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Cc: Bob Sanders, Vladimir Kashikhin

Subject: MICE Committee Recommendations

Steve, Mike, Alan,

Attached please find four appendices, (1) comments from our committee just after the meeting and tour at LBNL / Wang NMR in May; (2) an independent analysis of the Spectrometer Magnet Heat Load from Bob Sanders; (3) a note on potential vacuum system upgrades from Cary Kendziora; and (4) a review of possible electromagnetic failure scenarios by Vladimir Kashikhin. Though a complete set of drawings is not available, LBNL supplied pictures, notes, and other documents to support the efforts in a timely manner.

Currently the disassembly of magnet 2B is ongoing; the magnet is not opened such that the actual failure point of the leads in the last test has been seen, and reassembly and test of the next magnet is not expected before October of this year. It is our belief that the next test of a MICE Spectrometer Magnet must be a success. If no smoking gun is found during the disassembly or through continuing analysis by the MICE group, conservative steps should be taken to ensure that during the next test the magnet can be adequately cooled and protected (including instrumentation to confirm that this is so). In effect the next magnet should be treated as a fully instrumented prototype.

To create this prototype requires a thorough engineering understanding of the design. At this point we do not believe this understanding exists. Without this, the next iteration will continue more in the line of 'trial and error' as opposed to an engineering solution. As such, large contingencies in the cooling system would be required, and a very conservative approach required for the magnet protection. This could easily result in extra work in assembly that later on is discovered to not be needed. We do not believe this is the best course of action. We recommend:

- Implementation of the vacuum pumping system as recommended in attachment 3. Install radiation baffles in the shield to permit adequate vacuum pumping between the shield and the cold mass. Examples are available from CDF and Minerva.
- Create a set of drawings for the current design, and for all future modifications. At absolute minimum the drawings should document the design well enough to allow engineering calculations, and will be needed in any case for the safety review process as a subset of the required documentation.
- Review in detail/redo all calculations of the heat loads on the magnet. The use of cryocoolers makes the heat load analysis critical, given there is no margin to increase capacity after the fact. Though the analysis of Magnet 2 and our analysis basically agree, to move forward without applying a large contingency on the expected heat load would be risky. A more detailed analysis, based on the actual design, is required.

- Review in detail and redo all the electromagnetic calculations of the magnet system for both test and operational conditions.
- Review the instrumentation plan such that the thermal and electromagnetic calculations can be confirmed during the test.
- Complete calculations and documentation demonstrating the mechanical support of the magnet, leads, piping and other internal components are adequate including effects due to motion with cooldown.
- Consider if it is now time to remove the project from Wang NMR and complete the magnets elsewhere. We fully understand that a decision to move along this path has serious implications. However, we feel that this project is beyond the capabilities of Wang NMR and can only be successfully completed there if major engineering and technical resources (beyond the existing LBNL team) are supplied by the MICE collaboration or one of the national labs to assist Wang NMR. We have a concern that even if these additional resources are made available, intellectual property issues may make integration of these additional resources with the Wang NMR team problematic.

Finally in the current plan, the device will be operated at Fermilab and RAL. The MICE team should consult with the safety panels in both locations to confirm that the modifications being undertaken are consistent with end-user requirements, and the documentation required for the safety reviews is available to the respective review panels.

MICE Spectrometer Meeting

12 (LBNL) / 13(Wang NMR) May 2010 Meeting

Jim Kerby, Bob Sanders, Vladimir Kashikhin (committee)

Alan Bross (FNAL), Mike Zisman (LBNL), Steve Virostek (LBNL), Mike Green (LBNL – ret.) (MICE), Bert Wang (Wang NMR)

The committee was called by the Fermilab Directorate to assess and report on the status of the MICE Spectrometer Magnets 1 and 2. The conversations included in the two meetings on May 12 at LBNL and May 13 at Wang NMR were honest and open, and the committee thanks the MICE team for their supplying backup information and organizing the meetings on such short notice.

Findings:
The committee was supplied with engineering notes and drawings that largely supported the initial design of the magnets. These notes centered on cryostat and pressure vessel safety issues, including, for instance, a heat load estimate, and an analysis for the motion of the magnet support relative to the vacuum vessel with cooldown. Within the engineering notes as supplied, there were in places inconsistencies in numbers, and in at least one place several pages were missing.

The cryocooler performance as tested does appear consistent with that of the specifications. We did not see any calculations or test on the design of the plenum connecting the 2nd stage of the cryocoolers with the magnet helium circuit.

In addition, based on the results from Magnet 1, Magnet 2 underwent two serial modifications in an attempt to lower the operating shield temperature. First, a LN2 reservoir was added. After operational difficulties appeared with the reservoir, it was replaced by a single stage cryocooler. Both of these changes included modifications to the shield, MLI, and in places the vacuum vessel, which are not documented by drawings or calculations to support the changes. Beyond this, we did not see engineering drawings or heat transfer or mechanical calculations supporting the shield design changes being implemented in magnet 1.

The MICE solenoid vacuum can is approximately 3 m long with an outer radius of approximately 1.5 m. The inner bore is 40 cm. The pump out was done via a 25 mm KF flange and pipe through a roughly 2 m flex hose to a mechanical pump. There was an auxiliary pump out for attachment to a leak detector. Vacuum instrumentation consisted only of thermocouple gauges and therefore the actual vacuum could not be determined during cool down and during magnet operations. The magnets were successfully leak checked before each test.

In addition to the vacuum instrumentation mentioned, a complete instrumentation list now exists, though there are questions about what type and gauge of wire has been used in Magnet 2, and in some places there are doubts as to whether the sensors were properly affixed. There were no voltage taps or strain gauges read out during the test.

A visual inspection of magnet 2, including the partially disassembled vacuum jacket around the leads, revealed gaps in the MLI and shield that could lead to direct shine from the vacuum vessel to internal parts at lower temperatures. While the workmanship associated with MLI associated with the original shield and turret design appeared quite good, that around the leads and in the region of the turret extension for the additional cryocooler looked less good, and in fact quite limited by difficulties faced during construction of the added section. Visual inspection suggested that in addition to a section of ~12 sq inches of direct shine, there were several sections of MLI installed in such a way as to cause a thermal short, or where hotter surfaces of the leads could radiatively exchange with cooler surface of an adjacent lead.

Using the data available and by conducting several additional cryogenic tests, a report detailing the heat loads through various designs and tests of Magnet 1 and 2 has been completed. As a result the heat load is known with accuracy of several watts at the 4.2 K level and to within 100 W at 50- 80K.

The quench protection system is a passive type where all magnetic field energy is dissipated inside the cold mass of the LHe vessel. Such systems are regularly and successfully used for MRI magnets.

MICE Note 276 specifies the quench scenario should be OK without the coils heating to more than 204 K, inner coil voltages kept below 1.8 kV, and the 2.8 MJ magnetic field energy evenly dissipated in coils, Al 6061-T6 mandrel and the inner 20 mOhm shunts through bidirectional cold diodes. Furthermore the analysis assumes a fast ~2 s quench transfer between the solenoid section through “quench back” when eddy currents induced in the Al mandrel heat the mandrel, which then drives the superconducting coils into a normal resistive state.

