

Author(s): **Tapio Niinikoski & Steve Virostek**  
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**TECHNICAL NOTE**



## **MICE Spectrometer Solenoid: Review of the Magnet Design**

## 1. Introduction

This document summarizes the findings and analysis made on the design and tests of the superconducting magnets of MICE, built in two types of cryostats, one housing the spectrometer solenoid with compensating coils and two matching coils, and the other housing the coupling coil.

## 2. Current lead burnout

The current lead burnout happened at a short 1.3 mm OD circular section near the 4 K feedthrough: my conclusions are in agreement with the analysis of Mike Green; i.e. this wire has a high quench propagation velocity combined with very short minimum propagating zone length ( $L_{MPZ} = 2.9$  cm) at full current. Any  $T$  fluctuation (e.g. due to wire movement) above  $T_{max}$  can then burn out this section of the lead in a very short time ( $< 5$  s). This does not lead to a quench of the coil because the coil is not heated and the quench cannot propagate along the stabilized sections of the lead, as the propagation velocity is negative there. The solder joints don't have time to melt before the copper in the lead is molten in  $< 5$  s. The voltage drop over the circular section before burnout is compensated by that of the power supply up to its maximum output potential; beyond this, the current will start ramping down at the rate determined by the potential over the protection diodes. After burnout, the circuit is open and all current of the coil passes through the diodes.

One could somewhat reduce the risk of such a burnout if the output potential of the power supply is reduced so that the supply would run at the limit of potential control rather than in the current control mode with large margin to voltage control mode. The maximum potential over the heated wire would then be that of the protection diodes; a progressively increasing current would bypass the wire and pass through the diodes, avoiding the thermal run-away that leads to burnout. However, this technique would only slightly increase the maximum current at which the burnout can happen, and the risk could remain in one or more of the connection wires at nominal full current. Therefore, the best overall approach would be to stabilize all of the sections of 1.3 mm wire by adding additional copper.

## 3. MLI

On the basis of the drawings and photographs taken during and after the assembly of the magnets, it is clear that the application of the MLI blankets is complicated because of the numerous penetrations extending from the 4 K vessel and through the thermal shield, by the warm bore access tube, and by the fact that much welding has to take place with MLI partially in place. The MLI type and general assembly technique appears to be adequate overall, but there are some weak zones and open questions that are discussed below.

- The MLI wrap in the central bore is applied to the OD of the shield inner bore and on the OD of the room temperature bore tube for the space between the shield and outer vessel. While this method is very easy to carry out, it leaves potentially large annular gaps through which radiation can bypass the MLI blankets. The resulting possibly inadequate connection of the MLI blanket from the ends of the cold mass to the OD of the shield bore tube may produce a substantial defect in the MLI. The effect of

this, however, is difficult to evaluate. Similarly, the room temperature surfaces of the outer vessel shine into the gap between the bore tubes of the outer vessel and the shield and can substantially contribute to the heat load onto the shield bore tube.

- In general, the effectiveness of MLI applied onto the hot surface is worse by a factor of about two, compared to the application of the MLI on the cold surface. This effect occurs because the Fuchs conductivity (and therefore reflectivity) of the Al film increases when the temperature of the film is reduced at high temperatures. This issue applies particularly to the MLI wrapped on the room temperature bore tube.
- MLI wrapping on all penetrations, particularly on the cold mass supports, should be closely inspected during assembly (see further comments below).

During my visit to Wang NMR Inc. in Livermore, both cryostats were in the disassembled state, the 4K vessels were available for inspection, the MLI had been unwrapped from one magnet, and the shields were open. The following observations were noted:

- the MLI shows crossed cuts at pass-throughs; 5 cm long cuts were left without reflective adhesive that would prevent direct IR radiation coupling through the slot.
- The vent and fill pipes were wrapped with  $\approx 5$  layers of MLI; the curving fill pipe had a helical wrap.
- The MLI wrapping is very compressed on the warm bore tube ( $\approx 20$  layers/4 mm) and on the shield bore tube ( $\approx 30$  layers/7 mm). The compression to a packing density of 50 layers/cm leads to about 6 times higher heat load compared with the usual packing of 20 layers/cm. The heat load to the bore tube of the shield from the room temperature bore tube is then about 9.5 W, while the rest of the MLI would pass about 6 W (onto the outer cylinder and end plates of the shield). The effect of the compression might be smaller for the load onto the 4 K vessel, but we don't have experimental numbers for this effect at lower temperatures.
- The above figure of 9.5 W assumes that the MLI is applied onto the cold surface; we don't have experimental data on the increase of the heat load when the MLI is pressed on the warm side. On the basis of the temperature dependence of the sheet resistance of the Al film we may estimate that the increase cannot be much higher than a factor of two.
- The MLI near the weld seams, which have to be made up when mounting the central bore tubes and end flanges of the shield and of the room temperature vacuum vessel, were protected by fiberglass cloth. However, about a 10 mm wide gap appears to remain unshielded by MLI on the cylinders that become inaccessible after welding. These sections and the end plates will shine onto the surrounding unshielded inner surfaces of the shield and of the 4 K vessel. These effective radiator surfaces can be evaluated to be around  $250 \text{ cm}^2$  at each end, emitting as much as 25 W towards the shield and 200 mW towards the 4 K vessel. If the annular gap towards the center behaves as an ideal orifice for the radiation, more than  $\frac{1}{2}$  of these heat loads will be absorbed on the colder surfaces.

