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TECHNICAL NOTE

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MICE Spectrometer Solenoid: Responses to October 2010 Review Committee Recommendations

Introduction

On October 27, 2010, a review of the Spectrometer Solenoids was held in order to help develop a repair plan for the magnets. The plan is to include additional analysis of the existing design, incorporation of design improvements, and the development of an assembly and oversight plan. Serving on the committee were:

Pasquale Fabbricatore, chair (INFN-Genova)
Amalia Ballarino (CERN)
Elwyn Baynham (ITER)
Tom Bradshaw (STFC)
Mike Courthold (STFC)
Vladimir Kashikhin (Fermilab)
Robert Sanders (Fermilab)

The following MICE collaboration members attended the review:
Alain Blondel (U. Geneva)
Alan Bross (Fermilab)
Andy Nichols (SFTC)

The Spectrometer Solenoid team would like to thank the review committee for their hard work and very thorough analysis of the issues associated with the magnets. A committee report was issued on December 14, 2010 and included a series of recommendations. The following sections list these recommendations (in *italics*), followed by a response from the Spectrometer Solenoid team. Further details of the plan to move forward with design improvements and reassembly of the magnets will be available in the Spectrometer Solenoid Magnet Repair Plan.

Quench, Protection and Current Leads

Quench Issues

Recommendations:

- *Continue the analysis of the quench protection system, including coupled transient magnetic and thermal calculations, eddy currents in the aluminium mandrel, external circuits with shunt resistors.*
- *Investigate of different quench scenarios and definition of the hotspot temperatures of coils, leads and shunts.*
- *Define of peak voltages: to ground, and layer to layer.*
- *Define of the optimal shunt resistor values for all coils to reduce risk.*
- *Define of the allowable peak operating current to eliminate the risk of coil damage.*

At the end of CY2010, LBNL purchased the QUENCH module from the Vector Fields Corporation. This software module, which runs under the Opera CAE software suite for low frequency electromagnetic simulation, is capable of modeling the quenching process in superconducting materials. An analysis of the Spectrometer Solenoids using this software package is under way and will be complete by the end of January 2011. The analysis results will provide the following:

- Peak voltages to ground and inter-layer
- A more clear understanding of coupling between coils during various quench scenarios
- A detailed estimate of the current decay and current seen by the shunt resistors, and feedback on possible improvements to the selected resistance values
- An estimate of the role of quenchback from the aluminum mandrel

Recommendation:

- *Measure the leakage current to ground for each coil, to check the status of electrical insulation.*

The procedure to perform this measurement will be discussed with the vendor Wang NMR and will be carried out prior to further assembly of the magnets.

Recommendation:

- *Limit the test current to 200 A until all points above are verified and understood.*

It is anticipated that all of the above-mentioned analyses will be complete and well understood prior to conducting any powered tests of the Spectrometer Solenoids. As necessary, some low current testing will likely be carried out in order to verify the results of the analyses (where possible) prior to continuing with the full-current training of the magnets.

Recommendation:

- *Design the magnet test procedure ensuring a minimal risk of cold mass damage.*

A detailed, written procedure for operation of the Spectrometer Solenoids will be generated before testing of the magnets continues. The procedures will cover operation for coil training, normal operating mode, and any other testing modes to be used for verification. Also, LBNL and/or MICE personnel will be present at the vendor during all powered tests of the magnets.

<u>Current Lead Issues</u>

Recommendation:

- *The HTS leads and corresponding LTS leads bus shall be protected by an active system (monitoring does not serve for protection). Both resistive and HTS leads shall be separately protected at different voltage threshold – about 100 mV for the resistive part and 1 mV for the HTS part. Of course any active protection will be insufficient for protection of the HTS part of the lead if the time constant of the circuit is too long (> 1000 s). The need to protect the leads implies a revision of the electrical circuit feeding the coils with current.*

A definitive response to this recommendation is still under development, pending the results of the system analyses. The full capability to monitor temperatures and voltages across the leads is part of the reassembly plans. As it is currently designed, the system only provides for a long spin-down from full current (approximately 1800 seconds). It should be noted that the original design of the magnets included only passive quench protection intended to operate such that an active system would not be required. If simulations demonstrate quenched (i.e. resistive) leads (HTS and LTS) can handle the integrated joule heating during the decay, then the system will operate safely as it stands (with the addition of interlocked monitoring of temperature and perhaps voltage drop across the leads).

