MICE Coupling Coil Tests and Results at Fermilab

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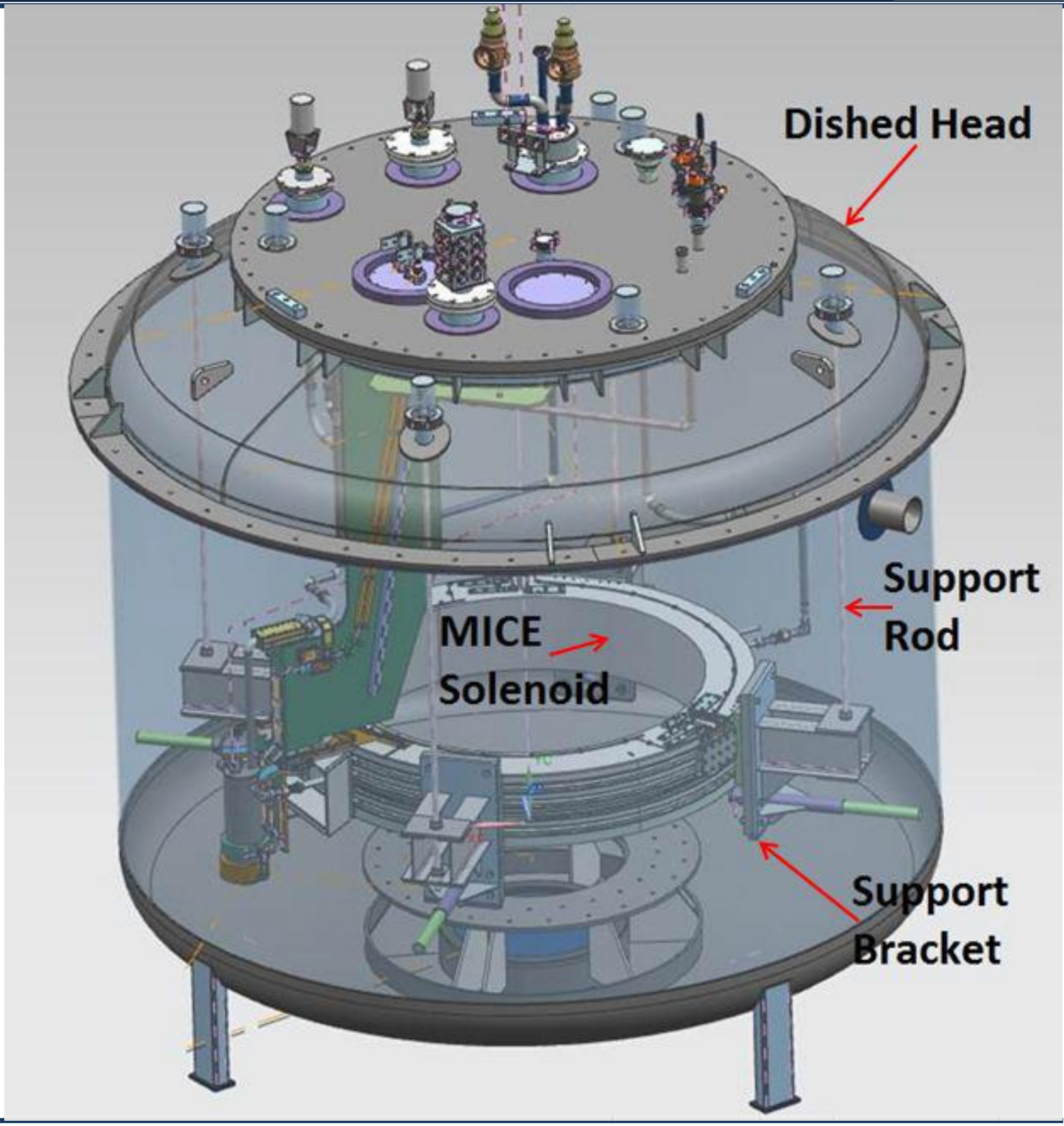
TD Test & Instrumentation Department
Fermilab Accerator Division Cryo Group
LBNL Magnet Division
And much support from many many contributors

MAP Collaboration Meeting
May 30, 2014

Overview

- This has been a very intense, consuming, high priority ~3-year collaborative effort between numerous laboratories, divisions, and experiments
- It has resulted in a successful test of the 1st MICE CC magnet, although the outcome did not completely achieve the desired goal (I_{max} x time)



Solenoid Test Facility (STF)

Fermilab recognized the need for a large solenoid magnet test capability: MICE and Mu2e

- Obtained a large SMES cryostat from the NHMFL/FSU (October 2011)
- Test Stand designed/built to test MICE Coupling Coil Magnet windings (total of 4)
- Evaluated several Fermilab locations for this facility (IB1, CDF, CHL). Recommended CHL
- Plan approved by Directorate in January 2012
  - An enormous amount of work took place to quickly build this facility, get it ready and reviewed for safe operation
- Obtained ORC April 17, 2013
  - Test of first MICE CC cold mass started in May 2013