Comments:

The engineering analysis of the original magnet design was not complete. The support of the shield with cooldown, the relative motions of the shield, magnet, and cryocoolers with cooldown, the forces associated with these thermal displacements, a FEM analysis of the solenoid mechanical structure after cooldown and at operation under Lorentz forces (including the prestress of the outer Al bandage), and a calculation of the influence of the ferromagnetic end plate on the inner solenoid mechanics are examples of detailed calculations that the committee did not see.
For instance, the Cryomech AL330 manual specifies vertical orientation only for the cryo cooler and a maximum weight of 22 lbs attached to the cold head. The cold head is mechanically attached to the shield and it is not obvious if the connection is flexible enough. If the shield moves laterally due to thermal contractions then lateral forces could result on the cold head, and would have the same effect as mounting the cryocooler horizontally. Not following the manufacturer’s specification could adversely affect the performance or possibly void the warranty.

The magnetic design initially was made by the MICE team and included in the specification for the manufacturer in the form of superconducting coil dimensions, number of turns, schematics, currents, and forces. We did not find the complete magnetic design document, including the main and fringe field maps (which are critical for superconducting coils and HTS leads operation). There is no evidence that mutual inductances between coils were taken into account during a quench coupled thermal-magnetic analysis. The results of full quench analysis were not reported in MICE notes.

Implementation of the passive quench protection system in the MICE magnet system, which is larger and more complex than a standard MRI system, requires a coupled analysis of all electromagnetic and transient processes. No documents exist describing such type analysis for the last 2B solenoid test when all coils were connected in series.

By inspection the shield conduction with the modifications as now completed in Magnet 1 should be greatly improved, however we have no way to verify the performance expected with the changes.

As the LN2 reservoir was added at step 2A, similar to that seen by the committee around the new cryocooler for version 2B, potentially the workmanship around the LN2 reservoir was also not up to normal standards and could explain some of the heat load increase.

The dismissal of temperature data due to assumed errors in installation, and lack of cold vacuum data makes the analysis of the thermal performance very difficult. The lack of strain gauges and voltage taps makes the analysis of quenches impossible. This is why the quench events: currents, voltages, quench propagation velocities, quench back effects, energy dissipation in different areas are experimentally unknown.

The engineering calculations of expected thermal heat loads are based on the design of previously manufactured MRI magnets. The MICE spectrometer magnets are larger and in some ways more complex than the NMR magnets, and perhaps more importantly the accuracy of these calculations is not enough for correct estimation of heat loads for a system using cryocoolers.

Confirming the vacuum during operation would also remove, or confirm, a major contributor to the heat load. Best practices for a vacuum space of this size would indicate a pump out port of a minimum of 4" and up to 6" pumped out with a 150-200 L/s turbo. The large volume of MLI used in this magnet also points to the need for much greater pump capacity. Vacuum instrumentation should include a device that can monitor the vacuum at all times, i.e., below that which a thermocouple gauge is sensitive.

The quench scenario in MICE Note 276 may be not correct if the heat transfer from the mandrel to the coils is slowed for several seconds due to the coil ground insulation (no less than 1.5 mm thick). It may be possible that a quench in one section will cause a current rise in neighboring short circuited sections going through coil shunts, and the induced current will circulate longer time than expected and quench will be longer than several seconds.

There have been two failures in the leads during the tests to date. The design of the leads, margin, and cooling should be checked.

Recommendations

The committee does not believe there is a single 'smoking gun' causing the magnet performance issues. The magnet system design has a very low operational margin, and the lack of a detailed analysis of the original design, and further of the implemented changes, makes recommending specific actions difficult. Initial recommendations therefore focus on information gathering and development of engineering tools consistent with the current designs. Further recommendations will depend on what the inspections and calculations reveal.

(1) LBNL personnel should be present for ALL aspects of the disassembly of Magnet 2 to document and photograph the as built design, the fabrication methods and techniques, and fully document the failure of Magnet 2B.
(2) Open the magnet 2B cold mass and investigate the area of open circuit in the coil E1 leads.
(3) Engineering drawings for the changes already made to Magnet 1 should be generated and used to verify by calculation the usefulness of the changes.
(4) Engineering drawings for any future changes to Magnet 1 must be made before fabrication continues.
(5) Redo the original heat load studies to set a baseline heat load estimate. Update the estimate for each of the configurations tested, and compare to the results. Use the Magnet 2B disassembly record to update the estimate for comparison with the tests.
(6) Complete the full 3D FEM thermal analysis including all heat loads.
(7) Carefully inspect the attachment of the temperature sensors in magnet 2B during the disassembly process.
(8) As much as possible cover the entire surface of the 4.5K components with the actively cooled shield. Where not perform calculations to see what the effect is.
(9) Wrap the individual leads with super insulation
(10)Add a step to the QA plan to inspect the insulation before it is sealed.
(11)Evaluate the heat load in the present design due to the cold mass supports. Include radiation and the thermal resistance of the copper strap that connects the shield to the cold mass intercept. Evaluate the heat load if the the shield were extended over the length of the coldmass support and the big hole around the cold mass support were shielded. Consider improving the copper strap if it provides much thermal resistance.
(12)Review the vent lines for potential thermal oscillations
(13)Evaluate the heat load through the vent lines and look for ways to improve.
(14)A complete evaluation of the displacements and forces due to cool down/shrinkage should be done. The loads imposed on the cryocoolers in particular should be checked.
(15)Replace copper instrumentation wires by CuNi to reduce a heat load. Consider instrumentation wires cross-section reduction to reduce the heat load.
(16)Perform coupled magnetic and thermal transient FEM analysis for varies quench scenarios.
(17) Improve the cold leads thermal and mechanical stability by adding a extra copper and superconductor.
(18)Implement before the next test a fast DAQ system for continuous monitoring voltage tap signals such as routinely used in LBNL (A. Litzke) and FNAL (R. Carcagno, D. Orris).
(19)Monitor during tests stress/strain and thermal loads on all supports.
(20)On the basis of tests define the optimal number of cryocoolers.
(21)Consider the opportunity of using a small cryoplant or LHe transfer line as opposed to cryocoolers. Compare capital and operational expenses between cryocoolers vs. cryoplant or dewars.
(22)A large pump port should be added to the magnet. It should have a gate valve so that the pumping system can be isolated and a 150-200 L/sec turbo pump should be used. Any auxiliary pumping ports should have isolation valves between the pump and the tank. Vacuum instrumentation such as a cold-cathode gauge should be added so that the vacuum can be monitored during the entire cooldown procedure.

