PSFC/JA-06-18

Test Results for:
Pre-Operational Testing of
MERIT BNL – E951/(n-ToF-11), 15T Pulsed Magnet
for Mercury Target Development Neutrino Factory
and Muon Collider Collaboration

P.H.Titus

June 2006

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA

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P.H.Titus, June 2006
MIT Plasma Science and Fusion Center
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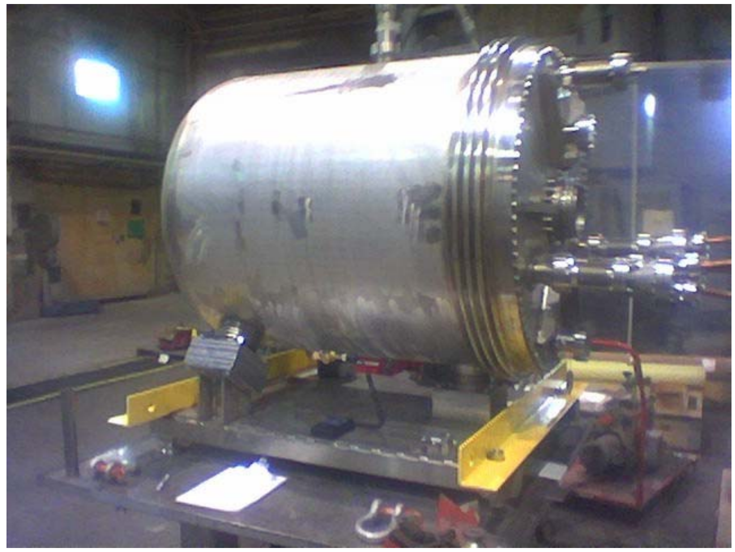
6896066

MERIT/BNL Pulsed Magnet –Inertially Cooled , LN2 or 30K He Gas Cooled Between Shots –MIT test will use only LN2

Table of Contents

Introduction

This report PSFC/JA-06-18 is the second report that documents the testing of the MERIT magnet. The companion document is the test plan, PSFC/JA-06-17, which evolved from the original contract scope document, as progress was made in preparing for arrival and testing of the magnet. This report concentrates on the results of testing.



The Magnet being prepared for shipment at CVIP with the yellow lift beams

The magnet was received from CVIP in the morning of Tuesday January 10 and it reached full field March 29 2006. The planned test levels were adjusted from the original plan somewhat by the necessity to adjust the control system power supplies, and concerns over temperature measurements.

Summary of Results

After understanding the field measurements, power supply performance, and temperature measurements, the magnet was found to perform electromagnetically as the original Bob Weggel (and later, P. Titus) simulations predicted.

Assembled Magnet Entering The Test Cell at MIT, Tuesday Jan 10 2006

The power supplies produced a lot of voltage oscillation, and the field levels of the shots in the test run were selected to support the effort to find appropriate control parameters for the power supply. During the test run, the CERNOX sensors were consistently reading high at temperatures between RT and LN2. The RT and LN2 readings were reliable but the temperatures in between seemed high. After some review of the data, it was found that the linearization of the calibration should have been based on a log scale. Because temperatures appeared to be above predicted levels, there was some concern for the safety of the magnet, and one of the high field (15T) shots was not performed. The last shot of the run was a 7 T shot that later was used to asses the actual temperature at the end of the full field shot.

The heat leak for Helium service was calculated to be 220 W in the design report. For LN2 coolant, this would scale to 176 Watts. The heat leak with LN2 coolant was measured using a weekend warm-up, and this produced a 314 watt leak. The difference is mainly due to leads being included in the heat leak inventory (Leads were assumed anchored at 80K for Helium service, and the 220 W was heat leak to

Helium). Also insulation material substitutions, and possibly a thermal short at the bore contributed to the measured heat leak.

Table 1
Shot Summary

Date	Shot Number	Start Temp	End Temp	Peak Field	
March 9 2006	1060309005	292	292	.6T	Before re-tap to higher voltage, 300 Amp Intended not to set off smoke detector.
March 28 06	1060328006	80K		.6T	
March 28 06	1060328006	80K		.6T	
March 29 06	1060329001	82	83	3.0T	
March 29 06	**1060329002**	85	94	7.0T	
March 29 06	**1060329003**			NA	Failed Shot (Interlocks still set ?)
March 29 06	**1060329004**		81 -91	7T	End temp measured before 2nd 7T shot of the day
March 29 06	**1060329005**		88-89	7T	Temp measured after series of 3 and 7 T shots
March 29 06	**1060330001-2**				Morning diagnostic shots, after disconnect of over current convertor
March 30 06	**1060330003**	80-85		3T	Tripped with L/R decay
March 30 06	**1060330004**			3T	
March 30 06	**1060330005**			3T	
March 30 06	**1060330006**			3T	
March 30 06	**1060330007**	77	90	10	Was to have been 13T but tripped at 10T with an L/R decay
March 30 06	**1060330008**	78	112-115	15.6T	Successful Full Field Test. Temperatures of 190 K were measured originally. Lower temperature results from calibration correction.
March 30 06	**1060330009**	115	129	7T	Was to have been the second 15T shot, Erroneous high temperature readings caused a 7T shot to be selected instead. Start and end temperatures are from analysis

Receipt Inspection and Tests

Tuesday morning January 10, 2006, the magnet was offloaded from the truck with the larger fork lift available at the PSFC. There was some difficulty because the skid under the magnet did not have space available for the tangs of the fork lift. The magnet had to be lifted with slings from the top and spacers were inserted. The magnet was then lifted of the truck successfully. Movies of these offloading operations have been placed on the website.

Vacuum Measurements

Records of vacuum measurements began in the CVIP shop. On Wed 1/4/2006, David Nguyen sent the following email:

> Peter
> We continue pumped the unit through the long weekend and it came down to 3 microns. We shut down the pump it off at 1:00AM this morning and it came back up to 5 microns at 4:30AM. We can assume that it is out gassing. We don't have the ship date yet. Is this Friday ok with you?
> The 10 Ton forklift should be enough to lift it.
> Dave

Baseline at CVIP	Jan 2006	5 millitorr minimum, 9 millitorr after shut down of vacuum pump, 100 millitorr after sitting over night
After receipt at MIT	Feb 7 2006	9.0 Torr = 9/760 = .012 atm
After an hour pump down	Feb8 2006	59 millitorr
Friday Feb 10		40 millitorr
Tuesday Feb 14 9:00 AM		60 millitorr
Thurs Feb 16 2:10 PM		60 millitorr
Friday August 25 2006		200 Millitorr

Vacuum Gauge supplied by CVIP. Only good below 2 Torr

Convectron Vacuum Gauge needed for ranges beyond 2 Torr. The range for this unit is 1e-3 to 1e3 Torr

Initial Meggar Test

Feb 16 the magnet was checked for breakdown from the series connected coils to ground and from coil to coil. 1000V was applied, and there was no breakdown. There were no measurable leakage currents. This tests were carried out in the same manner ast tests performed by P. Titus in the CVIP Shop.

Identification

Labels Applied to the Base of the Magnet System, February 21, 2006

Insulation Tests

The magnet cover and cryogenic lines including the feed and vent lines were to be insulated. Simple dunk tests were performed on a number of candidate materials for these applications. Magnet insulation is the more important material choice. Most of the magnet is covered by a vacuum jacket, and needs no more insulation than that provided by CVIP. The end cover is thermally connected to the liquid nitrogen and requires insulation that can be suitably applied to the surfaces without precluding access to bolted flanges. It was originally intended that a CTD foam material be used

Samples of two types of insulating "foam" have been provided by CTD. Both are supposed to be a strongly adhesive "foam" meant to adhere extremely well so that no liquid Oxygen can collect between the foam and cold vessel. It is also "hard as a rock" from informal discussions with CTD, and will be difficult if not impossible to chip away. For those areas where we want to be able to remove foam to get to flanges and bolts, another type of foam was purchased. This is a household insulating foam sealant from a local lumber and hardware store (Home Depot) it is called "Great Stuff" It has been used it in the lab, but it has no formal cryogenic credentials. The CTD materials trowel on. The household foam will be used only on the areas needed to access the mechanical connections.

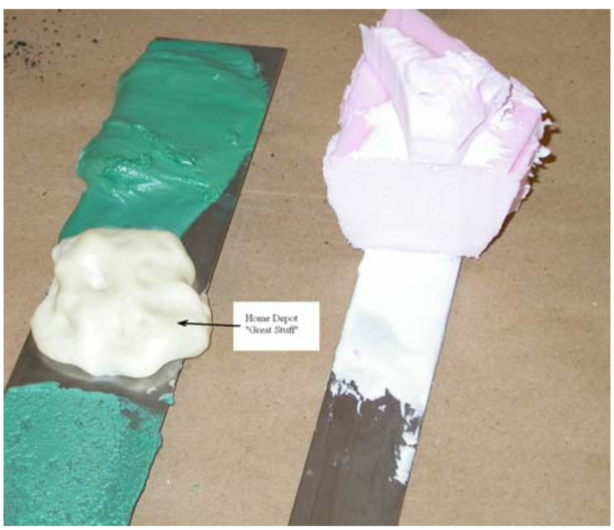
ARMACELL ARMAFLEX from Home Depot – but used extensively at the PSFC Feb 9 LN2 dunk test: The pipe covering (Left) survived well enough – was brittle at LN2 temp, but did not crumble. Properties were pretty much restored at RT. The adhesive tape (right) was not as good, but was acceptable.

ARMACELL and ARMAFLEX were both found acceptable during a Feb 9 LN2 dunk test: The pipe covering (Left) survived well enough – was brittle at LN2 temp, but did not crumble. Properties were pretty much restored at RT. The adhesive tape (right) was not as good, Armacell were from from Home Depot – but this material is used extensively at the PSFC.

The two CTD materials are troublesome because they run down a vertical surface, but they seem to work well as a glue, as long as the thickness of the material is small. A thicker sample of the "white" CTD material de-bonded.

Initially, after mixing, this material was too runny to be applied vertically.

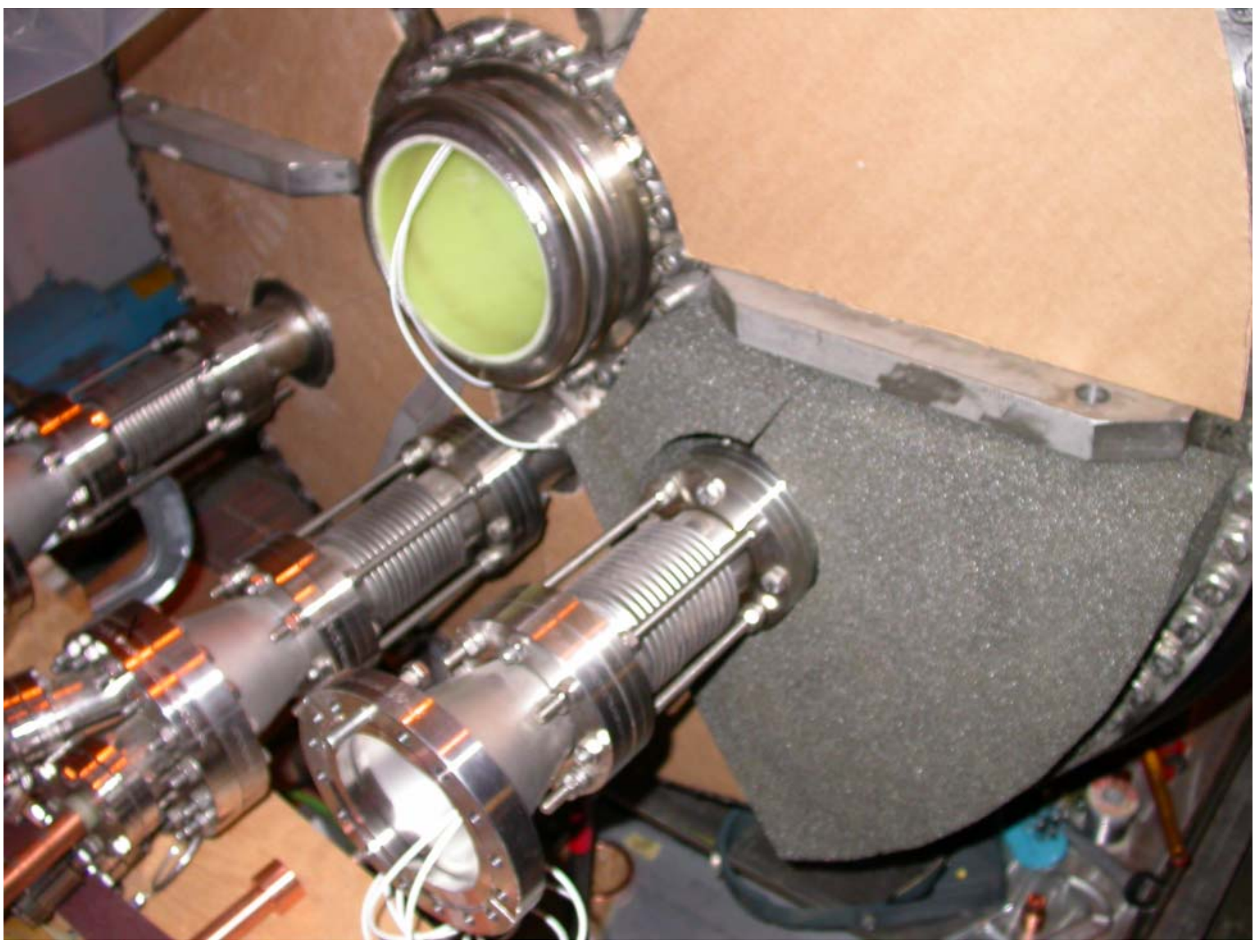
About 2 hours into the 8 hr. cure, the material stayed on a vertical surface.



"Great Stuff" Home insulation foam survived the dunk tests very well. The white CTD material, applied in a thick coat lost it's bond as a bulk material after a dunk test but behaved well as an adhesive for a foam insulation. "Great Stuff" is flammable.

"Great Stuff" on the left and the CTD "White" material on the right on a SST sample strip

Glass foam survived dunk tests well. Green is the CTD material. Blue is Stycast**.**



FoamGlas being fitted to the cover. Cardboard patterns are used for trial fit around penetrations

Power Lead Gland Seal Tests

The gland material was also tested and stood off 15kV during Scott Mahar' s tests of ITER insulation. The material appears to be silicon, and it is behaving well for the expected service. A dunk test was performed Feb 9 2006. The RT rubber-like compliance of the material was lost, but it was not brittle.

Gland or packing or compression seal material and the cutters used at CVIP to form the "donuts".

LN2 Dunk Test: Feb 9 2006 The gland for the power lead did not shatter – but it was rigid.

Low Current Power-Up - Magnetic Measurements, Feb 16, 2006

10 volts was applied over about 5 seconds and the current, as measured by the power supply meter, stabilized at 22 amps. stabilized at 22 amps. Welder current meter (hand held meter which forms a loop around the power lead) showed ~27 amps. The coil is at room temperature. These tests were performed without a current shunt installed in the 100 amp power supply. A shunt was later used to update the magnet constant. This is discussed in the section on field mapping.

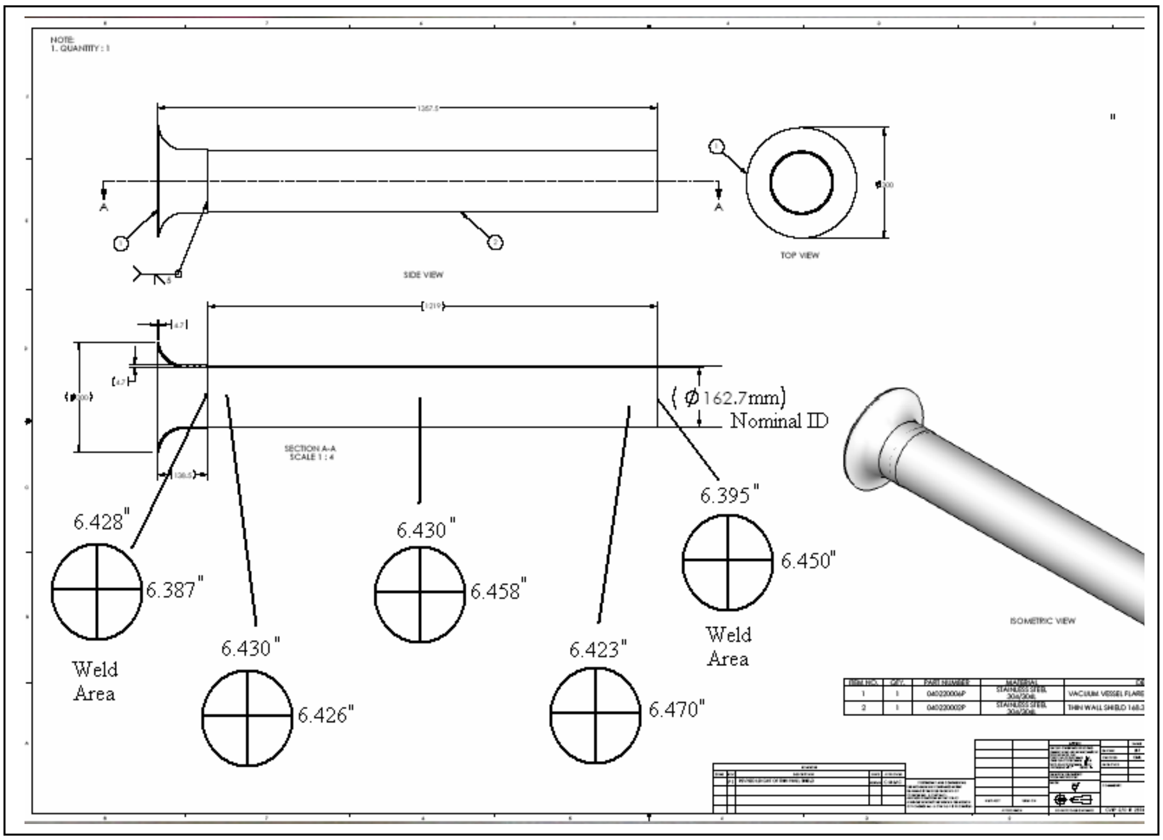
Date	Outer Segment #3	Inner Segment #1	Middle Segment #2	Coil	Current on Power Supply meter	Current From Welder Hand Held meter	Field Measured by the Gauss meter
Feb 16, 2006	4.55v	1.94v	3.25v	9.74v	22		85-25=60 milliT
Feb 16, 2006				9.77v	22	26.5A	85-25 =60 milliT

These measurements produce a magnet constant of .060/.0265 = 2.264 T/kA. The analytic simulations show 15T for 7200 amps or 2.0833 T/kA

After a day warm up. It zeroed properly and read 60 milliT

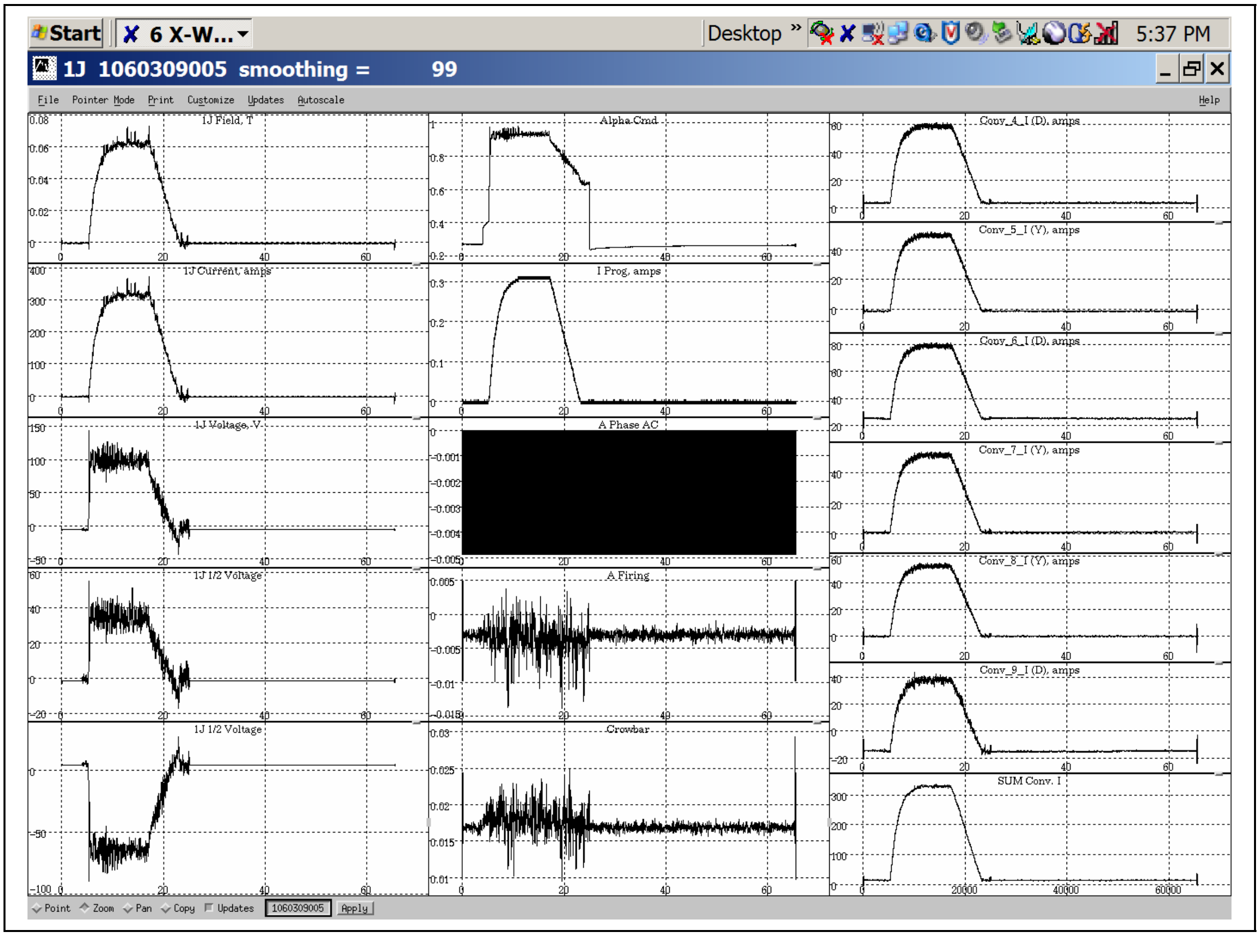

10 v 100 Amp Supply

Bore As-Builts



Thurs March 9 2006 Low Voltage and Current RT Test

The magnet was connected to the PTF power supply earlier in the day. In the evening the power supply was programmed with a 100 volt 300 amp trace. Everything seemed fine. We would have gone to a higher current but before we go higher, we have to disable the magnetic triggers on the smoke detectors in the cell. Next is to work on the LN2 cooling. Dave Tracey and the guys in the machine shop re-worked of the terminal bars. Phil stayed after hours to do the test(we had to wait until C-Mod finished their last run of the day)

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Peter,


I hate to be critical, but  as a point of information for future
reference the transformers in the west cell penthouse are always set
with 13.8 kV input to the transformer primary.  It is the secondary
taps that we change between experiments to better match the power
convertor output to the test
load.