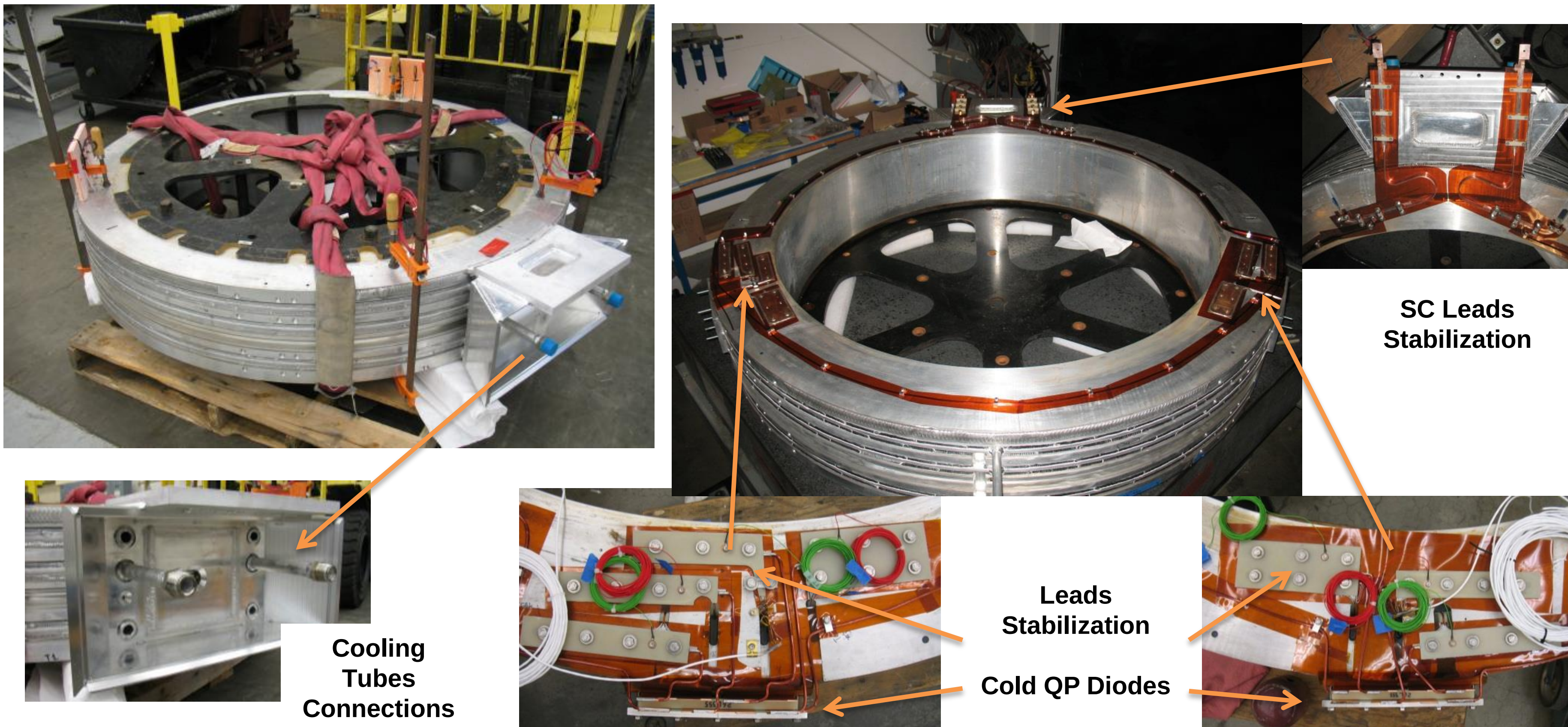
Operational Readiness

Operational Readiness Clearance (ORC) granted April 17, 2013

Fermilab

Cold Mass Preparations (LBNL)

- Included cooling tubes welding, installation of leads stabilization, passive QP (cold diodes), instrumentation, etc.
- Preparations took ~ 1 year ! (in parallel with test stand construction)

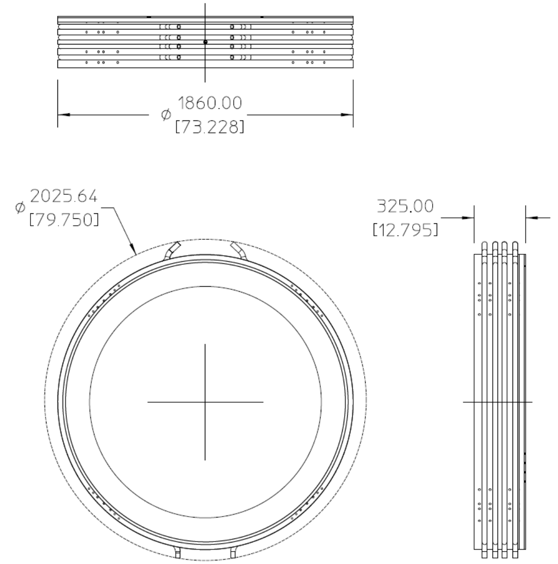


First MICE CC Arrived at Fermilab

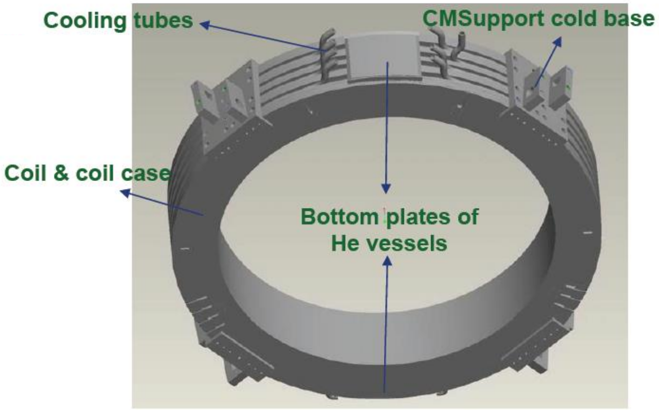
- First Coupling Coil arrived at Fermilab on January 31, 2013
- Coil passed hipot, leak check, and instrumentation check
- (hipot Voltage limited to 250 V at 300 K)

MICE Coupling Coil Parameters

Parameter	Value
Coil Length (mm)	285
Coil Inner Radius (mm)	750
Coil Thickness (mm)	102.5
Number of Layers	96
No. Turns per Layer	166
Assembly O.D. (without cooling tubes, mm)	1860.00
Assembly O.D. Envelope (with cooling tubes protrusion, mm)	2025.64
Assembly Height (mm)	325
Assembly Weight (tons)	2.2
Operating Current (A)	210
Maximum Test Current (A)	220
Self-Inductance (H)	596
Stored Energy at 210 A (MJ)	13
Stored Energy at 220 A (MJ)	14.4
Coil Temperature Margin (K)	0.77



- Magnetic Field at 210 A
  - Peak field in the coil: 7.5T
  - At center of coil: 2.6T
  - 600 G line radius: 9.8 ft
  - 100 G line radius: 16.4 ft
  - 5 G line raduius: 50 ft



