D-Zero Solenoid Quench Investigation:

Observations, tests, and commentary

Fall 2004 - Spring 2005

D-ZERO ENGINEERING NOTE # 3823.111-EN-576

March 24, 2005

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Summary
The D-Zero solenoid operated reliably at 4750 Amperes (2 Tesla) from its manufacture in 1997 through August of 2004. During the period of August thru November 2004, the solenoid was warmed to room temperature for maintenance work and then re-cooled. After re-cooling, the Solenoid was not able to reach full current.

An investigation began to understand the cause and ultimately how to limit or prevent further degradation in performance. A stable operating current of 4550 Amperes was chosen to allow physics analysis to continue at reduced magnetic field strength (1.92 Tesla).

The investigation revealed clear evidence of an excessively resistive solder joint in a conductor transition joint in the inner layer winding of the two layer solenoid coil. The resistive joint generates Ohmic heating and raises the local superconductor temperature to critical temperature at the magnetic field strength and current of about 4650 Amperes. This is believed to be the primary cause of the degradation in performance.

Temperature sensors located above the resistive joint area see a temperature increase from the resistive solder joint. Historical trending of these sensors at 0 current and full current gives a picture of the joint worsening with time. Coupling the trend with operational history leads one to believe that the joint degradation is connected with thermal cycles of the solenoid. We believe that preventing thermal cycling will prevent future degradation/increased resistance in the joint. Another interpretation of the data (although less compelling) is that the degradation could be time dependent or energization cycles. Although this conclusion is not as strong, we now also limit power cycles and field reversals.

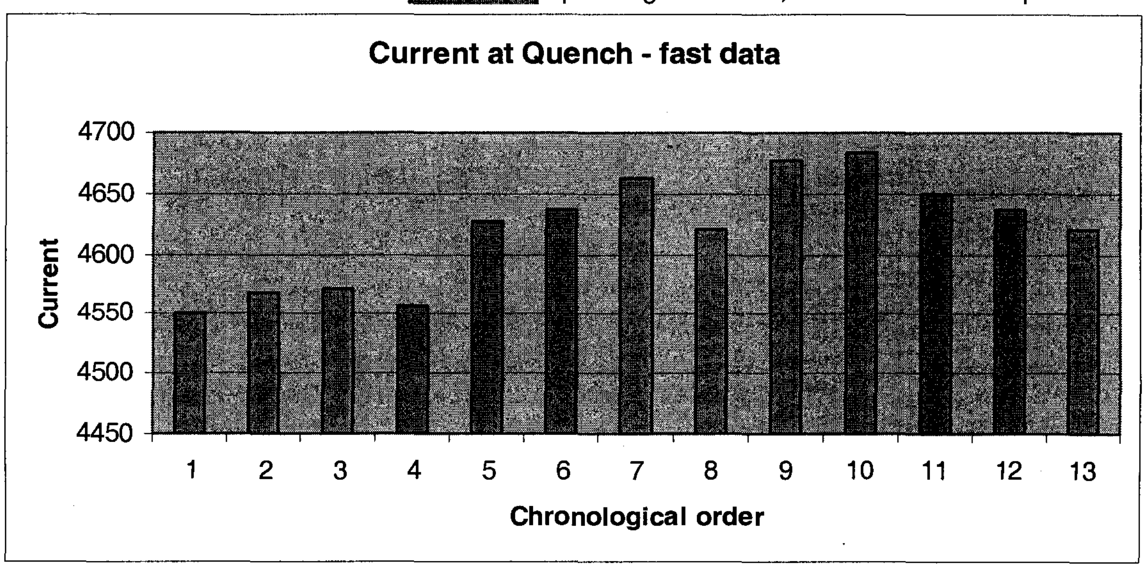
Procedures are in place to prevent warming the solenoid coil. Increased resolution temperature monitoring of the resistive joint has been in place since December 2004 and no increase in temperature elevation has been detected. A resistance monitoring system is being developed that should yield electrical resistance measurements of the degraded joint itself. A helium refrigerator upgrade consisting of a cold compressor is in progress. It will reduce the liquid helium coolant temperature for the solenoid and also the conductor winding to gain additional operating margin.

Preface
The purpose of this DZero Engineering note is to document in one place much of the information gathered and passed among experts through out the investigation. The writing style is not one of free flowing text rather it is subdivided into logical points of the investigation. Another paper "Present Status of the D0 Solenoid" primarily authored by Richard P. Smith and myself (co-author), March 26, 2005 contains much of the same information presented here (plus additional information) in a more narrative format.

Points of the investigation with commentary:

1. Prior to August 23, 2004 the solenoid operated reliably. It never quenched when charged and operated at 4750 Amperes (2 Tesla magnetic field). After a warm up and re-cooling in the fall of 2004, the magnet was found not to operate as before. The magnet was operated on November 18, 2004 and found to quench prematurely. It must be noted that the liquid helium mass flow during the November 18-19, 2004 quenches (3.5 to 3.8 g/s) was later found to be just adequate to balance the measured cryogenic heat load. To give sufficient margin, a liquid helium mass flow rate of 4.0 g/s or more is recommended. A quench current of about 4650 Amperes implies that the conductor temperature at the quench initiation site is about 7.4 Kelvin based on the conductor short sample data. A new operating point of 4550 Amperes has been chosen for the continuation of Run 2.