                         - Phil
```

At 10:06 AM 3/15/2006, you wrote:
>Bill:
>
> Please have the transformers for the PTF power supplies tapped to
> the
> 600v primary side voltage. The account number for this work is
6896066
>   – Peter Titus

Hi Darren,

I am not sure if you are aware of our test plans so I send you this brief
update.

Peter Titus recently completed fabrication of a liquid nitrogen cooled, 15-T pulse coil. This coil has been placed in the west cell in NW21, in the pit next to the PTF stands. Dave Tracey has been working to connect the coil to a data acquisition system, the PTF nitrogen feed line, a nitrogen vent line, and to the high current bus to the PTF power convertors.

Peter hopes to energize the magnet starting in early March by using the PTF power convertors . The exact plan for operating the power convertors is not completely clear (we need to iterate the procedures a little bit more with Gary Dekow). The test procedure will most likely involve the use of the camac serial highway on Jove to program the power convertor waveforms using the PTF Camac D/A module.

Hopefully we can coordinate the use of the serial highway driver so as not to interfere too much with the L-coil experimental test plan.

Thanks,
Phil

Retap of the Power Supplies to the higher Voltage, March 20 2006

Email from Phil

Gary,

Over the weekend Jimmy set the transformer taps in the West cell penthouse for convertors 4~9 to their highest settings. I forget which voltage level this is, somewhere around 580 V_ac. I believe this setting provides a maximum dc output voltage of roughly 800V.

In my notebook I found a short summary dated July 15, 2005 related to the test of 1J crowbar circuitry. My notes indicate that we checked the crowbar auto-trigger by gradually increasing the voltage applied to the bus monitor sense wires to 1 kV and checking for a thyristor gate pulse to trigger the crowbar SCRs. My notes do not confirm that the trip actually occurred at 1 kV, do your notes confirm the trigger voltage?

Also, is a 1 kV auto-trigger set point still appropriate for operation of
Pete Titus' MERIT magnet?

Thanks,
Phil

Email from Phil, March 24 2006

Peter,

Yesterday afternoon I talked with Bill Cochran. He was considering to verify the trip point setting for the magnet power system's auto crowbar circuit. We tested this setting during July 2005, but it seems that no one recorded the actual trip point value. It was sufficiently above the normal inversion voltage for the 1J magnet, but we are not certain that it is sufficiently high to guarantee the absence of errant crowbar trips for the MERIT magnet. To minimize possible electrical stress to the magnet caused by errant crowbar circuit trip we really should confirm this value. Also, earlier today I modified the feedback regulator circuit according to Gary's recommended resistor and capacitors for the LN2 cooled MERIT magnet. If you are ready, we should be able to do a few low to moderate
current pulses on Monday, once the auto crowbar setting is verified.

- Phil

Initial Cooldown, Dimensional Characterization

Initial Cooldown, is estimated to require a total of 550 liters of LN2, and was expected to take a couple of days

First Cooldown, Beginning Friday March 24 2006

Dave Tracey purged the system with dry Nitrogen gas from the nitrogen bottle. This was begun at around 6:30AM

Time	Cap Level #1 %	Cap Level#2 %	Seg 1 volt	Seg 2 volt	Seg 3 volt	Total Voltage Across Magnet	Magnet Current (Amps)	Ave Mag Temp (K)
	Friday	March	24	2006				
10.02						10v	20	292
10:30	100%	9.8%						
11:00	100%	10.8						
11:23	100%	11.2					25	230
11:15	100%	11.8						
12:20	100%	11.5						
13:12							29.5	200
14:45	100%	32.7						
14:59							35	180
17:30							52	140
17:40								
17:45	100%	17.3						
18:20	100%	12.7						
	Monday	March	27	2006				
9:15	7.3	9.9						
	Tuesday	March	28	2006				
9:30	100	50						
10:30	100	50						
10:45	100	73.4						
10:50	100	96						
11:45	100	53.8						

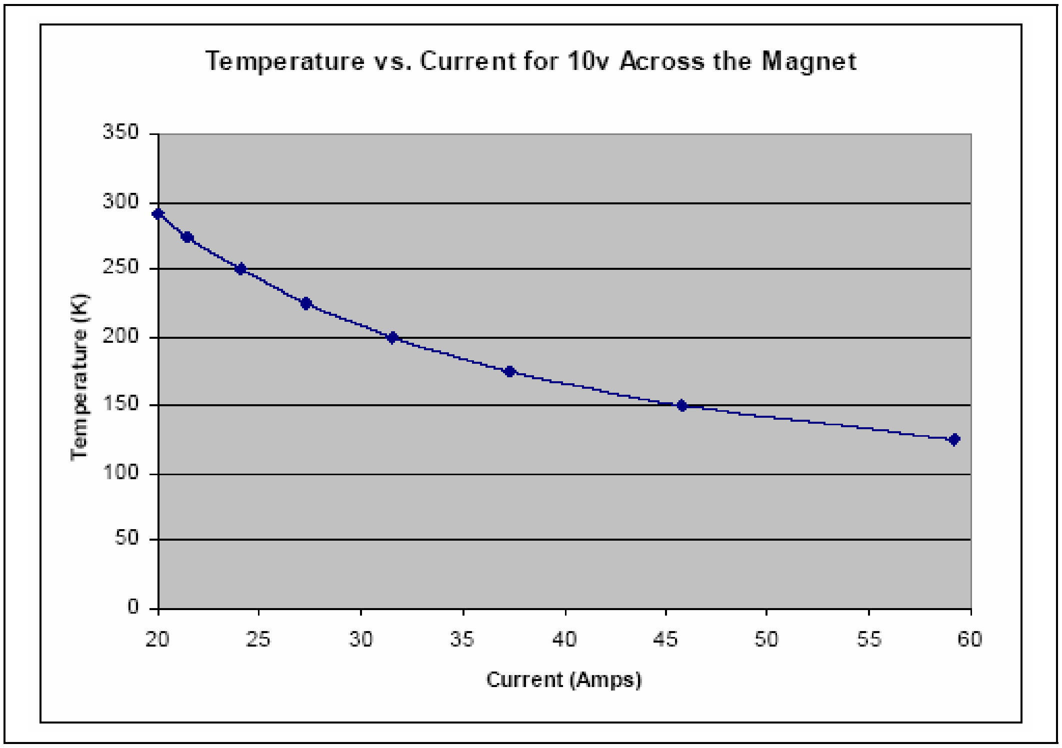
The roof vent was checked for proper venting of Gaseous Nitrogen

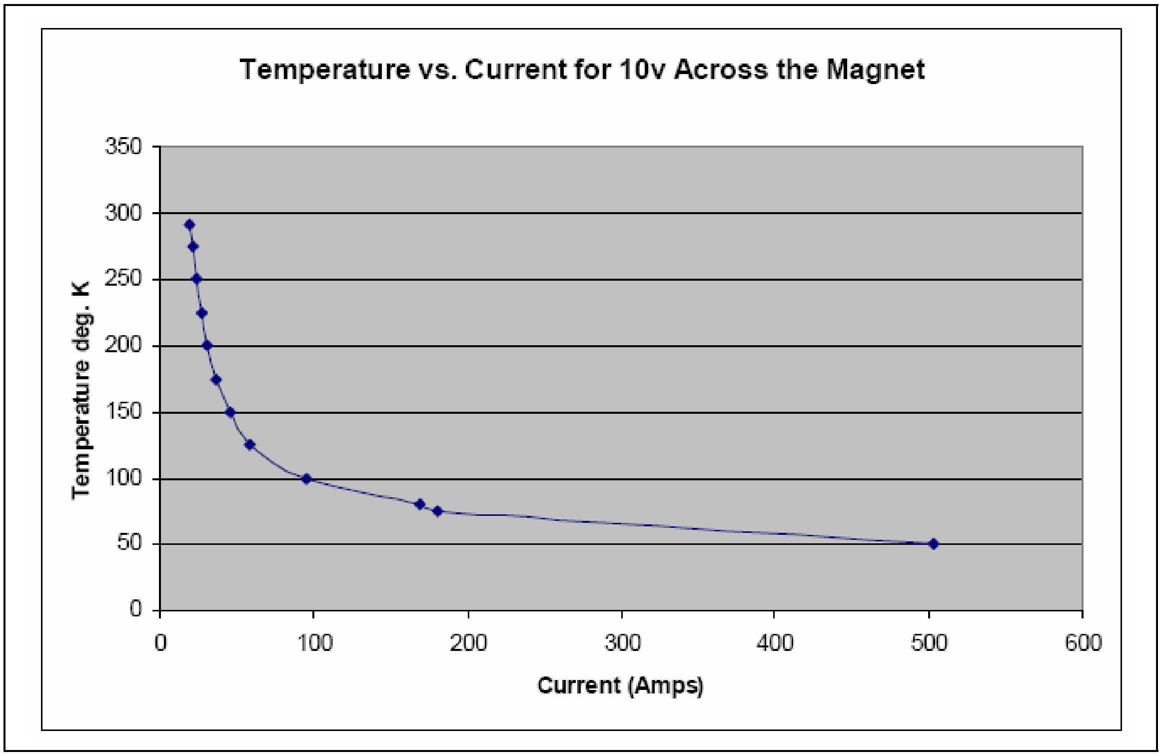
The electrical connections and vent lines were inspected for ice build up. There was none. Ice build up would develop in the second week of operation and remain in the bore of the magnet for another couple of weeks.

Nitrogen venting through the roof penetration during the first cooldown.

Monday March 27

Time	Seg 1 volt Ohm degK	Seg 2 volt Ohm degK	Seg 3 volt Ohm degK	Total Voltage Across Magnet	Magnet Current (Amps) PS Meter	Ave Mag Temp (K)
	1.94 .051 175	3.25 .0592 125	4.55 .1197 175	9.74	38	170
	2.38 .0793 280	3.71 .1236 255	3.49 .1633 225	9.59	30	210
	3.25 .0625 200	3.87 .0744 170	2.46 .0473 100	9.57	52	135
	1.94	3.19	4.49	9.63	37	175


Temperature vs. Current for 10v Across the Magnet
Temperature (K)
Current (Amps)
350
300
250
200
150
100
50
0
20
25
30
35
40
45
50
55
60


Temperature vs. Current for 10v Across the Magnet
Temperature deg. K
Current (Amps)
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600

Boil-Off – Heat Leak Test – Weekend Warm Tests March 24 to March 27

Measuring the level change with respect to time will give a measure of the magnet's heat leak. Use of a flow meter is not planned. Level changes in the dewar or magnet will need to be used. If the Magnet level change is used, the change in level with respect to change in LN2 volume is a geometric calculation of coolant space with respect to level in the magnet ands is complicated by additional structures and fillers in the cold volume. As an estimate consider the annular coolant channels at the equatorial plane, and consider the head and outer annulus filled with fiberglass epoxy. There are eight 2mm "slots" at the equatorial plane. The heat leak would be:

Heat Leak= Level change rate(m/sec)*8*.002* 1 m *804.3kg/m^3* 199000 Joule/kg

The heat leak was calculated to be 220 Watts for Helium gas service at 22K delta T. Roughly this would be 220*(220-80)/(220-22) = 172 watts for a LN2 system. The level change rate is then .0674mm/sec or about 4mm/minute. If the LN2 volumes in the plenums at the face and backside of the magnet and the effects of the circumferential grooves, and voids around the annular and head fiberglass fillers, are considered, 3mm/minute might be more representative. It was intended to record the level, and the level change in five minute intervals. The discrete level sensors were not working during the test. The capacitive sensors were working, but their accuracy was undermined by a small leak at one of the lead gland seals. In order to estimate the heat leak, a long term warm-up over a weekend was measured and simulated.

The magnet average temperature at 5:30PM Friday, March 24th was 135K. The LN2 flow was turned on at 10:02 that morning. The outer coil was much colder than the inner coils. I only have voltage measurements. I haven't converted them to temperatures yet.

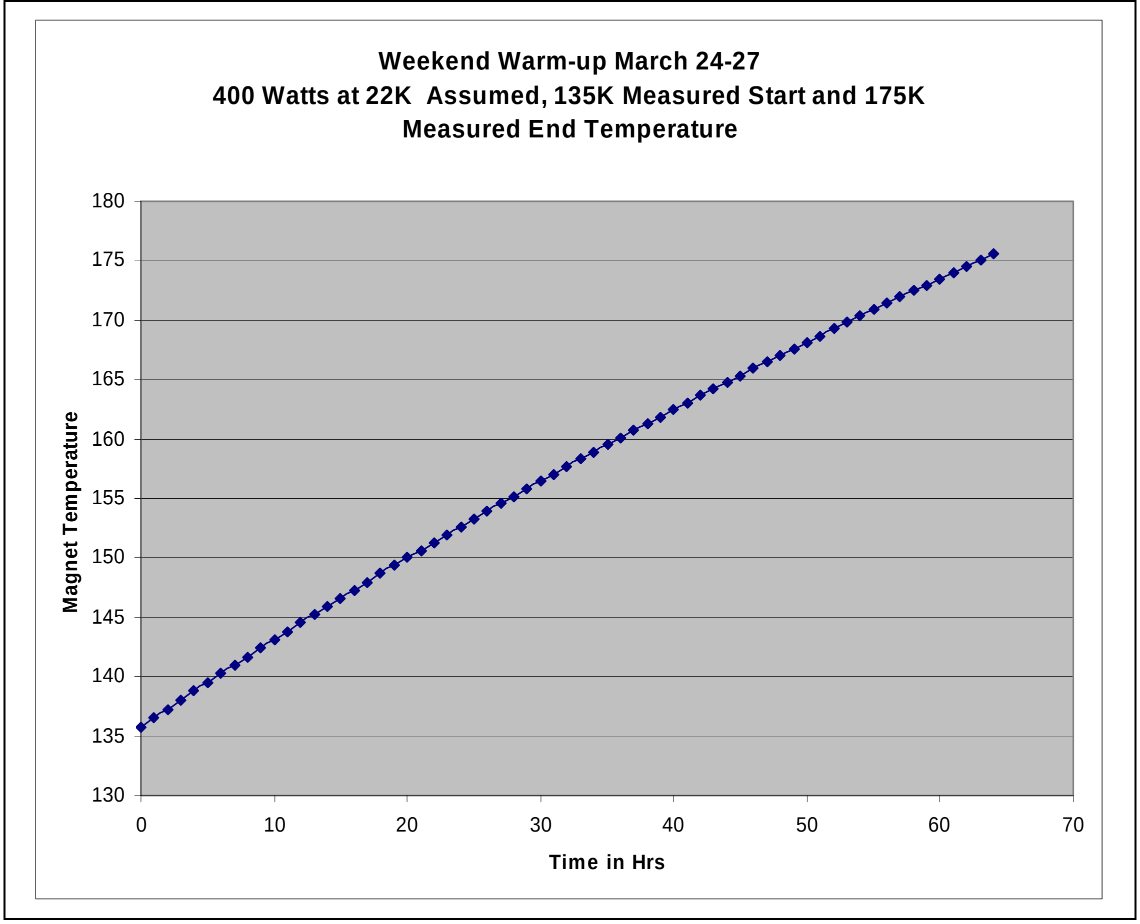
This Monday morning at 10:00 the magnet average temperature was 175K, and the temperature was uniform between the three segments

time	amps*	Ave Temp	Inner v	Middle v	Outer v	Total v	Field
Friday March 24							
10:02	20	292	1.94	3.25	4.55	9.74	
