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TECHNICAL NOTE

MICE Spectrometer Solenoid: Modification and Repair Plan

Introduction

A technical review committee formed by MICE management held a review of the Spectrometer Solenoid magnets on October 27, 2010. The committee was tasked to assess the current magnet design that had been produced by Wang NMR (a private company) and to evaluate the modification and repair plan proposed by LBNL. On December 14, 2010, the committee report was issued and contained a series of comments and recommendations. Since the time of the review, LBNL has performed additional analysis of the magnet design, particularly in the areas of thermal performance and magnetic/electrical characterization, in order to develop the modification and repair plan that is summarized here. Note that the plan includes additional analysis that is currently under way and that will have to be completed before the final design recommendations can be presented to Wang NMR. The plan also includes a preliminary schedule (subject to approval by the vendor), a cost to complete budget (for LBNL expenses) and a manpower summary. A separate document provides the LBNL Spectrometer Solenoid team's responses to the committee's recommendations.

1. Summary of LBNL Technical Tasks

LBNL has undertaken a series of tasks aimed at producing a set of final design changes that the vendor Wang NMR will carry out during the reassembly of the magnets. The two-step process is composed of understanding the current design and performance of the Spectrometer Solenoid magnets and developing a series of system design changes and enhancements that will allow the magnets to be trained to their design current and to operate without helium boil-off. A summary of the work that has been and is being carried out and the current list of design changes is presented in the following sections. Details of the related studies and analyses will be presented in supporting documents at the completion of these tasks.

The tasks that are being carried out in order to complete the plan are as follows:

- All heat loads have been reassessed to ensure that the LHe in the cold mass can be maintained with the final number of cryocoolers.
- The electromagnetic calculations are being redone and expanded upon to cover the cases of both testing and operation.
- A complete set of the latest as-built drawings (w/future changes in some cases) has been compiled. Missing details and drawings have been identified.
- The instrumentation plan has been modified to ensure that the thermal and EM calculations can be confirmed during testing.
- The mechanical support of the magnet, leads, piping and other internal components has been reassessed

a. Heat load analysis

In order to better understand the thermal performance of the helium cryostat of the MICE Spectrometer Solenoid, the heat leaks due to the dominant static sources have been re-evaluated. The focus of the calculations is the heat leaks into the 4.2K cold mass as these directly relate to the issue of LHe boil-off during operation. Other aspects of magnet thermal performance including heat loads on the shield and vacuum insulation have been considered as well and are being addressed by the plan. The dynamic heat loads that occur during cooldown or current ramp-up when the magnet system is not in equilibrium have been ignored in this evaluation. These heat loads are negligible during long-term operation of the magnets.

b. Electromagnetic calculations

A review and analysis of the design of the passive magnet protection system under the various operational regimes is under way and will be completed by the end of January 2011. The areas covered include analysis of the quench protection system, using coupled transient magnetic and thermal calculations, eddy currents in the aluminum mandrel, and external circuits with shunt resistors. The analysis will also investigate different quench scenarios and will determine the hotspot temperatures of coils, leads and shunts. Other parameters being determined include the peak voltages to ground, and layer to layer, the optimal shunt resistor values for all coils, and the allowable peak operating current to eliminate the risk of coil damage. The analysis also includes an assessment of the stability of the HTS and LTS leads to ensure that the system contains adequate protection against lead failure.

c. Fabrication drawings

A set of nearly 200 detail fabrication drawings representing the latest assembly of the Spectrometer Solenoid (Magnet 2B) has been collected from Wang NMR and has been organized in the form of a drawing-tree list. The drawings provide a nearly complete representation of the previously as-built magnet, although complete assembly drawings are generally missing. Some of the more recent drawings provide details of modifications to the system that have been proposed by Wang NMR, primarily related to improvements in the thermal shield. Where determined to be appropriate by our analyses, these design changes have been included in our proposed magnet modifications. LBNL will work with Wang NMR to ensure that a complete set of as-built drawings are delivered at project completion. In parallel with the effort to organize the drawings, LBNL is developing a detailed 3D CAD model of the Spectrometer Solenoids. Until now, the only model of the magnets was developed at RAL and was based on an early magnet design. Note that the vendor has not used 3D modeling during the design and fabrication of the magnets.