However, if the simulations show that the leads will burn out due to the long time constant, then an alternate scheme will have to be developed. This scenario will likely entail significant schedule and cost impacts. The most likely approach to an active system would be to provide some mechanism to initiate a quench, thereby dramatically increasing the current decay rate and protecting the leads. Incorporation of this type of system would likely involve significant change to the electrical circuitry and put a much heavier burden on the controls.

Recommendation:

- *Before a new run of the system, the question of the resistive heating in the HTS leads shall be fully understood (MICE Note 292). This could be due to problems associated with the HTS element itself, which would then appear again during the operation of the repaired system. The test of each HTS units in liquid nitrogen would be a simple way to verify the integrity of the components, which should be exchanged if needed.*

Prior to the operation of Magnet 2B, all sets of HTS leads and the associated warm leads used in the actual Spectrometer Solenoid were tested offline using a specially designed test cryostat. The cryostat incorporates a small LHe tank, a thermal shield, a pair of HTS and warm leads, a full set of voltage and temperature instrumentation, and a single two-stage cryocooler (Cryomech PT-415) for cooling of the shield and leads and for recondensing of the helium. This testing was used to verify that the HTS leads met the supplier's specifications and that the warm leads were optimally designed and constructed (by Wang NMR). All leads used in the future on the Spectrometer Solenoids will undergo this same qualification process.

Recommendation:

- *It should be verified that the LTS connection contains enough cross section of stabilizer to enable operation below Tc in the worst (higher heat load) condition. Since there is no instrumentation available, this aspect of the design could not be verified during the previous tests.*

Due to the burnout that occurred in Magnet 2B in the LTS leads, special attention has been paid to the analysis and redesign of the LTS leads and their stabilization. Wang NMR has developed and implemented (on Magnet 2B) a new configuration for these leads to ensure there is sufficient copper in their cross section. LBNL's preliminary analysis of the modified leads indicates that the design is sufficient. A final analysis is under way to confirm the design. Should additional stabilization be required, LBNL will work with Wang NMR to incorporate the necessary changes in both magnets.

Recommendation:

- *Powering shall be possible only if the temperature of the upper stage of the cryo-cooler and the liquid helium level are within specified values (cryo-OK signal). During powering, the loss of the cryo-OK shall generate a power abort.*

The MICE Spectrometer Solenoid team is currently working with engineers at Rutherford Appleton Lab and Daresbury Lab to develop the specification of the control system for the magnets. The system will incorporate various interlocks including the temperature of the HTS leads and the liquid helium level. It is anticipated that the system will be used during testing of the magnets at Wang NMR. It should be noted that a "power abort" in this case will likely be a controlled ramp down of the magnet current.

Recommendation:

- *The SS team is invited to implement thermometers on the feed-through top flange where the wires enter the cold mass. The information given by the thermometry in this particular location is necessary to verify that the repair has been successful and is adequate for normal operation.*

The overall instrumentation plan for the Spectrometer Solenoids has been reviewed by the magnet team. Several areas where the existing thermometry is not sufficient have been identified. The two LTS feedthrough flanges to the cold mass is an area where additional sensors will be incorporated and monitored.

<u>Electrical Circuit Issues</u>

Recommendation:

- *The electrical circuit shall be revised with the aim to protect the leads. There are different possibilities which shall be studied and decided in the more general frame of the whole MICE system also including other magnets.*

Any changes to the magnet power supply system will be integrated with the overall quench protection and lead protection plans as well as the control system currently under development. The Spectrometer Solenoid team is also working with the MICE Project technical management to ensure compatibility and consistency across all MICE superconducting magnet systems.