Order	Date	Quench Current	Polarity	Remarks
1	18-Nov-04	4550	Reverse	Normal ramp rate from 4000 A
2		4569	Reverse	Normal ramp rate from 4490 A
3		4571	Reverse	Slow ramp from 4490 A
4		4557	Forward	Slow ramp from 4491 A
5	19-Nov-04	4627	Forward	Normal ramp rate from 0 A
6		4636	Forward	Slow ramp from 4500 A
7		4663	Reverse	Normal ramp rate from 0 A
8		4620	Reverse	Operating at 4620 A, then raised He temp
9	26-Nov-04	4677	Reverse	Ramp from 4650 A. Higher mass flow = 5.2 g/s
10	29-Nov-04	4684	Reverse	Ramping from 4650 A
11	30-Nov-04	4650	Forward	Slow ramp from 4600 A
12	2-Dec-04	4636	Forward	Slow ramp from 4625 A.
13	9-Dec-04	4620	Forward	Operating at 4620 A, then raised He temp

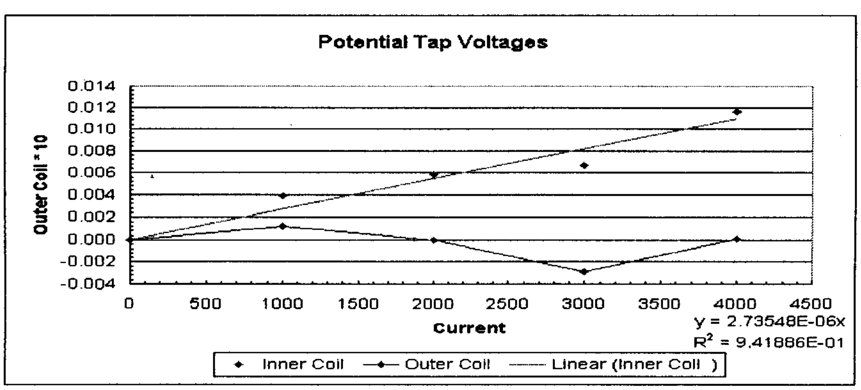


2. The magnet will quench at a steady current (non-changing magnetic field) of 4620 Amperes by raising the liquid helium coolant temperature. This implies that mechanical motion of the superconductor is not to blame for initiating the quench since a temperature increase alone initiates the quench.

3. At 0 Amperes, the heat load today (December 2004) is much higher (32 Watts) than when first operated the solenoid at Fermilab in 1998. At full current, the heat load is 40 Watts higher than in 1998. Nominal heat load & refrigeration heat load is: 56 Watts + 0.12 g/s at 0 Amperes, & 48.6 Watts + 0.76 g/s at 4550 Amperes. Accuracy is +/-2 Watts. About 15 +/-5 Watts can be attributed to additional heat due to the long transfer line into the collision hall. In 1998, the tests were done in the assembly hall and the transfer lines were about 50 feet long. Since 2001, the detector has been in the collision hall and the transfer lines are about 170 feet long and include additional heat load components such as non-radiation shielded flexible sections. That leaves 17 +/-5 Watts of the increase ill defined. See number 8 for additional commentary on this topic.

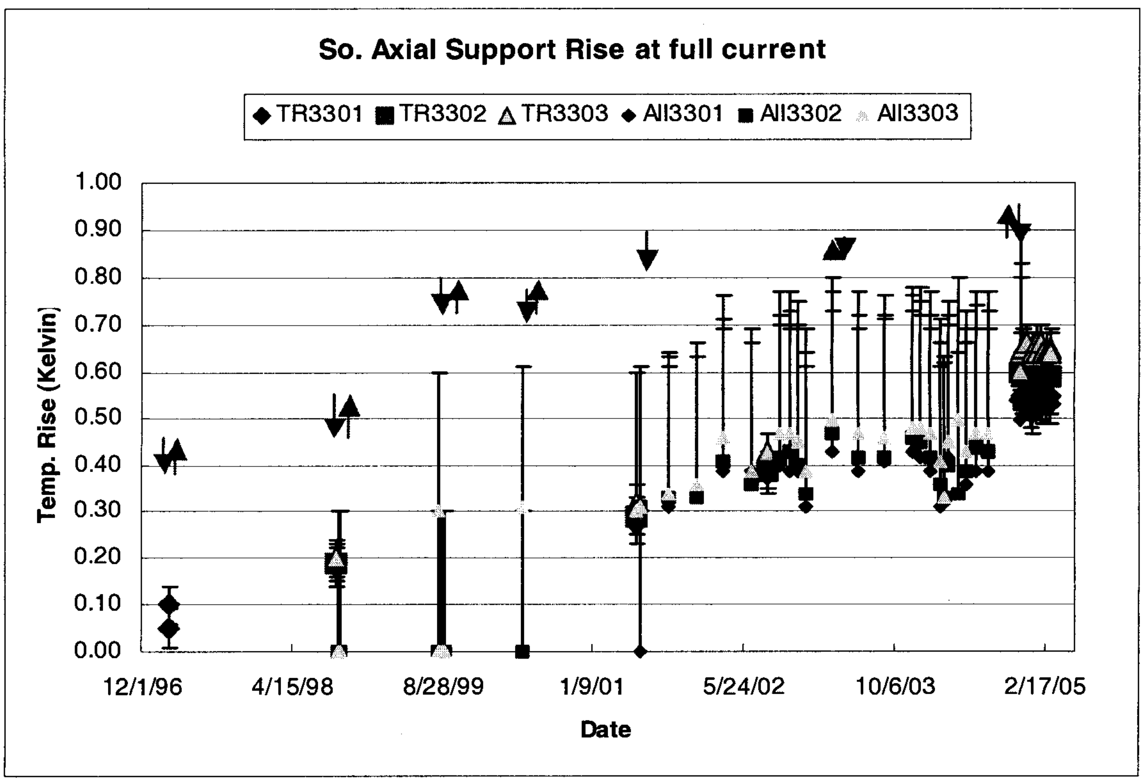
4. Cryogenic heat load measurements indicate about 8 +/-2 Watts additional heat load at full current versus 0 Amperes. These are based on comparisons to measurements made in 1998 when there was a measured 5 to 6 Watt total electrical heat load at full current. This indicates that there is some phenomena which causes heat input at full current. Eddy current heating due to fluctuating voltage has been ruled out by calculation. Resistive conductor joints (I^2R= 6 Watts at full current) have been measured electrically and appear to account for this observation.