d. Instrumentation plan

The current configuration of the instrumentation on the spectrometer solenoid magnets has been reviewed, and a series of changes and additions to the system have been specified and compiled in a separate document. The instrumentation plan includes temperature sensors, voltage taps, helium level gages, and pressure gages. In most cases, the proposed changes to the instrumentation scheme came about due to shortcomings that were identified during the previous rounds of magnet training and testing. Another area being addressed is the ability to record data relevant to the confirmation of our heat load analyses.

e. Mechanical support assessment

During the course of the magnet analyses, the internal mechanical support of the various magnet components has been reviewed. The primary issues in this area are 1) the mechanical stresses imposed on the components and supports due to thermal contraction during cooldown and by electromagnetic forces during operation, and 2) the relative movement of components caused by cooldown and operation that could cause a thermal short between components at different temperatures. The components reviewed are the cold mass supports, the thermal shield and its supports, and the support of the first stage copper plate and its relative movement with respect to the cryocoolers and the magnet leads (particularly the HTS leads). Overall, no serious thermal contraction issues have been identified in this analysis.

2. Modification and Repair Plan

Based on areas of concern that have arisen from magnet testing and through analysis and review of the design, an overall strategy was developed to address deficiencies in the magnet design. This strategy includes the following:

- reduction of heat leaks to the cold mass
- the addition of more cryo cooling power
- assessment of the suitability of the passive quench protection system
- modification of the LTS leads to prevent burn-out

The details of the plan (pending the final results of analyses) are described in the sections that follow.

a. Heat load reduction to 4.2K

One of the primary requirements of the Spectrometer Solenoid magnets is the ability to run in steady state at full operating current while maintaining the LHe in the cold mass with recondensation provided only by the cryocoolers (no boil-off). The following proposed design improvements are intended to directly reduce the heat load on the magnet cold mass:

- Improved vacuum pumping and instrumentation will be implemented to ensure adequate cold mass insulation. The pump port size will be enlarged from the current 25 mm to a DIN 100 flange with a gate valve. A 300 L/s turbo will be used as the primary pumping system with a dry scroll pump for roughing. Instrumentation will include thermocouple, Pirani and ionization gauges, and an RGA. The details of this system were developed at Fermilab, and the necessary components are being procured.
- All 4K areas will be covered with actively cooled shield where possible. One area not previously covered is around the cold mass supports where they penetrate the thermal shield. LBNL will work with Wang NMR to develop a design for this improvement to the shield.

- The cold mass vent lines will be modified by adding bends and 70K intercepts at appropriate locations to prevent direct radiation shine to 4.2K. The previous vent lines provided a straight path between the 4.2K cold mass and 300K surfaces.
- Possible thermo-acoustic oscillations in vent lines will be addressed by monitoring with fast pressure gauges read on an oscilloscope. Any significant observed oscillations will be addressed through a design change or by adding an appropriate damping material to the line.
- The cryocooler recondenser pipes will be connected directly to the cold mass and will not include any type of intermediate manifold (as in Magnets 2A and 2B). While the effect of the manifold on the efficiency of the cooling circuit is not known, all of the offline cryocooler verification and characterization tests performed at Wang NMR used the direct connection approach.
- Application of MLI on the cold mass bore will be improved by reducing the compression of the MLI layers and by applying it in a way that allows it to contact the colder surface. LBNL will work with Wang NMR to develop the design and technique for application of the MLI in this manner.
- Sensor wires will be optimized by ensuring that they are all phosphor bronze and with proper heat sinking. Quad flat 4-wire cable (phosphor bronze) made by LakeShore will be used where possible due to its superior electrical and thermal properties and the fact that it can be readily fixed to a first stage heat sinking surface.

b. Radiation shield heat load reduction:

Although the temperature of the radiation shield has less direct effect on the heat leak to the cold mass, several deficiencies in the design of the shield system have been identified. Correction of these issues during reassembly of the magnet is expected to result in reduced shield operating temperatures. These improvements to the shield will indirectly reduce the heat leak to 4.2K due to conduction in the cold mass supports and by radiation. The following proposed design improvements are intended to directly reduce the heat load on the shield and to improve its thermal conductivity:

- The thermal connection between the cooler first stage and the radiation shield will be improved by replacing the previous aluminum cylinders and flexible banding with copper sheets that form a box around the cryocooler area below the first stage copper plate. The vendor Wang NMR has already developed this design and generated the associated drawings.
- Portions of the thermal shield will be reinforced with copper and pure aluminum to improve thermal conductivity, particularly in the areas that will increase the cooling to the locations of the cold mass support intercepts. Wang NMR developed the design change and has incorporated this modification on one of the shields.
- Application of MLI on shield bore tube will be improved by reducing the compression of the MLI layers and by applying it in a way that allows it to contact the colder surface. LBNL will work with Wang NMR to develop the design and technique for application of the MLI in this manner.