#### 4. Helium Transfer and Cooldown Line(s)

- Helium transfer to the bottom of the magnet now happens via a pipe installed in the vacuum all the way from top of the cryostat to down below the magnet. It is not thermally clamped to 4K at the top of the helium vessel, and the section below the liquid level may see a substantial heat load from the shield. This pipe is a potential source of thermal acoustic oscillation or other types of instabilities related with the two phases of helium and boiling in the liquid phase.
- A refilling helium transfer line is recommended during the charging of current into the magnet, so as to keep the level all the time above the wire joint areas that are 45° off from the top of the magnet. Since hot helium gas should not be blown to the bottom of the magnet, it is suggested to add a fill line to the centre of one of the vent tubes. The tube can carry a few (2 or 3) semicircular baffles that reduce the access of thermal radiation from room temperature to 4K. The instrumentation wires can go down the same vent tube.
- If the new LHe fill line is judged to obstruct the vent line too much, we might consider adding a new LHe inlet line that terminates on top of the magnet. The vacuum isolated transfer line should have a diffuser at the end (to avoid the blowing of a warm jet of helium onto the coils). This new line will permit topping-up of the solenoid vessel during the charging of the magnet. Such refill may be important for the training, but possibly for normal operation as well. The refilling approach could be useful if one or more of the cryocoolers fail or become inefficient, or if thermal losses increase for any unforeseeable reason.
- Ideally, the cooldown line should run through one of the vent lines and should be extended to the manifold on the bottom of the solenoid vessel. This modification, however, would require the disassembly of the 4 K vessel and is out of question at this time. The present inlet line is likely to be thermally unstable, with the possibility of large thermal acoustic oscillations. A fast pressure gauge should be used at the inlet of this line to determine if there are oscillations present.

#### 5. Vent Lines

- Baffles should be used to help to reduce thermal radiation through the vent lines used for helium exhaust during a quench; however, care should be taken to keep the flow impedance sufficiently low so that the pressure will remain below the design limit inside the 4 K vessel.
- The baffles should be heat sunk to the shield; this will also help with the heat sinking of the leads.
- The turret for the vent tubes could also be made higher, thus reducing the heat leak to the shield.
- The vent tubes should be made larger, if possible, using thin-walled welded and rolled stainless steel tubes. Thinning by machining of thicker-walled pipes has been known to increase the risk of leaks, although the thinning method based on cold rolling is expensive (this is used in some dewar necks).

## 6. Thermal Shield

- The shield is made of 6061 Al, which has a lower thermal conductivity than 1100 Al.
- During the visit to Wang it was seen that the thermal connection to the Cu plate was made by flexible 1100 Al links.
- The observed large heat load is not well understood; a careful assembly of the MLI with a quality assurance procedure in parallel will likely help.
- The heat load along the cold mass supports to the shield may be poorly known and can possibly explain some of the excess heat load to 4K.
- The improvement of the thermal conductivity along the shield has already been implemented on one unit, but this will not affect the thermal load on the shield itself.
- The addition of more cryocoolers will substantially lower the temperature of the shield, and therefore the heat load to 4K through the supports will also be reduced.

## 7. Instrumentation Wires and Leads

- The type of wires used for instrumentation installed outside the helium circuit should be checked; any Cu wires should be replaced by phosphor bronze wires. These wires should also be used for any additional instrumentation. Quad flat 4-wire cable (phosphor bronze) made by LakeShore is very good for this application (good isolation, suitable resistivity and low conductivity, non-magnetic, easy to heat sink).
- Heat leak through the actual leads to 4K and to the 1st stage Cu plate has been measured in an off line apparatus; therefore these experimentally heat load values are considered reliable.
- The vent tube with instrumentation wires is not too crowded; a baffle insert can be installed if possible.

## 8. Instrumentation

- It would be useful to interlock the current supplies with the temperature sensors on the 1st stage cooling plate between the Cu and HTS leads; this feature could prevent the accidental burnout of the HTS leads in the case of a failure of the single-stage cryocooler.
- The temperature sensor types and locations are generally OK; some modifications will be needed to take into account the additional cryocoolers and improvements in the Cu plates and cryocooler sleeves. The thermometers outside the sleeves near the condensers can be removed, because the inner ones are sufficient for monitoring the operation of the second stages of the coolers.
- A temperature sensor should be added to the middle of the bore tube of the shield.
- An uninterruptible power supply could be considered for the single stage cryocooler and for the circuitry monitoring the critical potentials between the current lead taps.