5. The electrical resistance of the solenoid coil, chimney, lead system was deduced on Jan. 5, 2005 from recorded potential tap voltages at 1000 A, 2000 A, 3000 A, and 4000 Amperes. Averaging of the signals was necessary. It was concluded that one or both inner coil conductor joints is behaving ohmically such that at 4600 Amperes, the heat generation would be 5.9 Watts. [An earlier attempt to measure the coil, chimney, and lead resistance on Dec. 9, 2004 concluded no resistance present. These earlier measurements were less sophisticated with only one sample point chosen from a noisy fluctuating signal.] Graph and analysis of this point by Rich Smith.

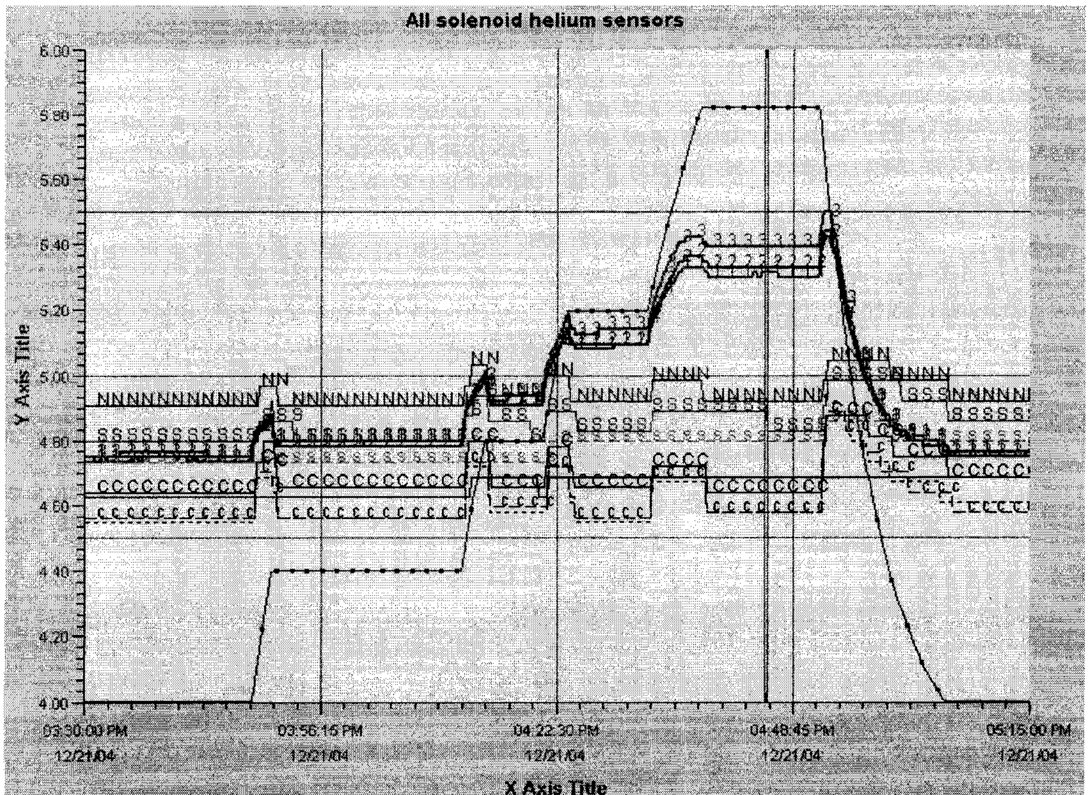


6. A temperature rise of 0.53, 0.58, and 0.64 Kelvin has been observed on the south end of the coil support cylinder when the solenoid is at full current. The temperature sensors are attached to three axial support links spaced around the perimeter of the coil and are located mid-way between cooling coil tube runs. The center and north end of the support cylinder see no (< 0.04 K) temperature changes between the zero and full current condition. This behavior was historically researched. It was found that small temperature increases (0.1 K) at full current were present when the magnet was operated for the first time at the Toshiba factory. The magnitude of this temperature increase has increased with time. The arrows on the graph below represent all cool downs and warm ups of the solenoid.

