Report on the polarized target failure

Brief Description of UVa polarized target

The UVa polarized target apparatus consist of a superconducting magnet and a refrigerator. A diagram of the apparatus is shown in Fig. 1. The magnet can be detached from the upper cryostat. Fig. 2 is a picture of the magnet after being detached from the upper cryostat and having the metal covering removed from the top of the magnet cryostat so that the quench protection circuitry can be seen. The magnet is a pair of superconducting Helmholtz coils which produces a field of 5.0 T at temperature of 4.2 K. Each Helmholtz coil physically consists of 10 separate coils. The magnet also has shim coils. The current needed to reach 5.1 T is 78.79A. The magnet inductance is 232H and the stored energy at 5.1 T is 724kJ. The magnet is designed to be run in persistent mode and has a persistent mode switch. The magnet is powered by an Oxford Instruments PS120-10 power supply which can be run from the front panel controls or remotely by LabView computer interface.

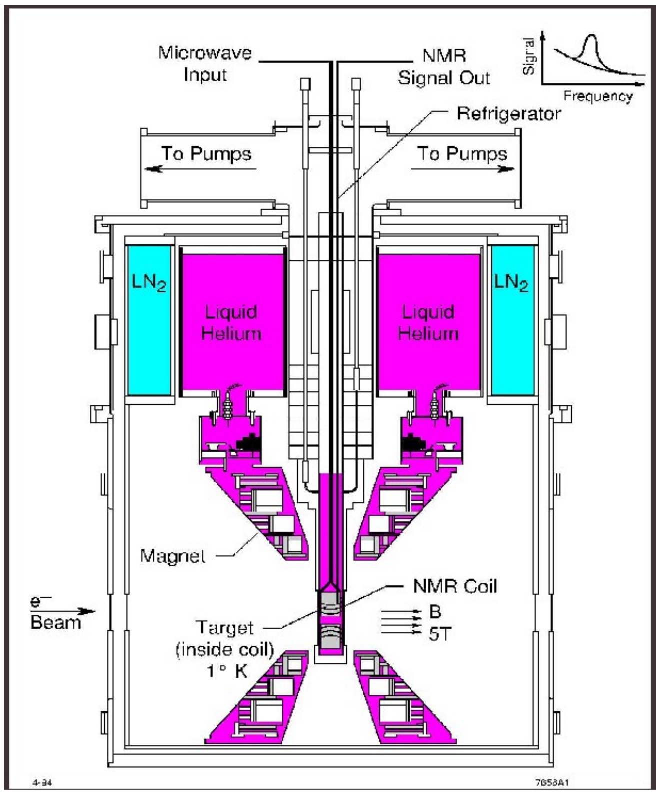


Figure 1. Diagram of UVa polarized target

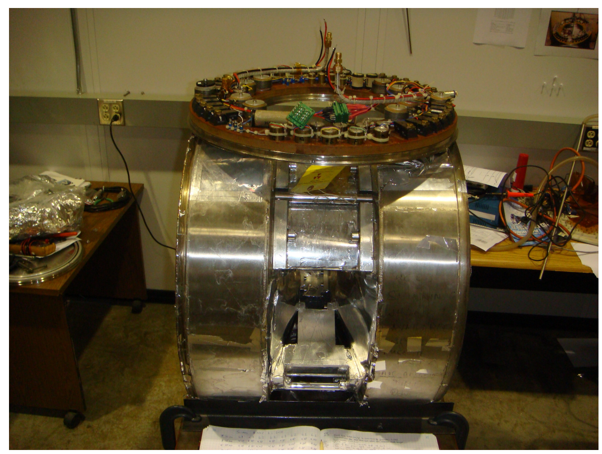
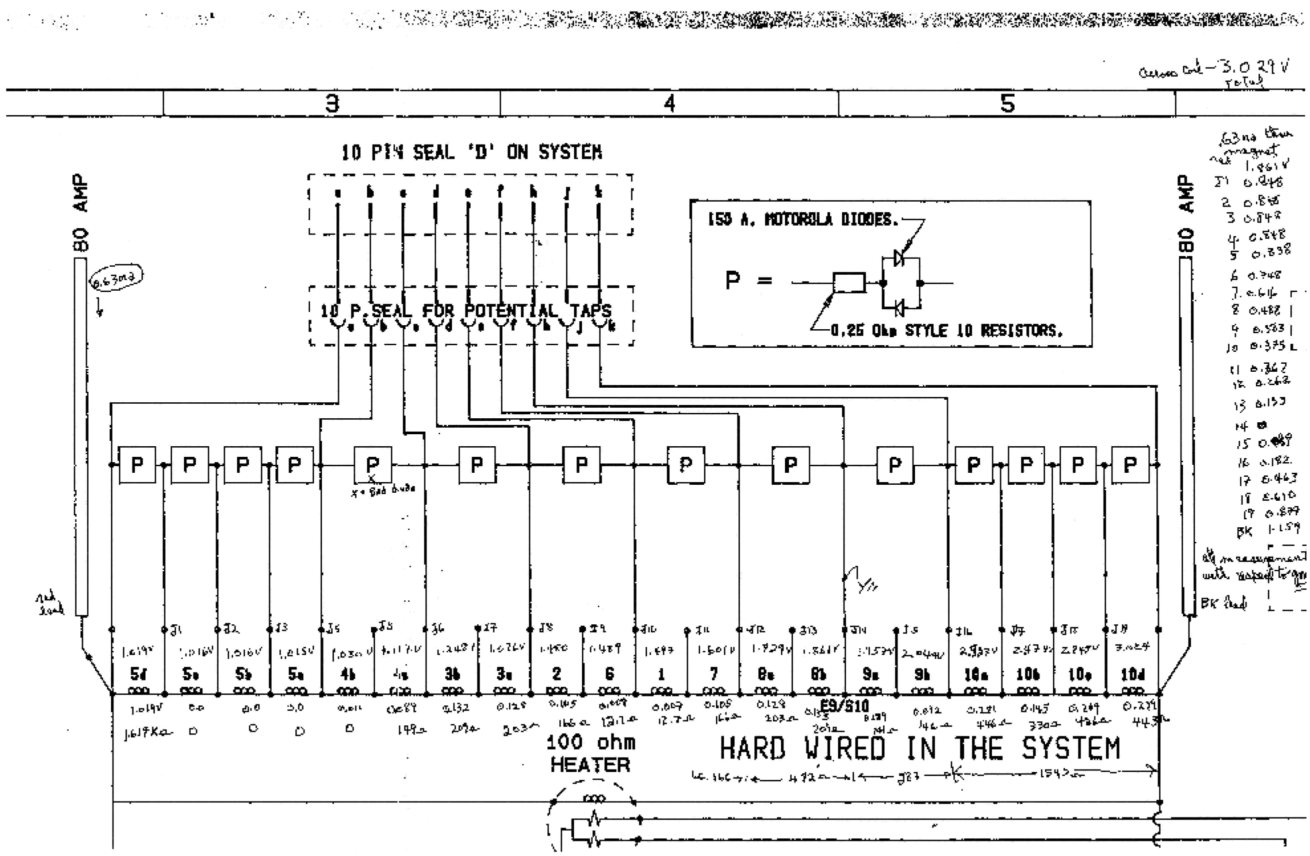


