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TECHNICAL NOTE

MICE Spectrometer Solenoid: Heat Load Analysis

1. Introduction

As an attempt to understand the thermal performance of the helium cryostat of the MICE Spectrometer Solenoid, we have re-evaluated the heat leaks due to the dominant static sources. Ignored in this evaluation are the dynamic heat loads, which primarily include the thermal relaxation of long parts cooled by thermal conduction (particularly the shield), the relaxation of non-equilibrium heat in solids, transient behavior of the insulation vacuum, magnetic flux jumps in superconducting filaments, and eddy current heating during current ramp up or down. Such heat loads are minimal after a week of operation at LHe temperature or when the current is ramped slowly enough.

2. Heat Load Estimates

The heat loads from the various sources to the 4.2 K helium system are summarized in Table 1. Column 1 identifies the source of the heat, column 2 lists the design values of MICE Note 236 [1], and column 3 shows the loads under the conditions of Test 2B evaluated by R. Sanders [2]. Column 4 shows basically the same values as column 3, with four of the values increased (in red) and one reduced (in blue). The last column lists the reference numbers for the notes presented later in this document that describe the method and status of the evaluation of each heat load source.

Table 1: Heat loads to the helium system of the Spectrometer Solenoid cold mass.

Source of heat	MICE Note 236, Ref. [1]	Test 2B conditions with shield at 98 K (Sanders, Ref. [2])	Update of September 2010	Item Nb, see Notes
	(W)	(W)	(W)	
Radiation from 80 K	0.050	0.252	1.002	1
Radiation from 300 K	0.000	1.000	1.000	2
Support rods	0.310	1.100	1.100	3
Neck tubes	0.060	0.060	0.060	4
Cooler sleeves	0.750	0.750	0.750	5
Instrument wires	0.050	0.310	0.050	6
Magnet leads	0.870	0.870	0.870	7
SC wire joints	0.400	0.400	0.400	8
Residual gases	0.000	0.000	0.110	9
Radiation through pipes	0.000	0.250	0.500	10
LHe level probes	0.000	0.000	0.261	11
Cold shorts	0.000	0.000	0.000	12
Cryocooler underperformance	0.000	0.000	0.000	13
TAO + LHe fill line instability	0.000	0.000	0.000	14
Sum	**2.490**	**4.992**	**6.103**	

3. Summary of findings for the 4.2 K system

a. Comparison with Test 2B results

Bob Sanders [2] estimated the experimental thermal losses from the results of Test 2B [3] as 6.61 W to the 4.2 K system, without current (or at low current) and therefore with no heating of the superconducting wire joints. Disregarding the 0.4 W heating evaluated for the wire joints in Table 1, column 4 still has a missing heat load of 6.61 W – (6.103 –

0.400) W = 0.907 W. The most likely sources of this missing heat load are the underestimated shield temperature and imperfections of its MLI cover (Item 1 in Table 1), poor heat sinking of the support rods (Item 3), magnet leads with hotter top ends (Item 7), residual gas pressure up to 10 times higher (Item 9), thermo-acoustic oscillations in all He filled lines and 2-phase instabilities in the LHe fill line (Item 14). Some of these alone could explain the missing 0.9 W thermal loss.

b. Suggested actions

Clearly, it is best to act on all substantial items of Table 1, because there is no obvious single problem to be cured in order to reach the goal that static losses to 4.2 K fall well below the cooling power of the cryocoolers. We recommend aiming at a minimum of 2 W of excess cooling power at the nominal operating temperature under steady state with full current, in order to allow current ramping at a slow speed, and to cover the initially higher heat loads due to transient effects.

It has been proposed to mount two additional 2-stage cryocoolers on the magnets to reach a total nominal cooling power of 7.5 W at 4.2K. This alone could solve the problem, unless the additional coolers will increase thermal losses as well, and unless the performance of the cryocoolers degrades with time.

Therefore, it is legitimate to do all straightforward improvements in the cryogenic system in order to reduce the thermal losses to the 4.2K vessel and its connecting pipe work. The following improvements to the system are proposed. Note that several of these had already begun to be implemented by the vendor at the time of the last magnet training.