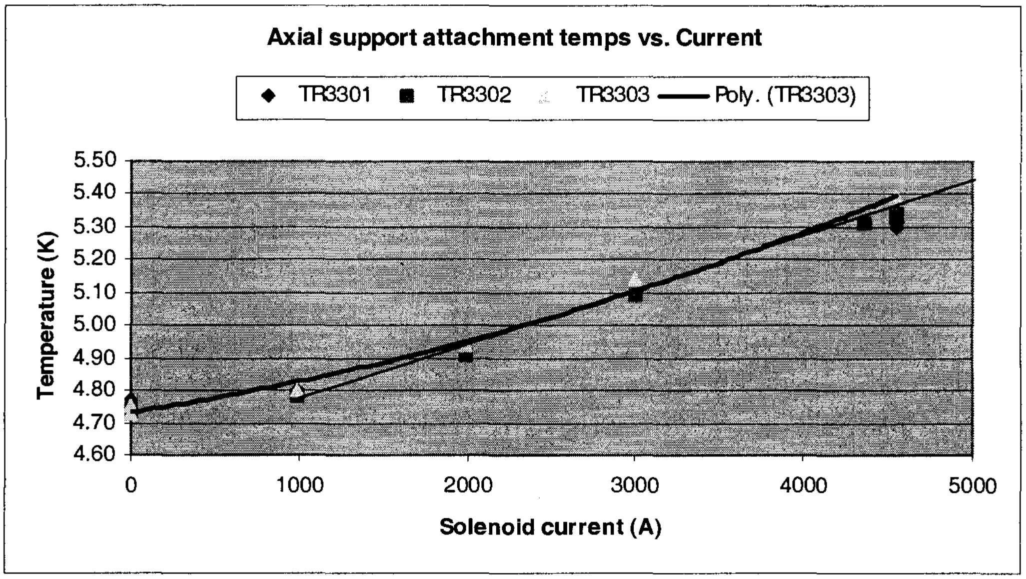
Thermal	
Cycles	**Date/Event**
1	1997 - Toshiba completes fabrication, factory test
2	September 1998 - First FNAL cool down & commissioning, full warm up afterward
3	August 1999 cooled down to verify chimney joint repairs, left to warm afterward
4	May 2000 cooled from 290 K, operated for <1 month then left to warm
5	April 2001 cooled from 290 K, beginning of Run 2.
Partial	January 2003, Coil warmed to 130 K and re-cooled, EVMF fixed.
6	August to Nov 2004, Full warm up and cool down. Lead leaks fixed, piping de-rimed.

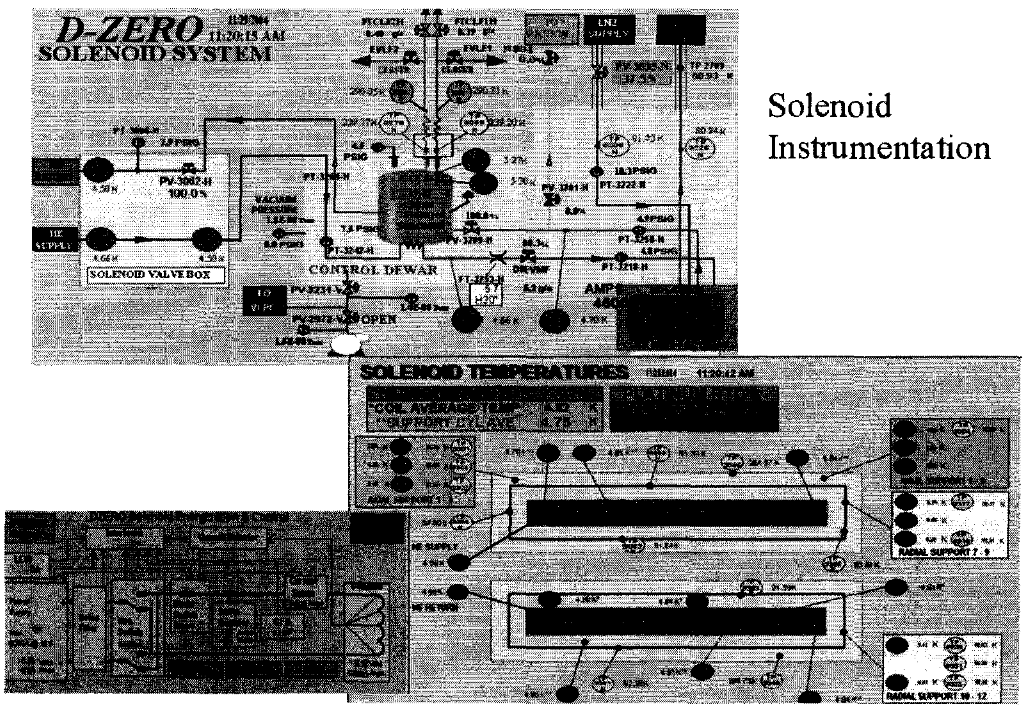


7. The temperature rise of the axial support links is directly related to solenoid current. The graph below demonstrates the rise in temperature with step changes being made to magnet current (red line with rectangular markers). The vertical scale is temperature in degrees Kelvin except for magnet current, which is 0-5000 Amperes. Axial temperature sensors TR3301, TR3302, and TR3303 increase during charging and remain elevated. It is inconclusive if the rise is linear or quadratic.



Tag Name	Description	Value	Eng Units
D0_CCRS1.TR3301-T.F_CV	Temperature for C16795 (TR-3301) RTD	5.31	K
D0_CCRS1.TR3302-T.F_CV	Temperature for C16796 (TR-3302) RTD	5.33	K
D0_CCRS1.TR3303-T.F_CV	**Temperature for C16797 (TR-3303) RTD**	**5.39**	**K**
D0_CCRS1.TR3330-T.F_CV	Temperature for C18819 (TR-3330) RTD	4.89	K
D0_CCRS1.TR3331-T.F_CV	Temperature for C18820 (TR-3331) RTD	4.68	K
D0_CCRS1.TR3333-T.F_CV	Temperature for C18[illegible] (TR-3333) RTD	4.8	K
D0_CCRS1.TR3334-T.F_CV	Temperature for C18823 (TR-3334) RTD	4.68	K
D0_CCRS1.TR3343H-T.F_CV	Temperature for C18825 (TR-3343-H) RTD	4.89	K
D0_CCRS1.TR3344H-T.F_CV	Temperature for C18826 (TR-3344-H) RTD	4.84	K
D0_CCRS1.TR3345H-T.F_CV	Temperature for C18827 (TR-3345-H) RTD	4.92	K
D0_CCRS1.DC_AI28.F_CV	0-10V Analog In - ABS I Xducer (ABS I-2)	4,640	Amps