Coil Construction

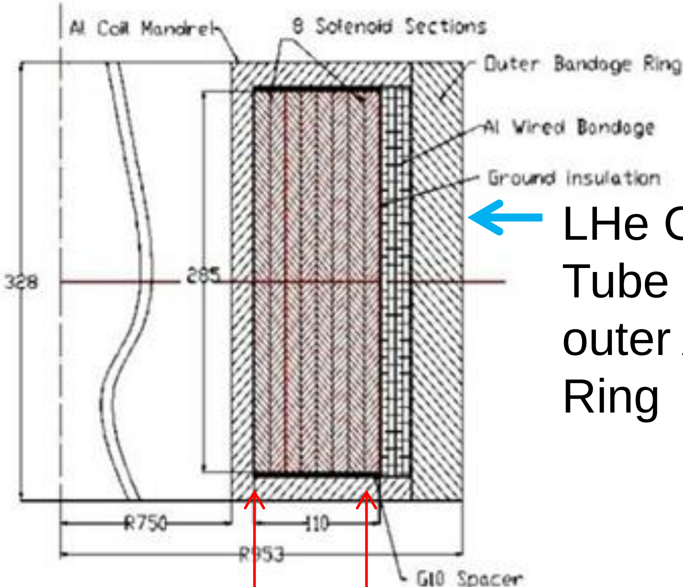


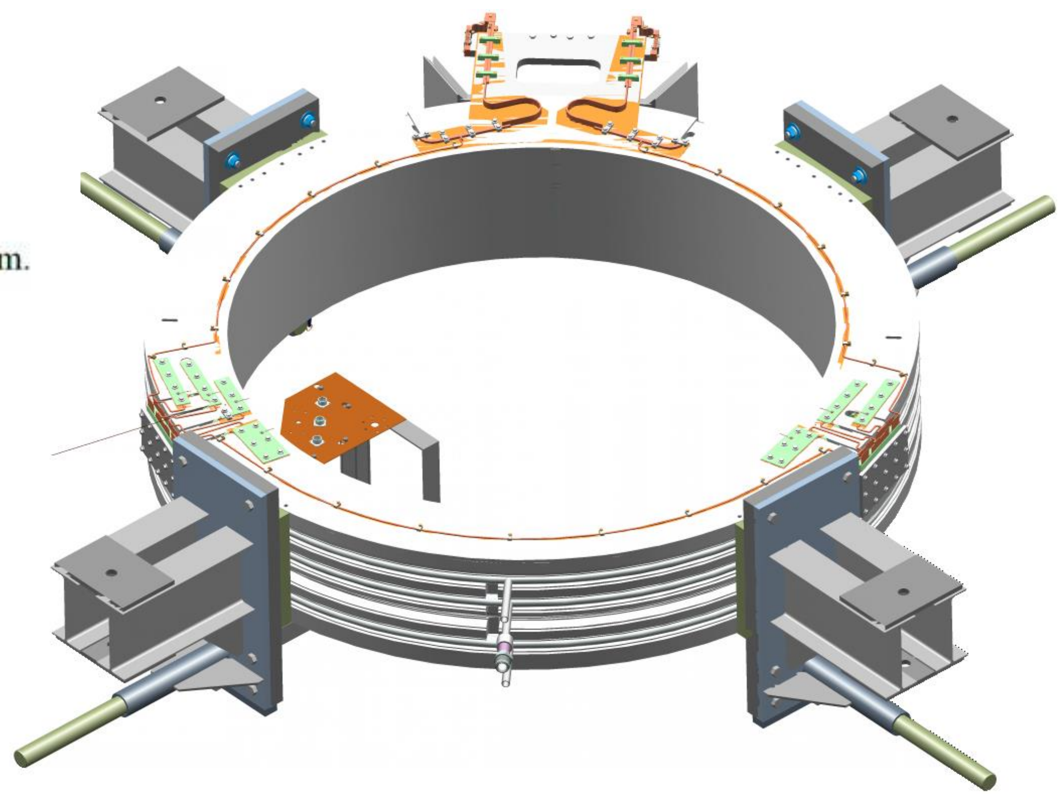
Fig. 1. Solenoid cross-section. All dimensions are in mm.

LHe Cooling Tube welded to outer Aluminum Ring

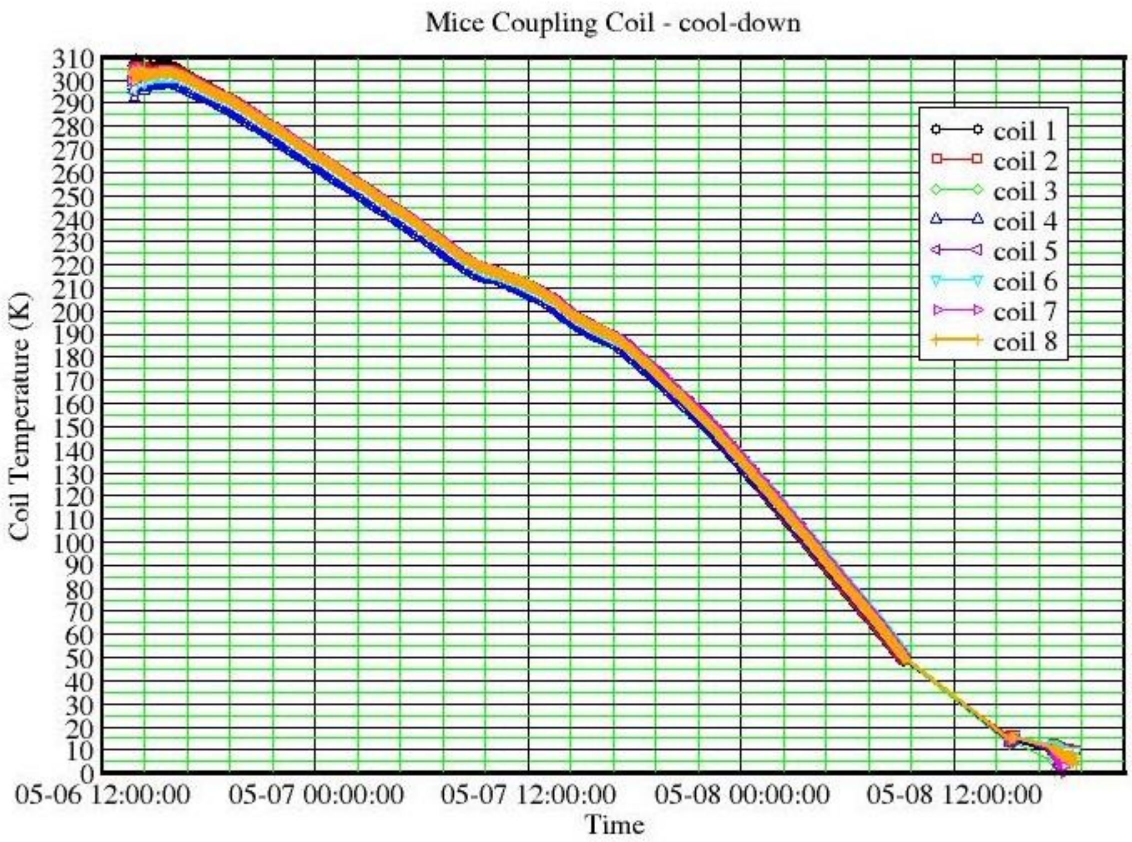
Coil 1 Coil 8

Voltage Taps, protection diodes across each coil (diodes in both polarities)

12 layers per coil, stycast "wet layup"
Cu/Nb-Ti Single Strand (L=600 H)
Slip planes to reduce shear stress (?)
There is no MICE Note or Publication on the actual coil fabrication
(There are for prototype test coils)



First Controlled Cooldown



- Started Monday 5/6/13 at noon
- Automatic cooldown with < 50 K Delta T proceeded very well
- Coil < 10 K by Wednesday 5/8/13 afternoon
- Helium to vacuum leak resulted in T limit to 9 K

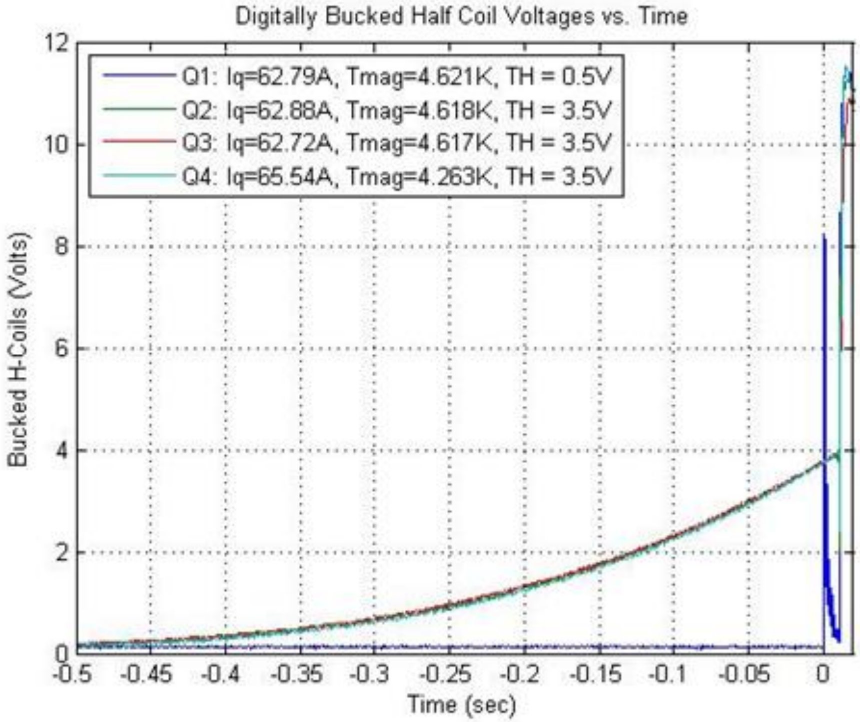
4-5 day cool down from 300 K to stable "4K" conditions has been typical for 5 Thermal cycles; warm up is also 3-4 days.