- The LN reservoir that was attached directly to the thermal shield in Magnets 2A and 2B will be eliminated. In practice, the reservoir was primarily useful during the initial cooldown of the shield and was generally not used after that point in the training process. Our calculations indicate that the reservoir became a net heat load on the shield and was responsible for a small portion of the observed extra heat load on the shield as compared to the tests on Magnet 1 (with no reservoir). Concerns about protection of the HTS leads in the event of a power failure are currently being assessed in conjunction with the magnetic analysis.

c. Cryocooling power:

As mentioned previously in this document, one of the critical areas of the magnet design that requires improvement is the chosen amount of cryocooling power available for recondensation of the liquid helium in the cold mass. The proposed modification to address this issue is summarized below.

- The total cooling power will be increased by adding an addition pair of two-stage coolers to the Magnet 2B configuration. In total, each magnet will use five 2-stage pulsed tube coolers and one single-stage cooler. While it is possible that the system could run with fewer coolers after the previously described improvements have been incorporated, a greater margin on the cooling power will substantially reduce the risk and allow for possible degradation of the system over time. A layout of the proposed design showing the positions of the six cryocoolers is given in Figure 1. This drawing represents a preliminary layout produced by Wang NMR. The detail drawings required for carrying out this approach will be generated by the vendor once the plan has been approved.

d. Quench Protection:

An area identified by the review committee as having a high risk with regard to possible magnet internal failures is the design of the quench protection system. The original design of the Spectrometer Solenoids incorporated a passive system with no active controls for quench protection of the coils and associated leads. To address the recommendation by the committee that an active protection system be incorporated, LBNL recently purchased the QUENCH module from the Vector Fields Corporation in order to analyze and better understand the existing system. 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

As currently designed, the Spectrometer Solenoids do not incorporate any mechanism for inducing a quench; the power supplies provide for a long ramp-down from full current (approximately 1800 seconds). If simulations demonstrate that quenched (i.e. resistive) leads (HTS and LTS) can handle the integrated joule heating during the extended 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. Until the quench analysis has been completed and the question of whether an active system is required has been answered, the magnet modification plan will not be complete.

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.

e. LTS and HTS leads:

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 to stiffen the leads to prevent movement caused by electromagnetic forces and to provide a more effective means of cooling through conduction. The modification consists of the addition of superconductor and copper wire that is soldered to the original leads over a length of approximately 40 cm on either side of the feedthrough. 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.

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.

f. Improvements to magnet QC/QA

To provide increased oversight of the magnet assembly process, to better document the details of the assembly of the magnets, and to assist the vendor with QC/QA, LBNL and other MICE collaborators will maintain a regular and continuous presence at the assembly plant during completion of the magnets. LBNL has the appropriate personnel available to carry out this task, and Wang NMR is agreeable to this arrangement.

One particular concern is the application of MLI to the 4.2K and thermal shield surfaces. LBNL is developing a QA plan to ensure that the MLI is adequately prepared, applied and inspected. Particular areas of concern include the cold mass and shield bores and the area on the shield where the cold mass supports pass through. LBNL engineers will be responsible for the implementation and ongoing oversight of the QA plan.