- Reduction of the temperature of the thermal shield by:
  - additional cryocooler capacity
  - local reinforcements of the shield using high-conductivity aluminum and copper
  - better assembly of the MLI blankets, notably on the bore tubes
  - improved thermal links to the 1st stages of the cryocoolers
- Reduction of the radiation heat load from 300K to 4.2K by:
  - improving coverage of holes in the shield using Cu foils, solid aluminum adhesive and MLI, and more careful assembly of the main MLI blankets
  - Coverage of the gap between the room temperature and shield bore tubes
- Reduction of the heat leak along the support rods by better intermediate heat sinking to the shield
- Improved thermal sinking of the instrumentation leads to the heat shield
- Reduction of the temperature of the hot ends of the HTS leads of the magnet
- Better insulation vacuum and its control by:
  - a larger pumpout port
  - use of a turbomolecular pump with high compression ratio for He gas
  - use of a cold cathode vacuum gauge, with a sensitivity better than 10^{-3} Pa; this will enable the monitoring of pumpdown and purge operations and monitoring of vacuum stability during operation
  - use of a helium leak detector to check the absence of a cold helium leak

- Use of LHe level gauge readout boxes with low duty cycle
- Installation and monitoring of fast pressure gauges on all lines susceptible to thermo-acoustic oscillations
- Heat sinking of the LHe precool line at the level of the top of the LHe vessel, and improved MLI wrapping of the line.

4. Notes for the 4.2 K system

The heat load to the 4.2 K system includes all heat input to parts at a temperature below that of the thermal shield, which acts as an intermediate heat sink and thermal intercept for thermal conduction, radiation and hot molecules. It is taken into account, however, that radiation and hot molecules may transport some heat to the 4.2 K system by direct leakage through various holes and gaps in the shield. The following comments refer to each line item of Table 1.

<u>Item 1:</u> The radiation from the thermal shield was found to be much larger than the design value for Magnet 2. The shield was expected to be normally well below 80K, as it was designed to operate in fact much colder locally because the top of the HTS leads is cooled by the same source of cold. Test 2B measurements indicate a 98K temperature close to the cryocooler connections. Given the fairly low heat conductivity of the Al 6061 material, the fact that the electrical split is in an unfavorable sector, the thinner material in the shield bore tube, and the large heat load to the shield bore tube, the average temperature of the shield was assumed to be 98K on the outer shell, 100K on the end plates, and 110K on the bore tube for this analysis. The MLI performance was taken from the measurements given in Ref. [3]; the packing density was estimated as 20 layers/cm everywhere except the shield bore tube, where the packing was evaluated to be about 50 layers/cm (measured roughly during a visit to Wang NMR Inc.). The radiation heat load on the 4.2 K vessel through the MLI then consists of 367 mW on the outer shell, 79 mW on the end plates, and 416 mW on the inner bore tube. The imperfections of the MLI were evaluated to yield 93 mW through cuts and joints, and 48 mW from the shield end plate through the gap between the shield and the helium vessel. Most of these numbers, in particular the temperatures in the various regions of the shield, are likely to still be optimistic.

<u>Item 2:</u> For the radiation leaking from 300K surfaces, the upper limit of Ref. [2] is assumed also in column 4. The value corresponds to 20 cm^2 total area of orifices connecting two cavities that behave similar to black bodies; this is plausible given the difficulty in blocking radiation through the 8 large supports of the 4.2K mass. It is worth noting that the thermal radiation also penetrates along the glass-epoxy composite of the cold mass support material.

<u>Item 3:</u> We have assumed the value evaluated in Ref. [2] here. This takes into account the hotter shield temperature (close to 100 K) and somewhat weak thermal links to the anchor points.

Items 4 and 5: These figures stem from the original design, and there is no argument against maintaining the values based on valid data and well-reported measurement.