	35	210	2.38	3.71	3.49	9.59	
	52	135	3.25	3.87	2.46	9.57	
Monday March 27							
10:00	35	175	1.94	3.19	4.49	9.63	100 mT

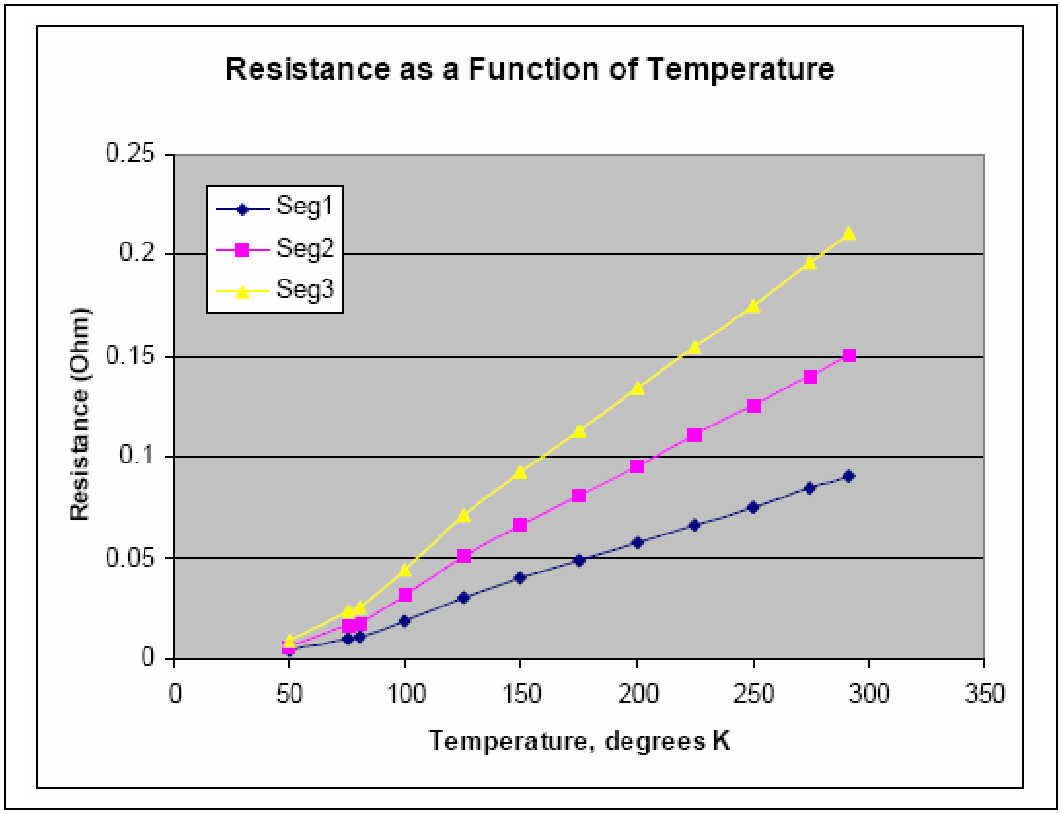
*Read from the power supply dial – The more accurate measure with a current shunt was not available when these measurements were taken. The current error would introduce an error in the temperature measurement, but the change in temperature should be more accurate.

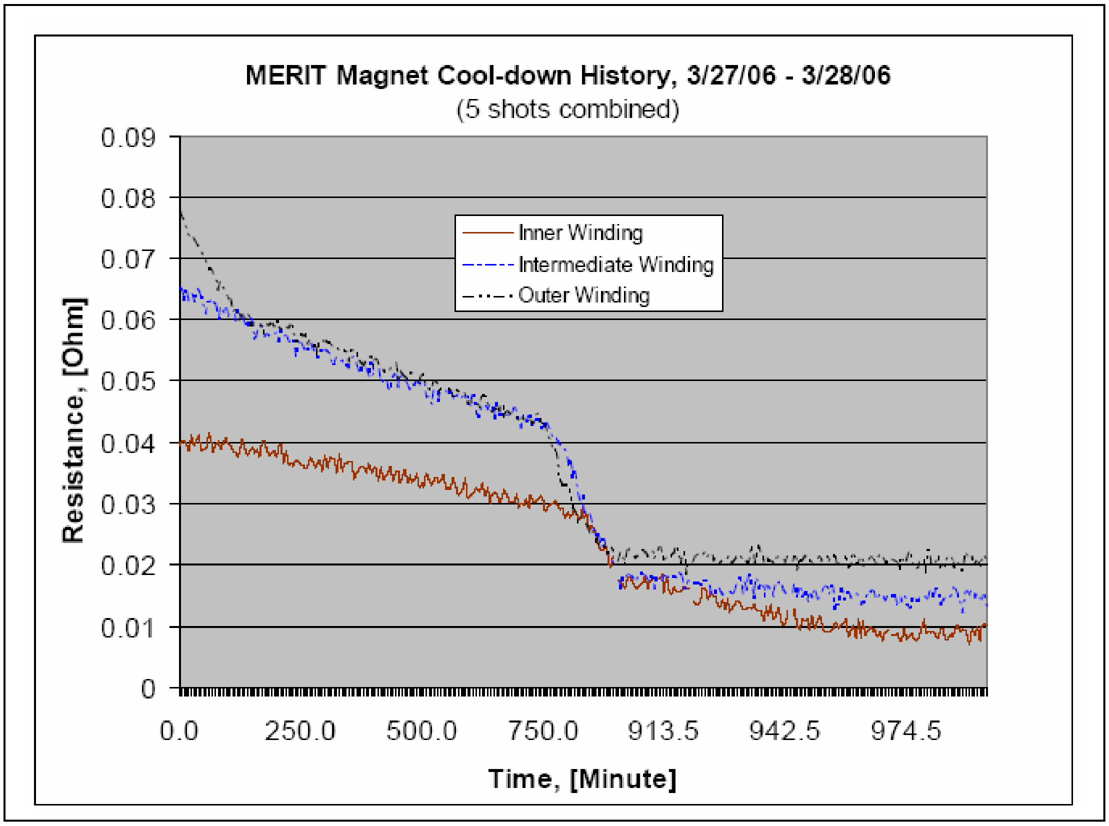
The 220 watt design heat leak (Helium temp service) is between the cold vessel and the outside. – Not between the magnet –to cold vessel- to outside, so the magnet should have stayed cold longer than the original calculations would have indicated.

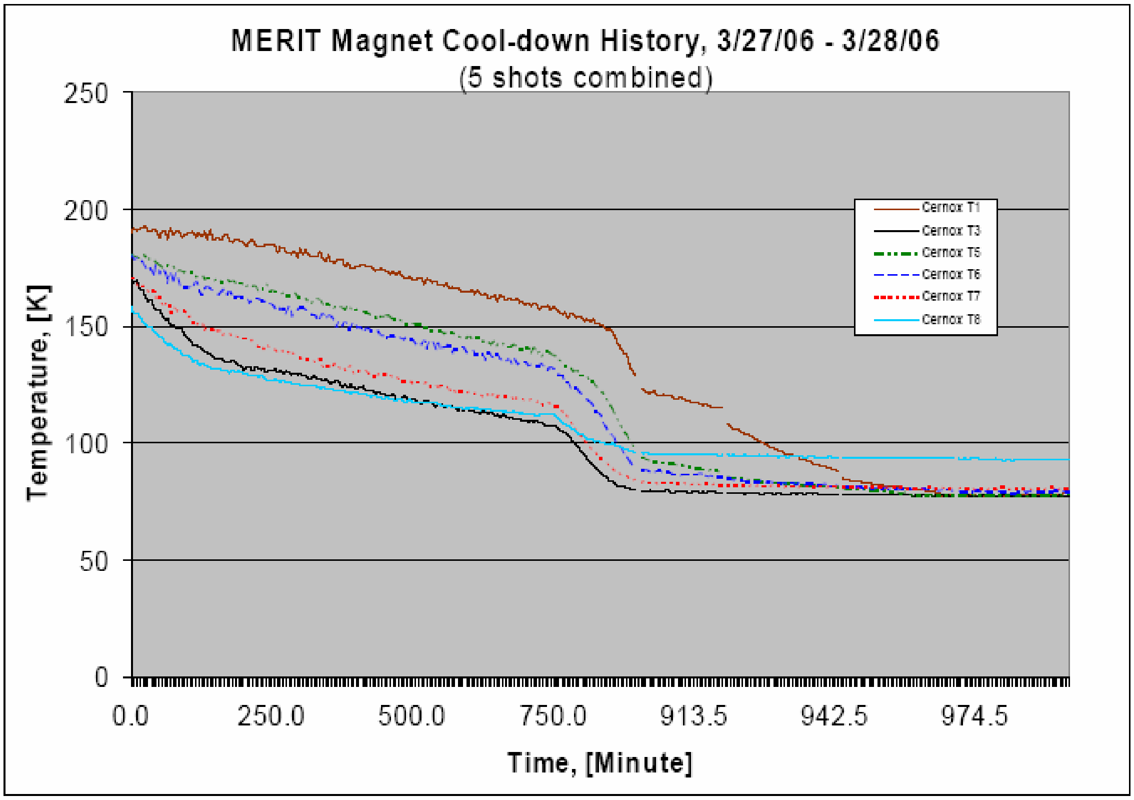
The simulation used the global heat transfer coefficient for the helium service calculations that predicted 220 watts, and scaled it up until the correct temperature change was obtained. A 400 Watt heat leak for Helium service had to be assumed to obtain the measured temperatures. This would correspond to 314 watts at 80K or LN2 service. The 150 watt bore heater was run at about 40% during the tests in which the bore remained ice free. 60 watts would then be attributable to the bore vacuum and as well as conduction through the bellows at one end and dished head at the other. The original calculations, in section 14 of the design report, estimated these heat leaks to be 24 watts. The original calculations assumed MLI would be added to the dished head, and ignored the g-10 support rings. The original calculations used the thermal conductivity for the CTD foam materal. The thermal conductivity of the foam glass and Armaflex



insulation, that were actually used, has not been quantified, but are expected to be similar to the CTD material. The big difference between the original calculations and the actual service conditions is that for 22 or 30 K Helium service, two of the lead pairs were to be anchored at LN2 temperature, and the other pair were to be insulated with an attempt to keep them at the Helium gas temperature. The heat leak calculations only tracked heat leak to the Helium volume –not to the LN2 anchors. For the MIT tests and CERN service, the magnet is at LN2 temperature, and the leads are thermally connected to bus bar at RT. The heat leak for the three lead pairs in the Helium cooled service was 50W. The adjustment for LN2 service would be 50*(292-80)/(80-22) -50 = 132 watts higher than would have been scaled from the Helium service.


Resistance as a Function of Temperature
0.25
0.2
0.15
0.1
0.05
0
Seg1
Seg2
Seg3
Resistance (Ohm)
0
50
100
150
200
250
300
350
Temperature, degrees K


MERIT Magnet Cool-down History, 3/27/06 - 3/28/06
(5 shots combined)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Inner Winding
Intermediate Winding
Outer Winding
Resistance, [Ohm]
0.0
250.0
500.0
750.0
913.5
942.5
974.5
Time, [Minute]



Second Cooldown, Tuesday March 28

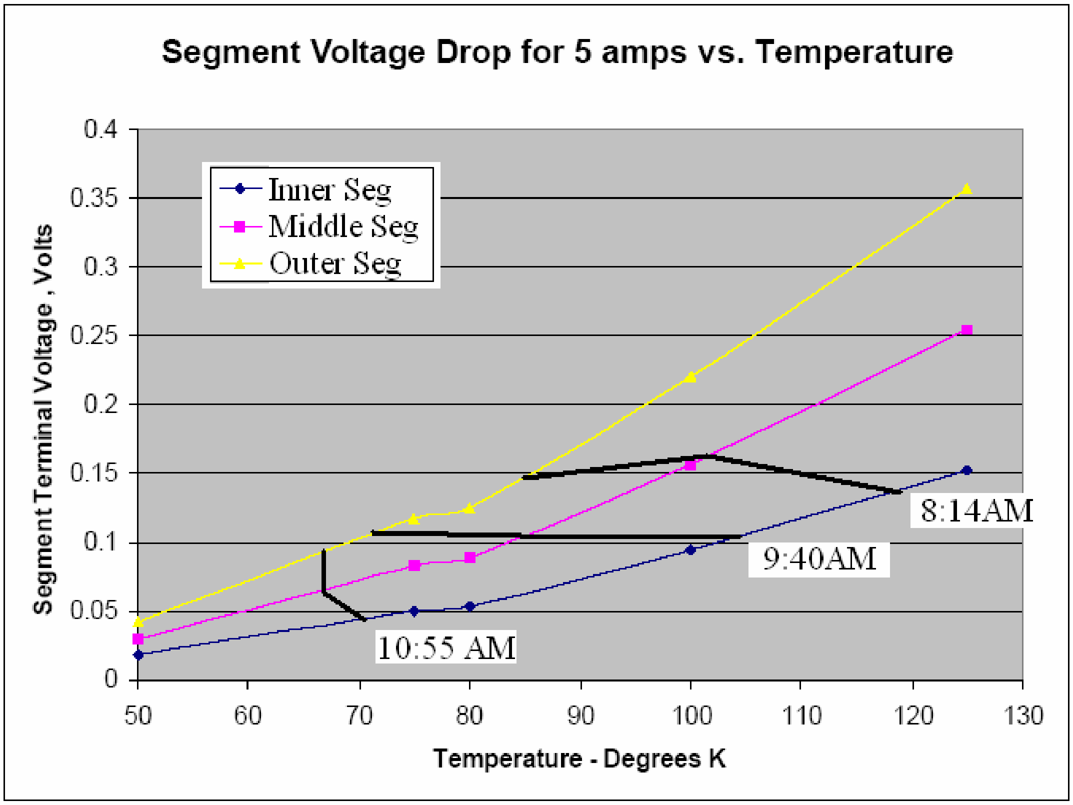
10.55 AM

For this cooldown, The small current source was being used to apply 5 amps to the magnet and voltage taps were connected to each of the three segments. The current shunt was being used to control the 5 amp current.

	Tuesday	March	28	2006
Time	Hor Cap Level	Vert Cap Level		
9:30	100	50		
10:30	100	50		
10:45	100	73.4		
10:50	100	96		
11:45	100	53.8		

Segment Voltage Drop for 5 Amps

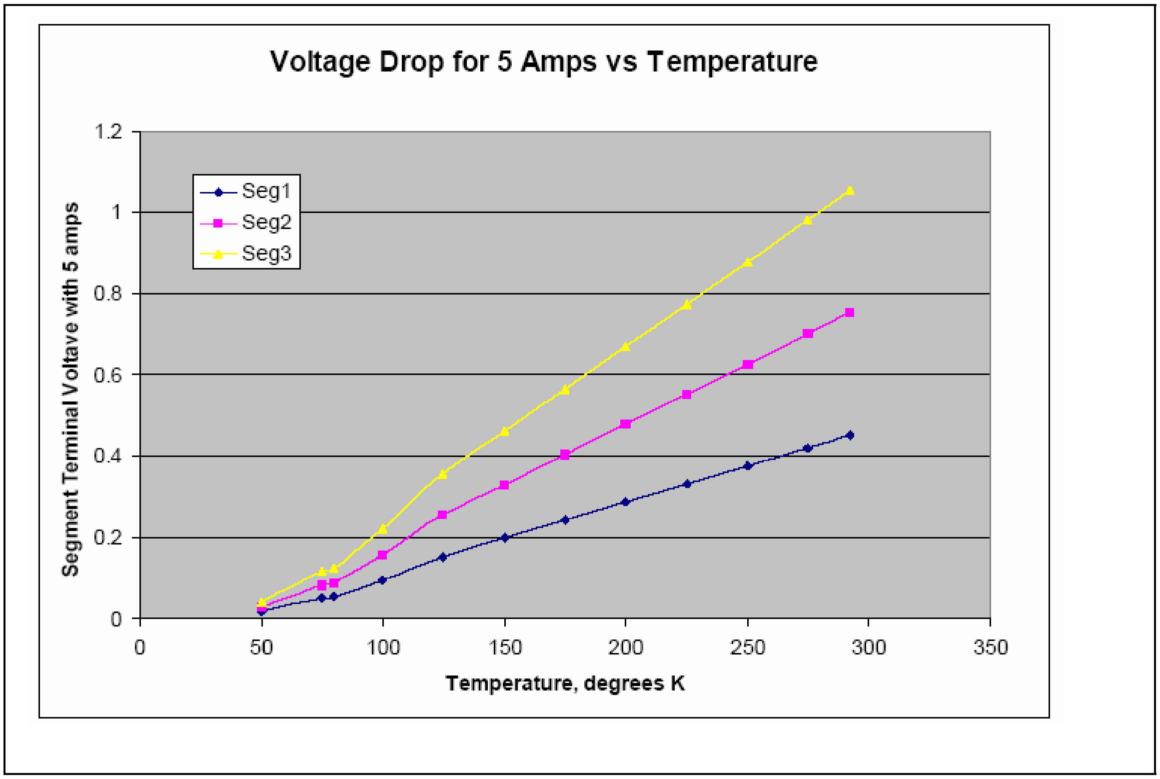
Time	Seg1 (Inner)	Seg 2 (Middle)	Seg 3 (Outer)	
8:14 AM	.1381	.1696	.146	11%
9:40 AM	.1058	.1036	.1108	45%
10:55 AM	.0427	.0705	.0979	89%

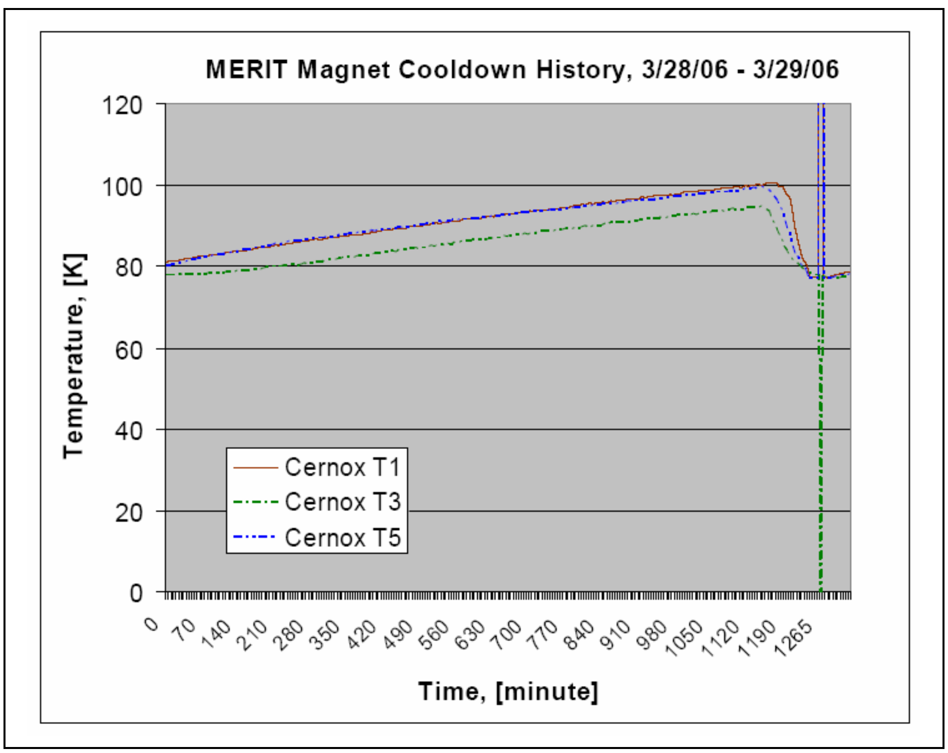


Tuesday March 28 Cooldown

Tuesday March 28, 10.55 AM 13.9%??

Sensor	T1	T2	T3	
Voltage	1.33	1.25	1.16	
Temperature	78	80	77	





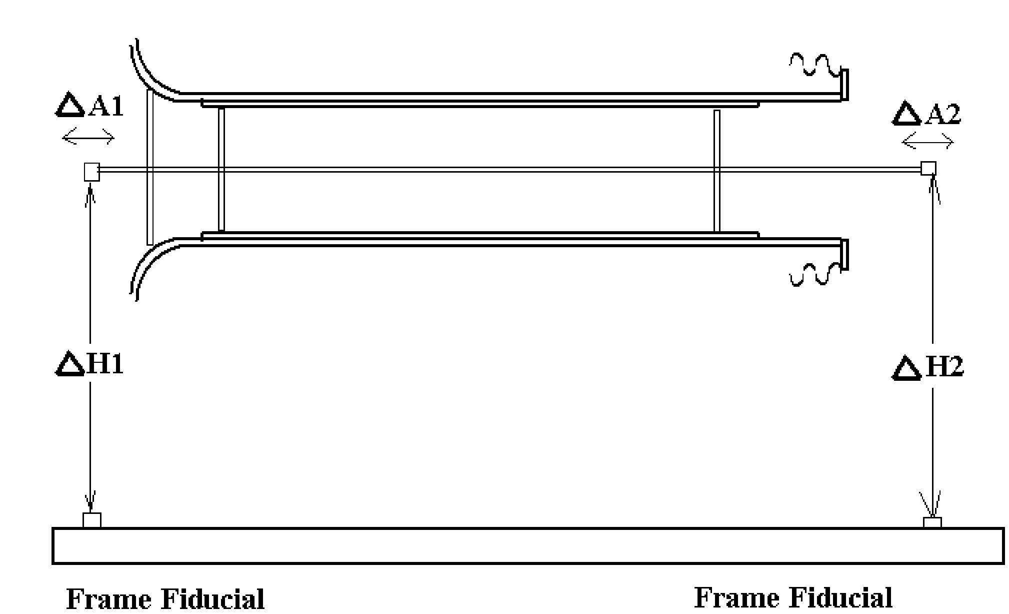
Tuesday March 28, 4:45PM

Sensor	T1	T2	T3	
Voltage	1.125	1.184	.9764	
Temperature	98	94	118	

The capacitive sensor read 100% on the lower tube and 13% on the upper tube.

Tuesday March 28, Record Cold Dimensional Changes

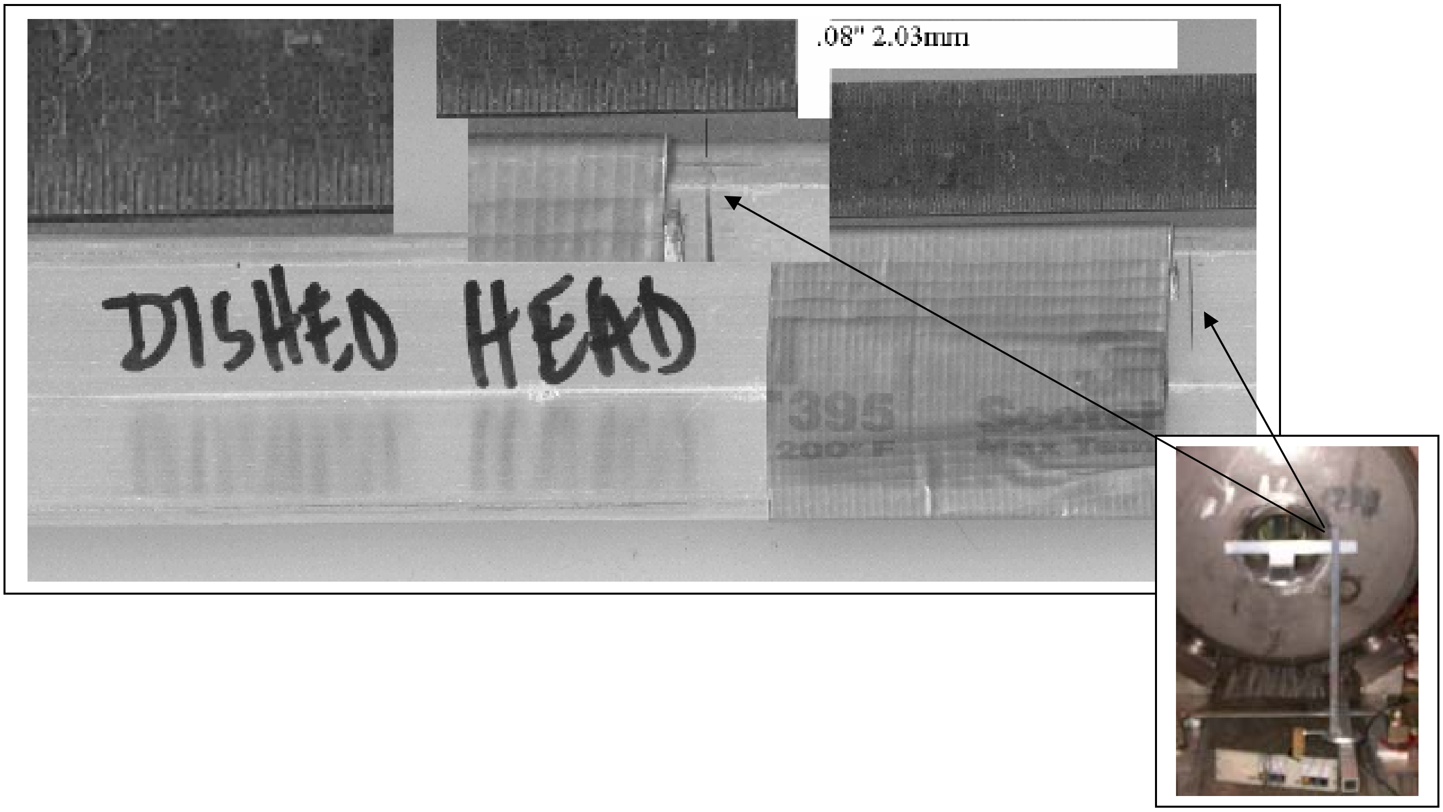
The proposed was modified to use heavier aluminum sections. The circular disk design was found to offer nothing better than having a heavy aluminum tube tube lying on the inner bore. Cross beams were clamped to the tube to form the gauge.

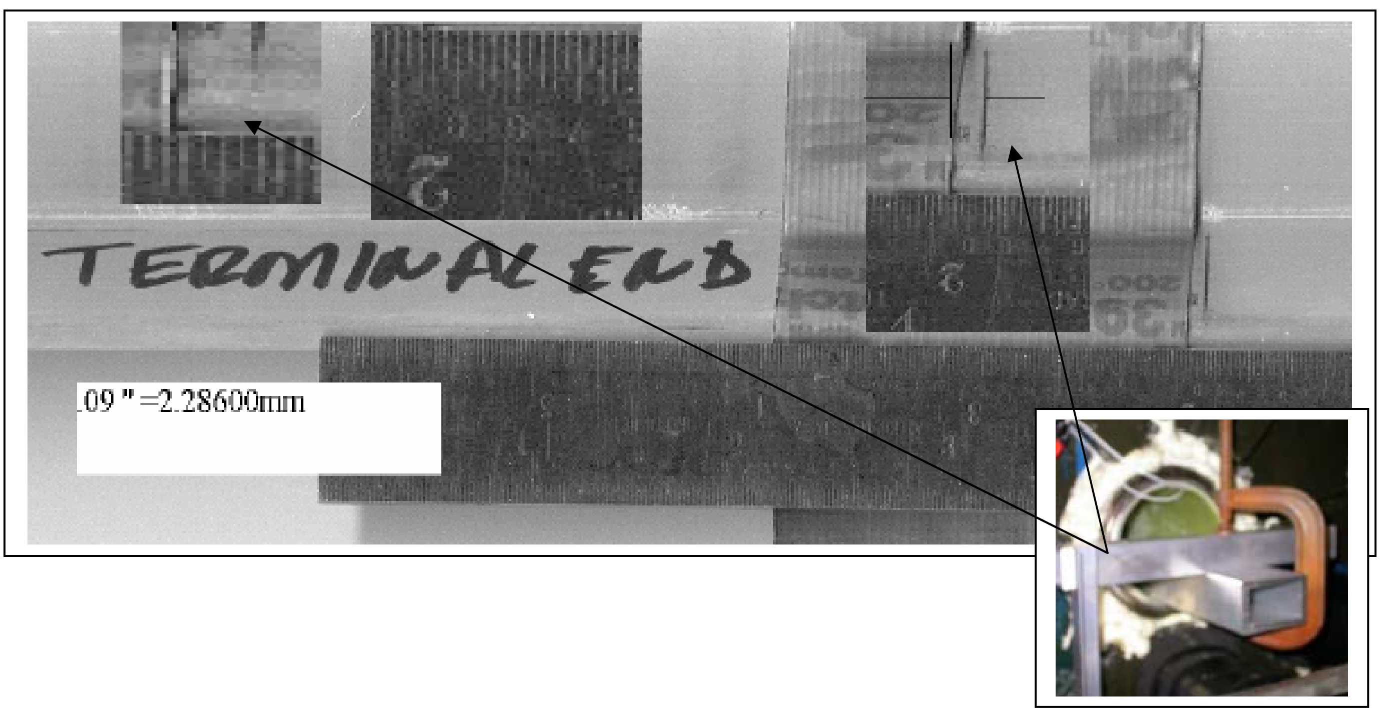


The proposed fixture was a rod or tube with circular disks that were to fit against the bore and flare in the vacuum jacket.

Cooldown displacement fixture.

Displacement Fixture at the Dished Head End

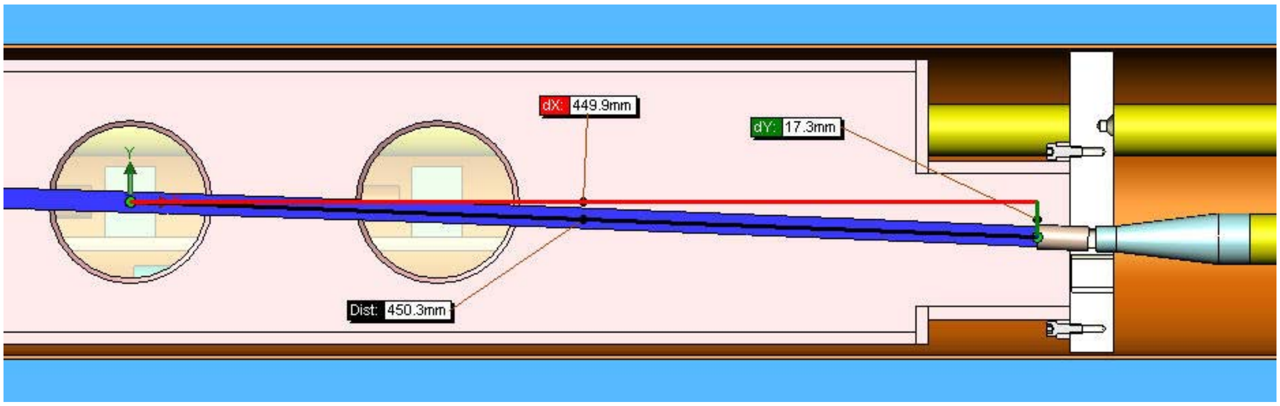

.08" 2.03mm
DISHED HEAD


TERMINAL END
.09 " =2.28600mm

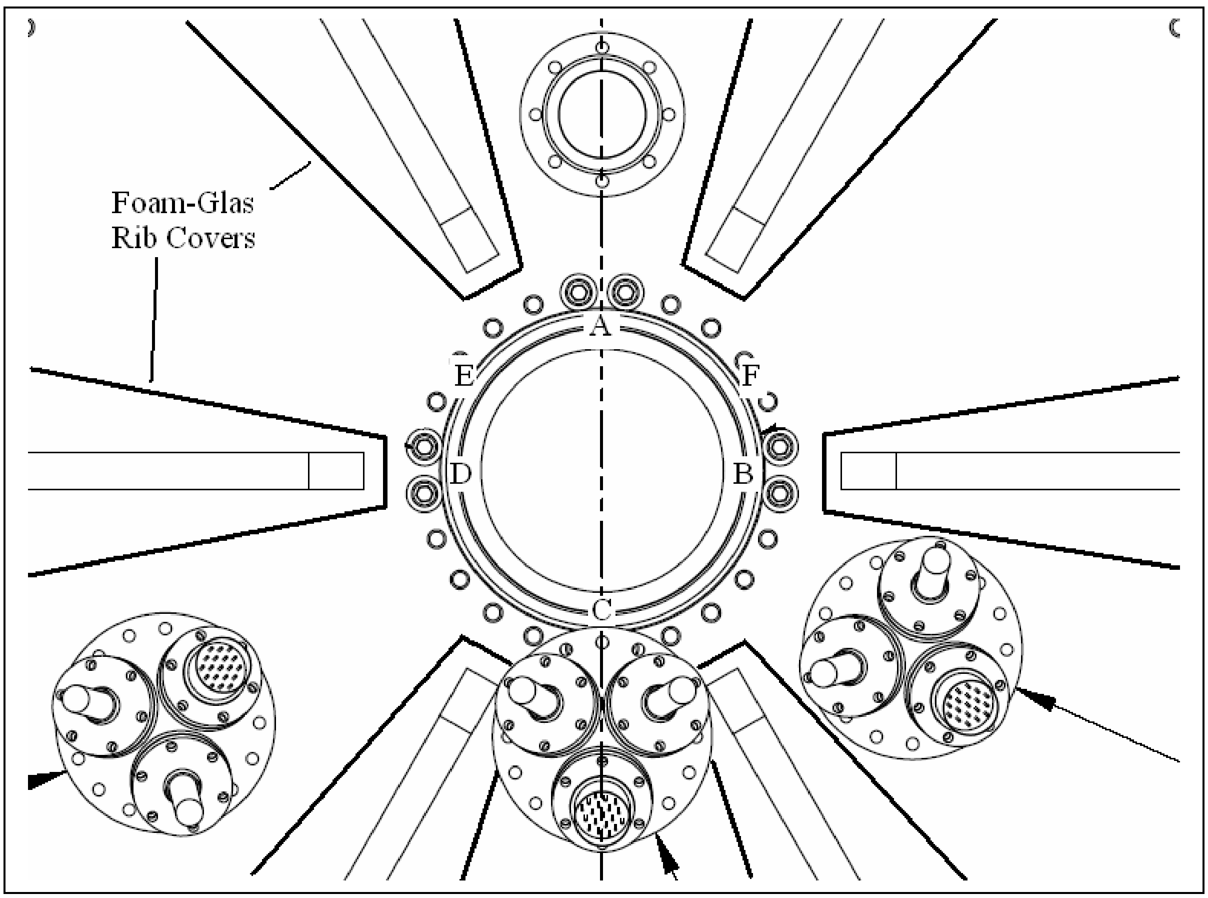
Field Mapping

Fields were measured a number of times during the tests using the Gauss meter. Tuesdays measured magnet constant = .16T/79 amps = 2.0253 T/kA. Power supply data acquisition has been updated with the measured magnet constant.

These measurements produce a magnet constant of .060/.0265 = 2.264 T/kA



Location of the inlet nozzle. This is where the fields should be mapped to identify any anomalies



Axial Field Measurements

A	B	C	D
170	171	174	170

Radial Field Measurements

E	F	Axial Max in Bore
.51 .58	.54	.82

Inductance Measurement

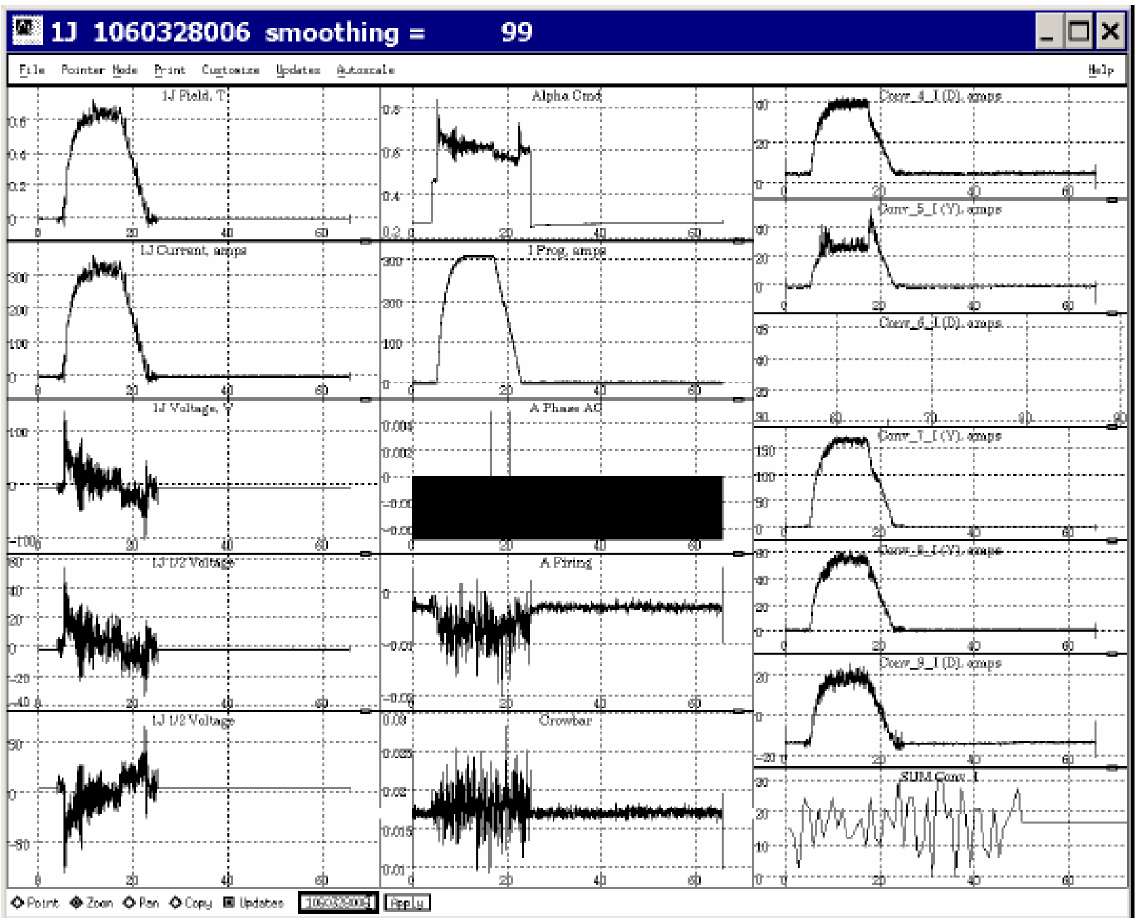
The original plan was to measure the inductance with a separate zero current dI/dt measurement. This was actually better done using the test current profiles, and will be discussed in the context of larger field shots.

We have done .6 and 1T shots starting from 80K using the higher voltage tap
We have cooled the magnet to 80 K Tuesday and This morning.
We have taken a lot of cooldown data. 5 CERNOX are giving data. T1 on the spline tube is working and measured temperatures are consistent with the a higher temp near the bore. We used coil resistances during cooldown to measure temp. – Data reduction still on-going.
There appears to be a larger heat leak in the bore than the bore heater, which is just positioned at the terminal end, can defrost. We will need bore heaters along the full length.

Discrete level sensor is not working. – Only one sensor goes green.-
Capacative sensors are fairly reliable qualitative indications of level. Not sure about absolute calibration yet.

Tuesday March 28, 0.6 and 1.0 T 80K Start Shots

Tuesday we pulsed the magnet with the high voltage taps and at LN2 temperatures. We did .6 and 1.0 T shots

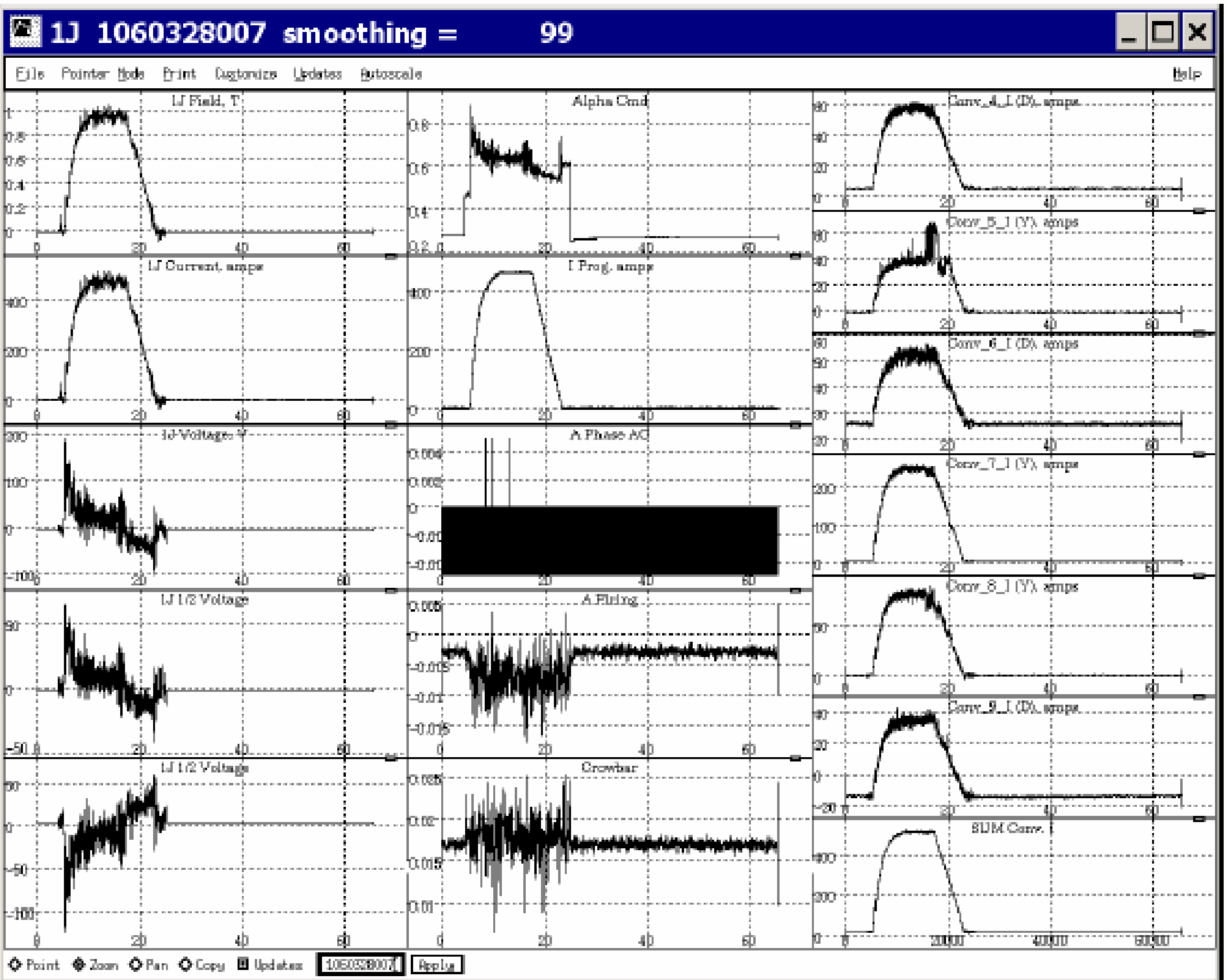


.6T 80K start Shot, Tuesday March 28

Run Test watching buss bars and Reese cables for excessive motion.

For an initial temp of 80 K the final coil temp should be _____ in all three coils. Fill in coil temperature data sheet(later). Temperatures in each of the three segments should be nearly identical.

Monitor and record pressure. Pressure in the inner vessel should be approximately ______Pa. The intention is to approach the intended operational surface heat flux in steps.



1T 80K Start Shot, Thursday March 28

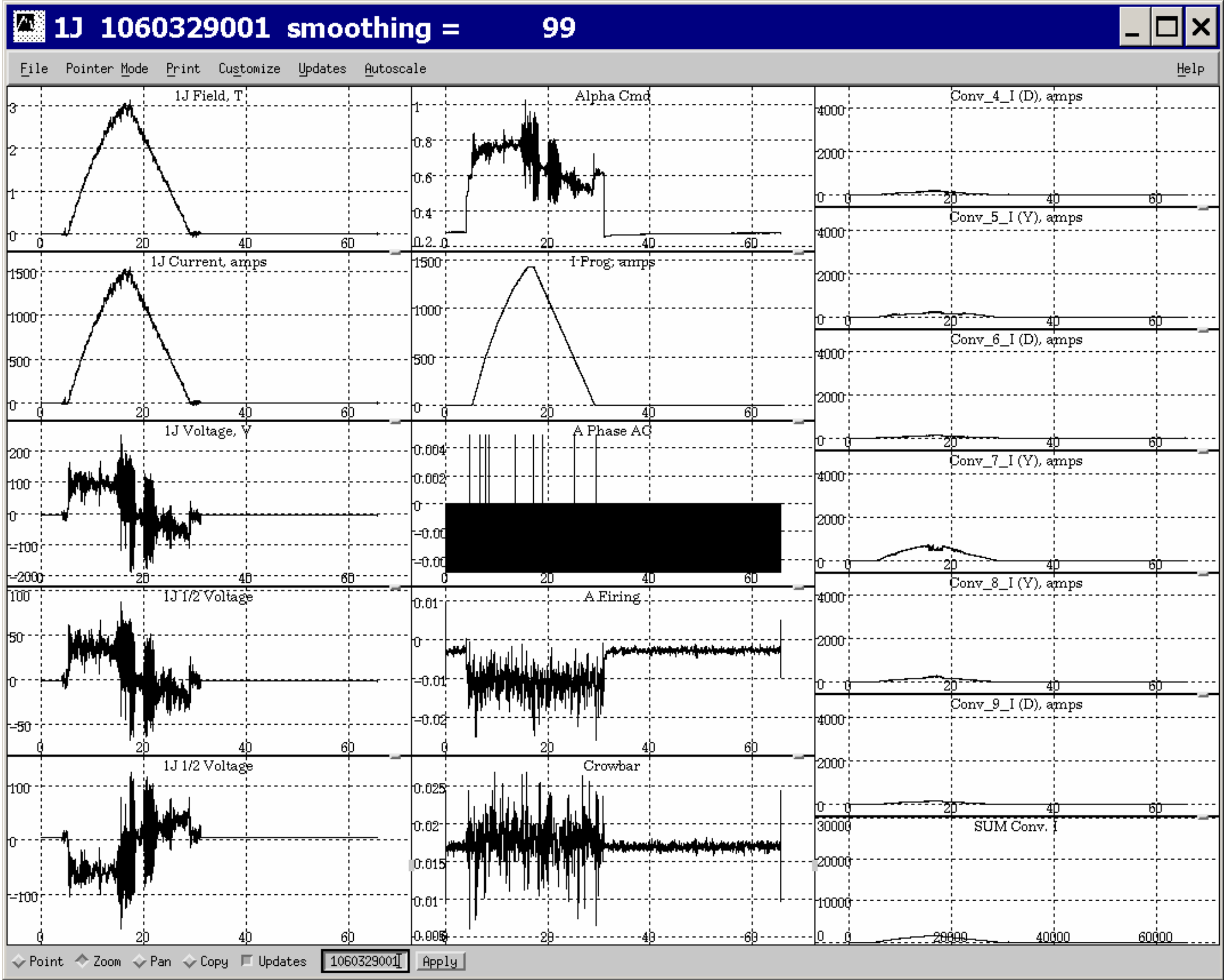
Add only as much LN2 as needed to maintain temperature. Cooling mode is to be primarily gaseous.

Wednesday March 29 2006

Wednesday we had a 3T and a 7 Tesla shot in the morning and two additional 7T shots in the afternoon.

.