Solenoid Test Facility (STF)

- 1^{st} TC in May 2013
  - reached 9K; He→vac leak
- Summer 2013:
  - re-design/make up (flexible) He connections
  - qualify stand cryogenics (zero magnet) - no leaks!
  - shorted bus & power supply endurance test to 220 A
  - lead thermal intercept improvements
  - Better vacuum gauges, He valve control
  - Increased cold surface area for cryo-pumping
- 2^{nd} TC September 2013
  - Cool down 9/09 to 9/13; Rate-of-T-rise Heat Load
    Calc: ~10 W Measurement: ~70 W
  - Power testing and quench training started, thru 9/27

Quench Performance

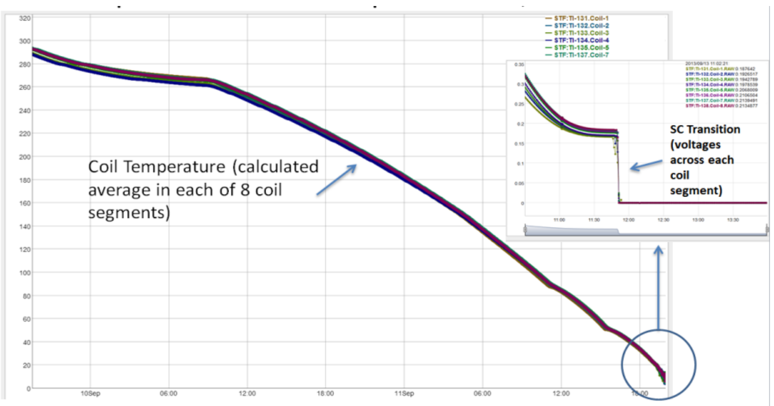
- Coil kept quenching at ~62A
  - Thermal Limit?
- Decision was to warm up and identify source of heat load



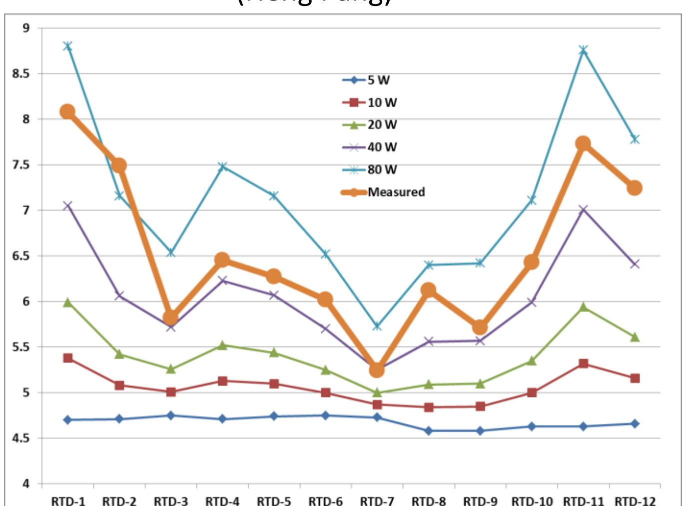
- Problem: MLI Installation
  - Inadequate venting provisions
  - Thermal shorts
  - Too tight
  - Missing MLI on support rods

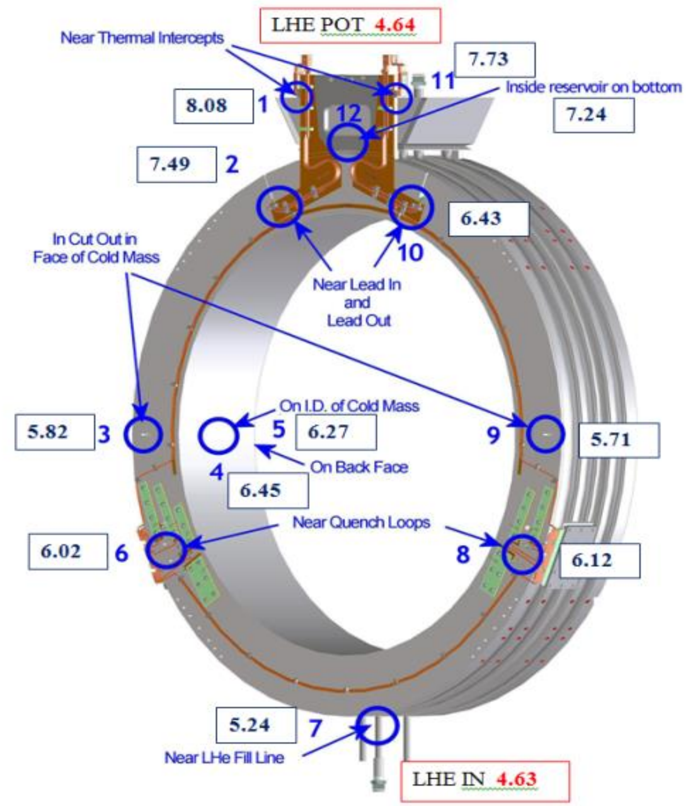
Second Cooldown

- Cold Mass surface temperatures reached equilibrium at temperatures higher than expected (5.2K-7.5K)



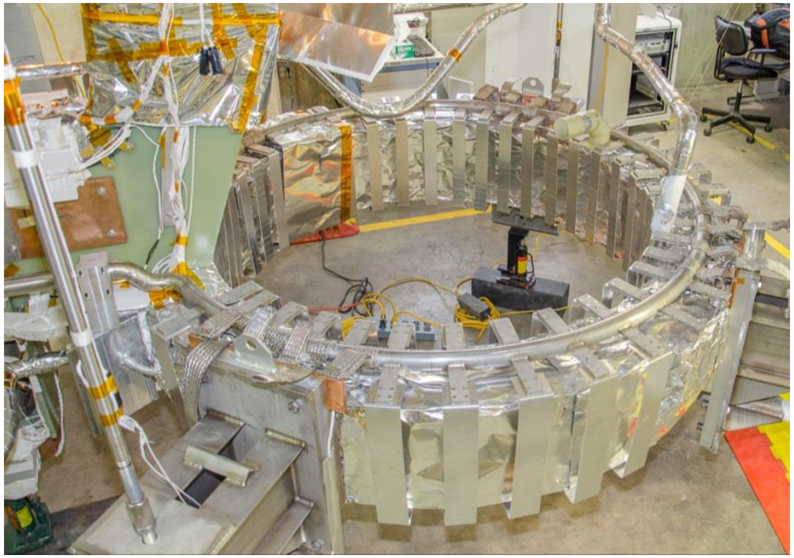
LBNL Thermal Model
(Heng Pang)