Spectrometer Magnet Heat Load

R Sanders, Fermilab
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

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10 July 2010

To: MICE Spectrometer Review Committee File

Subject: Recommendation on vacuum system for MICE magnet email

Findings

The MICE solenoid vacuum can is approximately 3 m long with an outer radius of approximately 1.5 m. The inner bore is 40 cm. The pump out was done via a 25 mm KF flange and pipe through a roughly 2 m flex hose to a mechanical pump. There was an auxiliary pump out for attachment to a leak detector. Vacuum instrumentation consisted only of thermocouple gauges and therefore the actual vacuum could not be determined during cool down and during magnet operations.

Comments

Best practices for a vacuum space of this size would indicate a pump out port of a minimum of 4" and up to 6" pumped out with a 150-200 L/s turbo. The large volume of MLI used in this magnet also points to the need for much greater pump capacity. Vacuum instrumentation should include a device that can monitor the vacuum at all times, i.e., below that which a thermocouple gauge is sensitive. A vacuum of 10^{-5} T assumes good performance. However, a vacuum better than 10^{-3} and greater than 10^{-5} does not guarantee the necessary performance as can be seen from the figure given below (from Boroski et al., FERMILAB Conf-92/96).

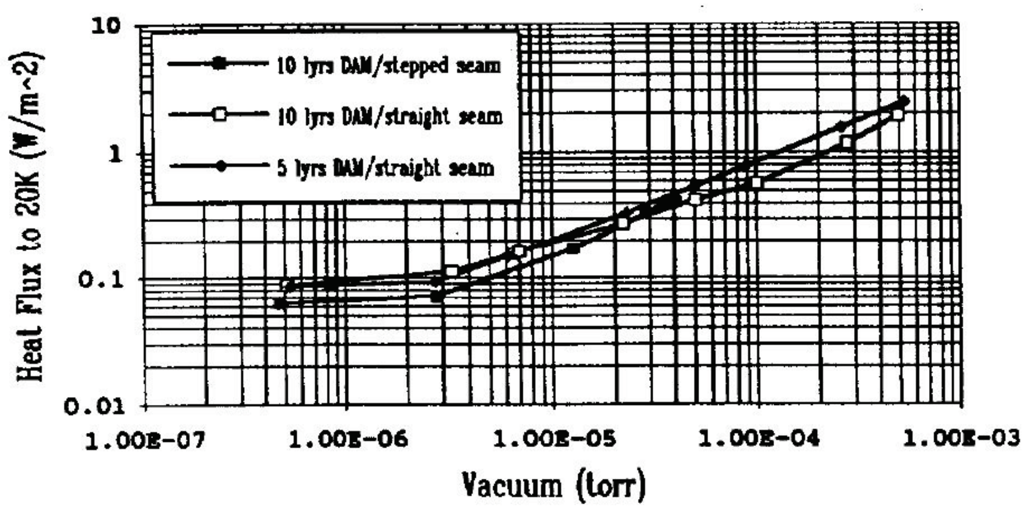

Figure 2. Heat flux through MLI systems near 20K

Recommendations

A large pump port should be added to the magnet. It should have a gate valve so that the pumping system can be isolated and a 150-200 L/sec turbo pump should be used. Any auxiliary pumping ports should have isolation valves between the pump and the tank. Vacuum instrumentation such as a cold-cathode gauge should be added so that the vacuum can be monitored during the entire cooldown procedure.

The following is taken from the text of an email sent 24 June 2010 from Cary Kendziora to Alan Bross regarding recommendations for the MICE vacuum system.

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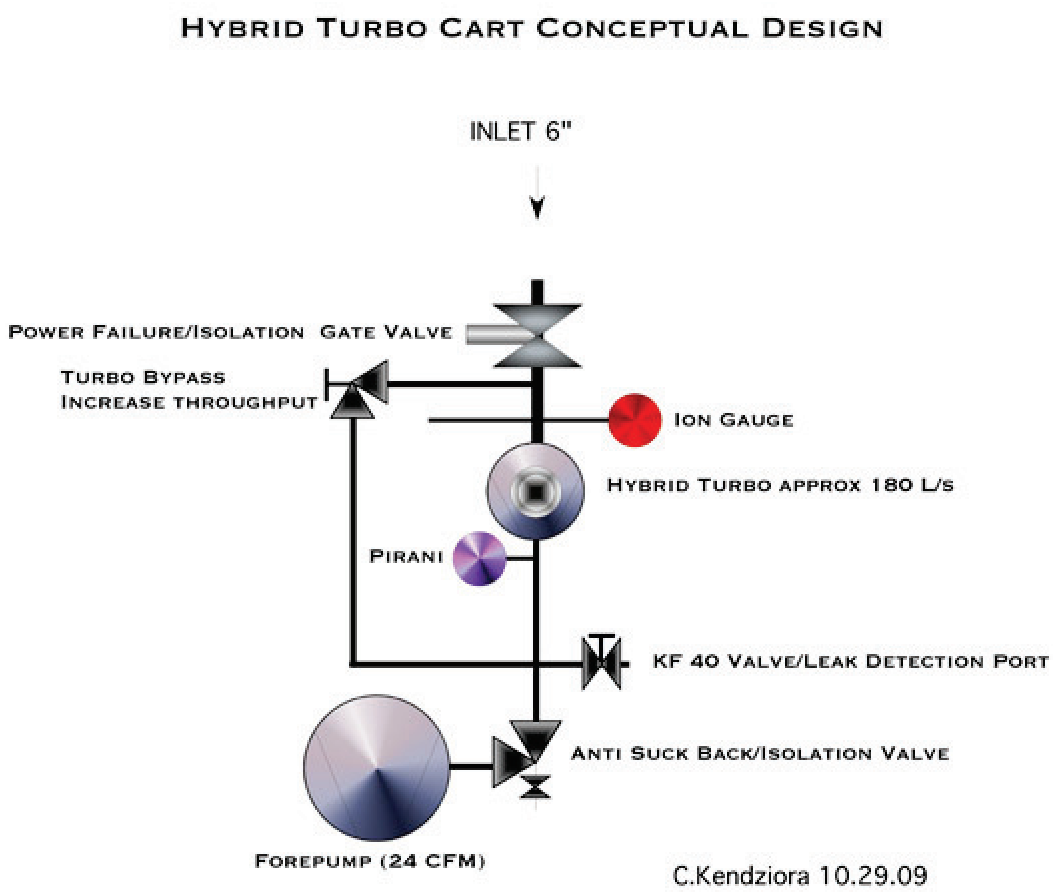
I suggest that the vacuum pressure required should be **10-5 torr**. Ultimately when the device is cold it will be at 10-7. In order to achieve this, care needs to put into the assembly to obtain a reasonable cleanliness, virtual leaks and materials that outgas should be avoided. There should be an isolation gate valve mounted directly on chamber and the turbo (preferably hybrid) directly mounted on the valve maximizing the throughput to the turbo. The foreline can be a KF 40. A design for a turbo that can be used as a baseline design is shown here:



MICE Spectrometer Solenoid 2B Issues

V.S. Kashikhin, July 19, 2010

The MICE Solenoid 2B review was requested by the FNAL Directorate because of several magnet system failures during tests at the vendor site. This report is based on findings during a vist to WANG NMR (See Appendix), discussions at LBNL, and MICE Notes [1] –[12]. The report is related to the possible failure scenarios and concentrates on the electromagnetic nature of these issues. In general there were two types of failures:

- Burned HTS current lead (See Fig. 1) at 238 A current and 81K leads temperature [11].
- Coil M2 open circuit after the 257 A quench.