```
Target Current (Phil adds a linear rampdown)
   Time Volt  Current  Field   Temp
  0 , 100 , 2.0661157 , 4.3255624e-3 , 82
 .5 , 100 , 103.02562 , .21569157 , 82.000218
 1. , 100 , 199.52188 , .41771345 , 82.001662
 1.5 , 100 , 291.75147 , .61080277 , 82.005399
 2. , 100 , 379.90131 , .79535082 , 82.012353
 2.5 , 100 , 464.14873 , .97172888 , 82.023319
 3. , 100 , 544.66174 , 1.1402887 , 82.038975
 3.5 , 100 , 621.5993 , 1.301363 , 82.059899
 4. , 100 , 695.11168 , 1.4552665 , 82.086576
 4.5 , 100 , 765.34085 , 1.6022963 , 82.119406
 5. , 100 , 832.42088 , 1.7427332 , 82.15872
 5.5 , 100 , 896.47839 , 1.8768422 , 82.204782
 6. , 100 , 957.63292 , 2.0048737 , 82.257796
 6.5 , 100 , 1015.9974 , 2.127064 , 82.317918
 7. , 100 , 1071.6787 , 2.2436367 , 82.385254
 7.5 , 100 , 1124.7777 , 2.3548032 , 82.459871
 8. , 100 , 1175.3899 , 2.4607636 , 82.541797
 8.5 , 100 , 1223.606 , 2.5617075 , 82.631031
 9. , 100 , 1269.5119 , 2.6578148 , 82.72754
 9.5 , 100 , 1313.1891 , 2.7492562 , 82.831265
 10. , 100 , 1354.7154 , 2.8361944 , 82.942125
 10.5 , 100 , 1394.1646 , 2.9187842 ,
83.060018
 11. , 100 , 1431.6073 , 2.9971733 , 83.184826
 11.5 , 100 , 1467.1111 , 3.071503 , 83.316412
 12. , 100 , 1500.7404 , 3.1419084 , 83.454625
```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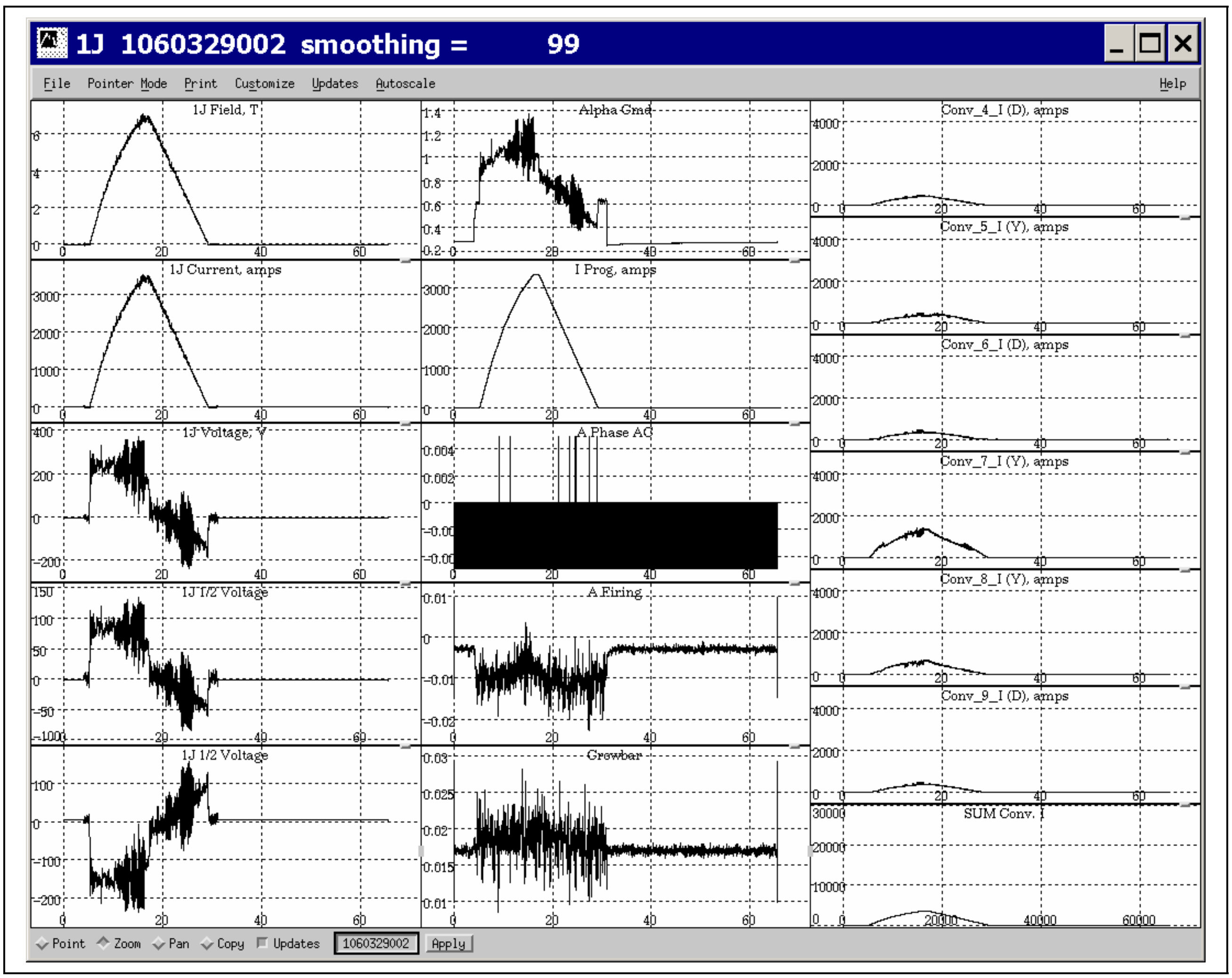
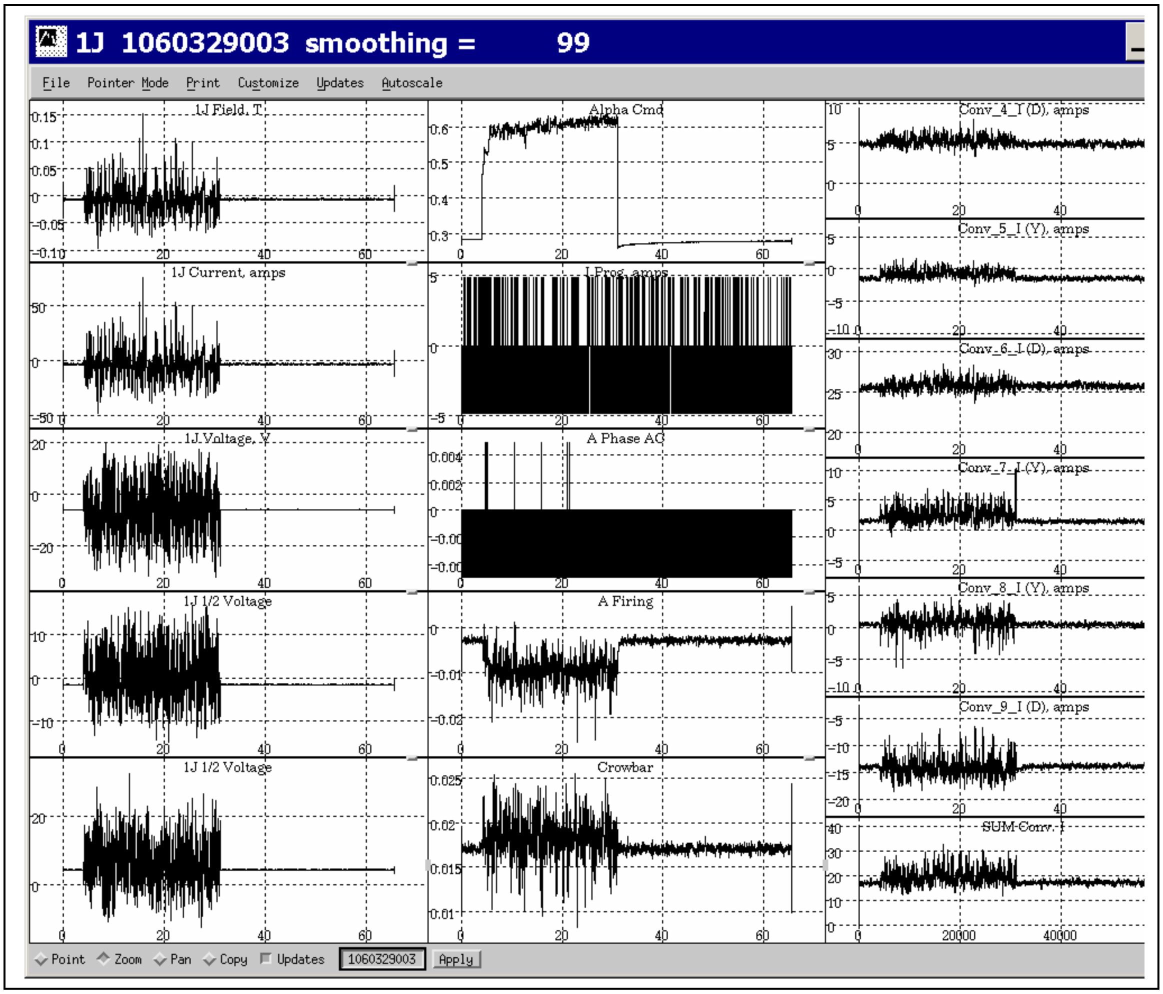
Alpha Cmd
Conv_4_I (D), amps
Conv_5_I (Y), amps
1J Current, amps
I Prog, amps
Conv_6_I (D), amps
1J Voltage, V
A Phase AC
Conv_7_I (Y), amps
1J 1/2 Voltage
A Firing
Conv_8_I (Y), amps
Conv_9_I (D), amps
1J 1/2 Voltage
Crowbar
SUM Conv. I
Point Zoom Pan Copy Updates 1060329001 Apply

3T Shot

Target Current (Phil adds a linear rampdown)