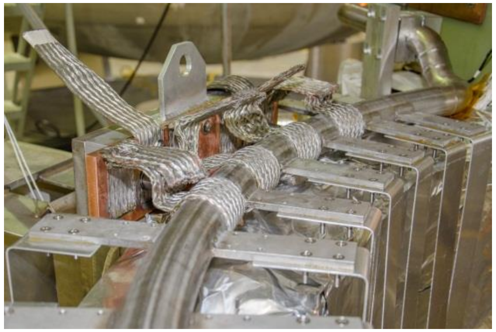


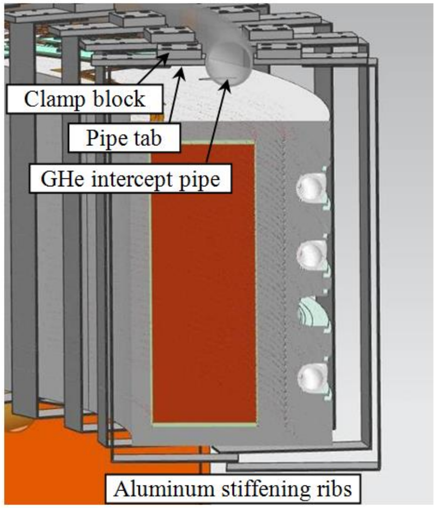


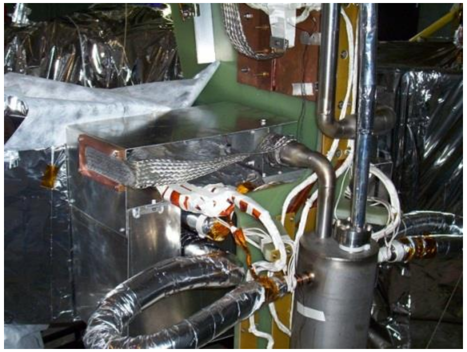
- Required Heat Load for Tcoil < 5.4K: < 15W
- Estimated Heat Load ~ 10W
- Measured Heat Load ~ 70-75W

Improvements









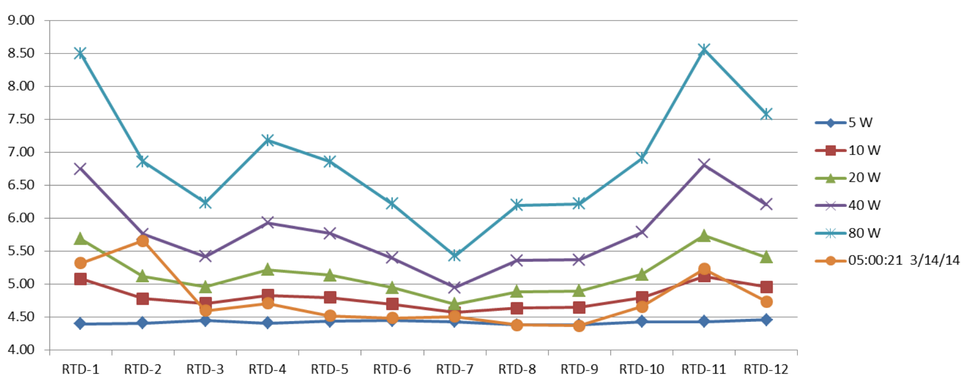
- Added Thermal Shield around cold mass, support brackets, and magnet reservoir
- Added thermal intercepts for mechanical supports
- Installed RGA, moved 400 l/s turbopump closer to cryostat
- Added thermometry
- Obtained technical support and blankets from Meyer Tool for MLI wrapping
- Calculated Heat Load with improvements: 2.8 W
  - http://tiweb.fnal.gov/website/controller/2637

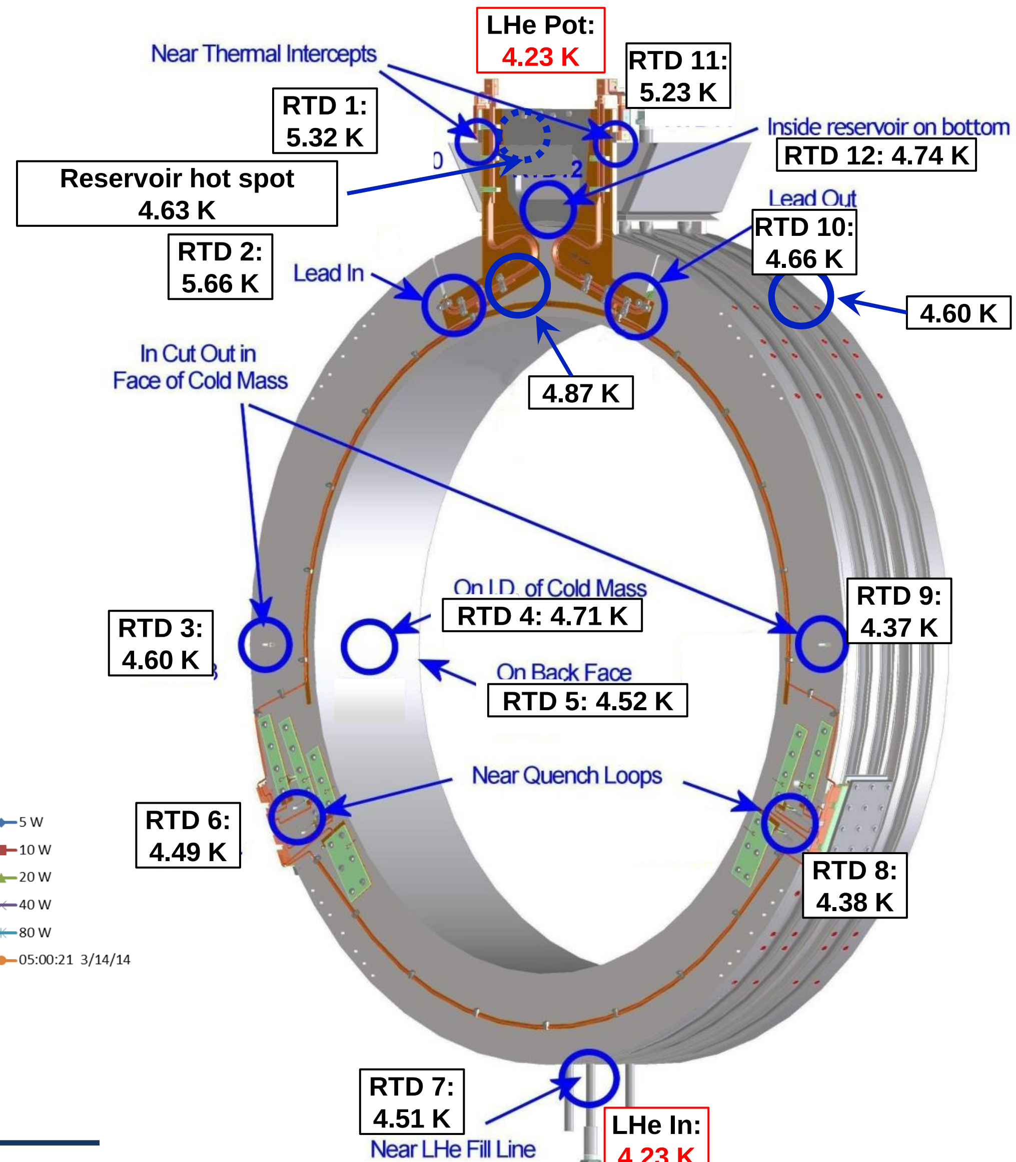
MLI Installation

- 40 layers of MLI in 5-layer blankets with aluminum tape
- Loosely wrapped
- 2” long slits every 6” for venting provisions
- Vent pipe

