Spectrometer Magnet Heat Load

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June 6, 2010

The following are my comments on the heat loads on the Spectrometer magnets.

4.2 K Heat Load Calculations

Table 1 below has three columns listing calculated heat loads on the 4.2K surfaces of the Spectrometer magnets. Column one has numbers from MICE design note 231. The third column has calculations for the Magnet 2B test where the shield temperature was measured in two locations at 84 K and 98 K, and for the purposes of calculations 98 K is used.

The second column assumes a perfect 80K shield with the cold mass support intercepts at 80 K, all 4.2 K surfaces completely covered by an actively cooled 80 K shield and all leads, G10 straps were individually wrapped in MLI. Perfection costs money, and perhaps not all of the improvements assumed in column 2 will occur because of excessive cost.

Table 1

	Base Design, MICE note 236 (W)	80K Shield (W) ideal design (no gaps in shield)	2B Test Conditions (98 K Shield) (W)
radiation from 80 K	~ 0.05	0.126	0.252
radiation from 300 K	not considered	0	0.1 - 1.0?
Cold Mass Support	~0.310	0.62	1.1
Neck Tubes	~0.060	use note 236 value	use note 236 value
Cooler Sleeve Tubes	~0.750	use note 236 value	use note 236 value
Instrument Wires	~0.050	0.05	0.05 - 0.31?
Magnet Leads	~0.87	use note 236 value	use note 236 value
Joule Heating in Joints	~0.40	use note 236 value	use note 236 value
Bad Vacuum Effect	not considered	0	??

	Base Design, MICE note 236 (W)	80K Shield (W) ideal design (no gaps in shield)	2B Test Conditions (98 K Shield) (W)
radiation in vent pipe	not considered	0	~ 0.25 max
AMI liquid level probe	0	0	?
cold short	0	?	?
cryocooler under performance	not considered	0	?
TOTAL	2.49	2.88	3.83 - 4.99

Radiation From 80 K Shield to Cold Mass

The design report (Ref 1, III-8-ii) gave a heat flux of 3.1e-7 W/cm^2 (3.1 e-3 W/m^2) due to radiation from an 80K shield with 15 layers of MLI. An investigation of the literature finds higher heat fluxes than the heat flux given in (Ref 1).

Figure 6 of Reference 2 shows heat flux measurements on 4.2 K surface from a 77K shield for NRC-2 insulation. For 10 - 30 layers the heat flux changes from 1.26e-2 to 1.30e-2 W/m^2. Table 1 of Reference 2 lists seven other insulation systems where the heat flux varied from 1.24e-2 to 2.88e-2 W/m^2.

Figure 3 of Reference 3 shows heat flux measurements for four types of multilayer insulation systems. For 10 to 20 layers, the heat flux varies from 3.5e-2 to 7.0e-2 W/m^2. Reference 4, Fig 2, shows 6.0e-2 to 9.0e-2 W/m^2 heat flux for three MLI system with 5 - 10 layers of MLI for radiation from a 80 K shield to a 20 K surface and a vacuum better than 1e-6 Torr.

Reference 5, Fig 3 shows 9.5e-3 to 2.e-2 W/m^2 heat flux to a 4.2 K surface from a 80K shield for six different insulation systems.

All of the heat flux data quoted above from the literature are significantly higher than the heat flux used in the Spectrometer magnet design calculations in Reference 1. The basis for this heat flux is not given in Reference 1. Until the basis for this heat flux is known it is prudent to consider the possibility of a heat flux that is consistent with data in the literature.

Assume the 1.26e-2 W/m^2 heat flux in reference 2 for an 80K shield, which is one of the lower numbers in the literature, but 4 times higher than the Spectrometer magnet design calculations in Reference 1. The surface area of the cold mass is about 10 m^2.

Using the 1.26e-2 W/m^2 heat flux of reference 2, the total radiation heat load from an 80 K is about 0.126 W.

Another factor to consider is the high shield temperature in the 2B magnet test. Reference 6 Table 8 reported two shield temperature in the 2B test 97.3 K and 84.3 K measured with platinum resistors at each end of the shield. Other sections of the shield must have been warmer, so assume an average temperature of 98 K for the 2B test.

Reference 5 presents heat flux onto a 4.2 K surface data from a variety of MLI insulation systems for shield temperatures from 40 K to over 120 K. Most of the data is for shields at 80 K and lower temperatures. If data points are picked (for the same insulation system) and interpolated at 98 K and compared to data at 80 K, the conclusion is that the radiation heat flux is about twice at 98 K as at 80 K. This is not very precise, but Reference 5 does show that changes in shield temperature will have a big effect on the radiation heat load. Assume for the 2B test that the radiation heat load was twice that at 80 K.

Radiation From 300K to Cold Mass

There are large gaps in the aluminum shield. There are eight 12” by 10” holes for the cold mass supports There are also holes for the cryocooler connections and leads. The total surface area of these holes is about ~1 m^2 If these holes are not properly covered with a metal material of significant thickness that is attached to and actively cooled by the shield then there will be significant additional radiation heat load on the 4.2 K cold mass. It it not sufficient to cover the holes with super insulation; that is merely adding additional layers of MLI to the 15 layers already on the cold mass.