Recommendation:

- *It is warmly recommended to study in much more detail the current flowing in the overheated protecting resistors before applying the fix proposed by the vendor (which in fact is a no-fix). The SS team shall consider increasing the mass of the cold resistors.*

The issue of the overheated quench resistors will be addressed through the previously described analyses along with any necessary physical modifications. Note that the extent of modification required cannot be determined until the analyses are complete. Possible scenarios include: changing the value of the resistance, better thermal isolation of the resistors and/or the addition of thermal mass to reduce peak temperature. Also, note that the heating of the resistors may be influenced by other factors that are being addressed such as the quench protection scheme and the characteristics of the power supply and its discharge system.

Magnet Heat Loads

Recommendation:

- *Repeat all shield heat load calculations without relying on Wang NMR reports or calculations. Do not use thermal conductivity integrals or thermal conductivity data from Wang NMR. Use thermal conductivity data from the literature for S2 fiber-glass and G10. If needed use G10 properties for S2 fiber-glass. In the calculations include the effect of radiation on the cold mass supports. Review all drawings and include all possible heat loads in the calculations. For example include the G10 thermal bumpers on drawing # MICE-6600.*

The heat load calculations completed by the MICE Spectrometer Solenoid team are based on the existing engineering drawings and on the MLI as assembled. While there are some drawings that are either not available or are incomplete, any missing information regarding the physical geometry of the as built magnet (2B) has been obtained through measurements of the actual hardware. The drawings for the proposed next iteration of the Spectrometer Solenoid are also not complete at this time. However, the relevant information needed for the calculation of the improvements to the thermal shield connections and conductivity has been obtained by working with Wang NMR. Refinements to these calculations are expected to be complete by the end of January.

Since the time of the October review, the Spectrometer Solenoid team has performed a literature search for S2 glass thermal properties. Several independent sources have been located and are being used in our analyses to determine a range for the heat leak value. A thermal conductivity integral measurement of the actual material used by Wang NMR is not being considered since this data would likely fall within the range of values obtained through our research. Also, the total heat load is not significantly affected by the S2 glass integral, within the nominal range of values.

Recommendation:

- *Complete the engineering drawings for the changes being made to the shield. By calculations that refer to the drawings and the above heat load calculations, determine the shield temperature in critical locations such as the bore and the cold mass support intercepts. It is highly desirable to keep the entire shield, including the cold mass support intercepts below 70K. Include the thermal resistance of the copper strap in determining the temperature of the cold mass support shield intercept.*

The primary change to the shield for the next iteration of the magnet will be in the connection from the first stage of the coolers to the top of the shield. Wang NMR has provided a series of drawings that describe these parts such that the thermal conductance could be calculated. Also, the proposed cryocooler scheme of five two-stage plus one single stage cooler will provide a total of 395 watts of first stage cooling power at 50K versus the 305 watts present during the testing of Magnet 2B. Based on these modifications to the system and the measured shield temperatures from previous testing, it is estimated that the upper portion of the shield will be 50 to 55K, the upper cold mass intercepts will be ~55K, and the lower intercepts and ends of the shield will be ~60K. Based on the relative temperatures obtained by previous FEA analysis of the shield, the bore tube will range from 65 to 70K. Since the indications are that the shield temperatures will be well within the desired range, no additional analysis such as a new FEA model is proposed at this time. Also, note that these calculations do not include any potential improvements to the MLI wrapping of the shield.