Figure 2. Picture of the magnet after removal from the refrigerator and having the metal covering removed from the top of the magnet cryostat.

Fig. 3 is a circuit diagram showing how the coils are connected together and how the quench protection is incorporated. The quench protection circuit consists of a 0.25 Ohm resistor and pair of barrier diodes (denoted by “P” in Fig. 3). One half of the Helmholtz pair consists of 10 coils (labeled 5a-d, 4ab, 3ab, 2 and 6 in Fig. 3) and the other half is matching set of 10 coils (labeled 10a-d, 9ab, 8ab, 7 and 1 in Fig. 3). Leads for the superconducting coils are brought out of each coil and superconducting connections are made from one coil to the next at the top of the magnet. The superconducting joint is made by soldering together the ends of 4ft of cable (from each coil) that has been first twisted together. This joint is placed in a cup that is then filled with Woods metal and a connection to the quench protection circuit is made. Taps are connected to circuit at selected points for diagnostics (This is indicated as 10 pin seal “D” in Fig. 3). The lead from the power supply is connected to coil 10d and the opposite power supply lead is connected to coil 5d. The power supply leads are connected in parallel to the persistent switch (resistance of 100 Ohms).



Instructions for ramping magnet

Typical operation of the magnet is done through the LabView computer interface. To ramp up the magnet to 5.0 T, requires the following operations:

1. Select polarity of the magnet and turn on power supply.
2. Turn on the shim coil power supply. Turn shim heater on to 0.1A.
3. Turn heater on for the persistent switch. This makes the superconducting wire in the switch normal. A wait period of 15 seconds (minimum) is necessary for the heater to get warm enough to make the superconductor normal. LabView has built in delay of 30 seconds.
4. Ramp up current in the magnet. Listed in Table 1 are the recommended maximum ramp rates for the case when the magnet has cooled to 4.2K after a long period of being warm. There are different ramp rates depending on the current in the magnet. The power supply has a CPU that can be programmed with maximum ramping rates also listed in Table 1. The ramping rate of 2A/min programmed for 0-60A current is the maximum ramping rate suggested by Oxford when the power supply leads are connected to the coils.

5. Once the desired current reading is obtained, then the persistent switch heater is turned off. After waiting at least 15 seconds, the power supply leads can be ramped down. LabView has built in delay of 30 seconds. At this point the power supply leads can be ramped down at 20A/min.

Table 1. Ramping rates for polarized target power supply

Current (amps)	"First run" ramping rate (amps/min)	Maximum programmed ramping rates (amps/min)
0-60	1.2	2
60-72	0.6	1.5
72-78.79	0.3	1.0

Description of polarized target failure

The UVa polarized target was being used in Hall C for E07-003 that started on Oct 24th, 2008. The magnet has been used in several experiments at JLab and SLAC which required shipping it back and forth. The magnet was bought in 1992. It had major repairs after an accident at JLab in 1998.The last time that the polarized target was used was for two experiments in Hall C which ended in Feb 2002. In preparation for E07-003, the polarized target was assembled in the EEL building during the summer of 2008 for test cool downs. The magnet was successfully cooled to 4.2K. During the final cool down the magnet quenched due to a rupture of the tailpiece when moving an insert. (This magnet has quenched on the order of ten to twenty times since it was acquired in the early 1990's.) The magnet was brought into the hall in early September 2008.

A short timeline of events in the hall is:

- Oct 31st : Target magnet in positive polarity was energized for the first time in Hall C. Magnete quenched when switching magnet in persistent mode. Details given on pages 4 and 5.
- Nov 1st : Magnet in positive polarity was successfully energized to 77.2A . Elastic ep data taken over the weekend.
- Nov 3rd 8am: Target magnet was being ramped down. Magnet quenched when current dropped below 60A. Details given on pages 6 and 7.
- Nov 3rd 5pm: Target magnet in negative polarity was being ramped up. Magnet quenched when current reached -26A. Details given on pages 8 and 9.

Quench on Oct 31st (Plots)