Regarding the first item above, after modifications the solenoid 2B was successfully cooled down to 4.5 K, the helium vessel filled with LHe, and HTS leads were operated at reasonable temperature, 50 K. Nevertheless, additional losses during quench could overheat HTS current leads, and busses. These areas should be properly modeled and investigated to avoid potential future HTS lead failures.

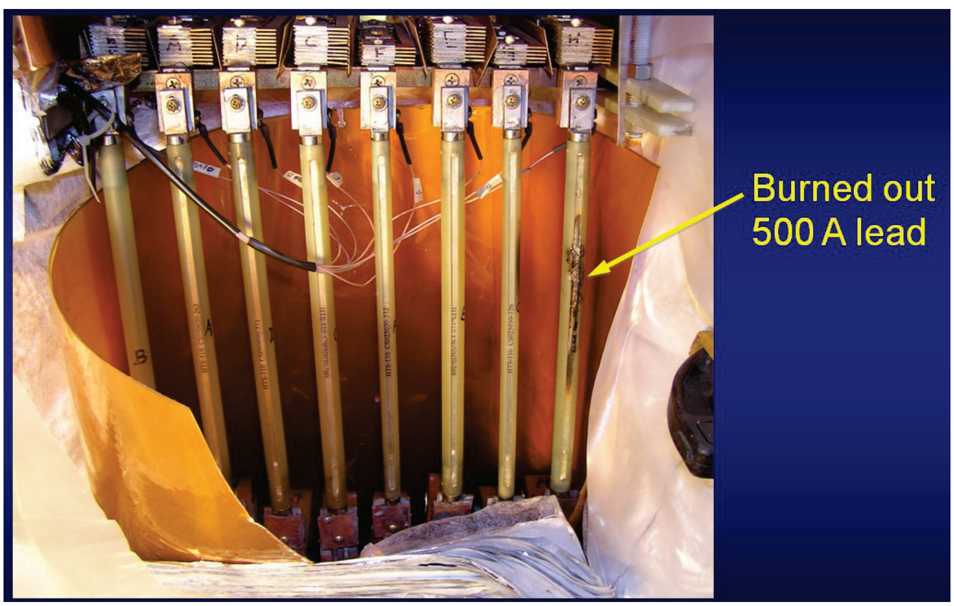


Fig. 1 Magnet 2 burned out HTS lead.

1. Solenoid Magnetic Field

The spectrometer solenoid consists of 5 superconducting coils (See Fig.2): matching coils M1, M2, end coils E1, E2, and the central coil C. The coils were wound on an Al 6061-T6 mandrel using a single strand of NbTi superconductor with outer dimensions 1.0 mm x 1.6 mm, Cu:Sc ratio 3.5, and a critical current >760 A at 4.2 K and 5 T magnetic field. The cold mass is mounted inside a LHe vessel.

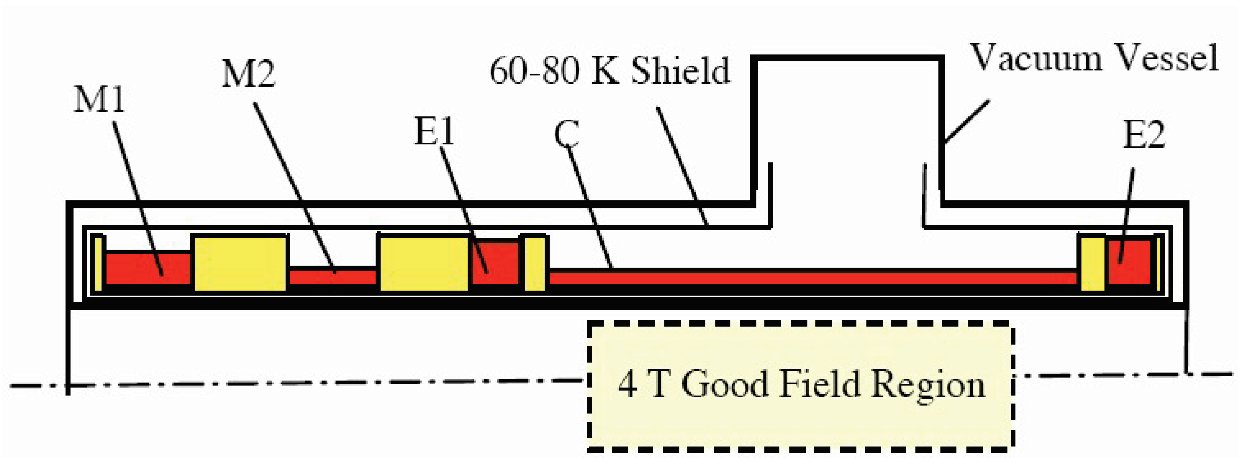


Fig. 2 Spectrometer Solenoid cross-section.

All coils, M1-M2-E1-C-E2, during tests were connected in series and powered from a single 300 A current main power supply (See Fig. 3, right). The magnetic field distribution at this DC current was checked using the OPERA2D code.

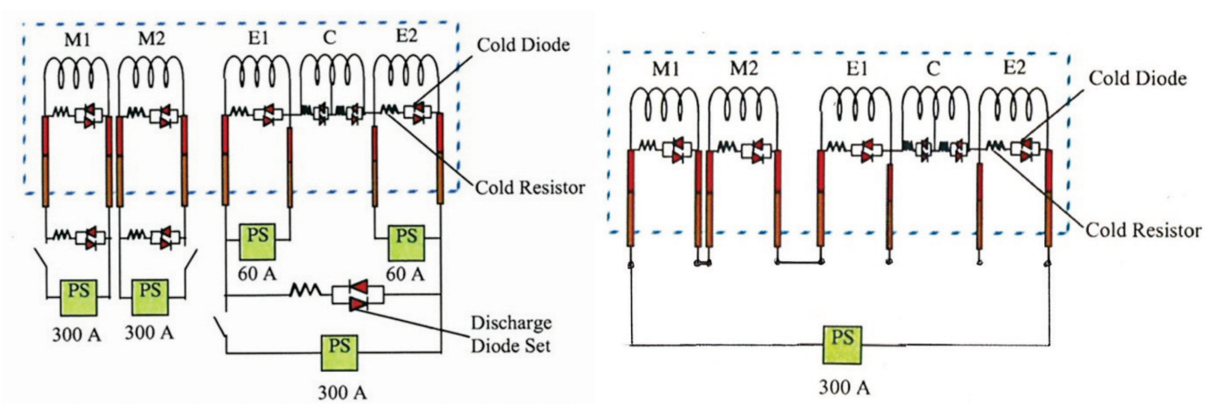


Fig. 3 Solenoid electrical circuit schemes: original (left), 2B test (right).