As a worst case heat load through holes in the shield assume 1 W/m^2 and 1 m^2 area not shielded.

Neck Tube

The Neck tube heat load has not been looked at closely but it is one of the smaller heat loads.

Cooler Sleeve Supports

The cryocooler tests described in Ref (7) used the same sleeves with a slip-in cooler design. A 1.3 W re-liquefying rate was measured during the tests implying a 0.2 W heat load per sleeve support.

Instrument Wires

A number of instrument wires run from the inner vessel to 300 K surfaces. The exact number, gage, conductor metal of each wire is not readily available. Most of the wires are copper-nickel, but some of them are copper, probably electric tough pitch copper. None of the wires were thermally anchored to the shield.

The instrument list diagram lists 144 wires, apparently for pin connections on feedthroughs. Assume half or 72 of these wires went to the cold mass and the rest connected to the shield area. Each wire was assumed to be 40 cm long and a rather large diameter 28 gage. Eight of the wires were counted as electric tough pitch copper.

A heat load of 0.31 W was calculated based on the above assumptions. The thermal conductivity of ETP copper is about 10 times that of copper-nickel. About half of the heat load was due to the eight copper wires. As long as there are not too many more than 8 copper wires, the calculated heat load is probably conservative.

Magnet Leads

These leads are a standard product of a company that routinely makes magnet leads. It is a standard product which gives confidence in the reliability of the heat load prediction. Ref 6 recommended further testing of the leads to rule out possible resistive heating in the leads

Joule Heating In Joints

It is not apparent how this number in Table 1 was determined. Could the joule heating in the joints be bigger? If possible this should be measured during the operation of the magnet by the use of voltage taps. During the excess heat load measurements with a flow meter described in reference 6, the magnet was not powered. Therefore in determining the total heat load on an operating magnet from the magnet 2B test, Joule heating must be accounted for.

Bad Vacuum Effect

Before the Magnet 2B test, the magnet had been pumped by a roughing pump through a KF 40 fitting. The vacuum was in the low micron range as measured by a thermocouple gage. No other vacuum measurements were made during the test.

There are no ports for vacuum pumping the space between the cold mass and the shield. In an attempt to reduce radiation heat, the shield and the super insulation on it provides a very low conductance for vacuum pumping around the cold mass.

A bad vacuum can cause a significantly worse heat load to both the shield and the cold mass. The possibility of a bad vacuum must be considered. A bad vacuum has the potential for creating large heat loads. There are three sources for a bad vacuum, helium leak, air leak and residual moisture in the G10 and other surfaces.

Radiation in Vent Pipe

There are two 1 1/2” vent pipes at the top of the magnet. These pipes run straight down to the cold mass with no bends or baffles to reduce heat load. One vent pipe is reportedly so full of instrument wires that little radiation will shine through. By looking some of the schematics, it appears that the vent pipes might be intercepted by a strap connected to the shield about half way down the length of the pipe.

The heat load due to black body radiation from the top of one of the vent pipes was considered. The calculated black body heat load was divided by two and entered into Table 1, since only a fraction of it would reach the cold mass.

AMI Liquid Level Probes

The magnets each have two AMI superconducting liquid helium level probes. These can generate a significant amount of heat when operated. The heat load depends on the length of the probe. The electronic chassis for these devices has a "sample and hold" feature which greatly reduces the heat load. If these electronic chassis were set for continuous reading instead of sample and hold there would have been a significant heat load. Otherwise the heat load would have been very small.

Cold Short

If a 4.2 K surface touched part of the shield, then a very large heat load to the 4.2 K surface would exist. This perhaps is not likely, but to be thorough this possibility is listed. A cold short by itself could explain the excessive heat load to the cold mass.

Cryocooler Under Performance

The temperatures on and near the first and second stages of the cryocooler reported in the magnet 2B test as reported by Ref 6 are appear reasonable and there do not appear to be major problems with the cryocoolers. It is believed that all of the cryocoolers were tested.

During the 2B magnet test it was noted that when the liquid level was low the performance was worse. At times the magnet liquid helium level was 50% or less. This effect could be caused by the helium vapor becoming super heated and the heat exchanger not being designed to de-superheat the vapor.

The plenum below the cryocoolers is connected to the cold mass by two side by side 1/2" holes through which all helium vapor to the cryocoolers goes up and all the helium liquid from the cryocoolers travels down by gravity feed. The vapor and liquid flows share the same holes. This may have caused a flow restriction and reduced the overall performance. Current plans are to open this plenum up which is a good idea.