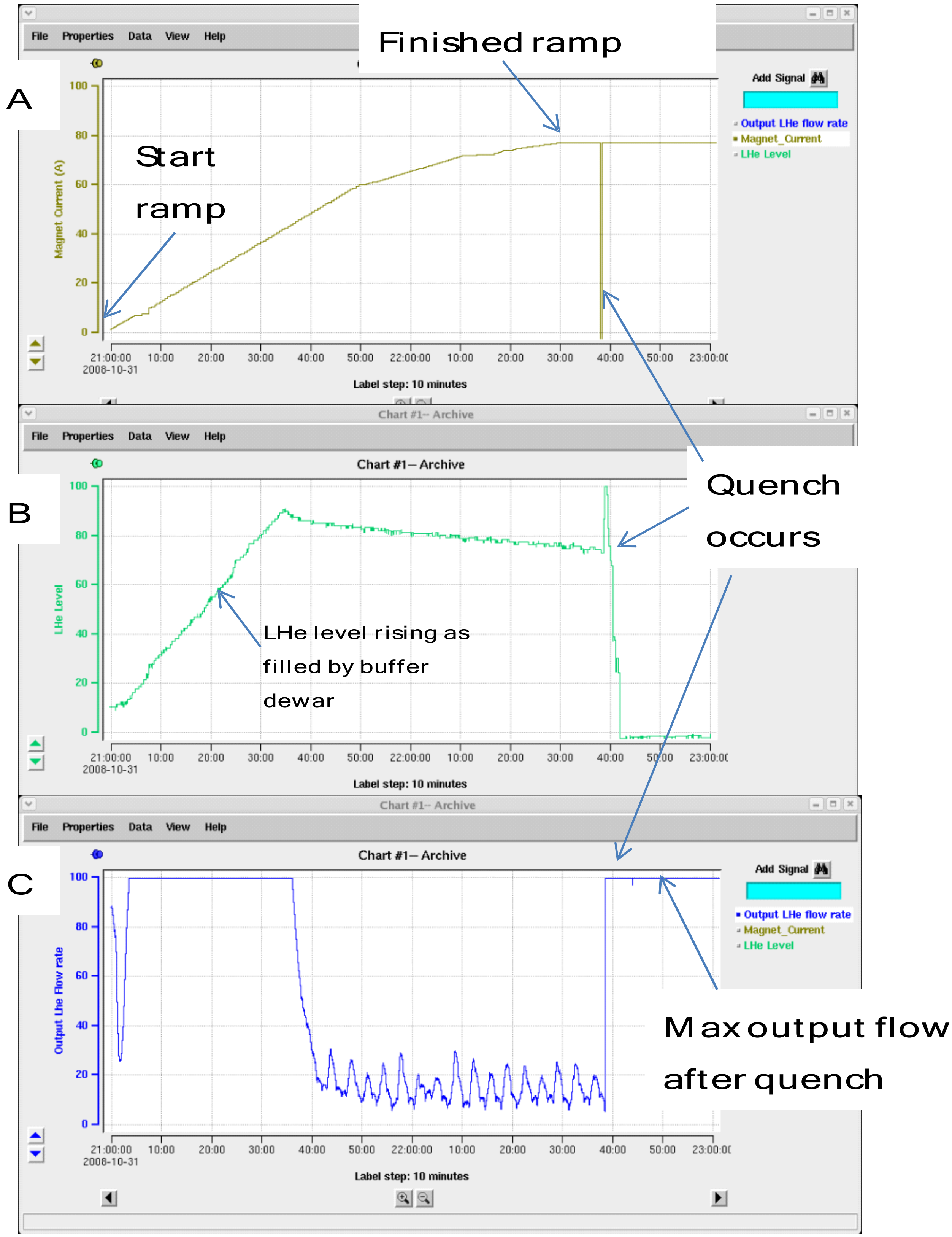


Figure 4 Strip charts of A) magnet current B) Liquid helium level and C) LHe output flow rate during quench on Oct 31st.

Quench on Oct 31st (Description)

The first attempt to ramp the magnet to full current was on the evening of Friday October 31st. The magnet was ramped in positive polarity to full current using the “First run” rates given in Table 1. The magnet was switched to persistent mode by turning off the heater to the switch and when the magnet power supply was ramped down the magnet quenched. Looking the log file, it was found that heater had been turned off for only 13 seconds before the power supply leads were ramped down. This means that the persistent switch had not gone superconducting, and this caused the quench. There is a timer which counts down 30 seconds to tell the target operator when to start ramping down the current in the leads, but there was communication error which delayed sending the signal to turn off the heater while the counter on the computer was counting down.

In Fig. 4 is a chart showing the power supply current (4A), the liquid helium level of the magnet (4B) and the liquid helium output flow or boil-off (4C). The level meter for the LHe is located about 1-2 inches above the bottom on the helium tank. Therefore when the LHe level reads 10%, there still is liquid helium in the magnet. Looking the LHe liquid level (shown in Fig. 4B) , a batch fill of the magnet dewar starts just as the magnet is being ramped which results in a rising LHe level. As a result of the batch fill, the output LHe flow is at 100 (see Fig4C) . The fill is completed at 21:40. The LHe flow drops back down to its normal level and the LHe level slowly drops while the magnet continues to ramp. This indicates that the magnet is superconducting. Magnet quenches at about 22:40. The flow pegs as a result. The level jumps to 100% (this behavior is due to pressure increase during quench) and then drops to 0%.

Quench on Nov 3rd 8am (Plots)