Solenoid Instrumentation

Russ Rucinski, PPD/MD/DZero Ops

8. Ang Lee (PPD/MD) created a finite element model which models a 30 degree segment of the coil, support cylinder, and cooling tube. The modeling predicts the support bracket temperature elevations corresponding to the measured 6 Watt heating rather well (0.5 K). The temperature it predicts for the conductor temperature due to heating however is only 6.4 K (given our average coil temperature of 4.90 K). This is ~1 K colder than the current sharing point of the conductor as given by the conductor short sample measurements (7.4 K). The reason for the discrepancy in model versus observed is not understood.

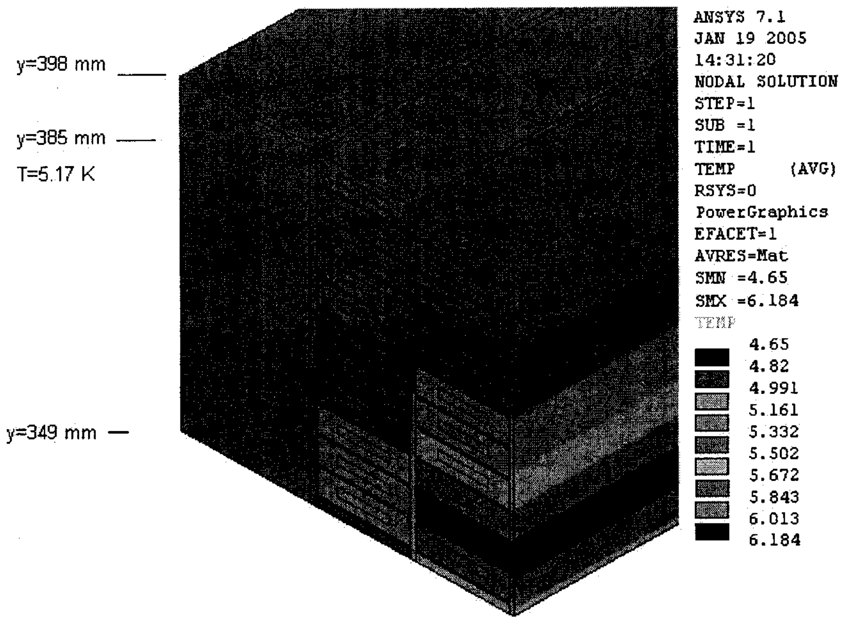
The following is copied from an e-mail dated Jan. 20, 2005 from Rich Smith.

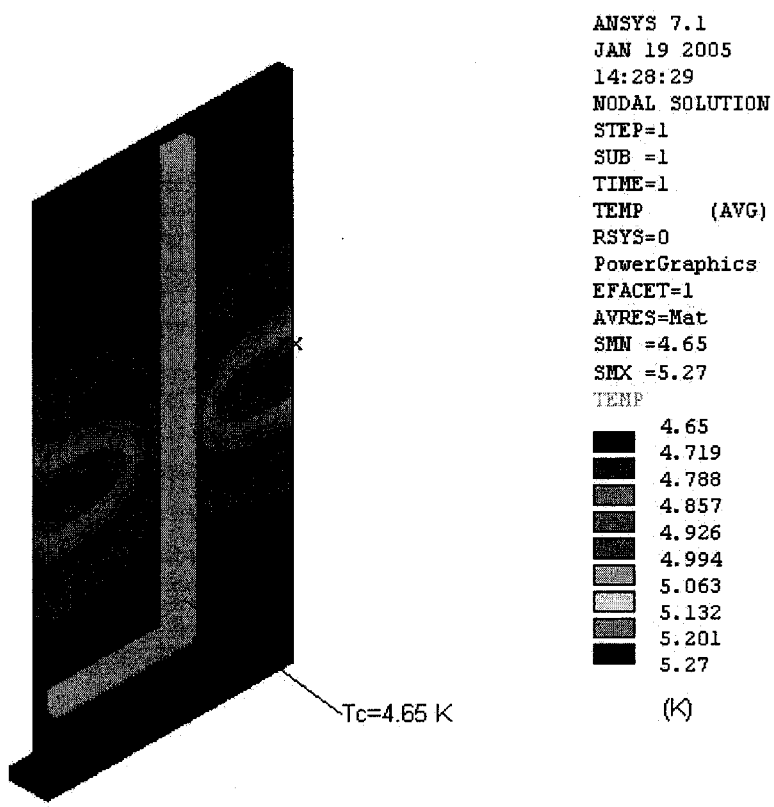
Colleagues,
Ang Lee has made a FEA (Ansys) modeling of the solenoid assuming a 5W heat load in the conductor grading joint near the S end of the inner layer (a distance of ~349 mm from the S end of the coil), and predicts the temperature to be observed on a S axial support bracket welded to the outer support cylinder (a distance of ~385 mm from the S end of the coil). He ignores any heating in the bracket due to heat conduction down the axial support link, and he assumes the surface of the outer support cylinder beneath the cooling tube is fixed at 4.65K.

He obtains a temperature at the bracket of 5.17 K, 0.49K warmer than the cooling tube. This is quite close to what Russ observes when the coil is energized and we measure ~5W loss in the inner layer of the coil as given by the potential tap data.