The model geometry and the flux density in the coils at 257 A is shown in Fig. 4, Fig. 5, and in the area of HTS current leads in Fig. 6.

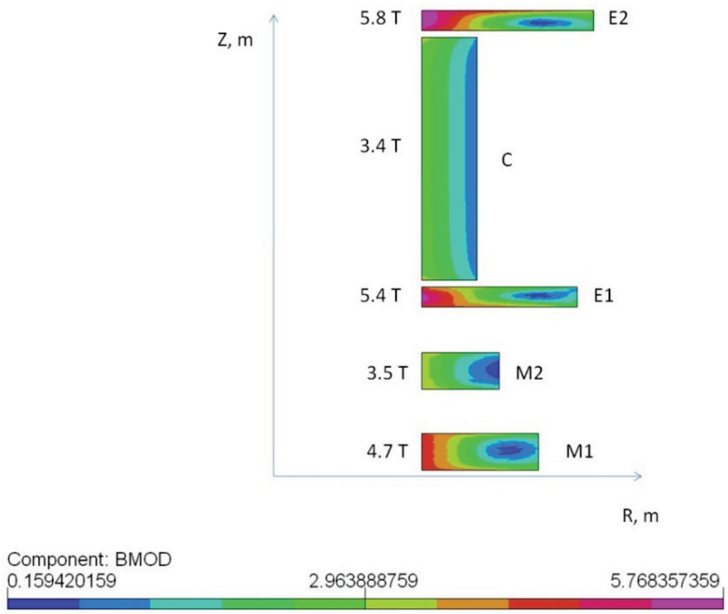


Fig. 4 Model geometry and flux density in the coils.

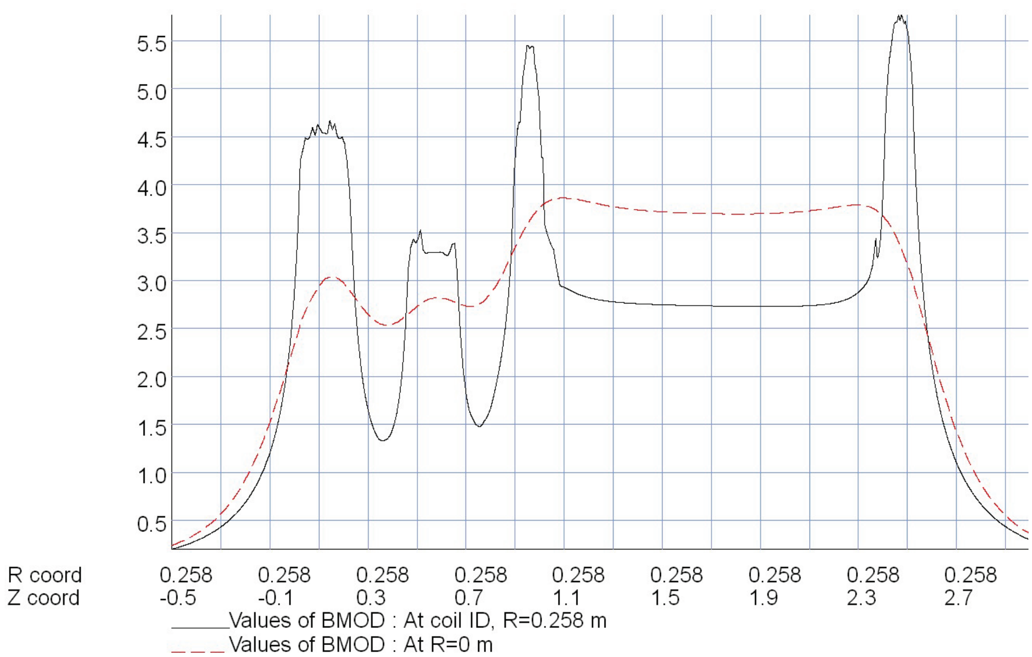


Fig. 5 Flux density distribution in Z – direction for the coil ID and the central axis Z at current 257 A.

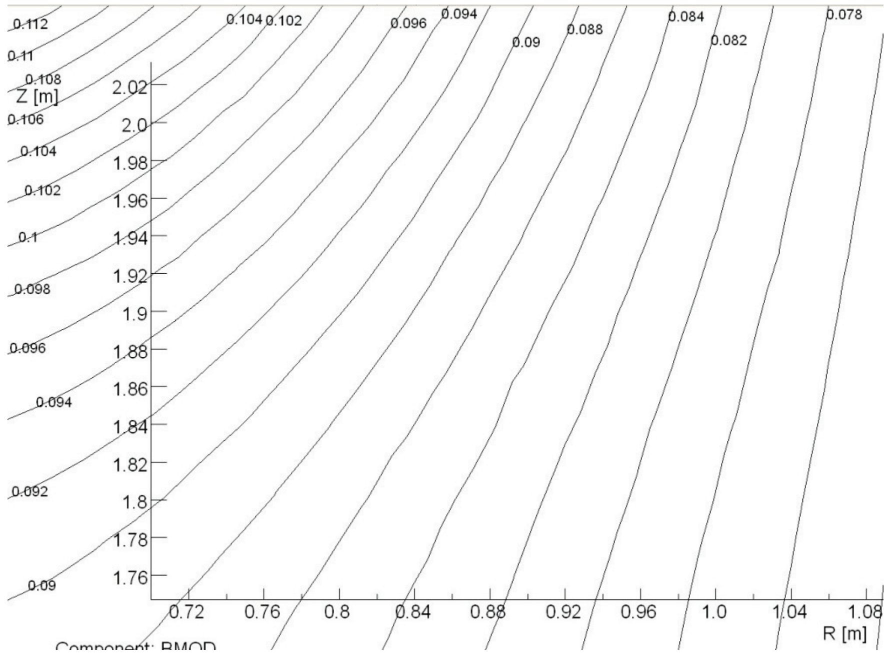


Fig. 6 Flux density Bmod, T in the HTS area at current 257 A.

2. HTS Lead Considerations

The steady state magnetic field analysis showed that the calculated peak fields are in agreement with the MICE documentation. Nevertheless, it should be noted that manner in which the current leads were installed does not necessarily result in the position of the leads being fully known after cooldown (See. Fig. 7, Fig. 8).