Item 6: During our visit to Wang NMR Inc., we could not identify any heavy Cu instrumentation wires. Although the heat sinking of most of the wires, based mainly on thermal radiation, is somewhat deficient, we may maintain that the lower value of Ref. [1] is correct. It should be noted that electrically insulated low-conductivity wires can be heat sinked by thermal radiation, but this is not effective if their emitted radiation is bypassing the shield and absorbed by parts that are at a temperature below that of the shield.

Item 7: The heat leak through the HTS magnet leads is likely based on the data of the supplier. The number relevant to Test 2B might have to be increased above this, because the supplier recommends much colder top end temperatures around 60 K. A measurement of the temperature and current dependence of this heat load might be required, if the supplier data cannot be extrapolated with reliability. It would be good to ask the supplier also to deliver information on the maximum current at which the HTS leads are intrinsically stable at their upper end.

Item 8: This value was taken from Ref. [1]; this is likely to be pessimistic, as it corresponds to a power dissipated by 200 A current in resistors of 10 μΩ total resistance. At LHC, friction welded wires of similar size have a joint resistance well below 6 nΩ; we believe that the soft soldered joints of the MICE magnets have resistances between 1 nΩ and 10 nΩ, and therefore total resistive losses several orders of magnitude lower than the estimate given in Ref. [1].

Item 9: Ref. [3] presents data that permits us to evaluate the additional heat load through MLI from 50K to 4K, due to residual He gas with pressure p , as

$$\frac{\dot{Q}}{A} = 10^4 p \frac{\text{mW}}{\text{m}^2\text{Pa}} .$$

Assuming a residual gas pressure of 10^{-3} Pa (= 10^{-2} μbar), we get a heat load of roughly 110 mW on the helium vessel and its appendages. We have, however, no idea what the pressure might be, because the vacuum pressure gauge used during Test 2B was not sensitive to pressures below 1 μbar. However, the elastomer o-rings used on the top manifold do permeate He gas from the ambient atmosphere (this is abundant during transfers and quenches). Such permeation can easily yield a helium pressure of 10^{-2} μbar in the insulation vacuum, in the absence of a pump capable of evacuating helium gas at low pressure. The pump used in these tests can even backstream helium to make such a pressure in its inlet; the partial pressure of He remains about 10^{-1} μbar in the inlet of a rotary blade pump, unless the pump is ballasted with a pure gas such as N_2.

Item 10: This figure is doubled from Ref [2] because radiation and conduction act in parallel in several of the pipe connections (2 vent pipes, LHe inlet pipe etc.). These pipes have no radiation baffles, and heat sinking was either absent or ineffective.

<u>Item 11:</u> This value is based on 2 AMI level probes with 75 mA current, 11.6 Ω/inch resistance at 20 K, 10 inch length exposed to gas phase, and 20% duty cycle. We should inquire as to what is the effective duty cycle of the readout instrument used in Test 2B.

<u>Items 12-14:</u> These were not evaluated because there was no evidence for such heat loads. However, thermo-acoustic oscillations or other non-linear transient instabilities could well occur in the LHe fill line that is fairly long and is filled with 2-phase He during normal operation. The heat leak to this line (not evaluated yet) should be added as a direct load to the 4.2K vessel. One of the improvements suggested for the future tests consists of making a good thermal anchor from this tube to the main 4.2K vessel at the level of the top of the vessel.

5. Heat leak to the shield

Reference [3] describes the method of determining the heat load on the shield based on the knowledge of the cooling power of the first stages of the three 2-stage cryocoolers and the one single-stage cryocooler. This methods is probably as accurate as the thermometry on which the result is based and allows us to say that the experimental load of 277 W with no current in the magnet has an excess of 100 W to 105 W over the load estimated for Magnet 1 tested in summer 2008 [3]; the first magnet had no LN reservoir connected to the shield. It should be noted that 100 W corresponds to a thermal radiation heat load to about 1 m^2 of oxidized aluminium surface.

With a 250 A current in all five coils, the estimated heat load on the shield absorbed by the cryocoolers was 308 W; at the full design current of 275 A, the load would have been 322 W [3].