Attached is a plot of Ang Lee's model, showing the outer support cylinder and cooling tube segment -- the coil is "unrolled" in phi and a 30-degree segment in phi X about 500mm long in the axial direction is modeled. The yellow region in the plot shows the path of the cooling tube on the support cylinder. In the second plot is shown a detail of the conductor winding at the heated turn (y=349 mm) and the temperature (5.17K) on the outer support cylinder at y = 385 mm (Ang's y is the coil axial direction) where the support bracket thermometer is.
Ang repeated his calculations for a cooling tube temperature 0.1K lower and finds the same temperature difference to the axial support bracket, and about 86% of that temperature depression at the suspect turn. This is good news for the plan to install a cold compressor.

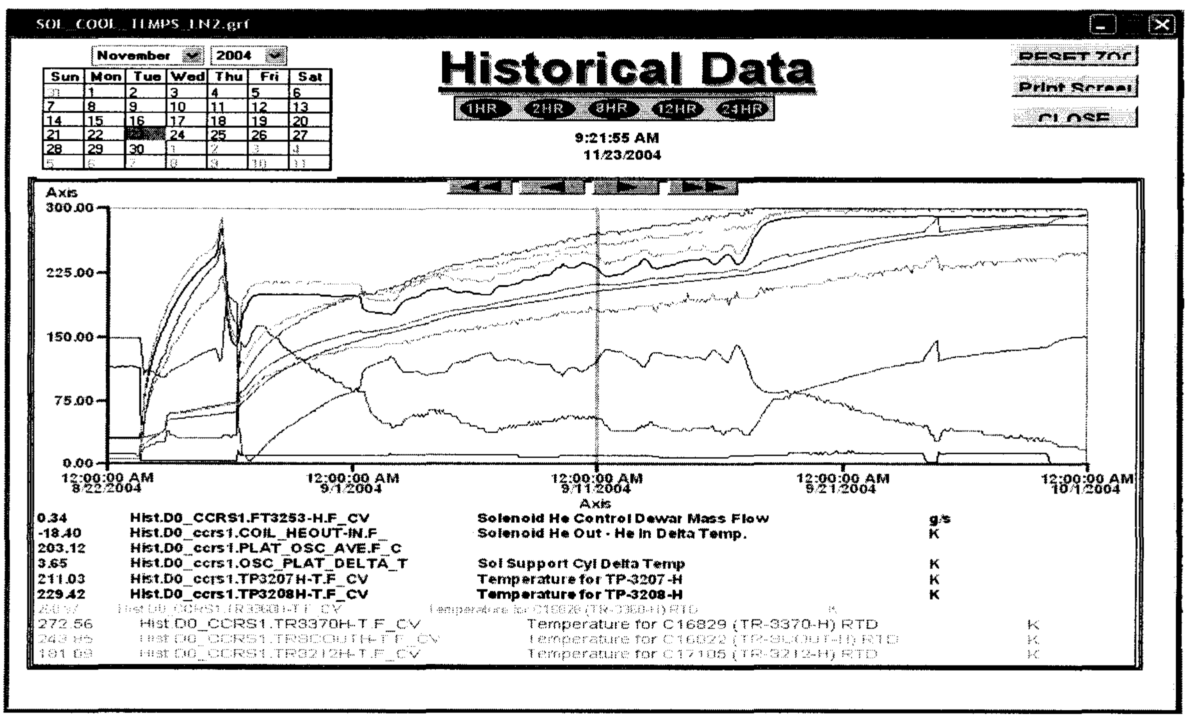
Rich

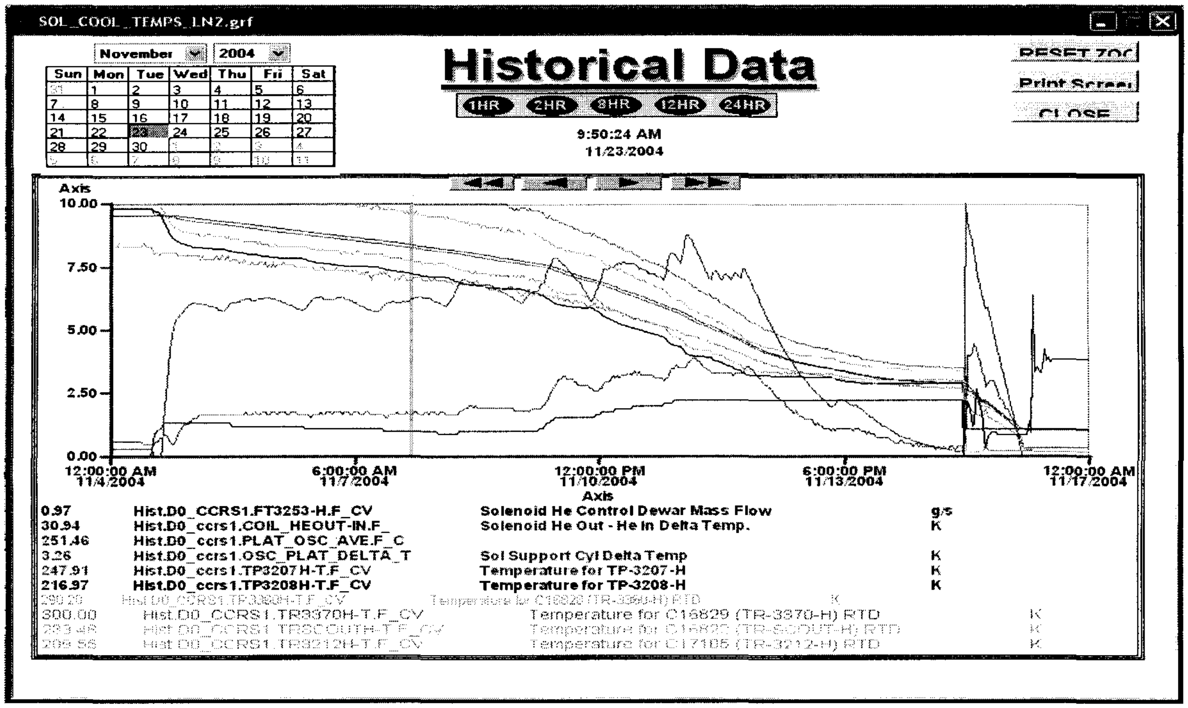

y=398 mm
y=385 mm
T=5.17 K
y=349 mm
ANSYS 7.1
JAN 19 2005
14:31:20
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
TEMP (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =4.65
SMX =6.184
TEMP
4.65
4.82
4.991
5.161
5.332
5.502
5.672
5.843
6.013
6.184


ANSYS 7.1
JAN 19 2005
14:28:29
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
TEMP (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =4.65
SMX =5.27
TEMP
4.65
4.719
4.788
4.857
4.926
4.994
5.063
5.132
5.201
5.27
(K)
Tc=4.65 K

9. A 25 Watt heat load increase over 1998 was detected by Feb. 3, 2003. Since 2003 the heat load increased an additional 5 to 7 watts bringing the heat load to about 32 watts higher now (Jan. 2005) than when the magnet was first received. Approximately 15 +/- 5 W can be attributed to the change in detector location. The post 2001 detector location requires an additional 120 feet of cryogenic transfer line. The location of this extra heat load does not appear to be in the chimney or solenoid coil and therefore does