```
 0 , 250 , 5.1652893 , 1.0813906e-2 , 85
.5 , 250 , 257.07213 , .53819907 , 85.00142
1. , 250 , 496.91421 , 1.0403258 , 85.010795
1.5 , 250 , 725.25743 , 1.5183788 , 85.034978
2. , 250 , 942.62452 , 1.9734525 , 85.07983
2.5 , 250 , 1149.4923 , 2.4065451 , 85.150342
3. , 250 , 1346.291 , 2.8185574 , 85.25074
3.5 , 250 , 1533.405 , 3.210294 , 85.384582
4. , 250 , 1711.1743 , 3.5824669 , 85.554833
4.5 , 250 , 1879.8972 , 3.9357005 , 85.763938
5. , 250 , 2039.8334 , 4.2705384 , 86.013876
5.5 , 250 , 2191.2071 , 4.5874503 , 86.30621
6. , 250 , 2334.2111 , 4.8868395 , 86.642128
6.5 , 250 , 2469.0104 , 5.1690516 , 87.022467
7. , 250 , 2595.7463 , 5.4343824 , 87.447748
7.5 , 250 , 2714.5406 , 5.6830868 , 87.918188
8. , 250 , 2825.4995 , 5.9153872 , 88.43372
8.5 , 250 , 2928.7178 , 6.1314822 , 88.994005
9. , 250 , 3024.2832 , 6.3315553 , 89.598442
9.5 , 250 , 3112.28 , 6.5157828 , 90.246176
10. , 250 , 3192.7928 , 6.6843422 , 90.93611
10.5 , 250 , 3265.9107 , 6.8374197 , 91.666908
11. , 250 , 3331.7303 , 6.9752178 , 92.437009
11.5 , 250 , 3390.3591 , 7.0979615 , 93.244635
12. , 250 , 3441.9182 , 7.2059041 , 94.087808
```

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Print
Customize
Updates
Autoscale
1J Field, T
Alpha Cmd
Conv_4_I (D), amps
1J Current, amps
I Prog, amps
Conv_5_I (Y), amps
Conv_6_I (D), amps
1J Voltage, V
A Phase AC
Conv_7_I (Y), amps
1J 1/2 Voltage
A Firing
Conv_8_I (Y), amps
Conv_9_I (D), amps
1J 1/2 Voltage
Crowbar
SUM Conv. I
Point
Zoom
Pan
Copy
Updates
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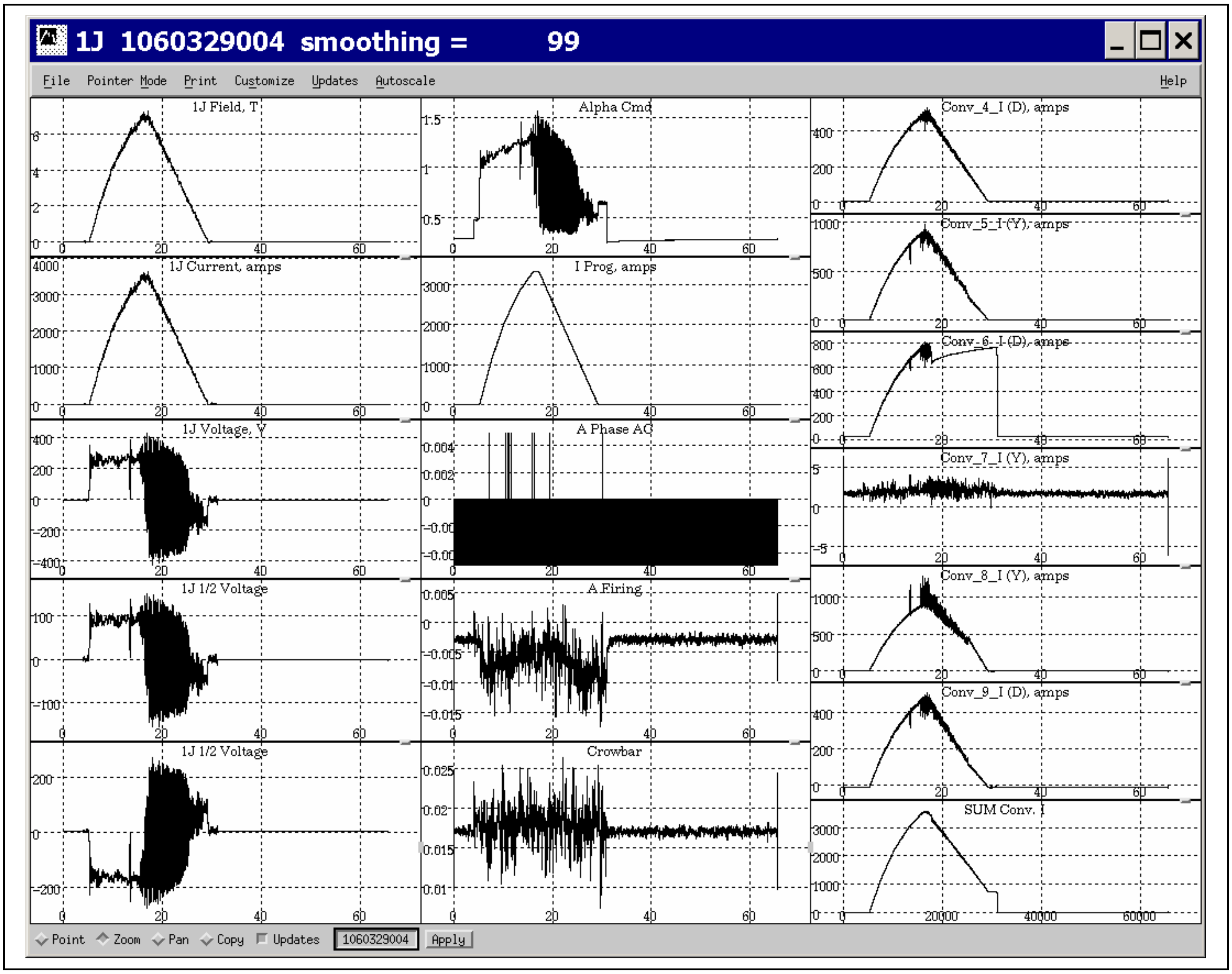
Apply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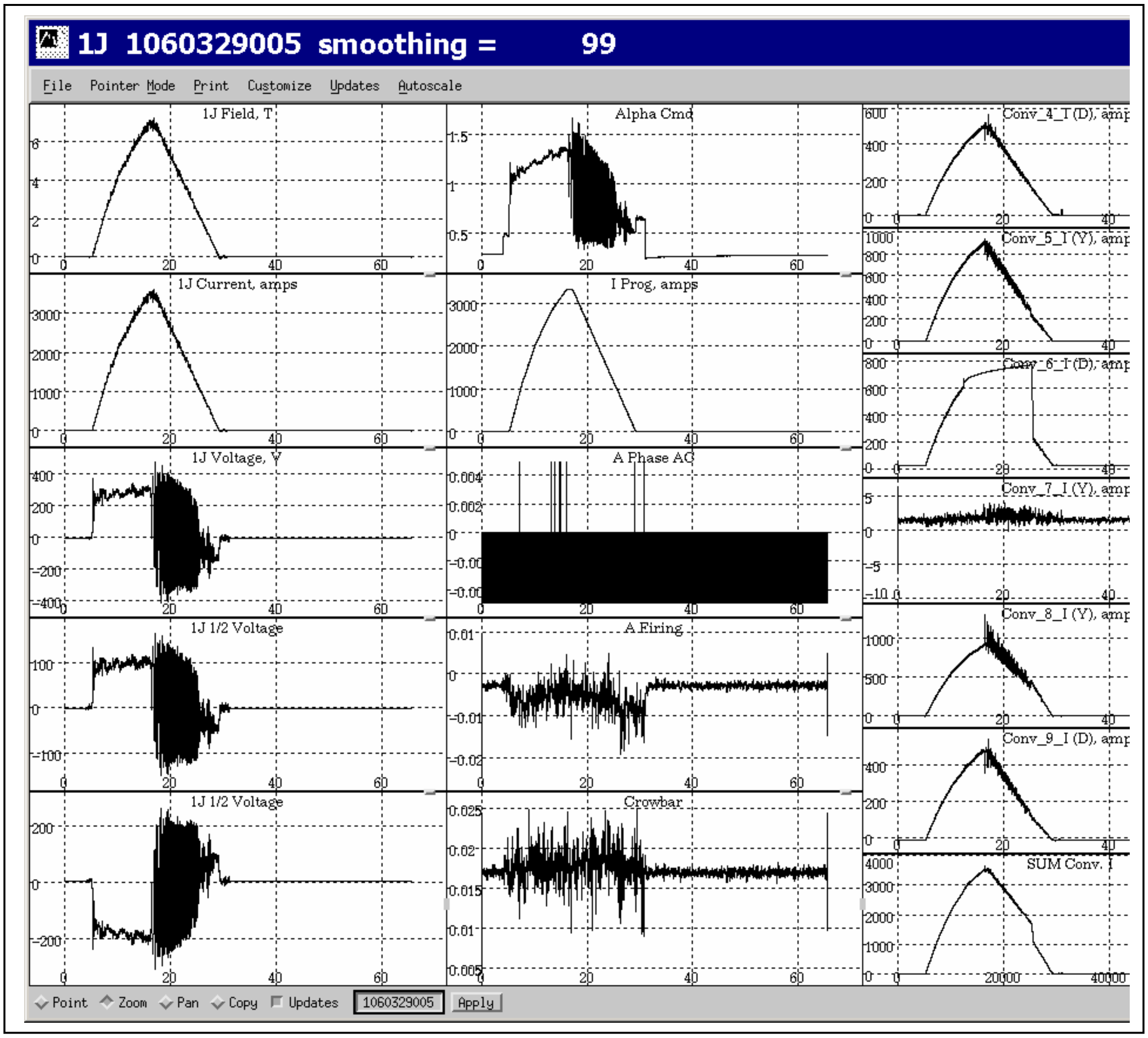
1J Voltage, V
1J 1/2 Voltage
1J 1/2 Voltage
Alpha Cmd
I Prog, amps
A Phase AC
A Firing
Crowbar
Conv_4_I (D), amps
Conv_5_I (Y), amps
Conv_6_I (D), amps
Conv_7_I (Y), amps
Conv_8_I (Y), amps
Conv_9_I (D), amps
SUM Conv. I
Point Zoom Pan Copy Updates 1060329004 Apply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Alpha Cmd
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Conv_5_I (Y), amp
1J Current, amps
I Prog, amps
Conv_6_I (D), amp
1J Voltage, V
A Phase AC
Conv_7_I (Y), amp
1J 1/2 Voltage
A Firing
Conv_8_I (Y), amp
Conv_9_I (D), amp
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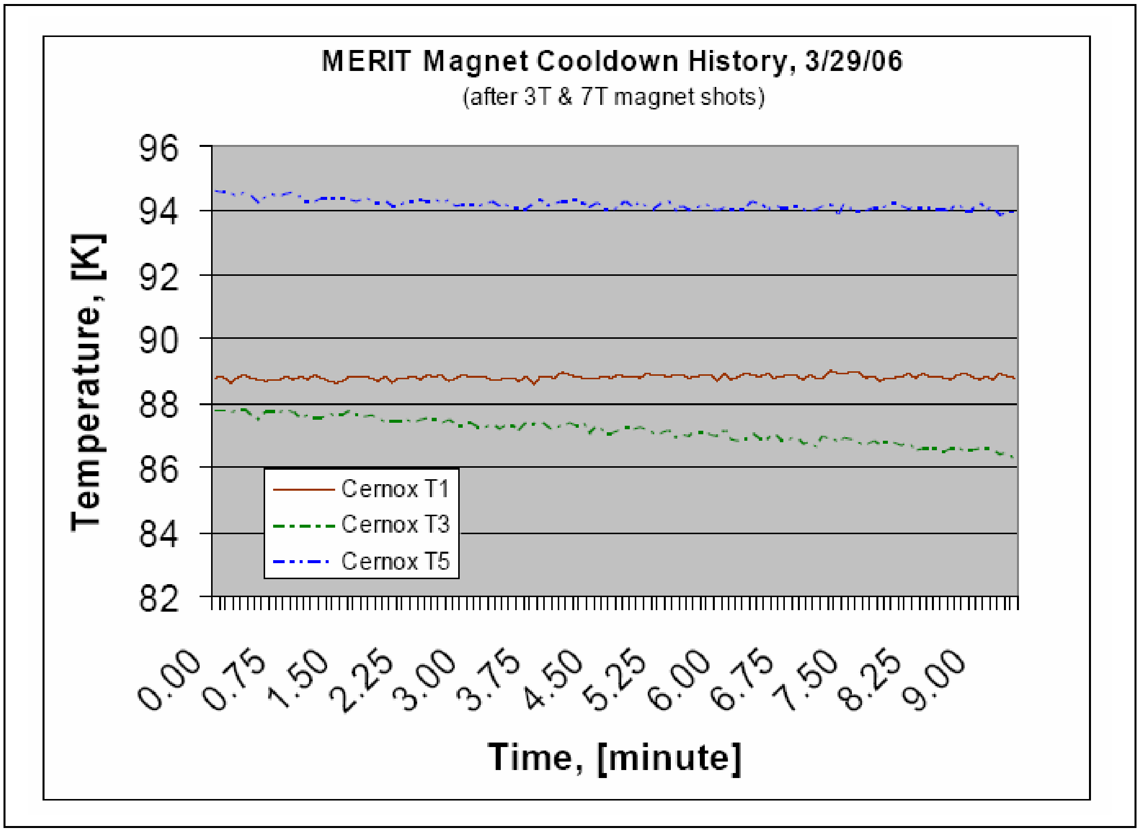
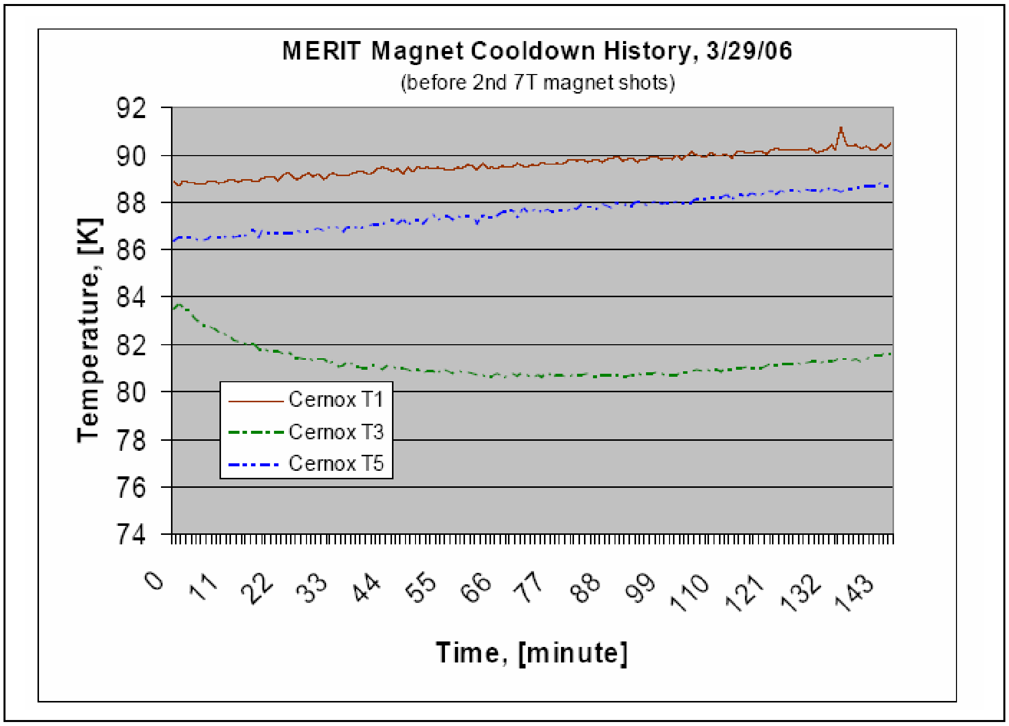
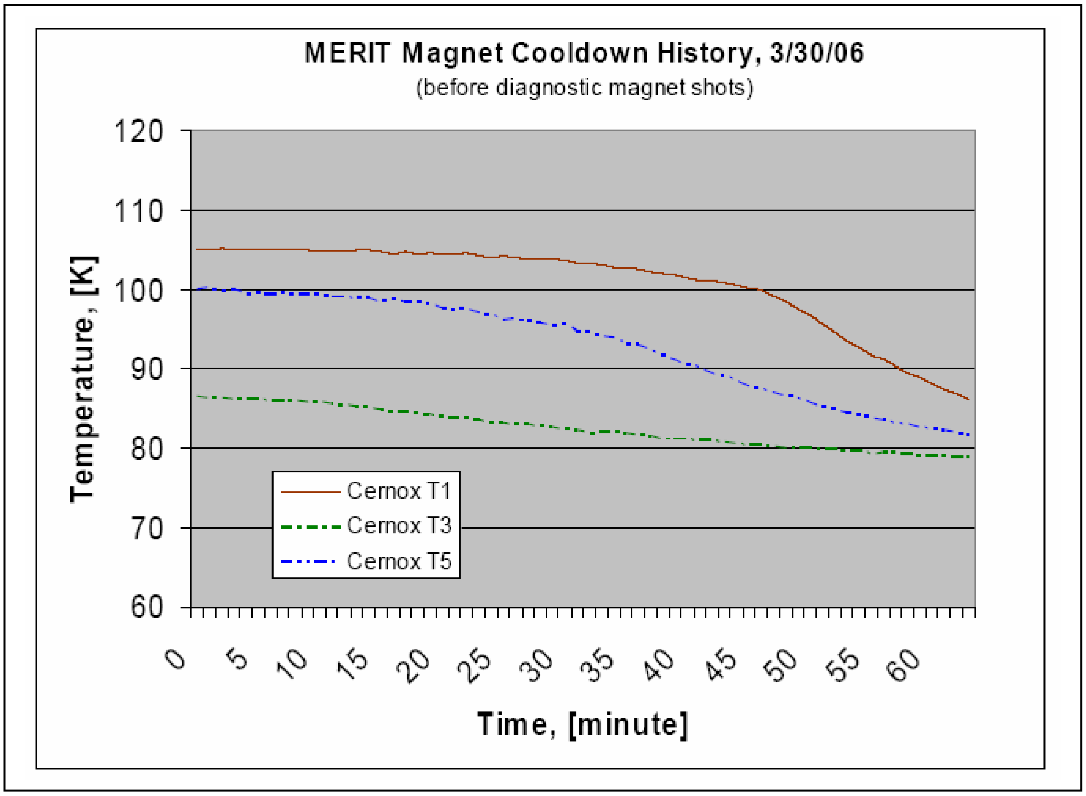
Crowbar
SUM Conv. I
Point Zoom Pan Copy Updates 1060329005 Apply

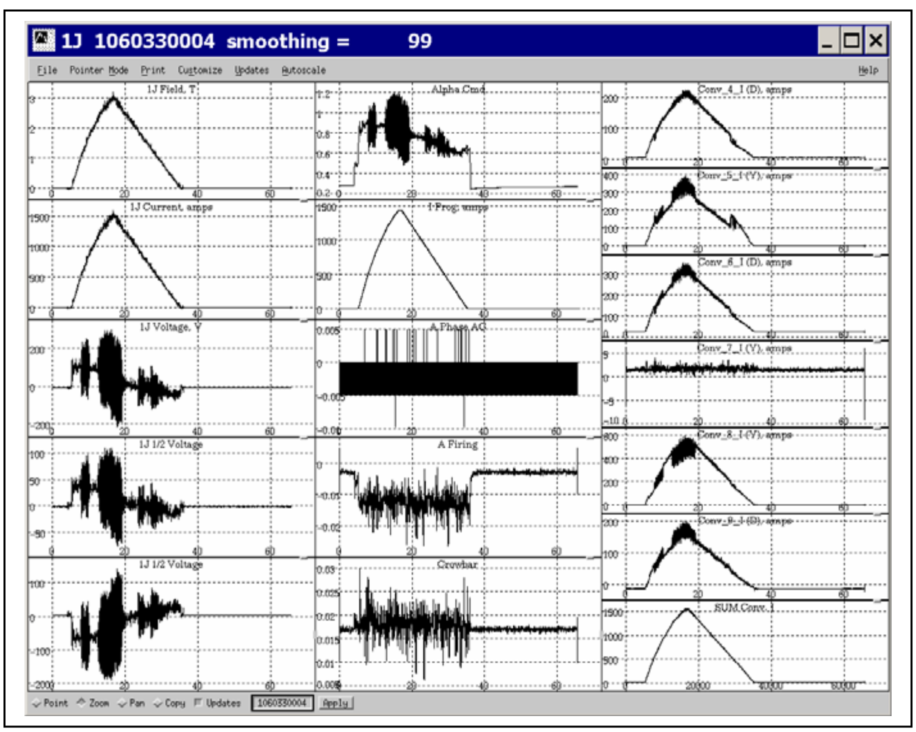
Cooldown After March 29 3 and 7Tesla Shots

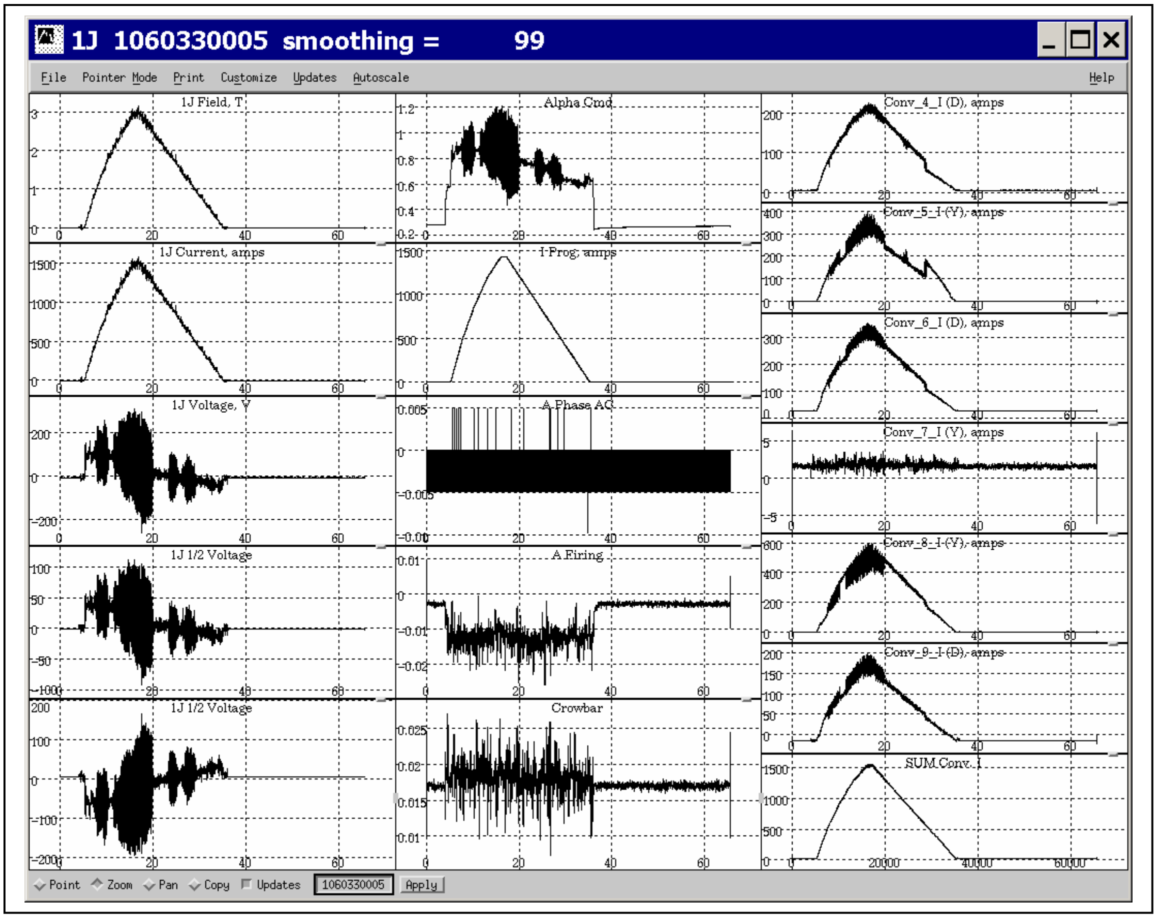




March 30, Cooldown Before Diagnostic Shots



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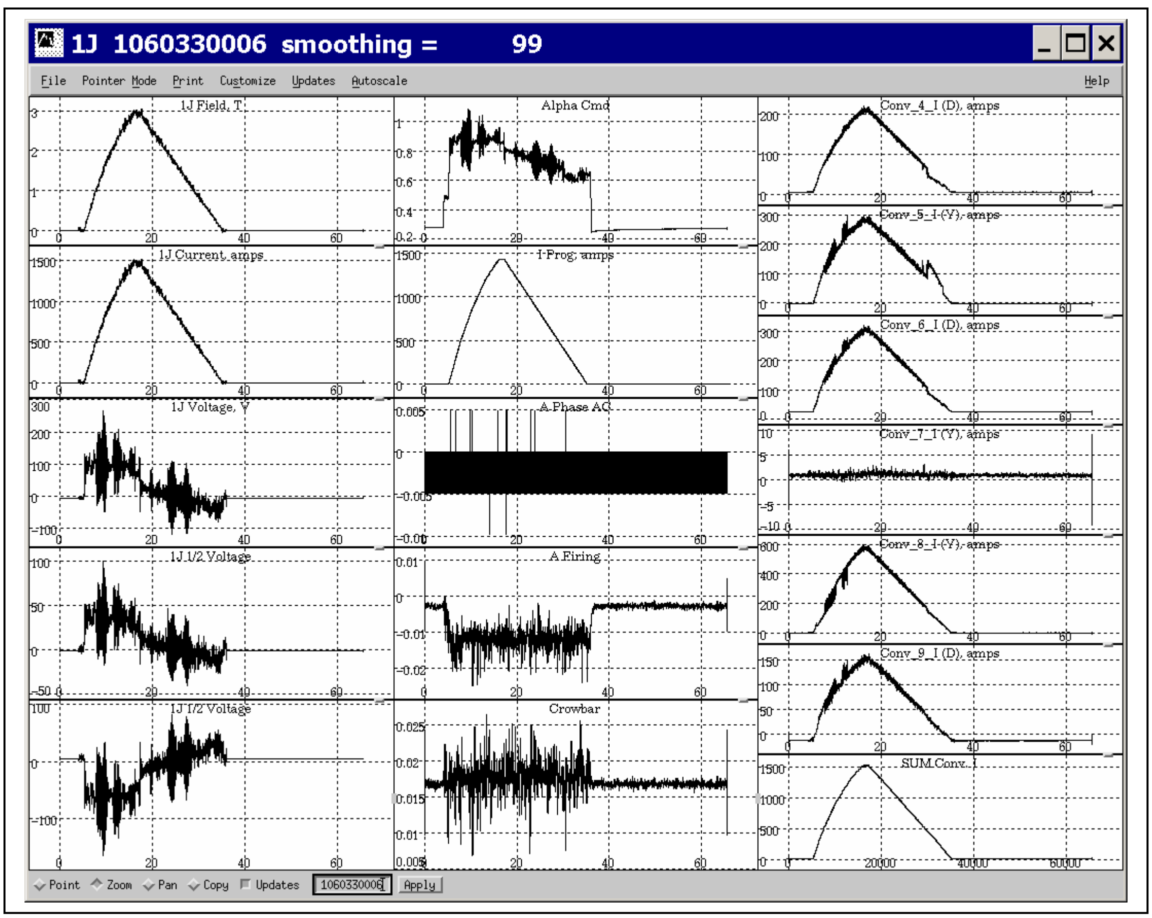
Conv_5_I (Y), amps
1J Current, amps
I Prog, amps
Conv_6_I (D), amps
1J Voltage, V
A Phase AC
Conv_7_I (Y), amps
1J 1/2 Voltage
A Firing
Conv_8_I (Y), amps
Conv_9_I (D), amps
1J 1/2 Voltage
Crowbar
SUM Conv_I
Point Zoom Pan Copy Updates 1060330005 Apply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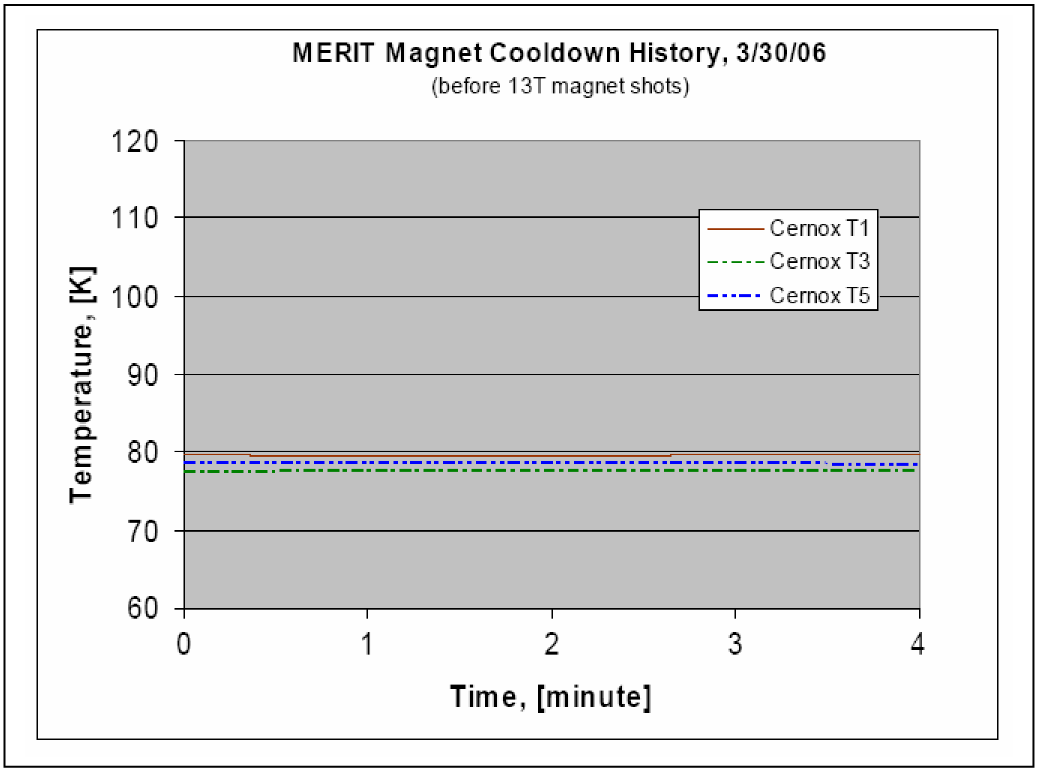
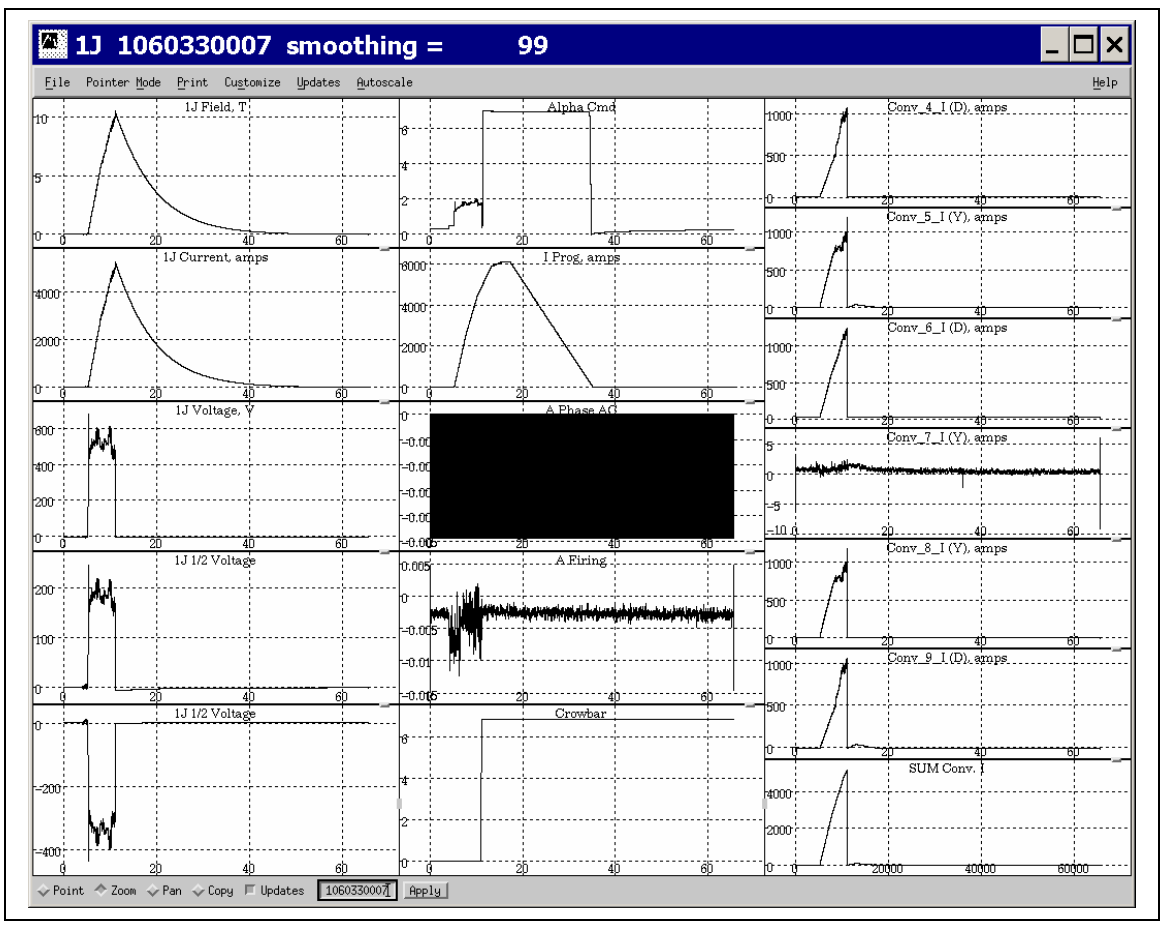
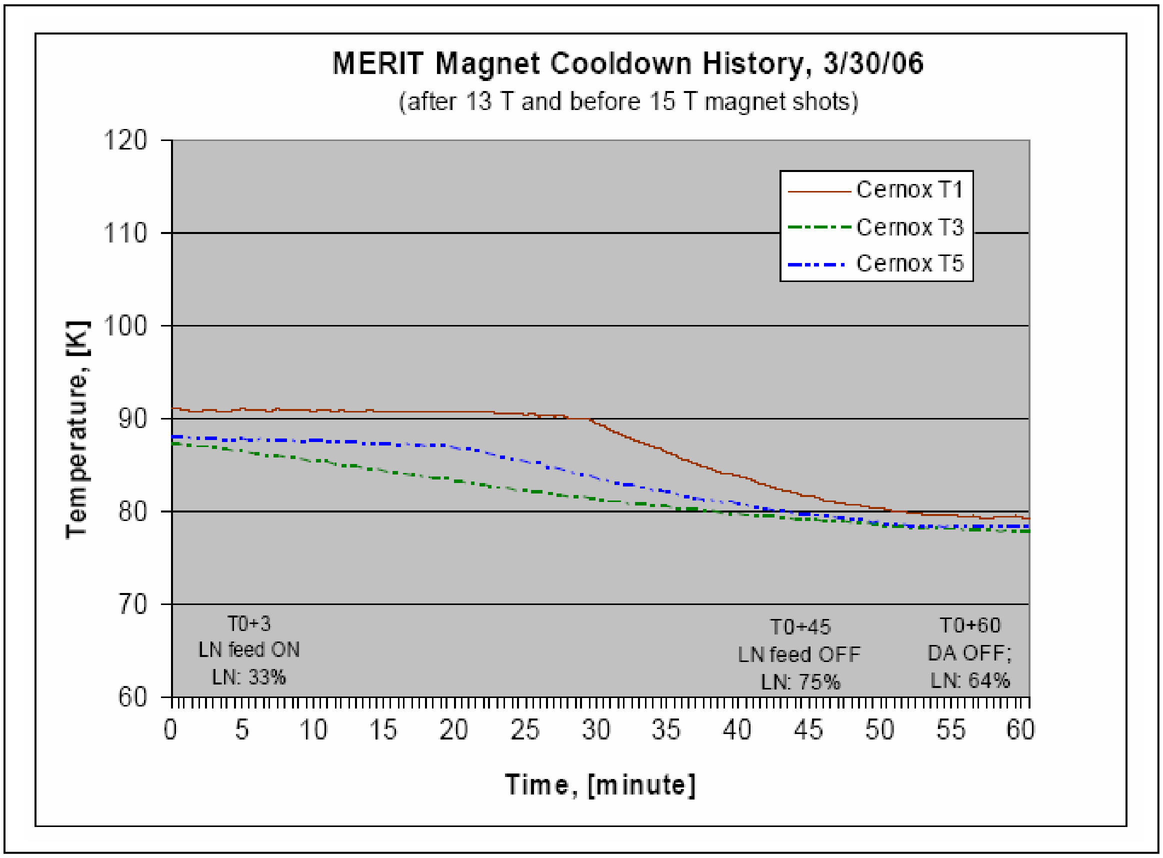
Alpha Cmd
Conv_4_I (D), amps
Conv_5_I (Y), amps
1J Current, amps
I Prog, amps
Conv_6_I (D), amps
1J Voltage, V
A Phase AC
Conv_7_I (Y), amps
1J 1/2 Voltage
A Firing
Conv_8_I (Y), amps
Conv_9_I (D), amps
1J 1/2 Voltage
Crowbar
SUM Conv_I
Point Zoom Pan Copy Updates 1060330006 Apply

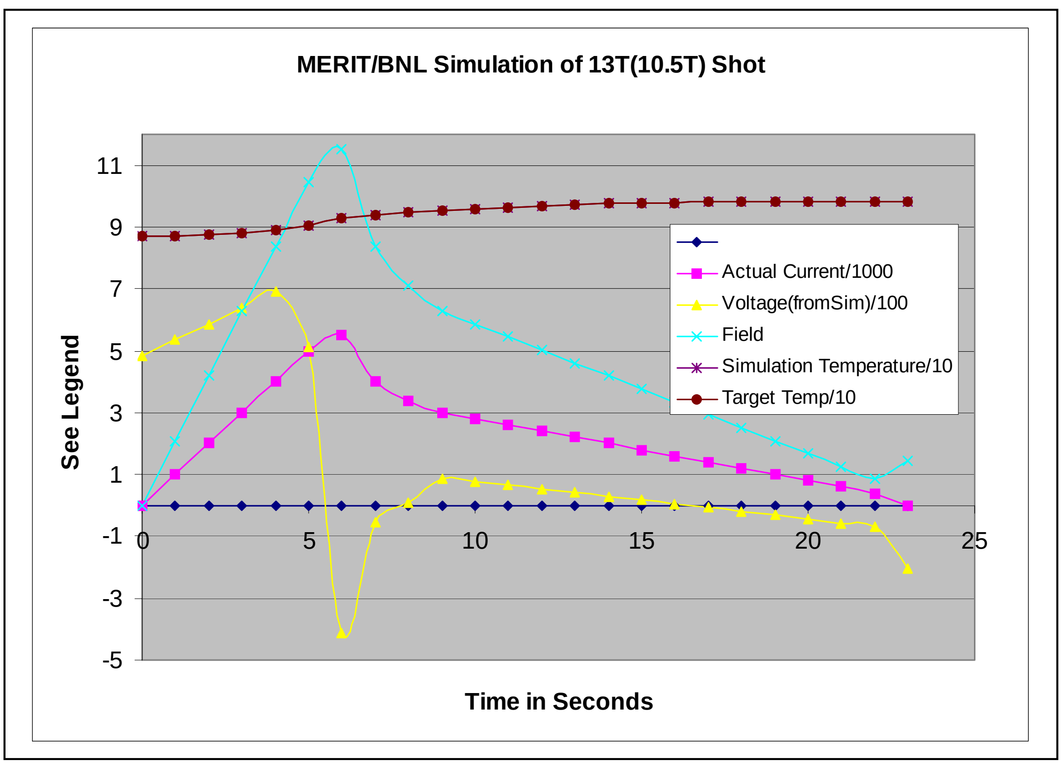
10T, Planned as a 13T Shot , 3/30/06



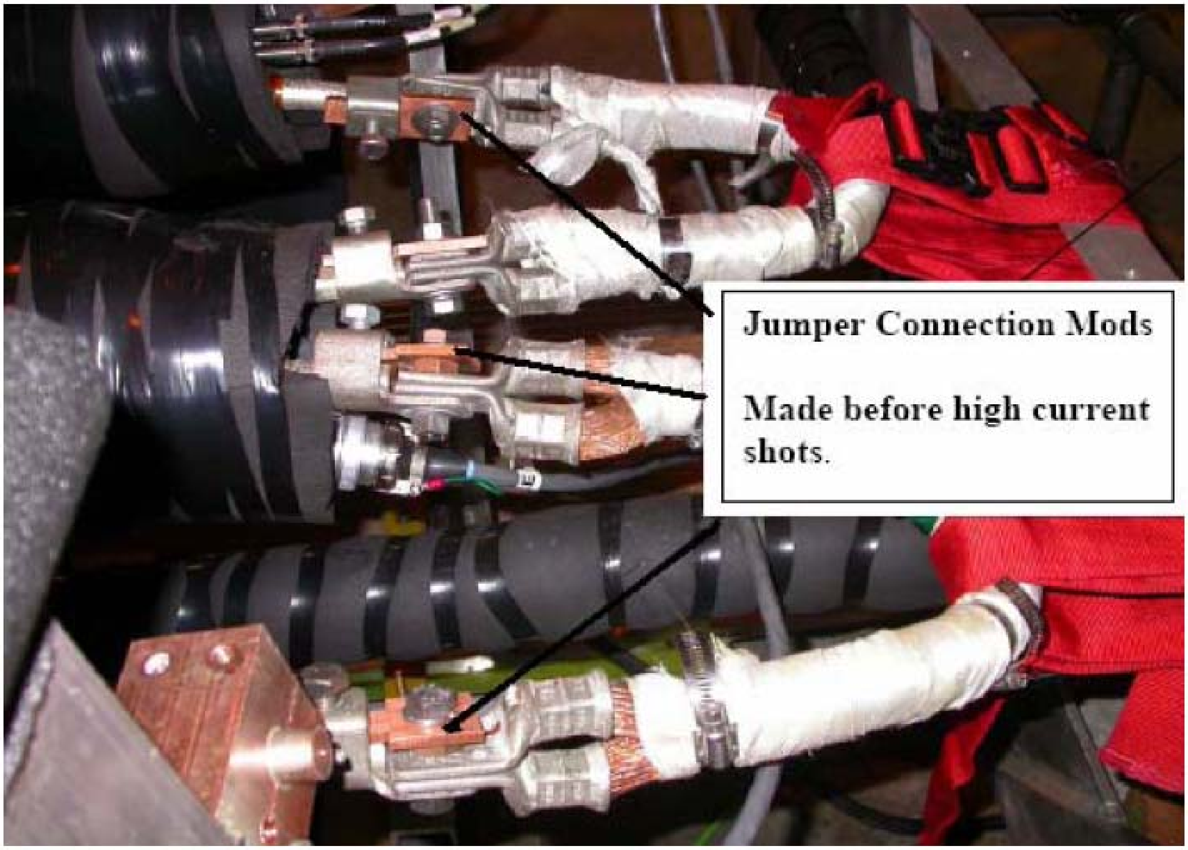


15T Test -Temperature Before the Shot





15T Test – Setup



Modifications to the Jumper Connections made Wednesday March 29 and installed the Morning of March 30

7200 amps was programmed into the power supply. Based on Bob Weggels (and P.Titus) calculations, this should be 15T ~7500 amps was reached by the power supply as reported by the power supply instrumentation. Based on the calculated magnet constant this would be 15.625T Based on gauss meter and small power supply current shunt, the magnet constant is:

`0.16T/79A = 0.0020253 T/A`

7200amps would be 14.58T

7500amps would be 15.19T

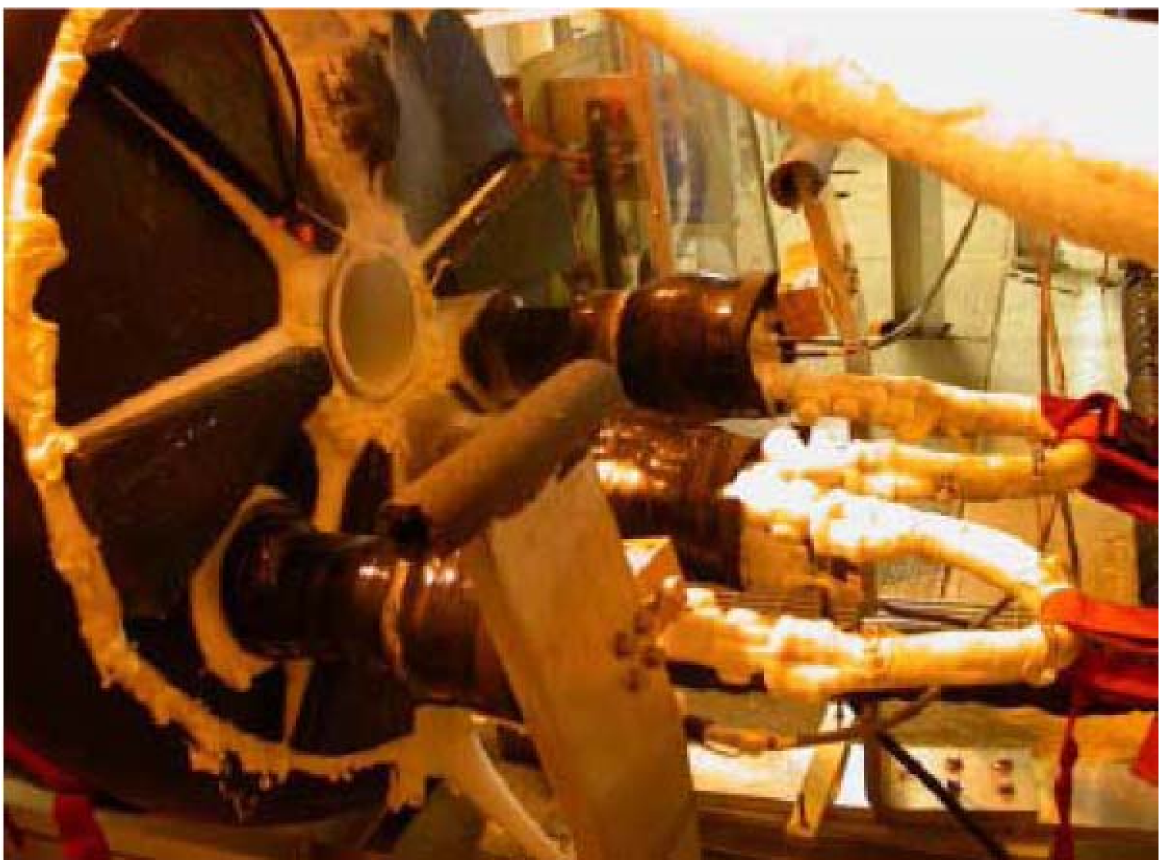
Movies of this pulse were taken and there was no visible motion of the bus bars and jumper cables.

Visually Inspect for Leaks around the cover gasket and bellows.

Cooldown after First 15T Shot

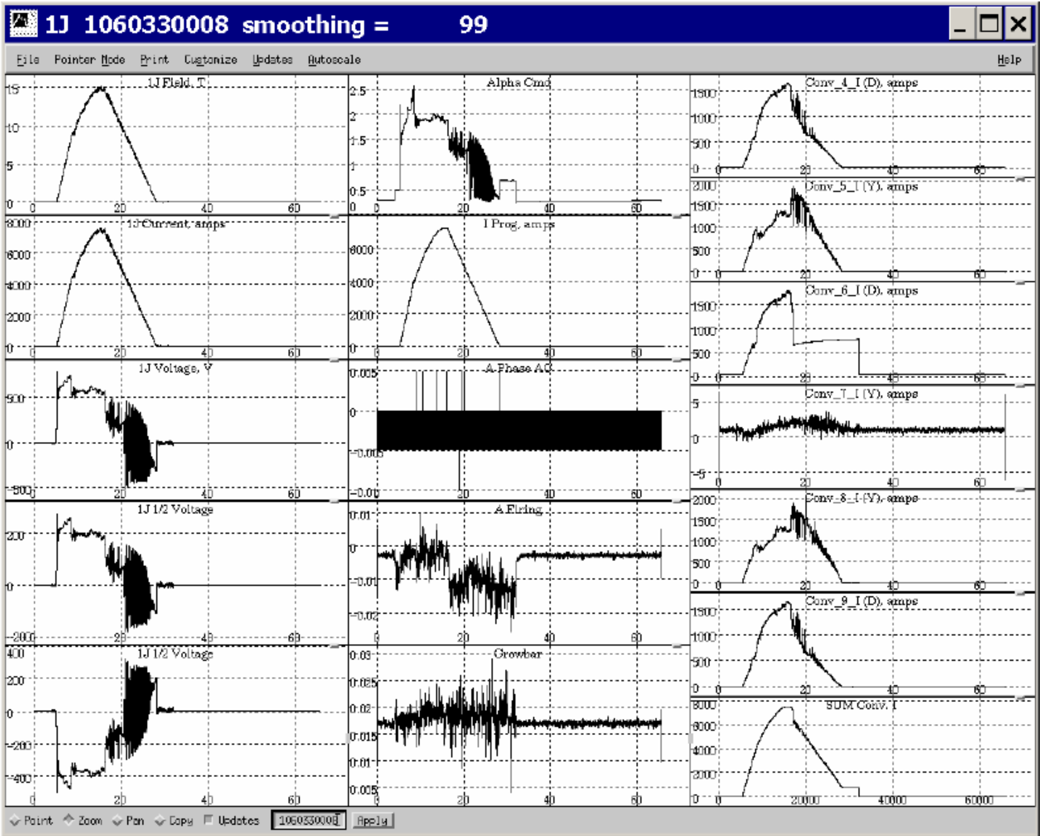
Post-Pulse Temperatures argue for the higher current. Why doesn't the simulation with the actual voltage trace reproduce the higher current? – We are checking data. Among other improvements, we need a better field measurement.
We are investigating a flux loop and integrating the dB/dt as measured by the voltage. .

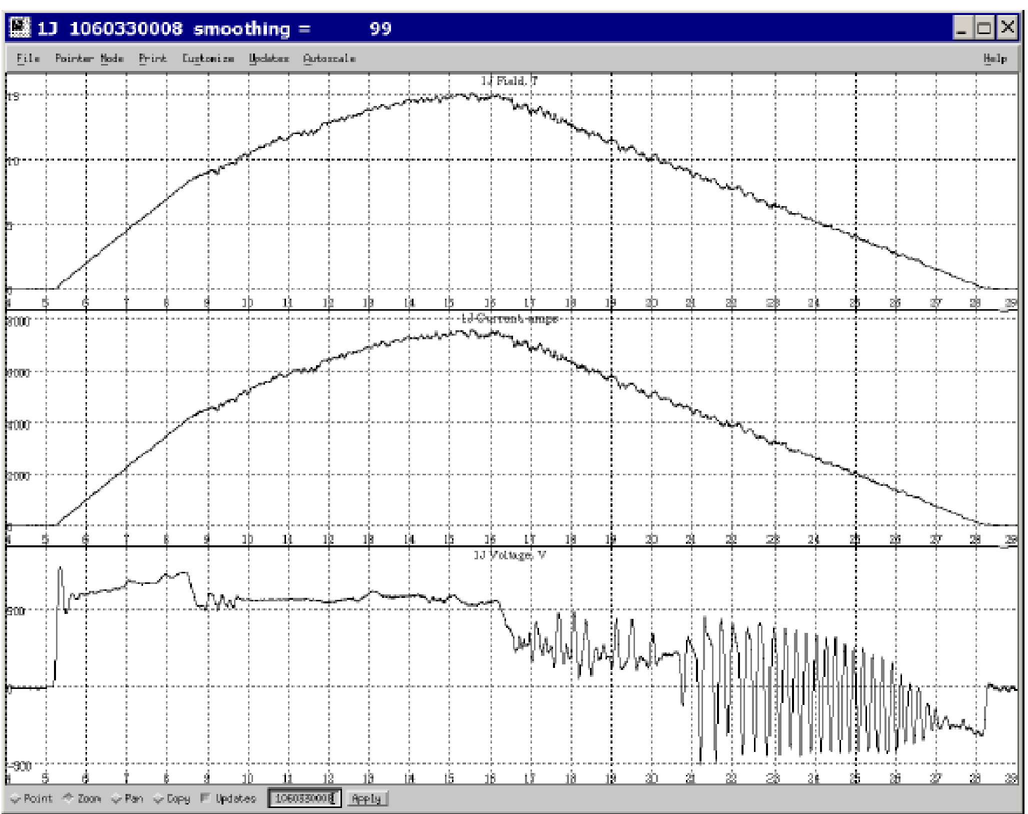
Thursday March 30



