LESSONS LEARNED FOR THE MICE COUPLING SOLENOID FROM THE MICE SPECTROMETER SOLENOIDS*

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Abstract

Tests of the spectrometer solenoids have taught us some important lessons. The spectrometer magnet lessons learned fall into two broad categories that involve the two stages of the coolers that are used to cool the magnets. On the first spectrometer magnet, the problems were centered on the connection of the cooler 2nd-stage to the magnet cold mass. On the first test of the second spectrometer magnet, the problems were centered on the cooler 1st-stage temperature and its effect on the operation of the HTS leads. The second time the second spectrometer magnet was tested; the cooling to the cold mass was still not adequate. The cryogenic designs of the MICE and MuCOOL coupling magnets are quite different, but the lessons learned from the tests of the spectrometer magnets have affected the design of the coupling magnets.

INTRODUCTION

The muon ionization cooling experiment (MICE) will be a demonstration of muon cooling in a configuration that may be useful for a neutrino factory [1]. Stage 6 of MICE (the final MICE channel) consists of: 1) two spectrometer modules used for analyzing muon beam emittance before and after cooling; 2) three absorber focus coil (AFC) modules used for muon ionization cooling in the absorbers in the focusing magnets; and 3) two RF coupling coil (RFCC) modules are used for reaccelerating the muon beam between the AFC modules.

The RFCC modules consist of a superconducting coupling solenoid, which surrounds a 1.4-meter diameter vacuum chamber that contains four separately powered conventional copper RF cavities that have a resonant frequency of 201.25 MHz. The individual RF cavity irises are closed by thin beryllium windows [2]. The coupling magnet will produce a large enough magnetic field to keep the beam within the iris of the RF cavities.

The magnets used in the MICE cooling channel are all superconducting solenoids. All of the MICE cooling channel magnet modules are cooled using two-stage pulse tube coolers that develop 1.5 W of cooling at 4.2 K while generating 50 W of cooling at 45 K [3]. The channel magnets are continuously powered by one or more pairs of leads that go from 300 K to the cold mass. The magnet current leads between the first and second stages of the coolers are made from HTS conductor. The leads from 300 K to the cooler first-stages are conduction cooled.

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This paper compares the magnet cryogenic design for the spectrometer magnet [4] and the coupling magnet [5]. The effect of magnetic fields on the high temperature superconductor (HTS) leads is discussed [6]. The experience gained from testing the spectrometer magnets has influenced the design of the coupling magnets. Lessons learned from the spectrometer magnets will likely affect the AFC magnet design [7] as well.

SPECTROMETER AND COUPLING MAGNET DESIGN COMPARISON

The spectrometer solenoid cryostat has an OD of 1.4 m and it is 2.7-m long. The coupling magnet cryostat has an OD of more than 2.2 m and a length of 0.49 m. The magnets are quite different. The spectrometer solenoid is long (2511 mm) compared to its coil ID of 516 mm. On other hand the coupling magnet coil is short (285 mm) compared to its coil ID of 1500 mm. As a result, the stray field outside the coupling magnet is large compared to the spectrometer magnet. The stray field of the coupling magnet affects the location and orientation of the HTS leads and it influences the design first-stage temperature for the coolers that cool the magnet. Table 1 compares the design heat loads for the two types of MICE magnets.

Table 1: A Comparison of the Design Cryogenic Heat Loads for the Spectrometer and Coupling Magnets

Parameter	Spectro.	Coupl.
Number of 4.2 K coolers	3	2
Total Lead Current (A) (No. Leads)	1770 (8)	420 (2)
Cold Mass Support Design Force (kN)	500	500
Total Shield Area (m^2)	~15	~8
Number of Wires to Shield	148	92
Number of wires to Cold Mass	84	68
Calculated 1st Stage Heat Loads		
Lead Conduction + I^2R heating (W)	~109	~24
Cold Mass Support heat Load (W)	~9	~9
MLI Heat Load (W)	~15	~8
Pipe and Sleeve Heat Load (W)	~12	~10
Instrumentation Heat Load (W	~2	~1
Total Design 1st Stage Heat Load (W)	~147	~52
Per Cooler 1st Stage Heat Load (W)	**~49**	**~26**
Calculated 2nd Stage Heat Loads		
Lead Conduction + I^2R heating (W)	~1.0	~0.3
Cold Mass Support heat Load (W)	~0.4	~0.4
MLI Heat Load (W)	~0.8	~0.5
Pipe and Sleeve Heat Load (W)	~1.4	~1.0
Instrumentation Heat Load (W)	~0.3	~0.2
Total Design 2nd Stage Heat Load (W)	~3.9	~2.4
Per Cooler 2nd Stage Heat Load (W)	**~1.3**	**~1.2**