not contribute to the quenching problem. Heat load measurements taken at zero current with 1 g/s of gas helium at an inlet temperature of about 10 K indicate an expected 7 +/-3 Watts for the chimney and solenoid coil paths. This amount of heat load is as designed and expected. The remaining locations where the heat load could be elevated include the control dewar reservoir, supply or return piping in the control dewar upstream of the chimney including the 170 foot long cryogenic transfer line that spans across the concrete shielding block wall and runs to the refrigeration plant.

10. The solenoid remained cold between Feb. 2003 and August 2004. It was then warmed to room temperature starting August 23rd 2004 and was re-cooled to operating point on Nov. 15th. All temperatures in the solenoid system were above ice temperature, 273 K for 39 days during this warm up. Coil/Support cylinder reached 286 K, Ln2 shield reached 288 K and were under full vacuum pressure conditions. These conditions should be adequate to have eliminated any cryo trapped moisture from the vacuum space. The heat load before and after the fall 2004 warm up cycle increased by 5 watts or less. Warm up and cool down rates and restrictions were observed. In fact, the rate of warm up and cool down for this last cycle was much slower and controlled than all other past thermal cycles.



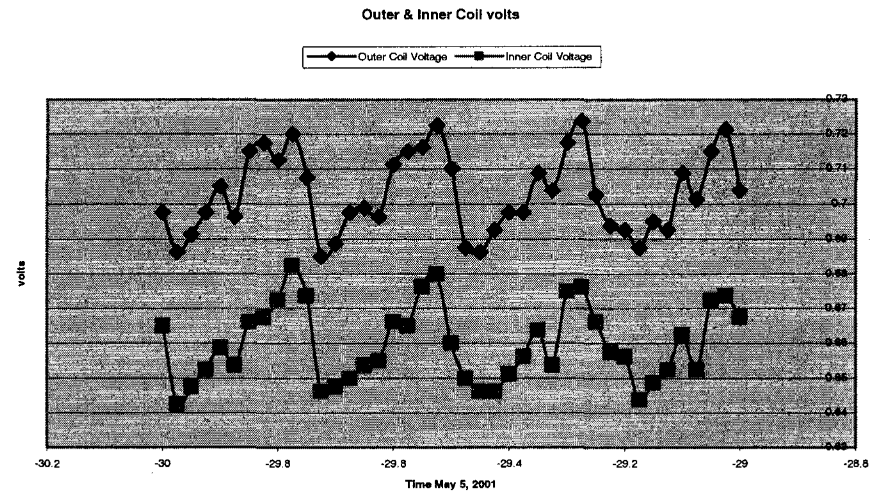


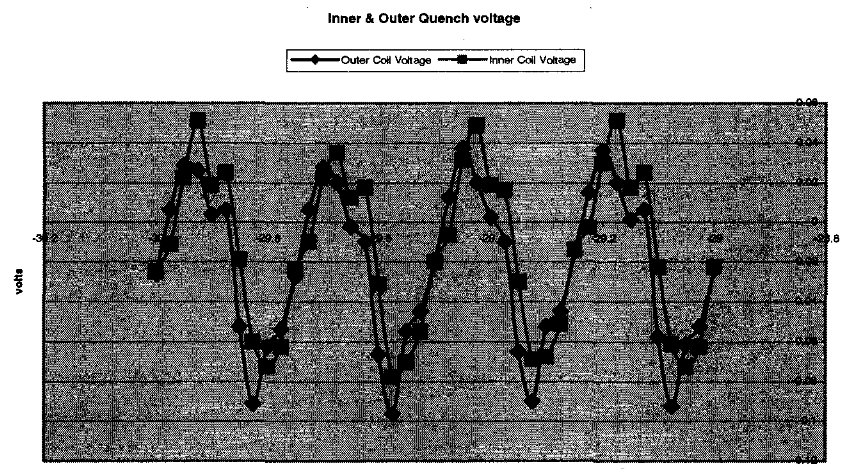
11. The solenoid vacuum jacket pressure is about 10E-7 Torr while isolated. Four different vacuum pressure transmitters correlate that the instrumentation is believable. The vacuum space is typically left isolated with no rate of pressure rise. The pressure is much lower than the 10E-4 Torr value that is required for MLI vacuum jackets to be effective. Vacuum jacket pressure is not believed to contribute to the observed heat load increases or to the recent quench behavior.