Thursday The cold end of the magnet. We had the bore heater off. Jumpers were not insulated.

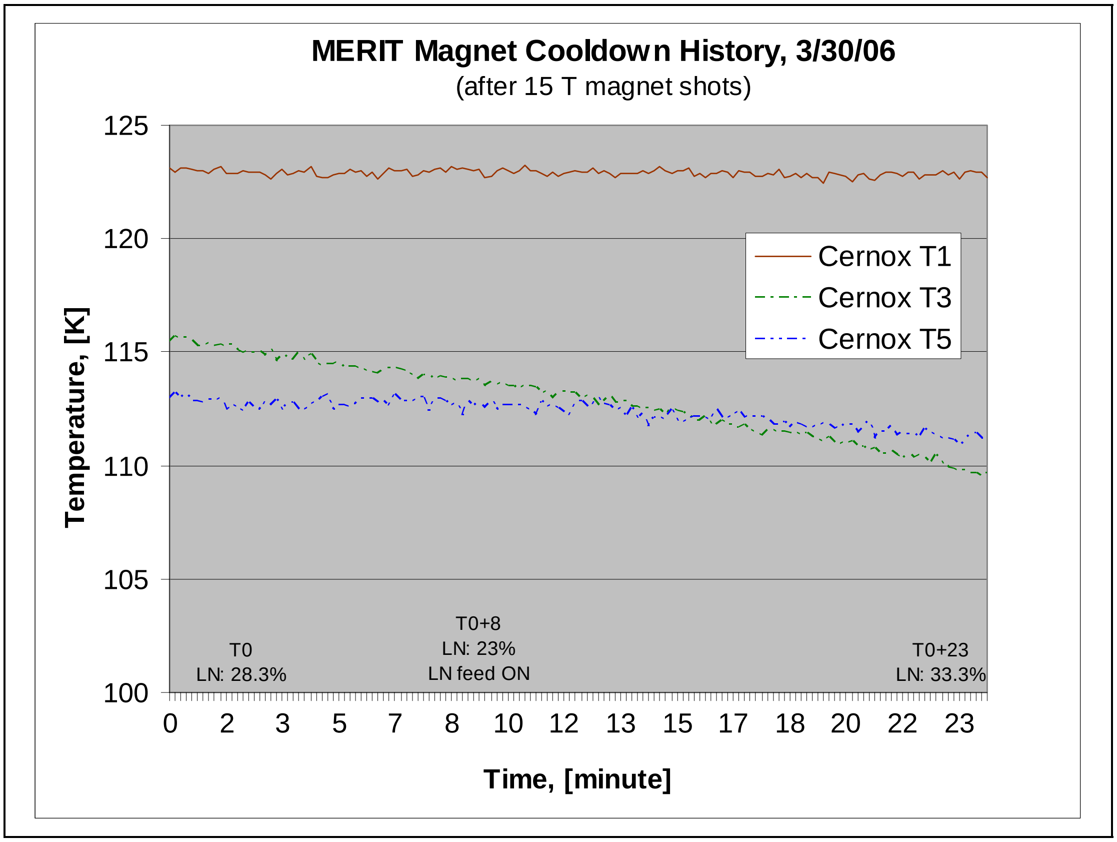
Current Traces

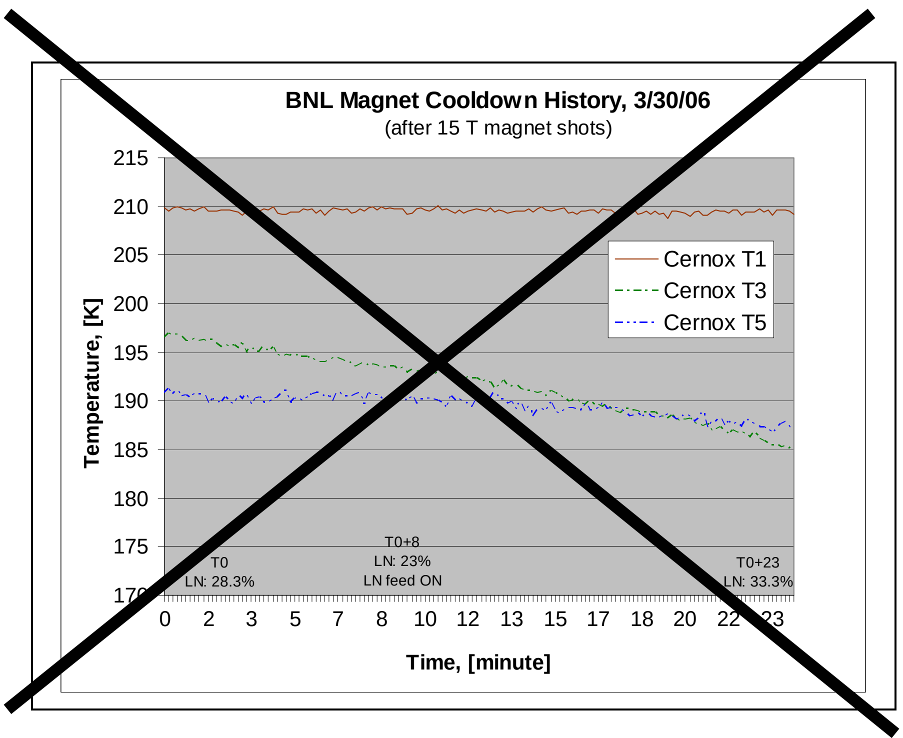




Expanded Current and Voltage Trace

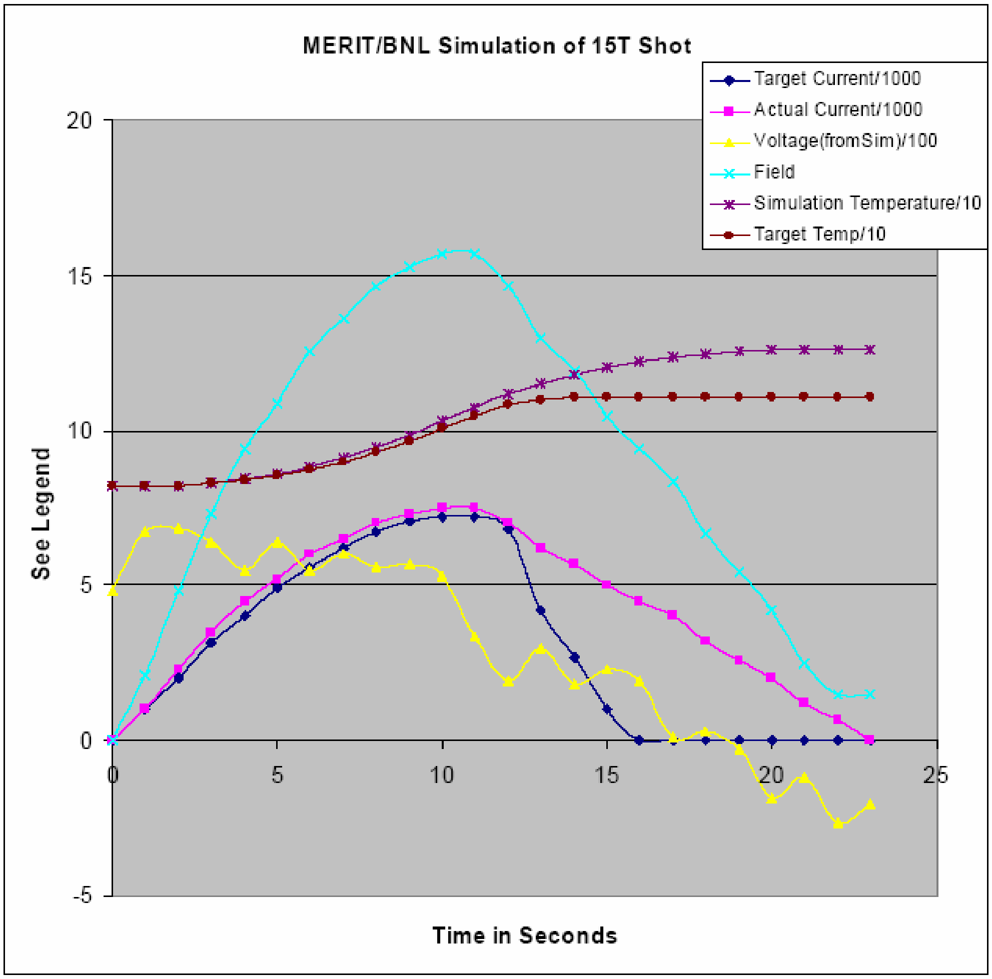
15T Shot Temperatures After the Shot





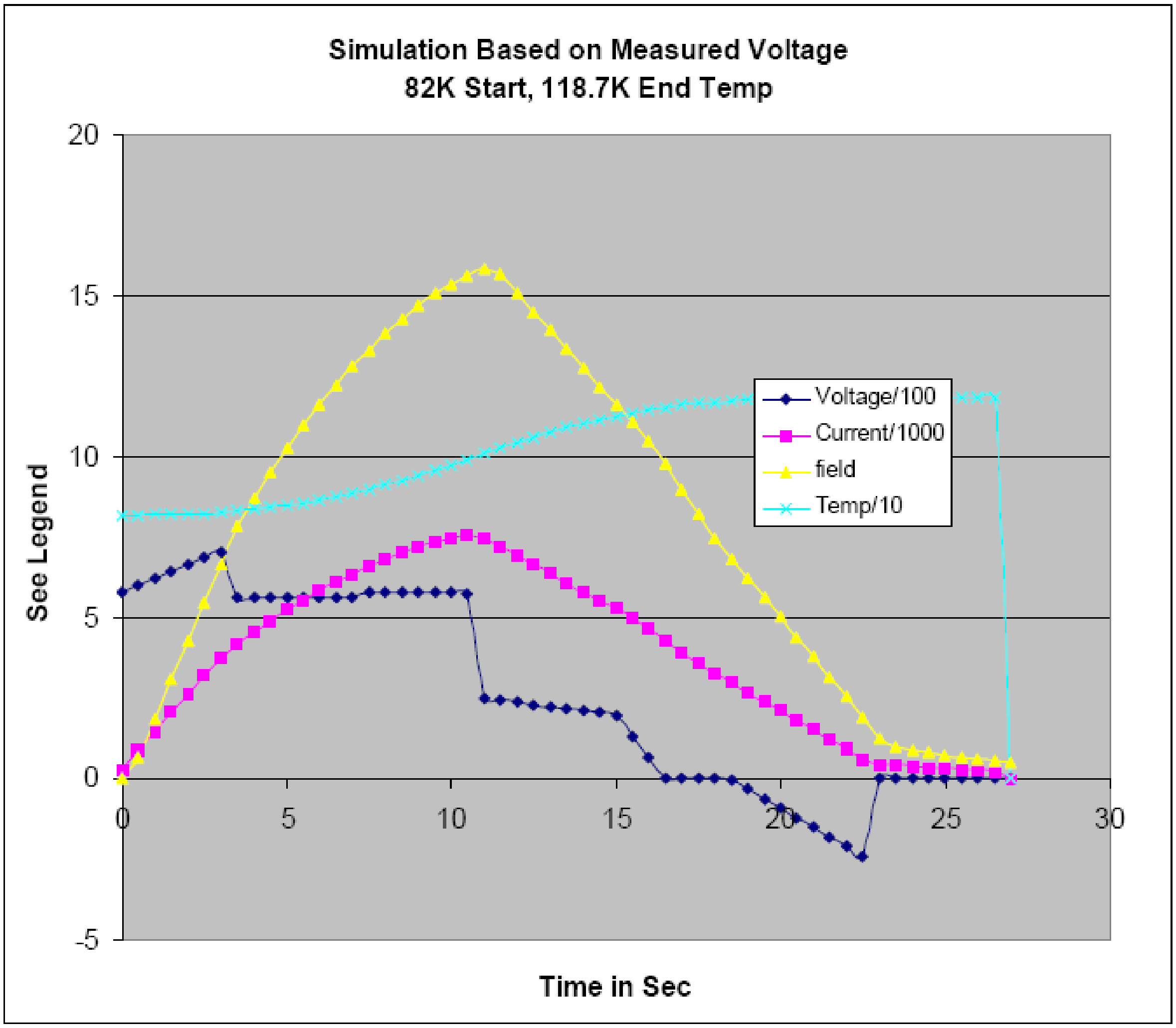
Simulations based on applied current and applied voltage

First, the current based simulation:



The target current profile has an 82K start and goes to 110.8K
The Simulation of the actual test current starts at 82 K goes to 126K
Temperatures of 113 to 123K were measured after the test pulse.

Next, the voltage based simulation:
Note that the average voltage is used rather than the voltage imposed by the control system oscillation.

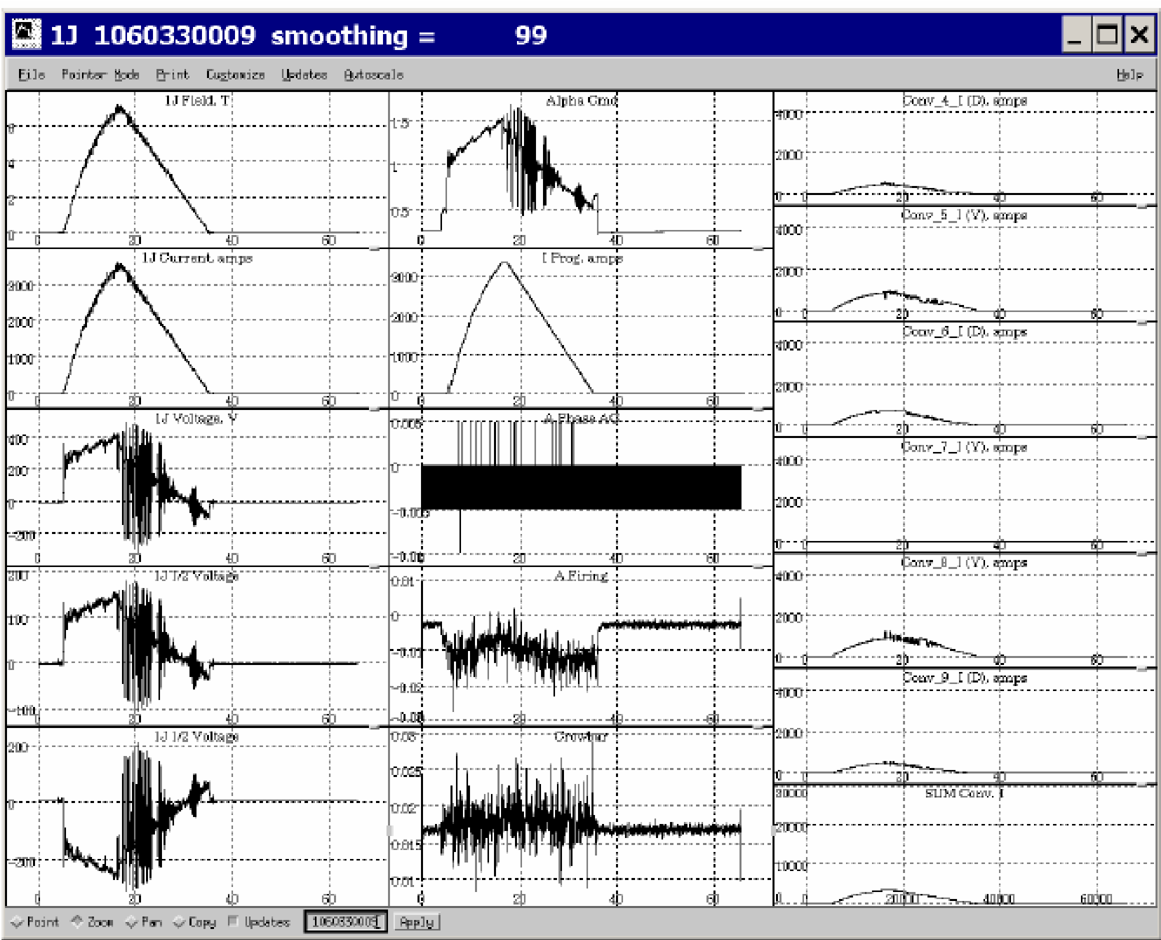


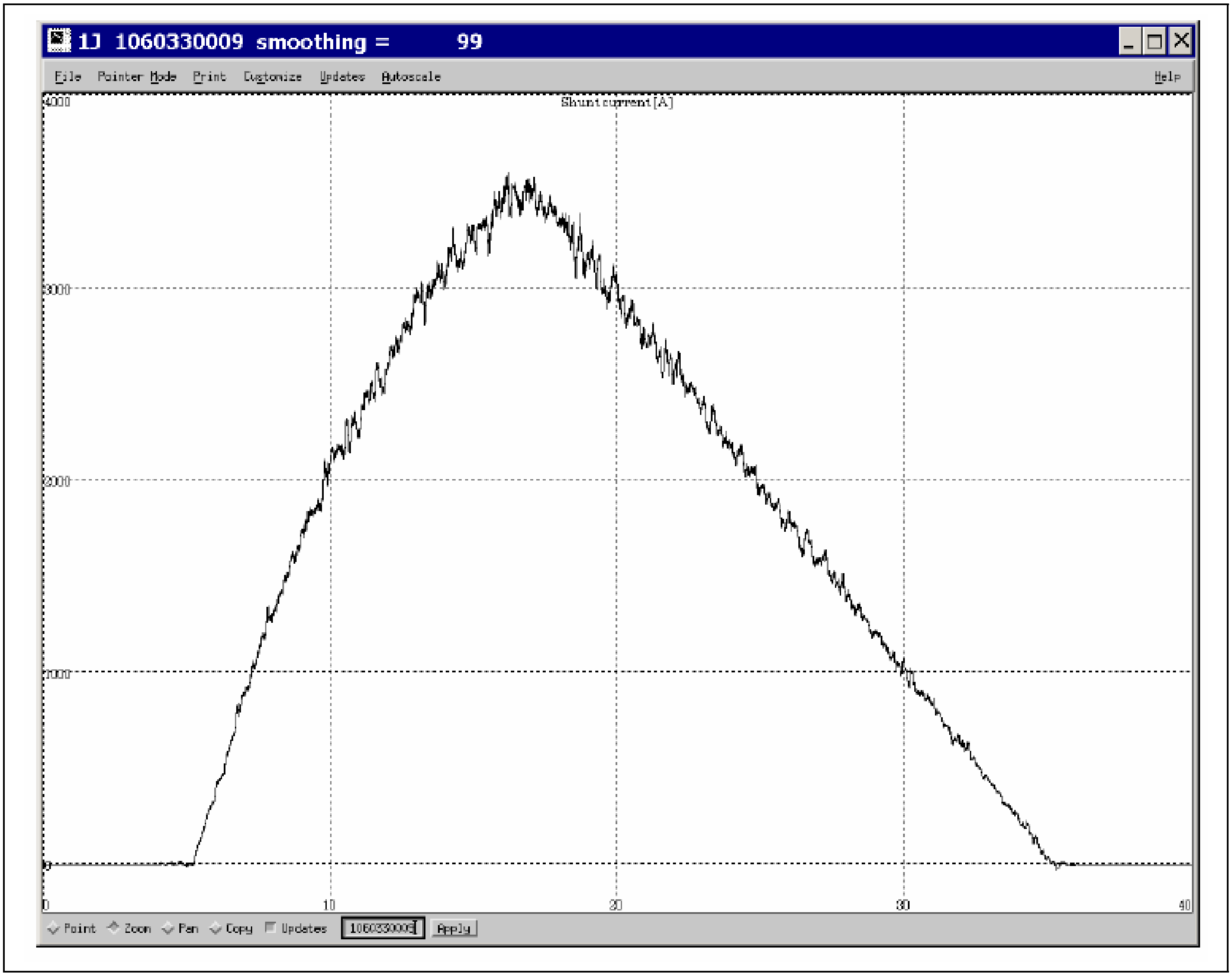
The Simulation based on voltage starts at 82K and goes to 119K.
The Simulation of the actual test current starts at 82 K goes to 126K
The expected temperature range for the desired current profile is 82K to 110.8K
Temperatures of 113 to 123K were measured after the test pulse

Last 7T Shot (Planned as the Second 15T Test) Thursday March 30

The second planned 15T shot was changed to a 7T shot because of the unexpectedly higher temperatures from the first 15T shot. This required some investigation after the test run to diagnose the difficulty. A simulation of the last 7T shot was performed This was the last day of testing. There were a number of shots used to diagnose a mal-distribution of current in the converters. We had one 13T shot that tripped (at 10T) on a control fault, then the successful 15 T shot, and the day was finished with a 7T shot. Stray field measurements were made for the 10 and 15T shots by the MIT main campus safety officer. These benchmarked well with the calculations of the stray field in the test procedure. The 10 and 15T shots began at 80 to 85K. After the 15 T shot there were CERNOX readings that were between 190 and 210 K, and this led to the decision to end the day of testing with a 7T shot. The 15 T shot should have only produced 118K end temperature. The high temperatures were a concern. They looked erroneous, but we did not wish to risk the coil with a full 15T shot. The last shot of the day went off successfully with no indication of electrical anomalies aside from the voltage oscillations that are the result of the power supply control system settings.

The coil numerical simulation was run for the 7T shot with the current trace as input. The results are shown in the last of the three figures. Start temperatures were assumed and the simulation was used to produce a voltage trace to compare with the actual. A start temperature of 115K was found to give reasonable agreement. This is consistent with the expected results for the 15T shot. At this time the only conclusion is that the CERNOX sensors were reading erroneously. After the weekend when the magnet was allowed to warm up, the CERNOX sensors were read, and these were consistent with temperatures obtained with resistance measurements using the small power supply. So the high CERNOX readings are still a mystery. We have not identified the source of the problems with the CERNOX sensors at this time. Measuring the resistance with a low current before each shot is the most reliable indication that the temperature is acceptable for a full field shot.





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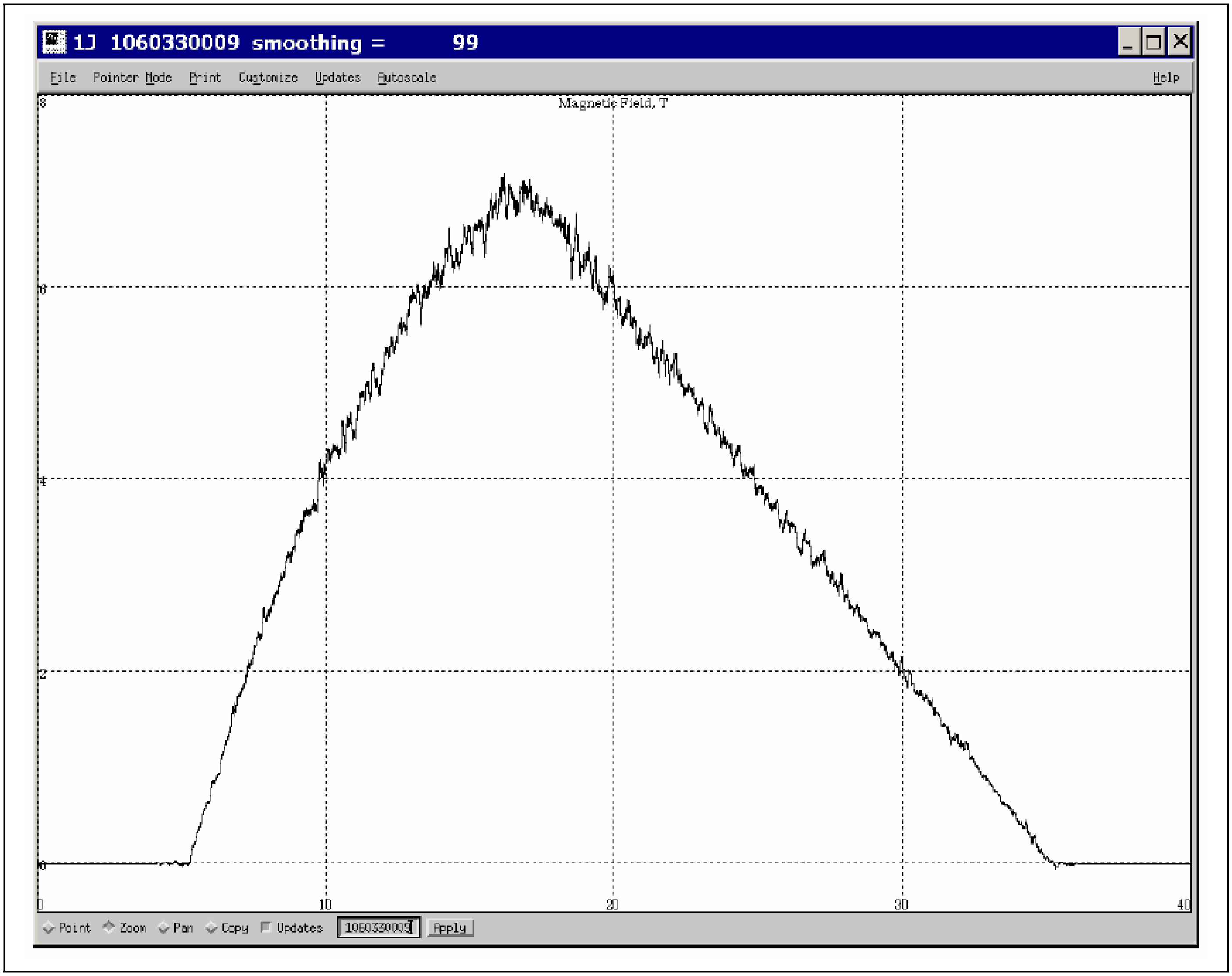
Help
Shunt current [A]
4000
3000
2000
1000
0
0
10
20
30
40
Point Zoom Pan Copy Updates
1060330009
Apply



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File
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Print
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Updates
Autoscale
Help
Magnetic Field, T
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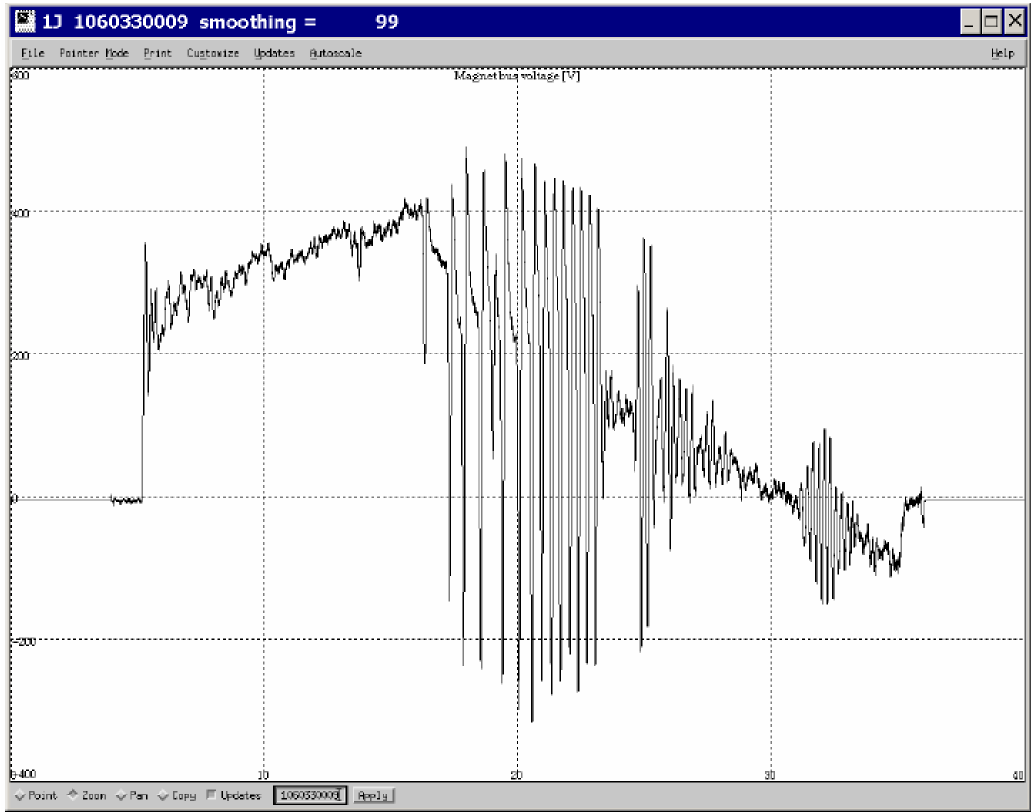
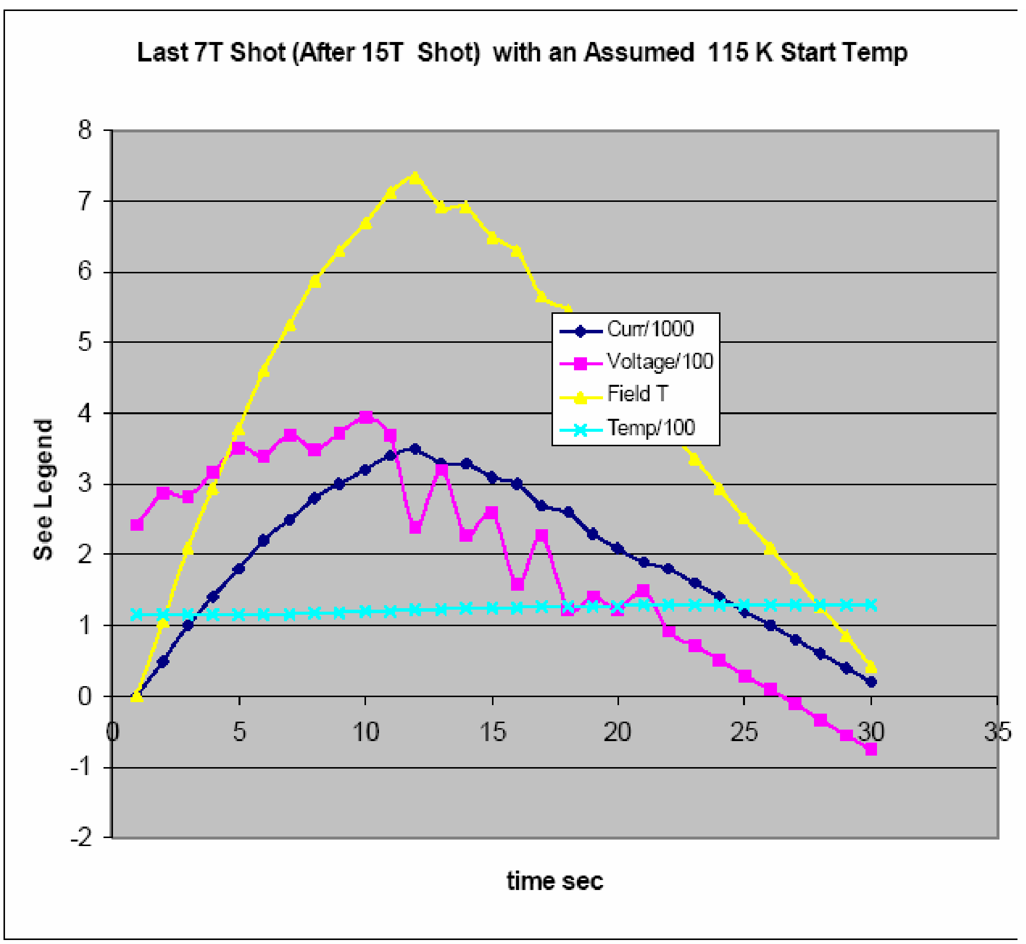


Voltage Trace for the Last 7T shot.



Simulation provides a good match with measured voltage. End temperature is 128 K

For an initial temp of 80 K the final coil temp should be _____ degrees higher than initial temp in all three coils. Fill in data sheet(later) Temperatures in each of the three segments

will be different by a bit more than the start temperature differences, and possibly by the magneto-resistive effects..

Visually inspect for leaks around the cover gasket ,bellows and magnet lead gland seals.

Final Room Temperature Electrical Tests