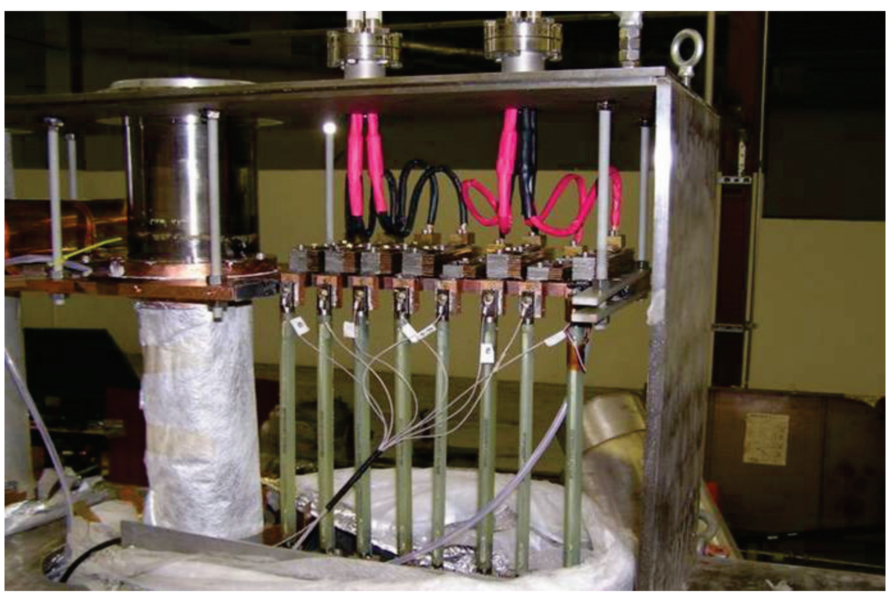


Fig. 7. Upper and HTS leads configuration.

In addition the cold mass axis position was not absolutely fixed during assembly, there is some chance that it could deviate from the outer vacuum vessel axis. Between the two effects, there is some chance the HTS current leads could catch substantial perpendicular field component which will reduce the lead performance (See Fig. 9). This field also could generate circulating currents in the HTS which will additionally heat up these leads during ramping. A more complete analysis and assembly plan should be completed to better understand the position of the leads. If warranted, the addition of a ferromagnetic shield around these current leads will eliminate this effect.

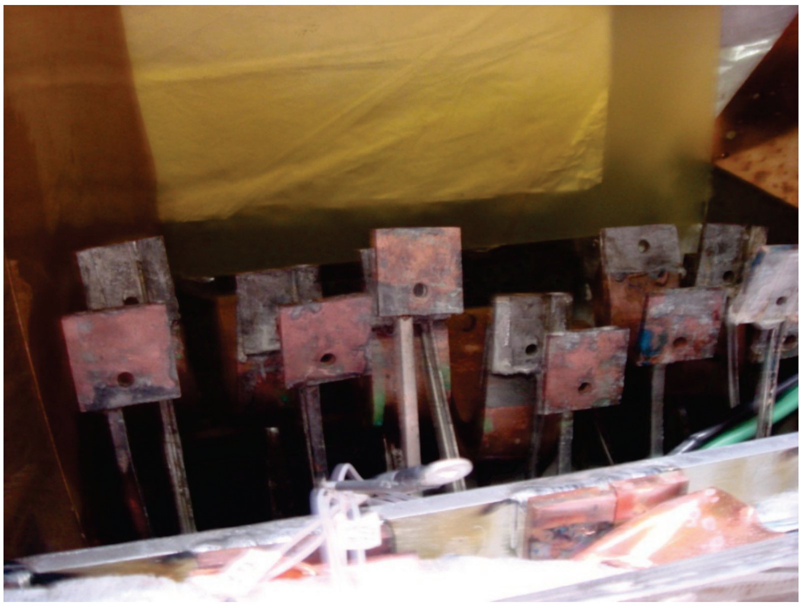


Fig. 8 Flags connected to HTS leads. Leads are removed.

The HTS-110 current lead is capable of carrying, without external magnetic field, 500 A at 65K measured at the warm end.

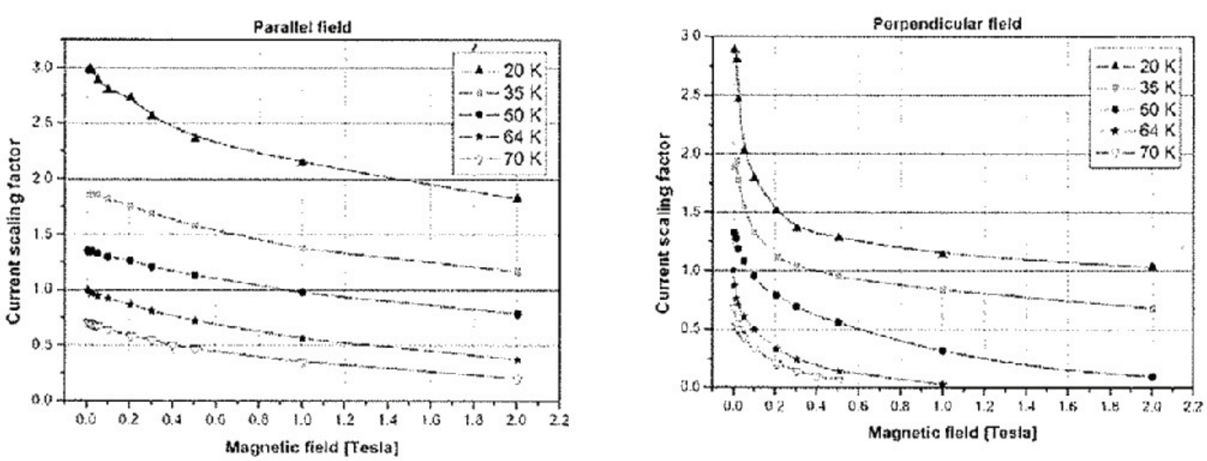


Fig. 9 HTS-110 current factor vs. field and temperature.

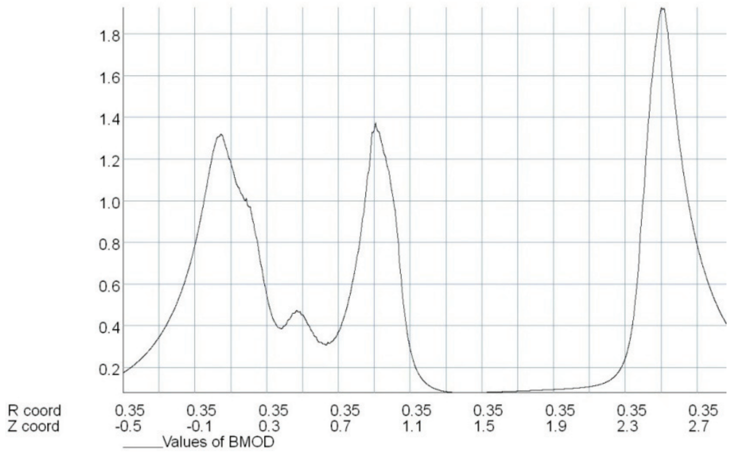


Fig. 10 Flux density on the surface of LHe vessel (R=0.35 m) and in a cold feedthrough areas (R=0.35 m, Z=~1.8 m).

3. LTS Lead Considerations

Our calculation showed that the field in the cold feedthrough area is less than 0.1 T (See Fig. 10). In this area there should not be any noticeable Lorentz forces and the field influence on the superconductor performance, even without further stabilization, should not be significant (See Fig. 11).