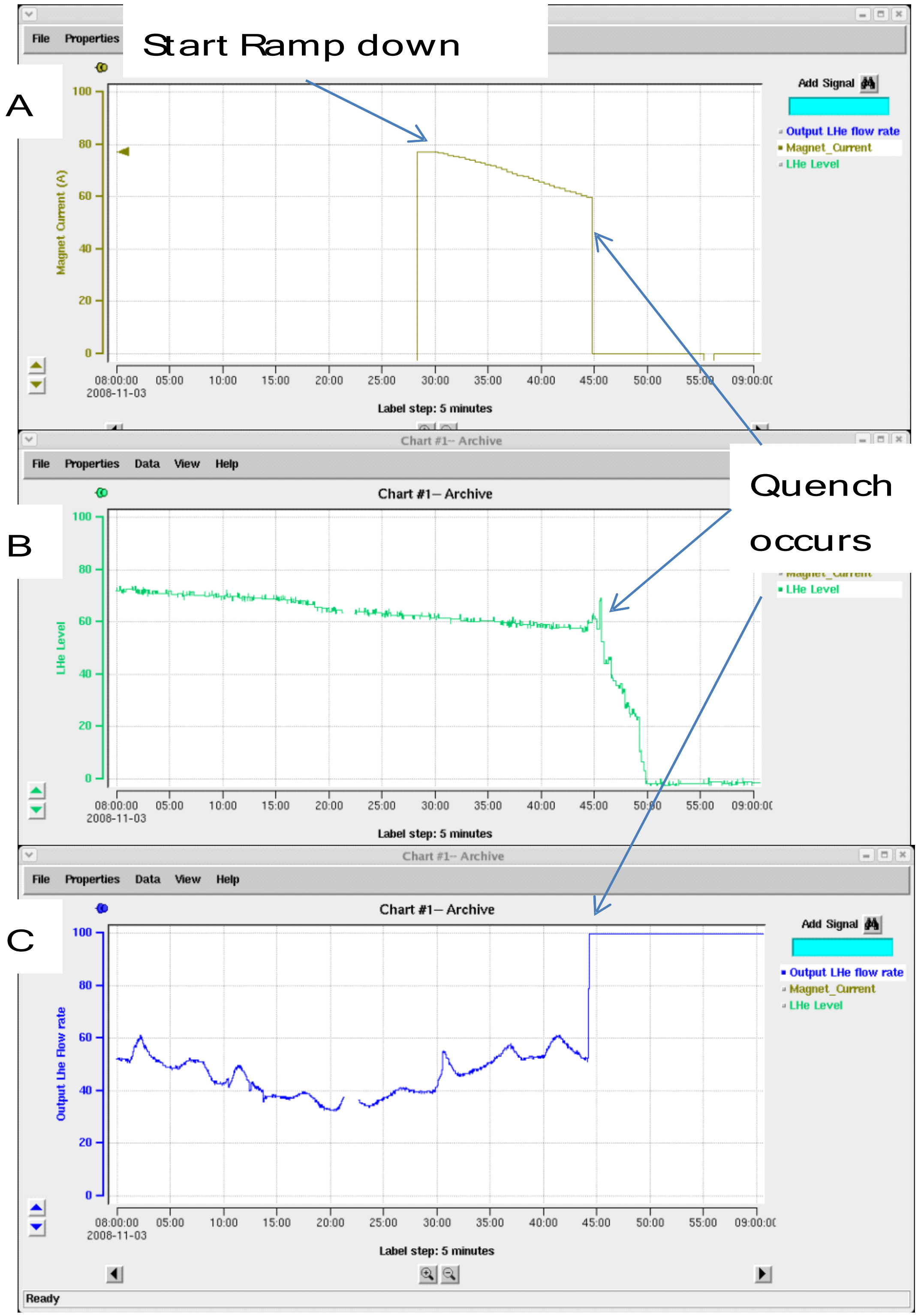


Figure 5 Strip charts of A) magnet current B) Liquid helium level and C) LHe output flow rate during quench on Nov 1st at 8am.

Quench on Nov 3rd at 8am (Description)

On Monday Nov 3rd at around 08:30am, the SANE experiment was planning on switching the polarity of the polarized target magnet. To do this the magnet first needed to be ramped down. In the process of this ramp down the magnet quenched. Though the target operator was familiar with polarized targets, this was the first time that the target operator had ramped down this particular magnet. The target operator (by entering data into the LabView control program) attempted to ramp down the magnet at 20A/min. The top panel for Figure 5 shows the current versus time for the quench. One can see that the actual ramp rate started out as 1.0A/min as programmed into the power supply. When the current dropped below 72A the ramp rate changed to 1.5A/min. The fact that the target operator was trying to ramp the magnet at a faster rate was ignored by the power supply. The magnet quenched when going below 60 amps and the ramp rate was increased to 2A/min.

Fig. 5 shows the liquid helium level in the magnet in the middle panel B and the LHe output flow rate or boil-off in the bottom panel C. A slow drop in LHe flow and level is see before the heater to the persistent switch is turned on and the ramping down of the magnet began. The magnet was at +77 amps when it was taken out of persistent mode at 8:27. Note that flow increases slightly (due to current in magnet leads and persistent switch heater), but is still reasonable. The magnet coils are still superconducting. The magnet quenches at 60 amp (08:45), immediately followed by a liquid level spike and a drop, and the LHe boil-off flow pegs at 100.

Quench on Nov 3rd 5pm (Plots)

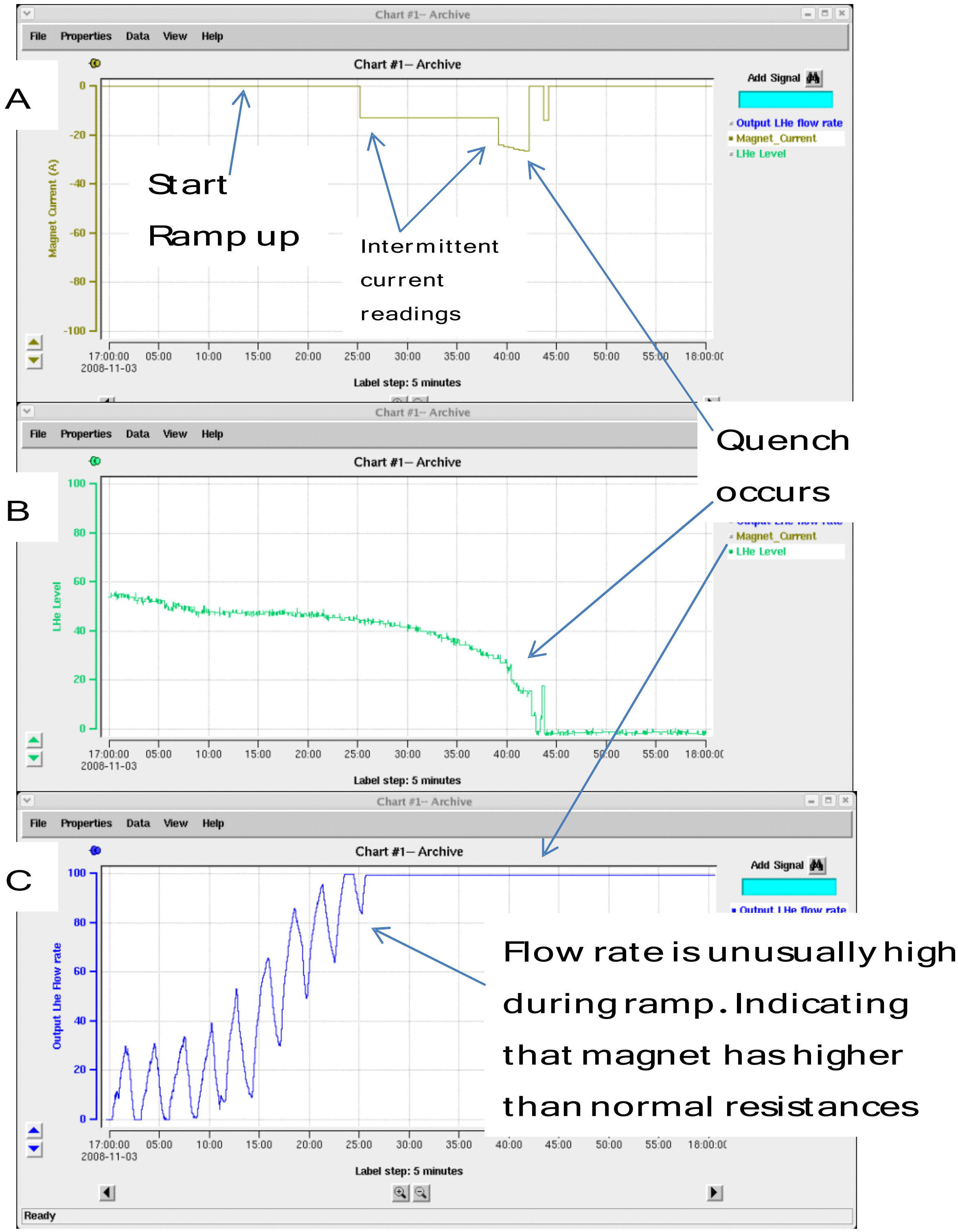


Figure 6 Strip charts of A) magnet current B) Liquid helium level and C) LHe output flow rate during quench on Nov 1st at 5pm.