The CERNOX temperature plots did not start at room temp. These plots were done in the middle of a cooldown. The ends of the CERNOX and resistance plots are assumed to be at 77K because they "bottomed-out". I plan on measuring the resistance at RT with a multimeter, but the magnet is still probably colder than RT now. I have attached a plot which expands the low end of the calculated range. It is still higher than measured. - .025 vs. .02 for the third segment. Remember that there is a factor of 7 change in resistance between RT and 77K so even a 25% error in measuring the resistance still allows it to be used as a reliable indication that you are at 80K. We are using the small power supply in current controlled mode - but reading current off the current shunt, and reading segment voltage directly from the terminals. I need to discuss the data with Chen-Yu. While we were running the data acquisition system the LED display of the currents varied.

We have some other measurements of resistance at RT, but they were based on measured voltage/current from the small power supply and weren't absolutely reliable. I was using them as a rough in indication of cooldown progress, and an indication of when the segments were in thermal equilibrium. The ratio's of the coil resistances will be the same throughout the temperature range if the three segments are at the same temperature. I will check both calculated and measured resistances. I am going to measure the resistance with the multimeter after the long weekend. I want to make sure it is back to RT.

Bore Heater Performance

Throughout the series of tests, the dished head end of the bore accumulated ice. A small 150 W heater is used at the terminal end. It is running at about 40% power set on the Variac that powers it. It covers around 75% of the circumference, and warms about 25% of the length of the bore. It actually covers only about 4 inches of the length that it is heating. It is a silicon type heater. Another in the middle and another at the dished head end should solve the problem. With three separate ones, you can control the temperature distribution.

All the frost was gone by April 13th 2006.

Condition of the Dished Head end Bore April 4 2006. There is a substantial ice build-up. This accumulated over the couple of weeks that the magnet was cold.

Condition of the Bore April 4 2006 There is no ice at this end. The white "stuff" is the "Great Stuff spray foam used to insulate the inner bolt circle.

Correspondence on The CERNOX Calibration

To: Peter Titus
Date: April 6, 2006
From: Chen-yu Gung
RE: Cernox response after high field tests of MERIT magnet in week of 3/26/2006

Sensor #	Cernox serial no.	Resistance [Ohm], calibration at 298K	Resistance [Ohm], measured on 4/6/06	Est. temperature [K], 4/6/2006
T1	X34219	147	237.4	281
T2	X34220	142	0	-
T3	X34221	143	238.6	279
T4	X34222	147	0	-
T5	X34223	137	219.6	280
T6	X34224	145	233.7	281
T7	X34225	139	217.1	282
T8	X34226	146	220.2	285

We have found the problem. -Peter

-----Original Message-----
From: Chen-yu Gung [mailto:gung@psfc.mit.edu]
Sent: Thursday, June 08, 2006 5:21 PM
To: Peter Titus
Subject: MERIT magnet temperatures, revision 1

Peter,

Congratulations. You are right. The updated cernox temperature conversion shows that T3 ~ 116 K and T5 ~ 113 K right after 15 T shot.

I discussed with Phil the issue of temperature in MERIT magnet, and I found that I mistakenly used linear interpolation to convert cernox resistance into temperature between 77K and 300 K. The linear correlation should be used in log-log scale. I have updated all the measured temperature data. Please discard all my previous excel files. I apologize for my mistake and the confusions.

For lack of calibration data of each cernox at intermediate T vs R, the updated temperatures should only be considered as first order estimations.

March 30th email:

Peter,

Attached is a collection of scopes traces from today's magnet pulses. I am not sure how broadly you should distribute the full data sets. Main results look much better than suggested by the full data set.

The first three runs were performed with a fixed "alpha" command provided to the master and varying the enable command to all convertors. This is not a very favorable way to operate.

The tuning for the regulator occurred for runs 4~6
Run 7 was our failed attempt to reach 13T
During run 8 we achieved 15T
Run 9 was a check of magnet at 7T.

The outputs from individual power supplies (especially convertor 6) appear questionable. The sum of convertor output signals approximately matches the signal from the bus current shunt, but not always.

Both the power sharing and oscillation seem slightly better than yesterday, but neither is all that good. Most likely some additional work would be needed on the convertors before the "production runs" begin during late summer, with the mercury jet installed in the bore of the magnet.

Please let me know your comments or suggestions.

- Phil

Final Electrical Tests April 12 2006

A 1kV Meggar test was performed on each of the three coil segments, and they passed.

Appendix A

Weekend Warm-up Simulation