3. Schedule, Budget and Manpower

The schedule, budget and manpower required to complete the Spectrometer Solenoid Project have been estimated and are presented and discussed here. Note that these are preliminary and are dependent on the approval of the magnet modification plan by MICE technical management. Also, the design change plans must be conveyed to the vendor and a fully resource loaded schedule developed. The details of these items along with the relevant assumptions are presented below.

a. Schedule

A detailed schedule has been assembled based on experience with assembly of the previous versions of the magnet. The schedule is essentially a straw man compilation of the tasks with an estimate of the required durations. A final, resource loaded schedule will be developed once the repair plan is complete and the vendor has provided additional input regarding resource availability. Also, some aspects of this schedule will depend on the final scope of modifications undertaken. One area that can have a potentially big impact on the schedule is the quench protection system. If it is determined that an active system is required, then a design and specification phase for this system will be necessary. The schedule that has been developed currently includes time to incorporate such a system. The resumption of the magnet design and assembly effort will also depend on how soon the modification plan can be approved by MAP and MICE.

b. Budget

An estimate of the remaining costs to MAP to complete the Spectrometer Solenoids has been compiled and is presented in Table 1. The costs include both LBNL manpower and hardware as described below:

<u>Manpower tasks</u>

- system analysis
- design for modifications
- assembly oversight

- project management
- magnet commissioning
- project documentation

Hardware
- additional cryocooler purchase
- cost of contract modifications for added scope
- utility and cryogen costs for magnet training
- shipping costs

The total estimated cost to complete both Spectrometer Solenoids for manpower and hardware is $708k. An additional contingency amount of $254k will be budgeted to account for any uncertainties in the design and assembly, including the possible need for and active protection system. The total contingency amount was calculated by assigning line-by-line percentages to the estimated costs in Table 1.

c. Manpower

The manpower required to carry out the tasks listed above has been identified and is available. The total effort listed in the budget currently amounts to more than 1.5 man-years. The bulk of the effort will be for monitoring the assembly process and for carrying out the magnet training and commissioning. Not reflected in the budget is the manpower that will be provided by the MICE Project. This includes the efforts of Roy Preece (ME from RAL) who will be providing continuous on-site oversight at Wang NMR during the assembly and testing efforts. Also, the control system for the magnets is being developed by engineers at Daresbury and Rutherford Appleton Labs.

The effort of the following individuals is listed in the LBNL budget for completing the specified tasks. Although not listed here, some additional help from FNAL may be available during magnet training (as has occurred in the past).

Steve Virostek - Sr. Mechanical Engineer (25% time during design, assembly and testing)
- overall project management
- some oversight of magnet assembly
- magnet training oversight
- documentation

Tapio Niinikoski - Sr. Cryogenic Engineer (50% time during design and assembly effort)
- CERN retiree, hired 1/2 time by LBNL
- magnet design analysis
- design modification recommendations
- some oversight of magnet assembly
- magnet training oversight

Soren Prestemon - Cryogenic Engineer (50% time during analysis and design effort)
- magnet design analysis
- design modification recommendations

- occasional oversight of magnet assembly

Nanyang Li - Mechanical Engineer (30% time during assembly and testing)
- continuous oversight of magnet assembly
- magnet training oversight
- documentation

Vladimir Kashikhin - Cryogenic Engineer @ FNAL (25% time during analysis & design)
- quench analysis
- quench and lead protection design
- power supply systems

Sisi Shan - Mechanical Engineering Student (ongoing effort on modeling and drawings)
- organization of magnet detail drawings
- development of magnet 3D CAD drawing