Quench on Nov 3rd at 5pm (Description)

The magnet was cooled down during the rest of day on Monday. Around 5pm, an attempt to ramp up the magnet in negative polarity was made, but the magnet quenched at 26A. In Fig.6, a chart shows the power supply current (top panel A), liquid helium level of the magnet (middle panel B) and the liquid helium output flow (bottom panel C) during this quench. Unfortunately the reading of the magnet current was intermittent at the beginning of the ramp so it is hard to see exactly when the ramping started. One point to note is that the magnet is ramping in negative polarity which is indicated by a negative current. By extrapolating back, the approximate start of the ramp is indicated in the top panel of Fig.6at about 17:10. There are current measurements of -12 amps at 17:25, and -23 amps at 17:38. After this reading, there is a steady reading of the current and one sees the current increasing steadily to -26.4 amps. The magnet quenches at 17:42. Looking at the LHe output flow in the bottom panel of Fig. 6, one sees that the output flow quickly rising at the magnet ramps up and is at 100 when the magnet is only at 12A. This indicates that the magnet has a higher than expected resistance and that there is a problem.

Investigation of magnet in Hall C

After this quench, the magnet was allowed to cool down. At around 11pm another attempt to ramp up the magnet was made. When trying to ramp up the magnet, the following problem was found. When ramping with a current of 3.5 A in the magnet, the voltage was 4.7 V - much more than expected from the leads. This indicated that there was extra resistance in the circuit. It was decided to not keep trying to set field in the magnet and investigate more on Tuesday.

Diagnostics on the magnet were performed on Tuesday, Nov 4th. In order to check that this apparent resistance (about 2 ohms) is coming from the magnet and not the power supply, the power supply leads were connected to one another and the power supply was ramped up. The expected resistance was seen (that 2 ohms was not coming from the supply or leads). Also, the supply's output was checked on a scope for irregularities. 50 mV 60Hz noise was found, but would not have caused the problems we have been seeing.

The following day, Wednesday Nov 5th, effort was made to slowly ramp the magnet up again and watch the current limit. It was hoped that the V *vs* I curve would flatten out enough that we could reach an operational magnetic field strength (2.5 T), but this did not prove to be possible.

Later on Wednesday, while the magnet was still cold, measurements were made of the voltages across the taps at seal "D" at 0.55A from the power supply. The results are listed in Table 2. One expects all the voltages to be zero. Also with the magnet cold and no current in the magnet the resistances were measured across various taps. A resistance of 1MOhm was measured across taps CD. From all these measurements and discussions with Oxford it was clear that there was a problem with magnet that only could be investigated and resolved by opening up the magnet. On Wednesday evening the magnet was allowed to warm up and it took until the following Monday, November 10th, before the magnet could be removed from the pivot.

Table 2: Voltages measured across different tap points in seal “D” (see Fig. 3) with the magnet cold and at 0.55A.

V_AB	V_BC	V_CD	V_DE	V_EF	V_HJ	V_JK	V_CE	V_AC	V_BK	V_AK
+1.465V	+0.536	-0.165	+0.165	0.0	0.0	0.0	0.0	2.0	0.536	2.0

Investigation of the magnet in the EEL

Once the target was warmed up and removed from the pivot, the magnet coil package was removed and taken out of the hall. It was taken to the EEL where the top cover of the magnet was cut off. Initial investigation found a diode that was broken, but no obvious signs of problems. The location of the broken diode is between coils 4b and 4a, as indicated in Fig. 7.