Third Cooldown

- Third cooldwon started February 18, 2014
- Cold Mass Temperatures reached equilibrium at ~ 4.4K-5.7K
- Measured shield T lower than predicted
  - Cold mass shield T < 10K
  - Support brackets shield T < 20K
  - MLI surface T 240-250K
- Insulating vacuum level is 4 x 10^{-6} Torr.
- T measurements comparison with model suggest a heat load of ~ 5 W
  - Measured (rate of rise) at 2 W !
- First coil quench at 127.7 A on 2/25/14
- T at neg lead still 1K higher than hottest coil surface temperature

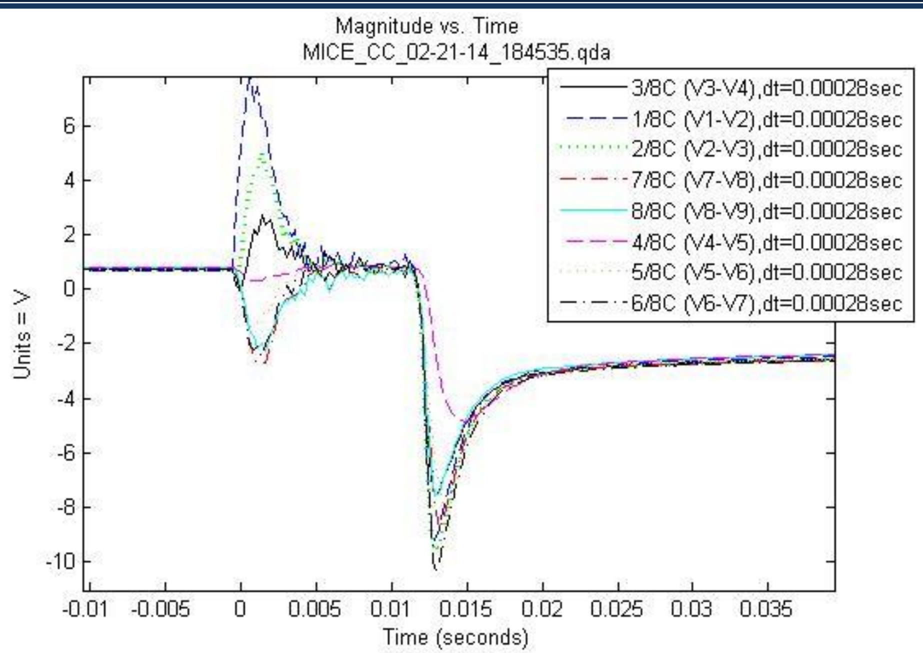




Quench Training

- Third cool down started 2/18/14
- TC3 Quench Training (21 Feb - 02 Apr 2014)
- Thermal Cycle (03 – 13 Apr)
- TC4 Quench Re-training (14 – 18 Apr)
  - test quench memory after a TC
- Thermal cycle (20 Apr – 06 May)
  - CHL compressor failure and repairs
- TC5 Quench Re-training (07 – 16 May)
  - test re-training after a 2nd TC
  - test in reverse polarity (diodes) and “soak test”

TC3 Q1 Iq=123.2A



Voltage Spike disturbance profiles are seen in most events at low current; simlar, only the amplitude changes.
Visible on QD monitor even after training

Diodes turn on in the range of 5 to 15 V

First "triggered" event is at about twice the current previously reached in Sept. 2013 (64A). The very first event seen in Sept. at 62A was a similar voltage spike.

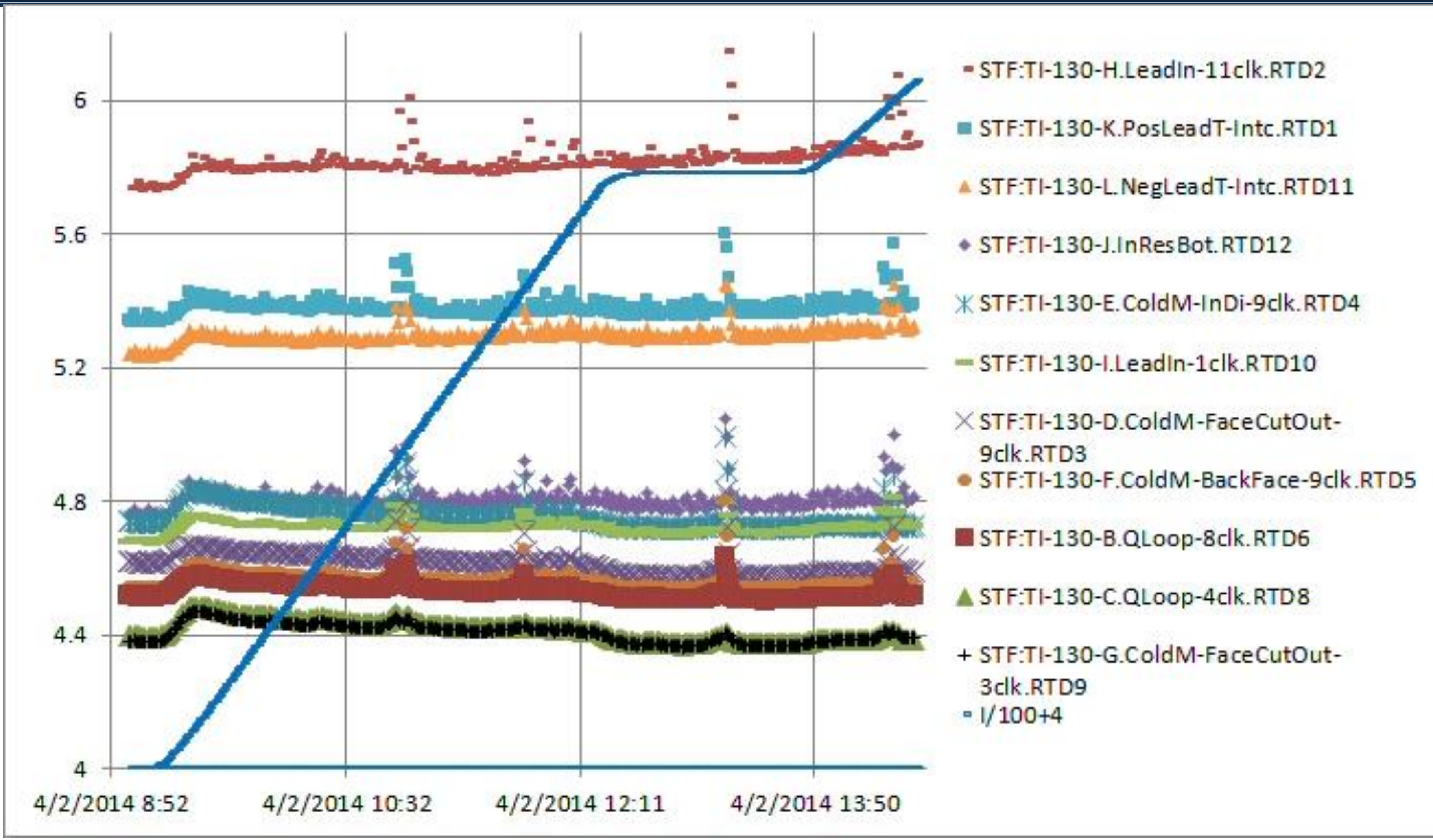
Quench Detection:
"Half coil difference" >3.0 V
Open PS contactors, forces current discharge through
2 Ohm dump resistor across coil
Large reverse voltage, forces all protection diodes to conduct (across each coil segment)