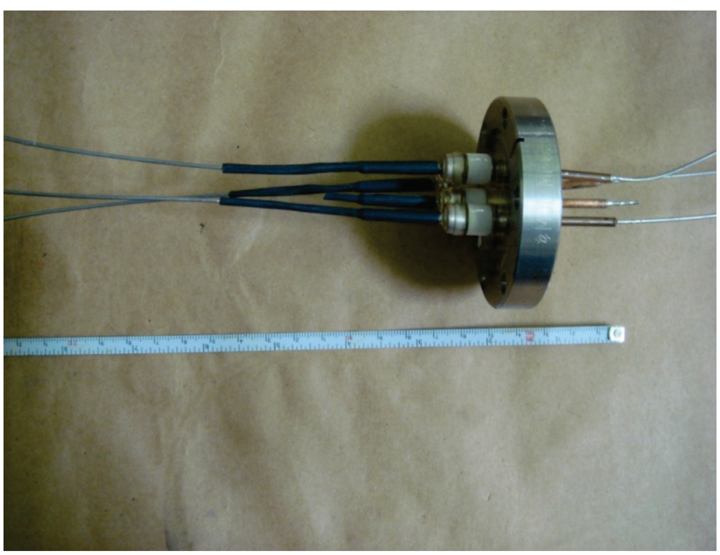


Fig. 11 Cold feedthrough view.

The superconducting wire on right side of the feedthrough was not additionally stabilized because of limited access to this area during assembly. This area may overheat during a quench.

4. Solenoid Magnetic Field Transient Analysis

After fabrication the spectrometer solenoid was trained to achieve the specified operational current of 270 A. All 5 coils of the solenoid were connected in series and powered by the 300 A power supply (See Fig. 3). After the quench at 257 A, the M1 coil showed an open circuit. It is possible the following quench scenario occurred:

- The quench started in the central coil, C, with a current decay ~ 5 s (test info).
- Eddy currents are induced in the coil mandrel.
- In all the other coils there is an induced additional current (in addition to the 257 A positive direction current) in an agreement with the Lentz law.
- The decay time of mandrel eddy currents is defined by the value of the power losses, material heating, heat capacity, and density.
- The decay time in the coils that have not quenched will depend on the value of the shunt resistor (20 mΩ).
- There is a "quench back" effect when the heat from the mandrel increases the coil temperatures and transfers them into a normal resistive condition.
- There is a strong coupling between the 5 coils. The coupling is proportional to the self and mutual coil inductances.
- The cold diodes open immediately after the quench.

For the quench modeling, we used the scheme [1] shown in Fig. 3 .

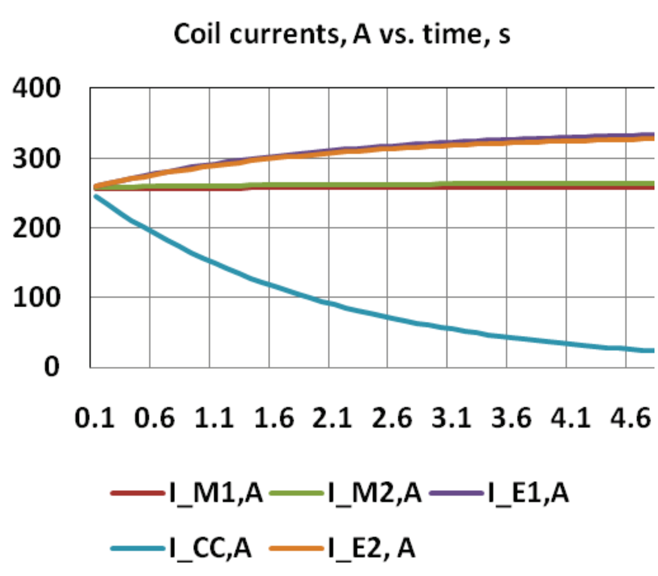
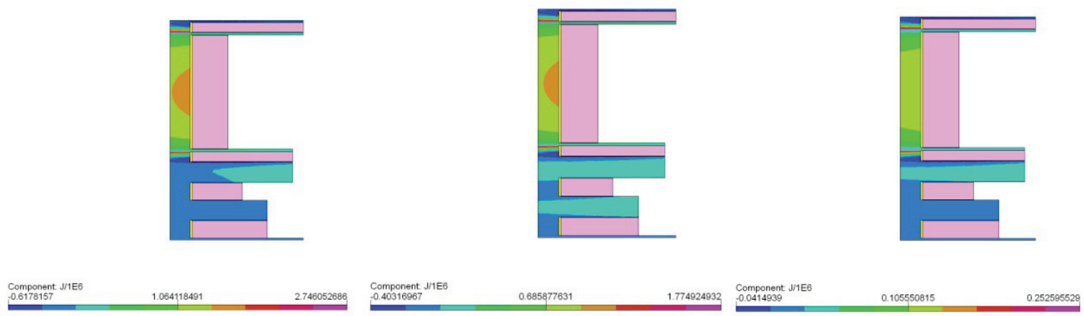


Fig. 12 Coil currents after the quench of the central coil.

One can see that after the quench the current in the central coil decays from 257 A to I_CC = 20 A after about 5s. But in all the other coils, the currents increase up to: I_M1 = 258 A, I_M2 = 264 A, I_E1 = 334 A, I_E2 = 328 A. Even for the M2 coil which has the lowest inductance, the time constant for the current to decay via the 20 mΩ shunt resistor is 250 s.



Time 0.1 s Time 1 s Time 5 s

Fig. 13 Aluminum mandrel current density distribution in A/mm^2 vs. time.

One can see in Fig. 13 that the current induced in the mandrel is concentrated under the quenched central coil (CC) section of mandrel.

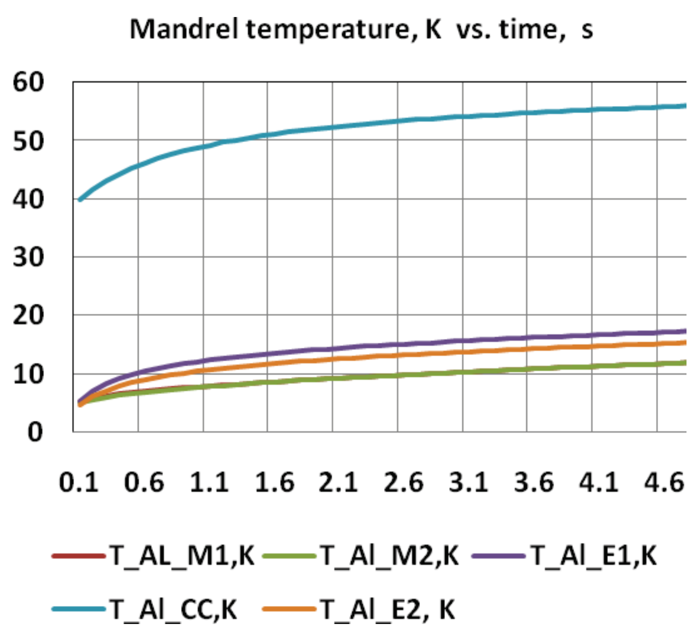


Fig. 14 Aluminum mandrel temperature rise vs. time under the coil centers.