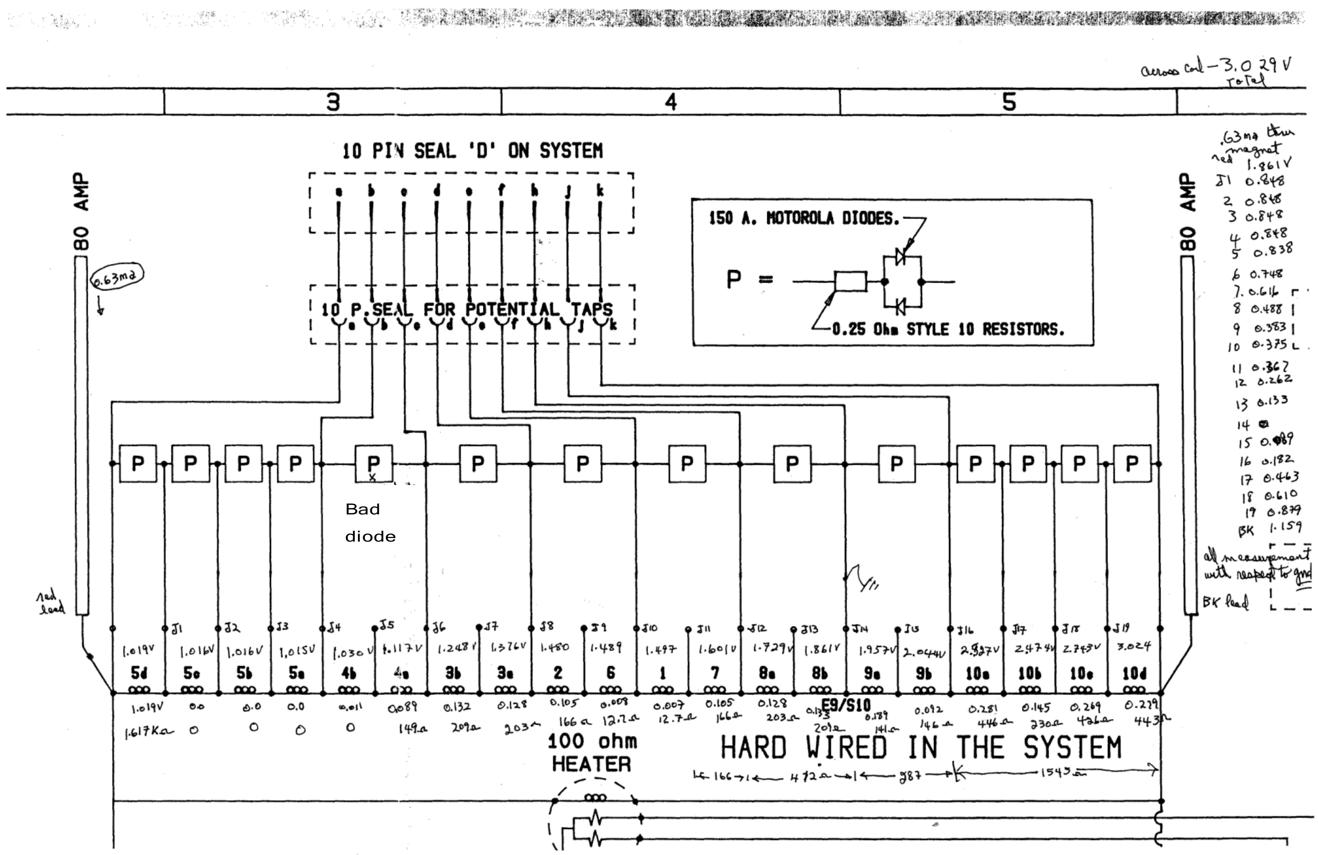


Figure 7 Circuit diagram of the magnet.

Bill Vulcan took some voltage measurements. First he disconnected the heater switch by taking out the solder from J0 and he also disconnected the diodes. He then put a source of 0.63mA through the circuit as indicated in the Fig. 8. In the Fig. 8 (above the 5d , 5c, etc) are the voltages relative to the red lead and below are the differential voltage and calculated resistance. For the one side of the magnet (coils 1, 7, 8a, 8b, 9a, 9b, 10a, 10b, 10c, 10d) the resistances agree fairly well those expected for the coils. The surprising discovery was that at J1 a resistance drop was measured which was what one expects by adding 5c+5b+5a+4b; however voltages drops across the individual J2 through J5 are zero. Bill also measured the junction points relative to ground that is the list of voltages on the right side of the Figure 8. After discussion with Oxford we decided to remove solder from joints J1 through J5 and measure the resistance of each coil individually.

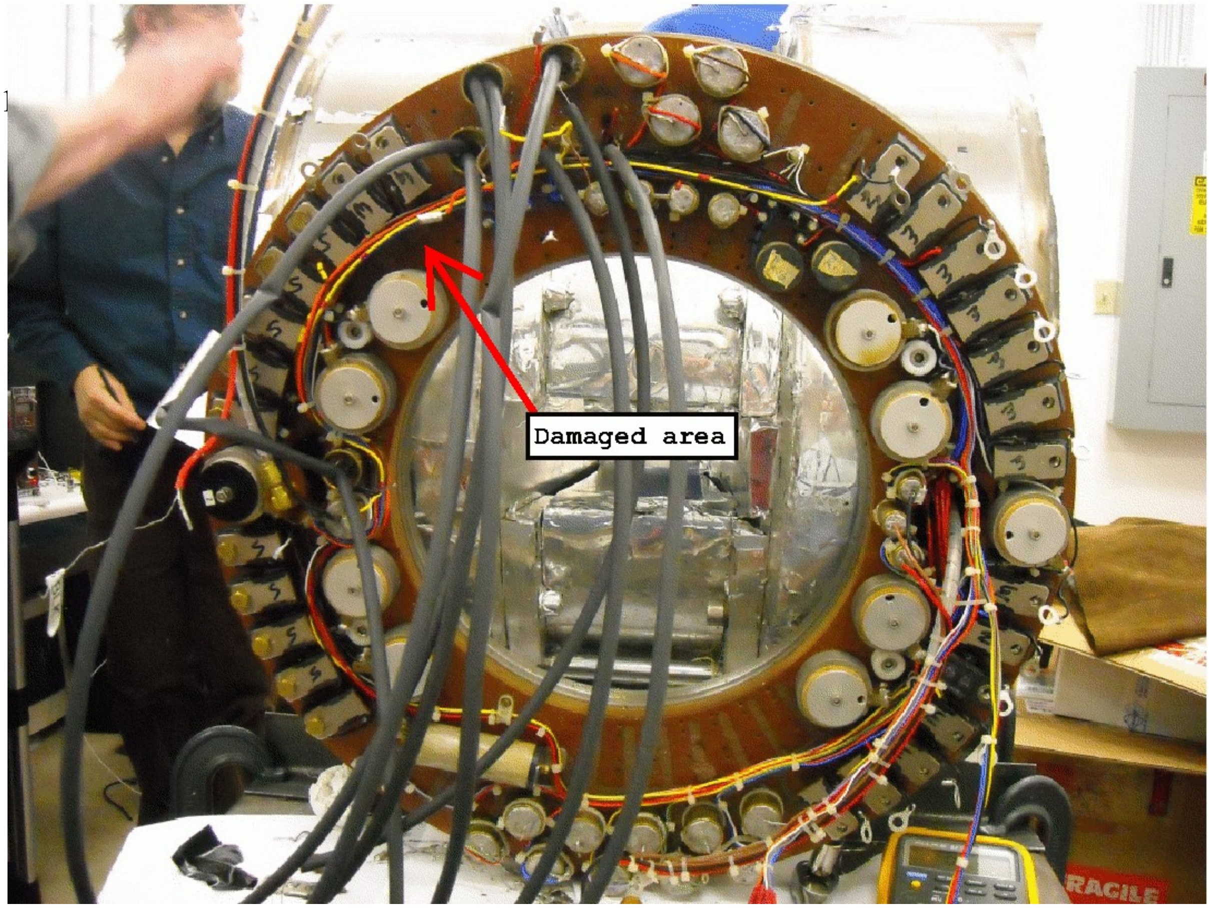


Figure 8: View of magnet electronics, with area of damage pointed out.

Each of the joints at J1-J5 was opened and the resistances were measured for each coil. The results were still puzzling. In contrast to the previous readings with the J1-J5 joints closed, several infinite resistances were found. While investigating a lead with infinite resistance, the superconducting wire was pulled out with only a short amount of extra cable. This indicated that the wire had broken in a location near the joint connection. The leads of coils are packed into a channel to get from the coils to the individual joint cups. In digging out the plasticene that held the wires in place damage to the wires was found. The location of the damage is shown in an overview in Figure 8. In Figure 9 is shown a close-up where damaged and/or broken wires were found. Six broken wires were found. After a systematic process of elimination that involved matching red to black (and vice-versa) leads, the 6 broken wires were identified and are listed in Table 3. Comparing the resistances between matching opposite coil found agreement at the 2% level indicating that the rest of the coil was in good shape. After consulting with Oxford, it was agreed that there was enough superconducting cable (about 4 inches) coming up through the hole that goes down to the coils to make a new joint for each damaged lead.