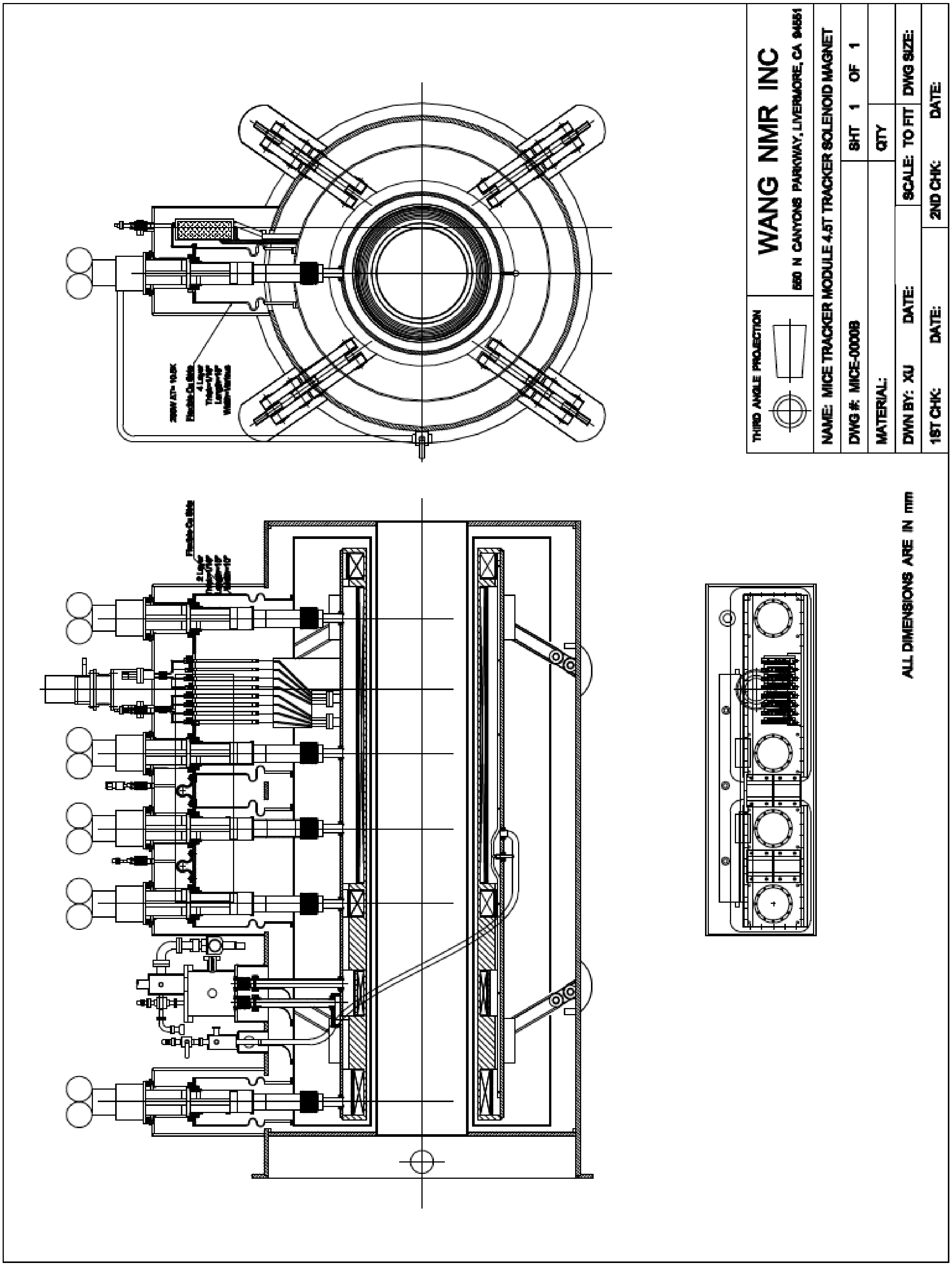

Figure 1: Preliminary layout of the modified cooler arrangement (5 ea 2-stage, 1 ea 1-stage)

Manpower	% Time*	Type	$/hr	Total (k$)
Analysis	25%	Cryo Engnr	160	53
Design Mods	25%	Cryo Engnr	160	53
Management	25%	Sr Mech Engnr	200	67
Fab Oversight	30%	Sr Cryo Engnr	140	56
Fab Oversight	30%	Mech Engnr	150	60
Quench prot/Pwr sup^	12%	Cryo Engnr	200	32
Controls+	20%	Elec Engnr	150	40
Testing/Training	12%	Sr Mech Engnr	200	32
Testing/Training	12%	Mech Engnr	150	24
Documentation	12%	Sr Mech Engnr	200	32
Documentation	12%	Mech Engnr	150	24
Travel FNAL-LBNL#				10
Fab/Procurement	**Qty**	**Unit**	**$k/ea**	**Total (k$)**
Cryocoolers (PT415)	1	ea	53	53
Contract Mods	2	magnets	25	50
Training Utilities	2	magnets	21	42
Training Cryogens	2	magnets	20	40
Shipping to RAL	2	ea	20	40
Spectrometer Solenoid Totals:				**708**
Contingency:				**254**

* average % time effort over the next 8 months
^ manpower help from FNAL
+ manpower help from RAL and Daresbury
# personnel from FNAL for testing/training

Table 1: Spectrometer Solenoid estimated cost to complete.