12. A test was done that consisted in throttling LN2 flow to a warm gas state. LN2 temperature sensors appeared to warm uniformly at the same rate for each type of component (shield, axial support, or radial support).

13. A water-ice short between the nitrogen shield and support cylinder or coil was calculated to be capable of transferring 30 watts of heat. Given delta T=88K – 5 K, distance between surfaces = 20 mm, and K_{ice} (at 50K)=11.3 W/m-K, then required area = 640 mm^2 = 1 in^2. One must note that in Oct-Nov. 2004 while vacuum pumping, the temperature of the coil/support cylinder and nitrogen shield was above 273 K for 39 days. Standard thinking is that all such contamination would have been removed at that time given the temperature and vacuum pressure conditions. Ice cubes (insulated from external heat input) pumped on in a bell jar disappear in a day.

14. The inner and outer coil voltages are fluctuating with a larger magnitude 0.12 volts versus 0.03 volts in 2001 at 4 Hz. Others have calculated the heating effect to be only 0.0002 Watts. A heat load of this type would input heat uniformly along the support cylinder where it would have little effect on temperature. The toroid magnet also experiences voltage fluctuations. It is believed that these fluctuations appeared only after the fall 2004 shutdown. Therefore it is possible that it is a result of major electrical infrastructure work done during the fall 2004 lab shutdown.

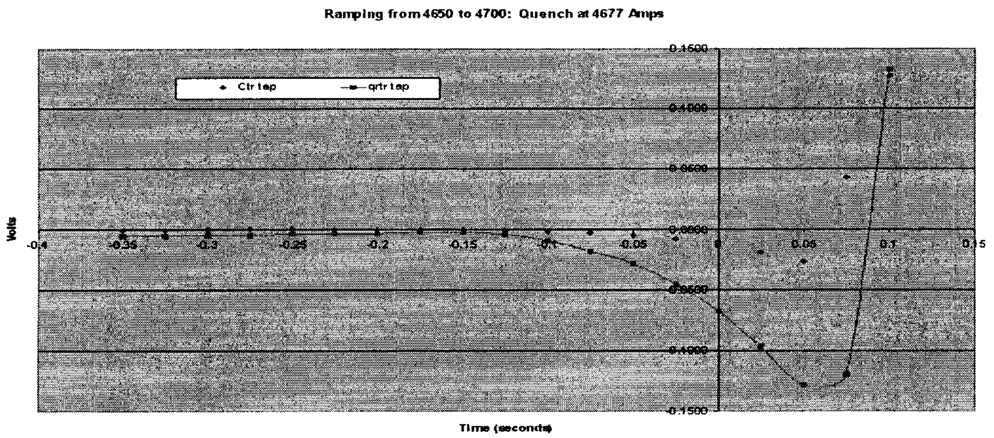




15. The temperature profile of the coil and support cylinder after a quench is typically: Maximum at the north end (37 K), 28 K at the south end, and 25 K at the center.

16. A comparison of the polarities of the bridge unbalance voltages created by the increasing resistance in the coil as the quenches progressed from the beginning indicates that the initiation site could not be in the North end of the inner layer, but could be in either the South end of the inner layer, or in the outer layer. It was noted that the ratio of the quarter tap imbalance voltage at quench to the center tap imbalance voltage is 4. The ratio should be 2 based on the design. This ratio discrepancy has not been resolved.

11/26 quench – Quarter tap voltage



Russ Rucinski, PPD/MD/DZero Ops

17. It is worth noting that the location of highest magnetic field is at the north and south ends of the magnet. Critical quenching current for the conductor is a function of magnetic field and temperature.

18. There may be a correlation such that at faster ramping rates a higher quench current is obtained. Slow ramping rates from an already established high current (~4600 A) give less than maximum quenching current. This may imply that heat and temperature build up when sitting at an established high current due to the current induced heat load. Although I see the correlation in the data, it is not readily apparent to others or easy to present proof of this.

19. Magnet flow is important and can influence the current at which the solenoid will quench. At least 3.6 g/s is required to balance heat load. 3.8 g/s is marginal. A flow rate of 4.5 g/s gives good flow and cold temperature (less back pressure in control dewar subcooler) and optimal chances at higher operating current. Flow rates higher than 4.5 g/s yield warmer temperatures due to increased pressure and may give lower quenching current. The November 18-19, 2004 quench events were at mass flow rates in the range of 3.5 g/s to 3.8 g/s. This range is now known to at the lower threshold required to balance the heat load.

20. Tests were done to determine the temperature relationship of the solenoid supply and return temperature versus the control dewar pressure. This helps estimate the potential decrease in coolant temperature when the refrigerator upgrade with cold compressor is put on-line. It is anticipated that we can easily lower the coolant temperature by 0.10 Kelvin. The components are being designed to achieve much more (0.3 K?) if necessary. Although it is possible to operate the control dewar sub-atmospheric, we will attempt to do so only if necessary.