"Bad" Coil	Black Lead from "Bad" Coil	Red Lead from "Bad" Coil	Measured Resistance of "Bad" Coil (ohms)	Matching Coil	Resistance for Matching Coil (ohms)
5D	J0	J1 (cut)	451	10D	443
5C	J1	J2 (cut)	436	10C	426
5B	J2 (cut)	J3	236	10B	230
5A	J3 (cut)	J4 (cut)	455	10A	446
4B	J4	J5 (cut)	150	9B	146
4A	J5	J6	143	9A	141

Table 3: Listing of damaged coils with corresponding leads and measured resistances. Also listed are the matching coils (in other half of magnet) along with their resistances.

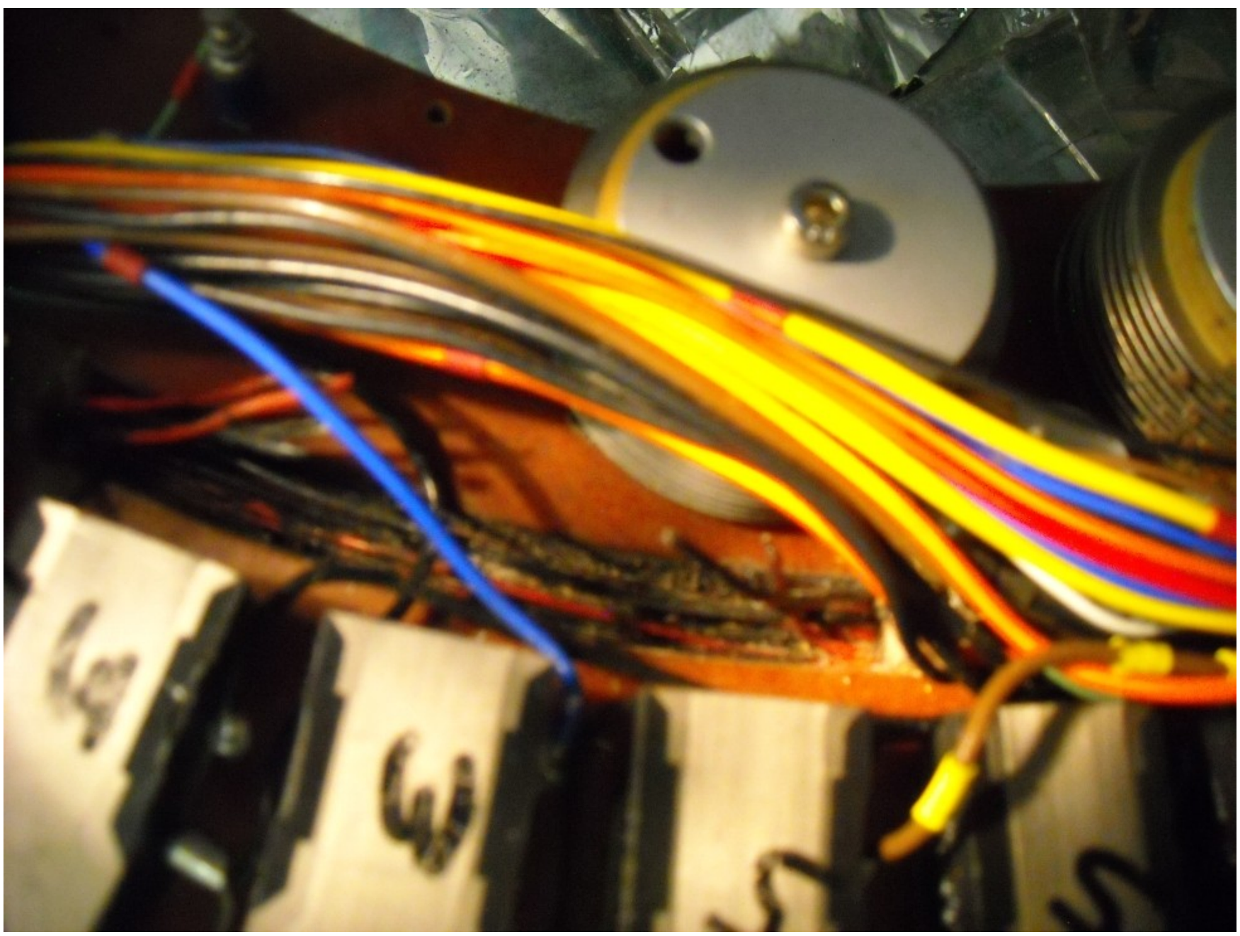


Figure 9: Close-up of magnet electronics, where broken and/or damaged wires were found.

Repair of magnet

On Monday Nov 24th, Oxford engineer Paul Brodie arrived to work on repair of the magnet. Joe Beaufait and Paul Brodie worked on making new joints for the broken wires. Oxford instruments shipped extra materials for the repairs and provided instructions for making repairs. After consultation with Joe it was decided to make a superconducting joint for the first inch and then a copper to copper connection for another 3 inches. The superconducting joint was made by stripping off the copper and using an ultrasonic soldering iron (provided by Mike Seely) to make the connection. The copper to copper was a regular solder connection. After the new joints were made, the resistance was measured to check that it was the same as before. To determine the polarity of the leads, current was sent through one good coil and the direction of the field determined with a compass. Each coil was connected to the supply and the polarity of the leads was determined by matching the direction of the field to the good coil. Once the polarity of the leads was determined, the leads from nearby coils were joined together as before and put in the joint cups. Connection to the rest of the circuitry was made. The bad diode was removed. It could not be directly replaced, but a new diode was put in place (see Fig. 10) and connected into the circuit with new cables. Because the new superconducting joints are short, the magnet will not be a “high” persistent mode magnet when it is re-installed. Originally, the magnet decay was 5 parts in 10^8 /hour. This is not a problem, as the polarized target will work with poorer magnet persistence. Therefore, once installed, we will set the magnet in persistent mode and see how the magnet field decays. If the magnet is not persistent, it can be run constantly from the power supply. The current from the power supply is stable at 1.5×10^{-4} which is sufficient for the experiment.