The design first-stage heat load per cooler is two times larger for the spectrometer magnet compared to the coupling magnet, whereas the design second-stage heat load is about the same for both magnet types. The spectrometer magnet is bath cooled in a 185 L helium tank. The coupling magnet is cooled by conduction from tubes that are welded into the cover plate of the magnet. The helium circulates through the tubes attached to the magnet by natural convection. Cold liquid helium from the coolers enters the magnet in a tank at the bottom of the magnet. The gas going back to the coolers leaves the tank at the top of the magnet. If the tubes to the bottom tank are large enough, the coolers can cool-down the magnet [8], but the cool-down would take a long time. The helium volume in contact with the magnet is ~20 L. The coupling magnet cold mass is shown Fig. 1.

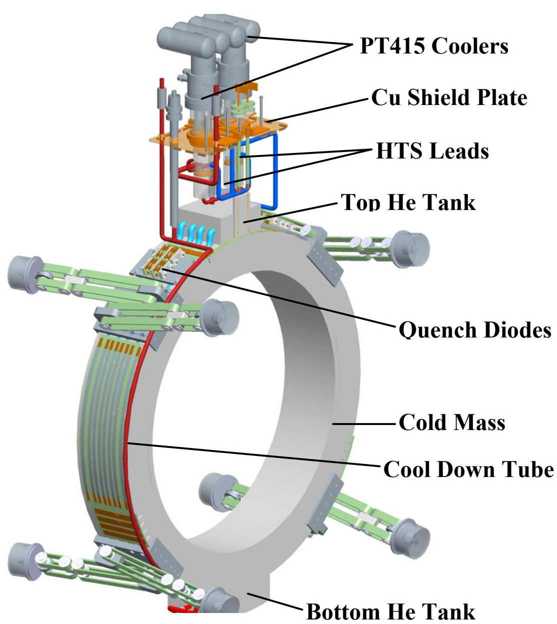

Fig 1: A 3D View of the Coupling Magnet Cold Mass.

The tops of the HTS leads are cooled from the copper shield plate. This means that the heat flowing down the copper leads from room temperature must go to the cooler first-stages. The temperature of the copper shield plate is strongly influenced by the heat flow into that plate. The temperature drop from the HTS leads to the cooler first stage is an important factor for the MICE magnets.

The current capacity of the HTS lead is a function of the magnitude of the magnetic field, the orientation of the field with respect to the BSCCO-2232 tape, and the lead temperature. In general the current capacity of the HTS lead is lowest at the top of the leads (near the copper shield plate). Figure 2, presents the HTS lead scaling parameter as a function of induction and temperature for the HTS lead in it most favorable orientation. Figure 3 shows the favorable orientation for the HTS material in the lead and the lead itself. The most favorable orientation is parallel to the flat face of the conductor.

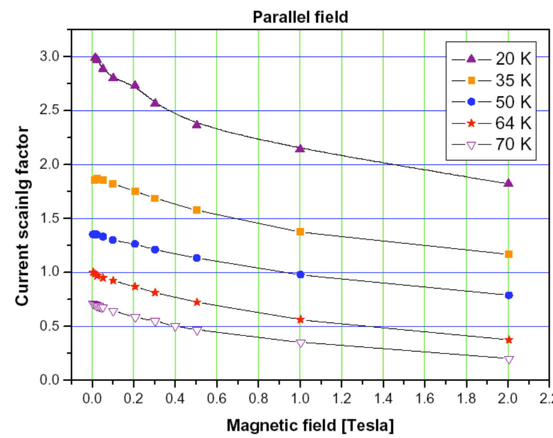

Fig. 2: The HTS Lead Current Scaling Factor as Function of Magnetic Induction and Temperature with the Magnetic Field Parallel to the Conductor Face.

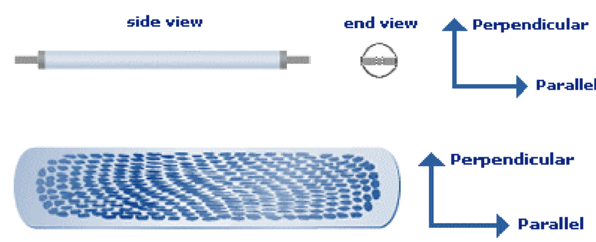

Fig. 3: The Favorable Field Direction (parallel) for the HTS-110 Lead and the BSCCO Conductor in the Lead.