```
!   Heat Leak Calculation Based on March 24th-March 27 heat-up


let nomHeatLeak=220   ! Watts an 22 K  Calculated
let nomHeatLeak=400   ! Guess
let NomHeatLeak=NomHeatLeak*(292-80)/(292-22)   !Watts adjusted for LN2
data 1 , .25 ,0, .3, 1.00 ,15,15
read pfn,r,z,dr,dz,nx,ny
let r1=r-dr/2
let r2=r+dr/2
let packfract=.85
let deltat=60*60
let coilvol=pi*(r2^2-r1^2)*dz*packfract
let tottime=((3*24-7)*60-45)*60   !5:30 Fri to 10:00am Monday
let InitHeatLeak=NomHeatLeak/(292-80)     ! watt/deg. K heat leak
let inittemp=135
let temp=inittemp
print "Nominal Heal Leak Based on Calculations:"; NomHeatLeak;"watts"
print "Initial Temperature=";inttemp;" K"
print "Total time=";tottime;" sec";tottime/3600;" Hrs"
print "Coil Volume=";coilvol;" m^3"
get key kinp
!set window 0,70,100,300
for ti=0 to tottime step deltat
let heatleak=initheatleak*(292-temp)
call copprop(temp,rho,cp)
let temp=temp+heatleak*deltat/coilvol/cp
!plot ti/3600,temp;
print ti/3600;",";temp
next ti
stop
end
sub copprop(temp,rho,cp)
if temp<80 then let rho=.218e-8
if temp>=80 then let rho=.218e-8+(.572e-8-.218e-8)/50*(temp-80)
if temp>=130 then let rho=.572e-8+(.925e-8-.572e-8)/50*(temp-130)
if temp>=180 then let rho=.925e-8+(1.703e-8-.925e-8)/110*(temp-180)
if temp>=290 then let rho=1.703e-8+(2.480e-8-1.703e-8)/110*(temp-290)
if temp<=80 then let cp=205
if temp>=80 then let cp=205+(301-205)/50*(temp-80)
if temp>=130 then let cp=301+(346-301)/50*(temp-130)
if temp>=180 then let cp=346+(384-346)/110*(temp-180)
if temp>=290 then let cp=384+(396-384)/110*(temp-290)
let cp=cp*8950   !  Conversion from cm to m
!!   ANSYS uses a specific heat based on mass at 130 deg K and bsed on
!!   meters c is input as 310. Multiply this by a mass density of
!!   8950 and divide by 1e9 = 2.77e-3. The above relation yields
2.677e-3
!     UNITS of CP ARE JOULE/(CM^3-DEG K) , ONE JOULE = ONE WATT-SEC
!
let tc=temp
!From Bob Weggel for Tc=20 to 100 K:  The electrical
!resistivity (for copper with a residual resistivity of 0.05
```

```
!microhm-centimeters, a residual resistivity ratio of only about 34), 
the fit
!is (0.0498 - 0.1075 T^2 - 0.5670 T^3 + 2.5157 T^4) / (1 + 0.5706 T^2 +
!3.7308 T^3).
If tc<100 then
let rho= (0.0498-0.1075*(Tc/100)^2-
0.5670*(tc/100)^3+2.5157*(tc/100)^4)/(1+0.5706*(tc/100)^2+3.7308*(tc/10
0)^3)
let rho=rho/1e8  !convert from microhm-cm to ohm-m
let cp=(0.4353-0.2763*(tc/100)+21.0459*(tc/100)^2)*(tc/100)^2/(1-
2.6997*(tc/100)+7.4479*(tc/100)^2-2.5654*(tc/100)^3+6.5265*(tc/100)^4)
let cp=cp*1e6   ! convert from J/cm^3K to J/m^3K
end if
end sub
```