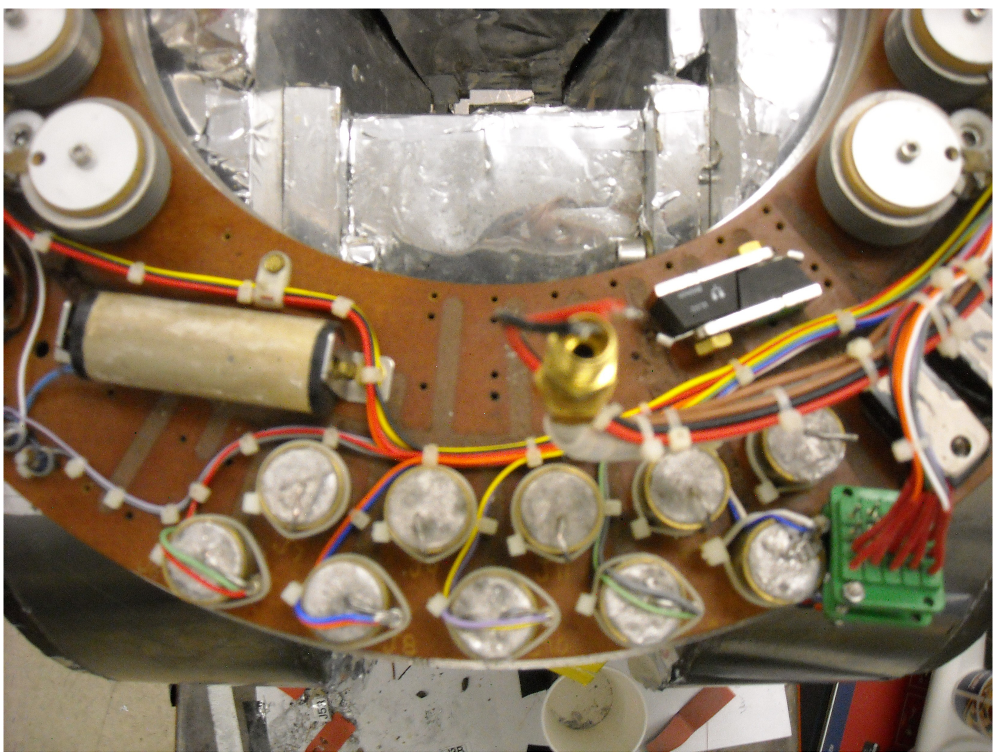


Figure 10: Picture of top of magnet showing the new diode location.

Cause of the polarized target failure

It is clear that after the quench of the morning of Nov 3rd that the magnet no longer worked. When did the diode break? Did diode break during the quench in the summer or the quench on Oct 31st? The magnet was ramped up to full current on Nov 1st using ramp rates recommended for the "First Run" (listed in Table 1). The bad diode would not have been noticed, since the diodes only are important when the magnet quenches. When the magnet was being ramped down on the morning of Nov 3rd, the maximum programmed ramp rates were used. The switch to 2A/min at 60A caused a quench and maybe the diode was already bad which made the current in the leads too large and caused them to melt. The subsequent attempt to ramp the magnet in the early evening of Nov 3rd could have made the damage worse. Unfortunately no measurement of the voltage or resistances at the tap points in seal "D" was made between the two quenches. But it is possible that the diode breakage and wires melting were all caused during the Nov 3rd morning quench. When using the magnet for experiment in fall of 2001 there were quenches when the magnet was ramping up at 1.5A/min and when ramping down at 2A/min. Both these quenches didn't result in damage to diode, so one would not expect the Nov 3rd morning quench to break a diode.

The main lessons learned are that efforts should be made to minimize quenches and that proper training of magnet operators is an important part of minimizing the possibility of a quench. There needs to be an emphasis on operators paying attention to the voltage in the coil when ramping the magnet. Another cause of quenches in the past was not turning the shim coil heater on before ramping up the magnet. Even though the shim coils are not used the shim heater needs to be turned on. Below is a list of administrative and engineering actions items to minimize the likelihood of quenches.

Action items

In order to reduce the likelihood of another quench from happening we have made a list of actions to carry out, along with names of individuals who will be responsible for doing them. Once an item is done or confirmed the responsible individual(s) will sign and date next to their printed name(s).

Administrative actions

a) Detailed step-by-step procedure for ramping the magnet will be written up. This will include information on how the power supply and magnet works, so operators know what to expect and what to look out for.

Responsible people: James Maxwell ___________ Don Crabb ____________________

b) Magnet power supply will only be operated by a very small number of experts for duration of experiment. This is the list. Donal Day, Don Crabb, James Maxwell, Jonathan Mulholland

c) Will adjust run plan to minimize number of times magnet is ramped up or down. It will never be reversed.

Responsible people: Oscar Rondon ____________ Mark Jones ___________________

d) Modify COO and ESAD so that the magnet does not need to be powered down when in Restricted access.

Responsible people: Narbe Kalantarians ____

Engineering Actions

a) Put a UPS on the power supply to avoid quenches from site power glitches or short outages.

Responsible people: Bill Vulcan _________ Joe Beaufait ______________________

b) Program the internal settings of the power supply so that the maximum ramp rates are the"First Time" ramp rates listed in Table 1. Modified LabView interface so that it stops ramping between each current region (0-60A,60-72A and 72-79A) and forces the user to enter a new ramp rate. In addition, the power supply is put in “Hold” when the ramp rate or set point is changed.

Responsible people: Jonathan Mulholland ___________ Oscar Rondon

c)Implement equipment that allows the operator to determine that the shim coil power supply is turned on.

Responsible people: James Maxwell ______________

d) Add a warning LabView interface so that operator knows if the main switch heater as been on or off long enough to ramp magnet.

Responsible people: James Maxwell ______________

e) LabView currently displays the voltage across the leads at the supply. Monitor the coil voltage (L dI/dt) when the magnet current is ramping by measuring at the “D” connector or at the lead connections at the magnet. A DVM will monitor this voltage and it will also be read into LabView.

Responsible people: James Maxwell ________________

f) Existing cameras need to be fixed, and possibly a few more added, if needed, so that operators can see all relevant equipment remotely.

Responsible people: Joe Beaufait _________ James Maxwell ________ Narbe Kalantarians ____

g) All the above steps will be thoroughly checked with the power supply leads shorted together (not hook up to the magnet) and other suitable simulations of the actual situation, before hooking up the magnet again.