The peak field in the coupling coil lead is from 0.3 to 0.4 T at the top of the lead. This lead will carry 210 A when the magnet runs at full current. The large spectrometer magnet leads operate at 275 A in a field that is <0.1 T. From Fig. 2, it is clear that coupling magnet HTS leads must operate at a lower temperature than the leads for the spectrometer solenoid. The leads for both magnets are designed to carry 500 A at 64 K with no external magnetic field (scaling factor = 1 in Fig. 2).

From Fig. 3, it is clear that the HTS-110 leads have two favorable orientations (out of three). HTS leads mounted in an axi-symmetrical solenoid will have the parallel (favorable) orientation in the r and z directions.

WHAT WAS LEARNED FROM THE SPECTROMETER SOLENOID?

The three tests of the spectrometer magnets have taught us some important lessons: 1) Helium must circulate properly within the cold mass, if the magnet cold mass is to be kept cold by the cooler second-stages [9]. 2) The first stage temperature is very important. If this temperature is too high the HTS leads will burn out at high currents [10]. When the first-stage temperature is high, the second stage temperature will be higher for a given heat flow into the second stage. 3) The copper lead IL/A must be correct for minimum heat flow down the copper leads [11].

The first stage of the spectrometer magnet heat flow was higher than the design values given in Table 1, for both magnets 1 and 2. The heat load into the cooler first-stages for magnet 2 was ~90 W higher than it was for magnet 1. During the first test of magnet 2, the cooler 1st-stage temperatures were too high. With no current, the Cu plate temperature near the lead farthest from the coolers was ~81 K. At this temperature the lead can carry only 200 A. With 238 A in the leads the plate temperature was ~93 K. As a result, the lead burned out and quenched the magnet. Adding an AL-330 single-stage GM cooler reduced the Cu plate temperature by more than 30 K. The shield temperature went down by ~20 K. Adding a GM cooler to the spectrometer magnet was an option, because the field at the cooler is low.

The heat flow into the 2nd-stages of the coolers for magnet 2 was about fifty percent higher than the value given in Table 1. A number of reasons for this have been identified. At this time, it is not clear that one can reduce the 4.2 K heat load enough to prevent having to add more two-stage coolers. Adding one cooler adds ~1.2 W of net cooling to the cold mass. The cooler sleeve for the drop-in coolers accounts for most of the missing 0.3 W of cooling at 4.2 K. It should be pointed out that some of the apparent excess heat flow into the cold mass may be due to inefficiencies of the connection between the cooler 2nd-stage cold head and the cold mass.

COUPLING MAGNET DESIGN CHANGES

A number design changes in the coupling magnet have been made as a result of lessons learned from tests of the spectrometer solenoid. The changes made are as follows: 1) The current leads are split so that there is one 210 A lead per cooler. 2) The copper lead intercept on the copper plate is designed to spread the heat into the copper plate. 3) The coil current leads will be physically close to the cooler first stage. 4) The copper shield plate will be made thicker. These four changes will reduce the ΔT between the HTS current lead and the cooler. As a result, the HTS lead temperature margin will be increased.

The coupling coil shield was re-designed to minimize the ΔT between the cold mass support intercepts and the coolers. 1) The shield will be connected to the first-stage copper plate through a copper box. 2) The shield will be fabricated using 6-mm thick 1100-O aluminum plate.

Pipes from the sleeve below the condenser to the bottom tank will be made larger. In principle, this permits the coupling magnet to be cooled down using the coolers alone. The liquid helium pipes from the condenser to the bottom tank must be insulated from the cold mass.

There are a number of other changes to the coupling magnet that could be considered based on spectrometer magnet tests. These changes are: 1) Reduce the cold mass heat leak by lengthening the cold mass fill and vent tubes. 2) Reduce the cold mass heat leak by covering the region around the cold mass supports with the shield. 3) Make a provision for adding another two-stage cooler to the magnet. Adding a single stage GM cooler is not an option, because of the high stray magnetic field. 4) One should have the option of cooling the MuCool coupling magnet using the MTA refrigerator.

Reducing the heat flow to the cooler 1st-stages increases the temperature margin of the HTS leads, and it improves the performance of the cooler 2nd-stages. Reducing the heat leaks into the 2nd-stage must be done in a systematic way. The connection between the cooler 2nd-stage and the cold mass is very important. One must separate the liquid helium stream from the condenser from the helium gas stream going back to the condenser.

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