The critical current for the E1 and E2 coils is around 370 A. A quench in these coils which should only occur at fields of 5.4 T and 5.8 T, respectively, (See Fig. 4) may happened because due to training and thus may occur at lower currents. A coil current of 264 A in the M2 coil corresponds to a field of 3.6 T, which is far away from the critical value of 480 A. Only a “quench back” effect from the aluminum mandrel or coil leads heated by a shunt resistor could transfer the coil M2 into a normal condition. In this situation only a transient thermal analysis can help estimate the time of quench in the M2 coil.

5. Solenoid Thermal Transient Analysis

The “quench back” effect due to the aluminum mandrel can be estimated using a solenoid thermal model. The key parameter for this analysis is the thickness of ground insulation between the mandrel outer surface and coil inner surface. In the solenoid documentation it was indicated that the thickness of the ground insulation (G10 + kapton) is 1 mm on the coil inner surface and 3.2 mm on coil sides. This insulation thickness defines the coil temperature rise time and corresponding thermally induced quench time.

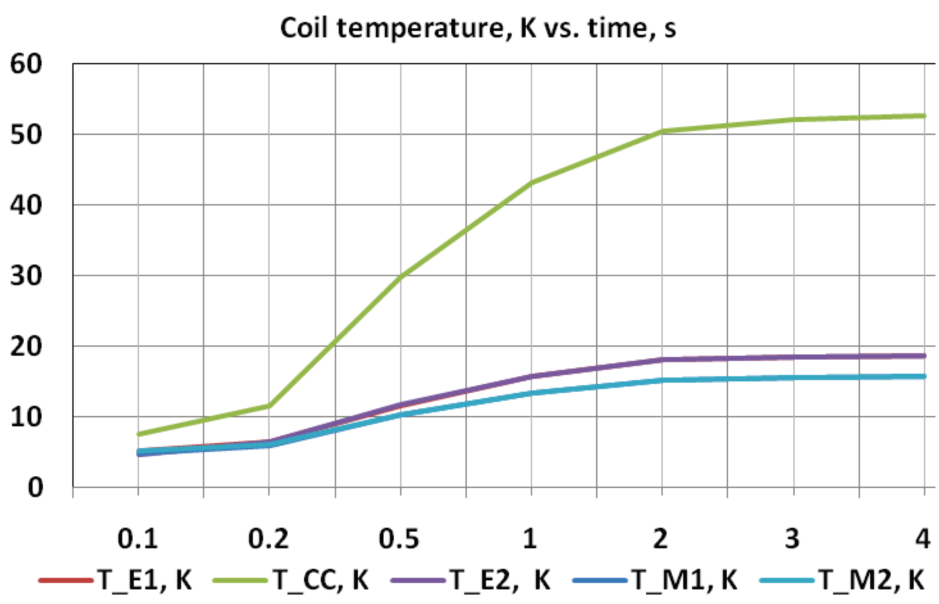


Fig. 15 Coil temperature rise during quench because of mandrel heating.

Because the induced current in the mandrel is concentrated under the quenched central coil CC, the central coil is heated to 50 K after 2 s. This is in an addition to any resistive coil heating. The time of the other coil quenches is the sum of the Al mandrel heating time and the heat transfer from mandrel to the coil. Coils E1 and E2 will be quenched after ~ 1.5 s. Coils M1 and

M2 will see “quench back” effect after ~ 2.2 s. If the real thickness of ground insulation is larger than 1 mm, this delay will be even larger due to the additional thermal resistance of the insulation layer. Fig. 15 shows the coil temperatures at different times. It should be noted that power losses in the mandrel during magnet charging with rate of 0.06 A/s is only 0.065 W and does not produce substantial additional heat load. In [5] these losses were estimated at 0.036 W and the AC superconductor hysteresis losses at 1.01 W during the solenoid charge time 4620 s.

Another dangerous scenario is an E2 coil quench. This coil has the highest peak field and volumetric Lorentz forces, but has a very low coupling with the E1, M1, M2 coils. That is why the “quench back” effect for these (E1, M1, M2) coils will be delayed even more than for the first scenario.

6. Possible areas for the failure

The “quench back” effect for the un-quenched coils can be substantially delayed. Coils M1 and M2 will be, from this point of view, in the most dangerous situation. The currents in these coils will circulate until the resistive losses on the 20 mΩ shunt resistor transfers the leads into the normal condition. The coil leads are heavily stabilized by an extra copper stabilizer and, because of that, have a large temperature margin. The weak areas are the cold feedthrough (See Fig. 11) and the transition area where coil lead copper stabilizer ends and there is only a single strand conductor. A rough estimation shows that the temperature of a single strand will rise with the rate of 300 °C/s. The solder in the feedthrough area will melt at 200 °C after 0.7 s at current 257 A. The strand copper will melt at 1084 °C after 3.6 s. The real scenario will strongly depend on the manufacturing quality, geometry, and exact materials that were used. It is assumed that all coil currents will be short circuited by the cold diodes through the shunt resistors. The delay time for this process is defined by the voltage to open the diodes. In addition some current will continue go through the external HTS current leads because the power supply has low inner resistance. (Note: The power supply was not disconnected during quench.) This current may cause additional HTS lead heating. The value of this current depends on the resistance of the external circuit. If the external circuit resistance is much larger than the 0.1 Ω - total shunt resistance, than this effect will be low.

7. Recommendations

The above preliminary analysis shows the possibility of a quench initially in one coil will slowly propagation along the Al mandrel, and the timing of the other coil quenches is uncertain. The sequence of coil quenches depends on where the first quench occurs and is related to the quench current and the field-temperature margin in the other coils. In this situation it seems reasonable to recommend:

- Make a full quench analysis covering the test and operating scenarios. The model must include the real solenoid geometry and material properties;
- Modify the test procedure so all coils are not connected in series for training;
- Consider lower risk solenoid training. For example initially train coils M1 and M2. After that E1, E2, CC with coils M1-M2 powered from a separate power supply at the peak current achieved during training for M1-M2. In this case the M1-M2 circuit will have a small current-field margin and will be quenched almost simultaneously with E1-CC-E2.

At the time of this writing, the solenoid has not been opened up to determine the location of the failure. There seem to be two possibilities:

- If the failure is between the shunt resistor and the feedthrough, Improve the cold feedthrough area and other areas with a single superconductor strand by adding extra copper stabilization;
- If the failure is between the shunt resistor and the coil, the quench protection system should be completely reanalyzed and the modified such that the coils are adequately protected. This could include the introduction of an active quench protection system, or re-optimization of the shunt resistors, for example. Further stabilization of the superconductor strand near the feed through is probably a safe modification in this case as well.
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Summary

The goal of this report is to identify possible issues and ways to improve the magnet system. The preliminary analysis showed a high probability that a quench in one coil will initiate a quench in neighboring coil sections with a relatively long delay time. This may cause overheating in some parts of the leads. A quench monitoring system is needed to understand the total effect caused by “quench back”+ coil mechanical stability + quench propagation velocity. Implementation in the solenoid design of an active protection system may help to resolve some of these issues.

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