4.2 K Heat Load Measurements

Reference 6 determined 1.4 - 1.55W excess heat load in the 2B Magnet test from the helium vent rate from the magnet measured using a positive displacement flow meter. Since the pressure and temperature of the helium gas going through the flow meter was known the flow rate measurement was very accurate. However, the venting helium would have acted as a heat intercept in the vent pipe and would have reduced the heat load. This measurement was performed with the solenoid liquid level less than half full. Any superheating in the vapor passing through the gas cooled parts of the magnet would have caused an error in the excess heat flow calculation.

During part of the measurement process, the magnet was powered to only 100A, but no higher. Therefore the excess heat load measurement does not take into account the Joule heating in the coil joints.

It appears that Reference 6 might not have taken into account the fact that when the in the magnet is boiled off, the liquid volume must be replaced by an equal volume of vapor. The density of helium vapor is ~10% that of the liquid. Assume the excess heat load measurement is 10% over 1.55 W or 1.71 W. Add in the Joule heating from Table 1; the excess heat load becomes 2.11 W.

Add the total cryocooler cooling capacity (3 X 1.5 W per cryocooler) and the total heat load is 6.61 W. Compare that to the total calculated heat load for the 2B magnet test in column 3 of Table 1. The difference is 1.6 to 2.8 W of heat load unaccounted for.

Where could that extra heat load be coming from? The most likely culprits are bad vacuum and cold short. The rest the entries in Table 1 are not be completely accurate, but it seems unlikely they are more than a few tenths of a Watt off and will come no where near close to the 1.6-2.8 W unaccounted-for heat load.

Observations on the Thermal Shield.

The following are a list of observations related to the possible affects of a bad vacuum on the heat load.

Z'Ts calculations show that using the properties of G10, the heat load to the shield was twice as high as previous calculations. It is likely that the other G10 supports on the shield have higher heat loads than previously thought.

It appears that there might be shield intercepts on the vent pipes. If they exist, it is not clear if calculations have been done for the shield heat load due to those intercepts.

The cylindrical thermal shield (excluding the turret on top) has very few possible heat sources: radiation, its supports to the vacuum vessel, shield intercepts, a few instrument wires, and a possible cold short (which may not exist) to the vacuum vessel. That is all; any unexplained heat load on the cylindrical thermal shield comes from those sources and none other.

There were no significant cold shorts between the shield and the vacuum vessel. Such a cold short would have created a cold spot on the vacuum jacket surface. During magnet tests, the vacuum vessel external surface was careful looked over for cold spots and none was found.

Reference 8, page 3, (i) states that (for Magnet 2A test I think it was) they did calculations assuming the measured 105 K thermal shield temperature and 70 K copper plate temperature then calculated 69 W of heat flow from the thermal shield to the copper plate. It appears that the review panel did not think a 65 W heat load credible because it would have required a 4 W/m^2 radiation heat load. The review panel postulated that this 65 W heat load was not real and instead there could have been a "extremely bad contact in the chain connecting copper plate and shield". Note that the review panel was not faulting a too thin piece of metal or too low thermal conductivity to conduct the expected 10-15W heat load, but a bad contact i.e. a gap or imperfect joints.

In magnet 2B, major changes were made to the connections between the copper plate and the thermal shield. The temperatures reported in reference 6 show that both the thermal shield and the copper plate are lower in temperature, but the temperature difference between the copper plate and shield remained huge, ~ 20 - 30K. Either magnet 2B still has a bad contact (this essentially means flawed workmanship) in the connection between the shield and the copper plate or the 65 W heat load calculated in reference 8 in the thermal shield is real and still exists in magnet 2B.

Reference 6 determined the overall shield heat load (including the copper plate) from the cryocooler 1st stage temperatures. The overall shield heat load of 272 W was 100 W in excess over the calculated 80K heat load. It appears likely that a large fraction of the excess shield heat load is due to the 65 W calculated by Reference 8. Part of the 65 W could be due to radiation made worse by a bad vacuum.

References:

(1) Chapter III, Design Of Cryostat Assembly from Final Engineering Design For MICE Spectrometer Solenoid Magnets, LBL P/ O. 6806258

(2) Techniques For Reducing Radiation Heat Transfer Between 77 And 4.2 K, E. M. W. Leuung et. al., Advances In Cryogenic Engineering, Vol 25, p 489

(3) Thermal Performance Of Multilayer Insulation Down To 4.2 K, A. Senthil Kumar et. al., Advances In Cryogenic Engineering, Vol 45, p 1675

(4) Thermal Performance of Various Multilayer Insulation Systems Below 80K, W. N. Boroski, April 1992, Fermilab-Conf-92/96

(5) Experimental Studies Of MLI Systems At Very Low Boundary Temperatures, I. E. Spradley et. al., Advances In Cryogenic Engineering, Vol 35, p477, Plenum Press, New York 1990

(6) What Happened with Spectrometer Magnet 2B, M.A.Green, LBNL, May 7, 2010

(7) Greens work on Cooler Test

(8) Preliminary Report of the MICE Spectrometer Solenoid Review Committee, Nov 19, 2009

(9) About Mice Spectrometer Solenoid / Heat Load though Cold Mass Support, Zhijing Tang, June 2, 2010, Fermilab