Thermal radiation through well-applied blankets can only contribute about 12 W of heat load on the shield. A substantial defect of the MLI was observed on the central bore, with a packing density of about 50 layers/cm; this issue could add about 10 W to the heat load. The direct radiation from the end plates of the vacuum vessel through the gap between the room temperature bore tube MLI wrap and the inner surface of the shield bore tube can add another 4 W (if the gap area is about 150 cm^2). Radiation leakage through cuts and joints that are poorly covered, corresponding to orifices of about 500 cm^2 total area, would contribute about 13 W. The total thermal radiation power on the shield would thus be 39 W, which cannot be adjusted much higher without discovering large surfaces unprotected by MLI.

There remain few additional sources of heat on the shield: the 8 shield supports, the heat sinks of the 8 helium vessel cold mass supports, and the conduction through pipe connections and wires. Because the conduction through pipes and wires is small compared with the supports made of fiberglass/epoxy, it would be legitimate to measure the thermal conduction integral through such supports under conditions resembling the 2B testing.

Reference [3] does not discuss the possible impact of the added LN reservoir on the heat load on the magnet shield. This reservoir was supposed to be thermally inert under the conditions of Test 2B. We have not fully verified the quality of the MLI in the area of the LN reservoir.

While the power of the first stages of even the three 2-stage cryocoolers and one single stage cryocooler is clearly sufficient to absorb the total heat load of 322 W on the shield with a reasonable cooler head temperature around 50K, Ref. [3] identified a problem of heat transport from the sources of the heat to the cold heads, which is being corrected with the proposed modifications. This problem cannot be solved by additional cryocoolers, but requires rather the improvement in the transfer of the heat from the various sources on one hand, and in the method and care of applying the MLI blankets and of covering the joints and feedthrough areas of pipe and other connections with solid Cu sheet, MLI and solid Al or Cu adhesive tape. Moreover, the heat sinking of the supports should be improved substantially with the improvements to the shield. These measures will at the same time reduce the heat load to the 4.2K system.

Summarizing, the following improvements are suggested, beyond the added cryocooler capacity:

- Improved wrapping of MLI blankets on the shield (2 x 15 layer blankets, density 20 layers/cm, with joints shifted; joints using Velcro attachments as in the LHC magnets).
- Improved coverage of MLI defects at the feedthroughs of pipes and supports.
- Improved MLI wrapping on the bore tubes, with 20 layers/cm density, with as many layers as can fit into the gap. The goal is to approximately close the gap, without much care to avoid the touching of MLI on both surfaces – this is likely to be much better than the compressed wrapping that was applied in the present blankets.

6. Additional Upgrades

The following upgrades are also being considered.

1) Installation of baffles in the vent lines to prevent direct radiation shine.
2) Addition of an LHe fill line into one of the vent lines, or addition of another input line for filling the LHe bath while the magnet has current. This line should terminate at a phase separator sitting above the surface of the LHe bath surface; the gas from the phase separator should be extracted so that is does not pass in the main LHe vessel.
3) Addition of a small gas outlet line passing through an exchanger that cools the joint area between the Cu and HTS leads. If the magnet is ramped down rapidly, the boil-off gas would cool the lead joints even if the single-stage cryocooler has failed.
4) UPS-powered interlocks that provide safe landing of the system when the magnet has current and there is a power failure.

7. References

1. MICE Note 236.
2. R. Sanders, “Spectrometer Magnet Heat Load”, Fermilab June 6, 2010.
3. Michael A. Green, “What happened with Spectrometer Magnet 2B”, LBNL 7 May 2010.
4. L. Dufay, C. Policella, J.-M. Rieubland and G. Vandoni, “A large test facility for heat load measurement down to 1.9 K”, LHC Project Report 510 (paper presented at CEC/ICMC 2001, July 2001, Madison, Wisconsin, USA).
5. L. Mazzone, G. Ratcliffe, J.M. Rieubland and G. Vandoni, “Measurements of Multilayer Insulation at High Boundary Temperature, Using Simple, Non-calorimetric Method”, Report CERN LHC /2002-18, presented at ICEC 19, Grenoble, July 2002.