Recommendation:

- *Determine the affect of thermal contractions on the tapered contact between the cryo-cooler 1st stages and the copper plate. Include the forces exerted by the main aluminum shield on the copper plate. By calculation determine the thermal resistance of the gap. There might be natural convection in the gap. Make design changes if the thermal resistance is too large.*

Based on the current configuration of the first stage cryocooler connection to the copper plate, the Spectrometer Solenoid team does not believe that this joint is an issue. The cryocoolers are installed using a specially designed flange that allows the o-ring seal to be a sliding diameter seal rather than a flange face seal. This technique allows there to be a gap between the cooler mounting flange and its mounting surface such that a preload on the tapered first stage joint can always be maintained. Wang NMR checks the torque on the flange bolts after cooldown of the magnet as this torque translates directly to force on the joint. A thermally conductive grease is also used in the joint to enhance the connection. This same configuration has been used in Wang NMR's off line cooler tests and found to result in a temperature drop across the joint of ~1K.

While it appears these joints have not been a source of any issues, some improvements are proposed. The white thermal grease currently being used in the joints will be replaced with Apiezon N grease due to its superior performance in this type of application. Also, a series of Belleville washers will be used under the cryocooler flange bolts such that a total force of at least 500 N is maintained at all times for each joint. The bolt torques and the flange gaps will be checked after cooldown to obtain information regarding movements due to thermal dilatation.

Recommendation:

- *Compare the exact physical location of the thermometry used to measure the cryo-cooler 1st stage temperature to the exact location of thermometry the manufacturer uses to measure cryo-cooler performance. For example Cryomech on a AL300 measures the cold head temperature on the upper side of the cold head during a performance test.*

The location of the temperature measurement on the cold heads for the Spectrometer Solenoid has not been compared to Cryomech's performance testing configuration. In the case of the two-stage coolers (PT-415), the first and second stage interfaces are copper disks that would be expected to have very little temperature gradient over their surfaces. In any case, the temperature measurement configuration for both cooler types will be confirmed with Cryomech to ensure that the cold head temperatures being used to determine the net heat removal (from Cryomech's performance curves) are appropriate.

Recommendation:

- *The accuracy (and position) of thermometry used to measure cryo-cooler 1st stage temperature is critical in evaluating cryo-cooler performance. Is the accuracy of the thermometry sufficient? Determine if heat conduction through the wires or radiation heat loads affect the accuracy.*

The technique and type of sensor being used by the vendor to measure the first and second stage cold head temperatures will be reviewed in detail. If necessary, the sensors will be replaced to ensure an appropriate level of accuracy. This could entail replacing the platinum resistor sensors that are currently being used with a calibrated Cernox type sensor. Also, the first stage sensors are currently being applied to the copper surface using Stycast epoxy. If an alternate sensor is used, then the mounting technique will likely be changed to one where the sensor is affixed using a screw and thermal grease in the interface.

Manpower

Committee Comments:

Eight persons are committed to the repair task for a total FTE of 2.45. The ratio FTE/persons denotes an excessive and not recommendable subdivision of the work. However it is recognized that the project is followed much more consistently than in the past. As correctly stressed by Steve Virostek, it is important to have the appropriate knowledgeable and experienced individuals on site during the critical operations. At present it seems that this task cannot be fulfilled 100%. The review committee thinks that a continuous and well coordinated follow-up of all operations at the vendor is fundamental for the success of the repair plan. The review committee thinks that many times in the past the information flow between the vendor and the SS team was insufficient and lacking important details.

Since the October 2010 review, the Spectrometer Solenoid team has reassessed the manpower level that is considered necessary to complete the project, taking into account the availability of qualified personnel as well as the projected budget. Since the review, additional help has been obtained from MICE resources in the UK. Roy Preece is a RAL mechanical engineer who will be working full time on the MICE magnets. During the assembly of the Spectrometer Solenoids, Roy is planning to spend close to full time overseeing and tracking the progress of the assembly work at Wang NMR. It is recognized that once the analyses and design modifications are complete, a continuous presence at Wang NMR will be required to oversee and document the magnet assembly. Details of this manpower arrangement are available in the magnet repair plan.