Initial dI/dt=0.6A/min
(>3 hour ramp to 120A)
(PS voltage limit, large L)

More Improvements

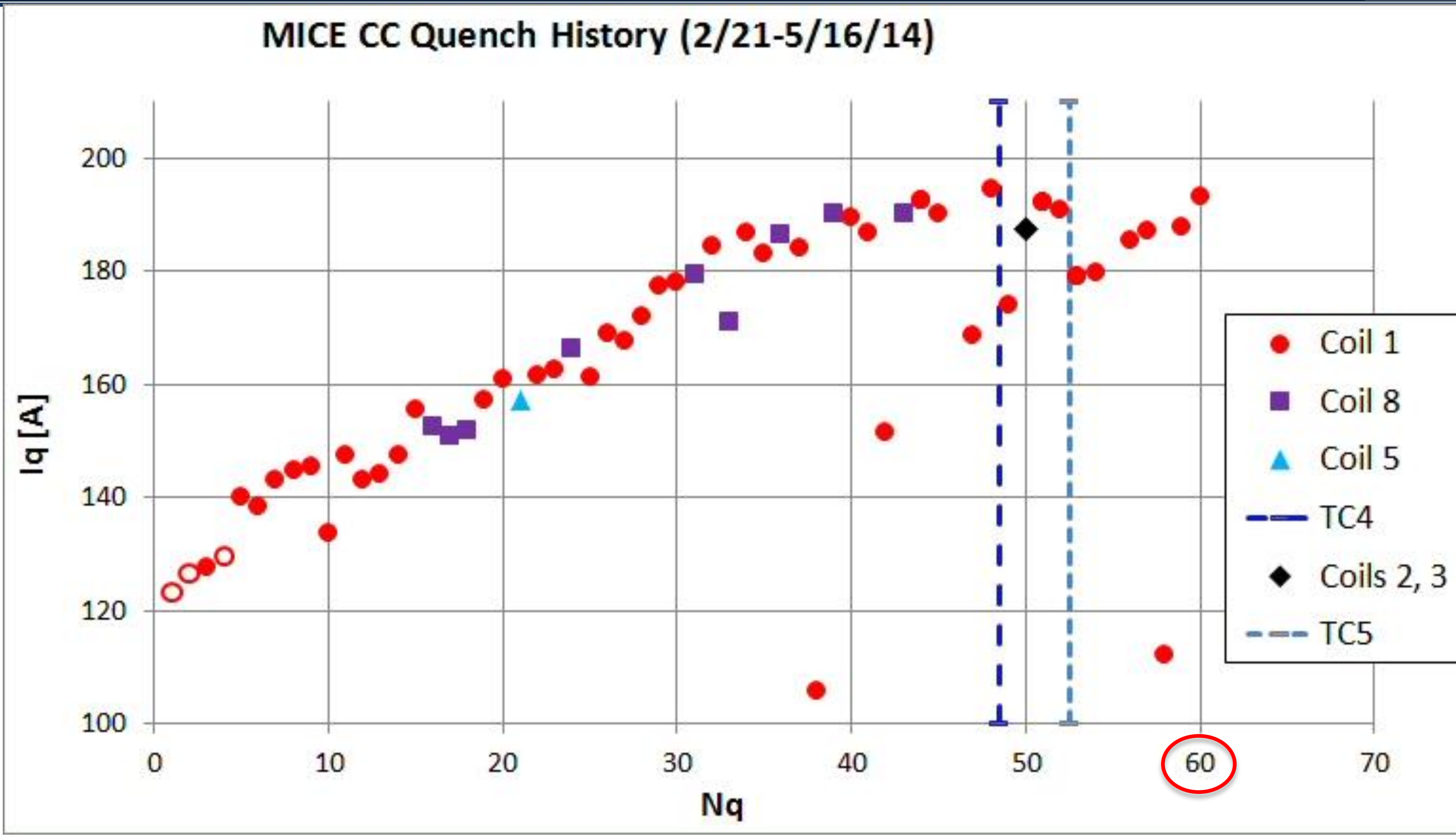
- To prevent nuisance trips due to conductor-motion voltage spikes (not necessarily quench)
  - Raise Half-coil QD threshold to 4.5 V
  - Introduce 15 ms validation delay above threshold
- Add a second power supply
  - Peak ramp rate 30 mA/second
  - (initial eddy current T-rise of ~100 mK)
- Recover and ramp again (2/day)
  - Slow training, long ramp time
  - Only at low Current: Recovery time grows with I^2
- Many attempts made to improve cryo stability
  - Several low current quenches caused by temperature excursions

"Typical" Ramp to Quench



Ramp 48, Iq=194.5A

Quench History



Slow but steady training (~1.5 A/quench), mostly “remembered” after each TC !

