MICE Spectrometer Meeting

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

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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.