a quench with two magnets in series yielded a significantly higher (but still safe) hot-spot temperature than for a single magnet alone. The coupling magnets will be separately powered to reduce the magnet charge time and have a lower quench hot spot temperature. Both the focusing and coupling magnets will have diodes and resistors across their coils to limit the voltages to ground that develop during a quench.

#### 4. The power supplies for the MICE magnets

Since all of the MICE magnets will be cooled using one or more 4.2 K coolers, the maximum lead current for the magnets must be less than 300 A. The main magnets for MICE will be powered by supplies that generate a current from 0 to 300 A and voltages of  $\pm 10$  V. Small 0 to 50 A and  $\pm 10$  V power supplies will be used to tune some magnets in MICE. The design power supply voltage ripple frequency is 600 Hz. The maximum allowable current ripple is less than  $\pm 0.03$  percent, but over the range of operating currents it will be closer to  $\pm 0.01$  percent. The required magnet current regulation is  $\pm 0.03$  percent over a range of currents from 30 to 90 percent of the maximum current delivered by the power supply. Figure 3 shows the three focusing magnets in series along with the passive quench protection diodes and resistors. The magnet mandrel is the secondary circuit shown in Fig. 3. (Note: the self inductance of the circuits is larger than the sum of the three magnet self inductances, because of coupling between the magnets.)

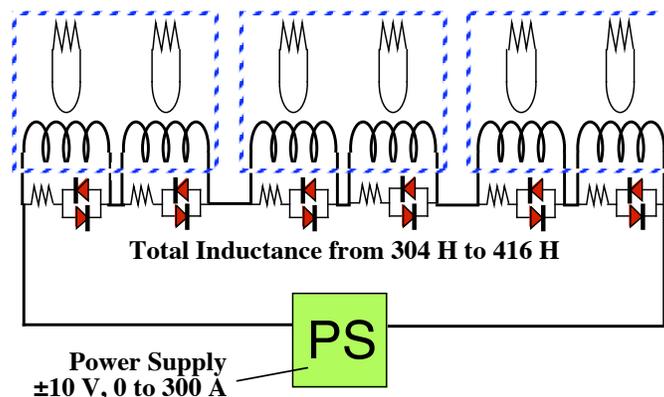


Figure 3. Power supply and the passive quench protection system for the three focusing magnets.

## 5. Concluding Comments

The MICE focusing and coupling magnets can be charged to full field in a reasonable time (2.4 hrs for three focusing magnets in series to 3.9 hrs for a single focusing magnet). The three focusing magnet will be connected in series. The focusing magnet may be operated in either the flip mode or the non-flip mode. The two coupling magnets will be separately powered in order to reduce the time needed to charge them to full current. Separately powering the magnets will also result in a lower quench hot-spot temperature.

The MICE magnets use a passive quench protection scheme where quench-back drives the coils fully normal faster than they would go normal through quench propagation in the windings. Voltages to ground in the coil packages are limited by a system of diodes and resistors that bypass the coils.

The MICE magnets will be powered by 300 A power supplies that can produce voltages of  $\pm 10$  V. Small 50 A power supplies will be used to tune some of the MICE magnets. The current regulation will be better than  $\pm 0.03$  percent over a wide range of operating currents. The ripple current will be less than  $\pm 0.03$  percent of the operating current.

## Acknowledgments

A portion of this work was supported by the Oxford University Physics Department and the Particle Physics and Astronomy Research Council of the United Kingdom. The rest of the work was done at the Lawrence Berkeley National Laboratory with the support of the Office of High Energy Physics, United States Department of Energy under DOE contract DE-AC02-05CH11231. DOE funding for the US Neutrino Factory and Muon Collider Collaboration is gratefully acknowledged.

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