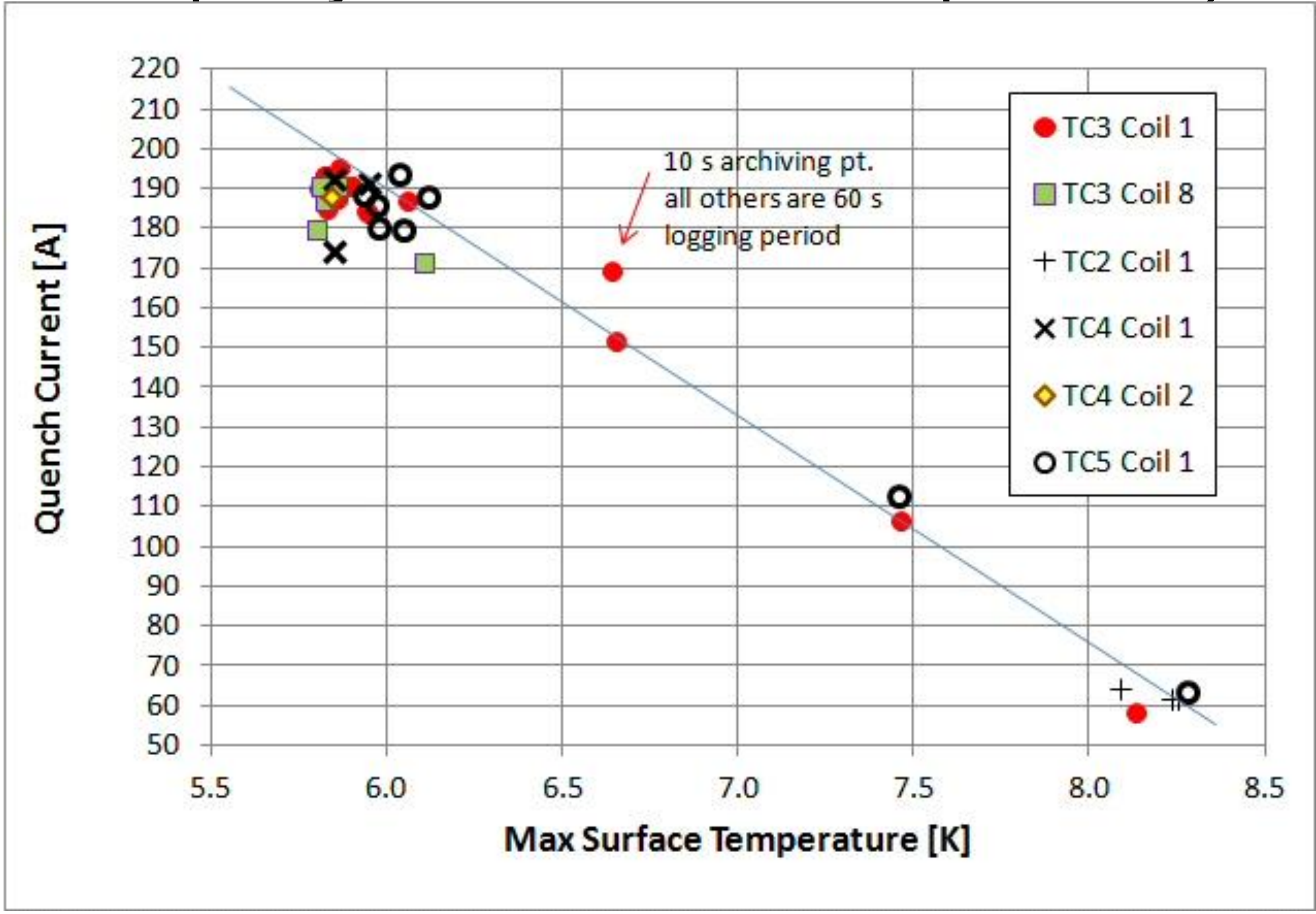
Critical Temperature

Quench Current vs Maximum Surface Temperature

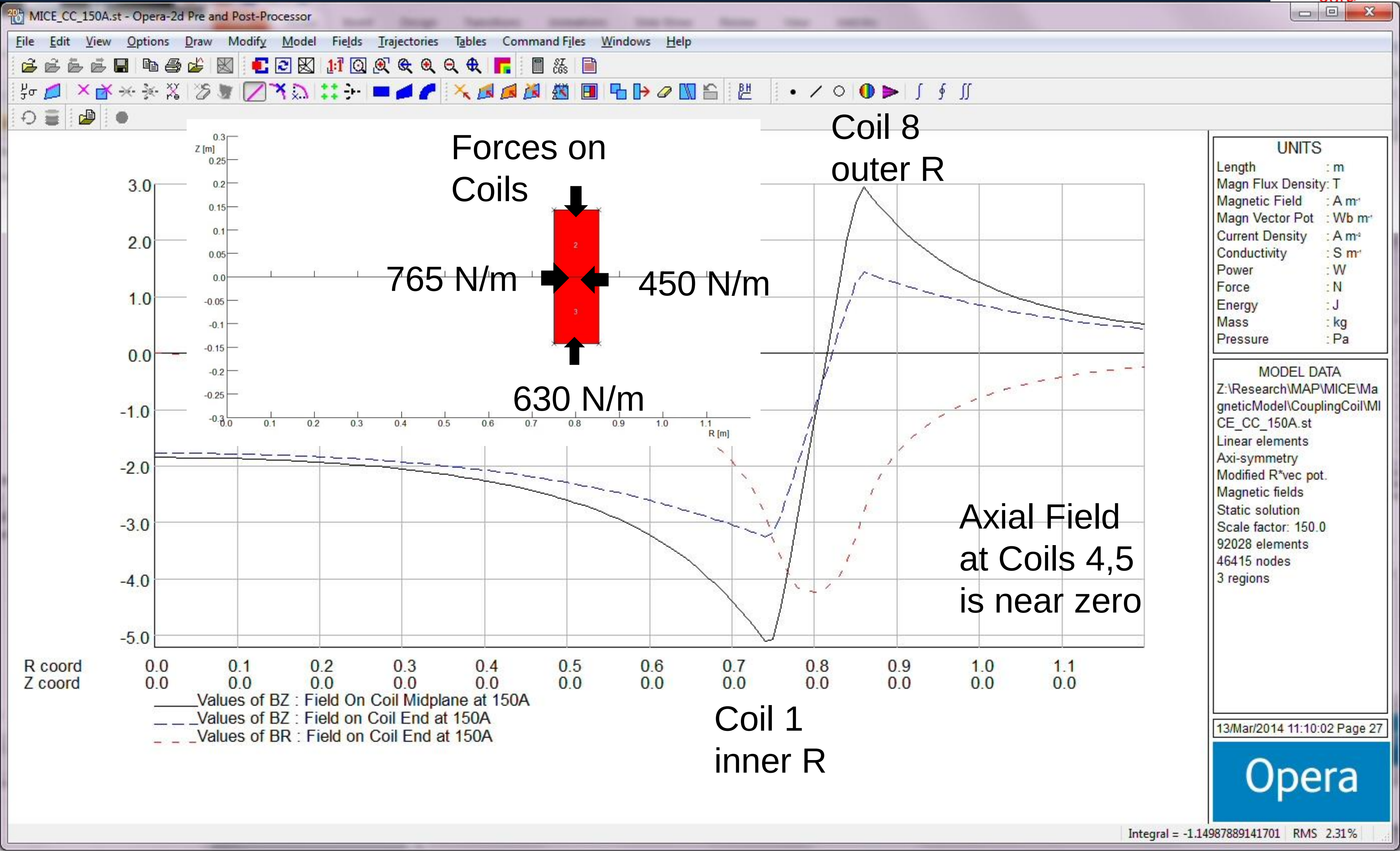
(at negative lead; proxy for actual coil temperature)

Ability to maintain steady temperature conditions (2 phase helium) limited ability to reach high currents and hold for long periods
Peak Iq=194.5A

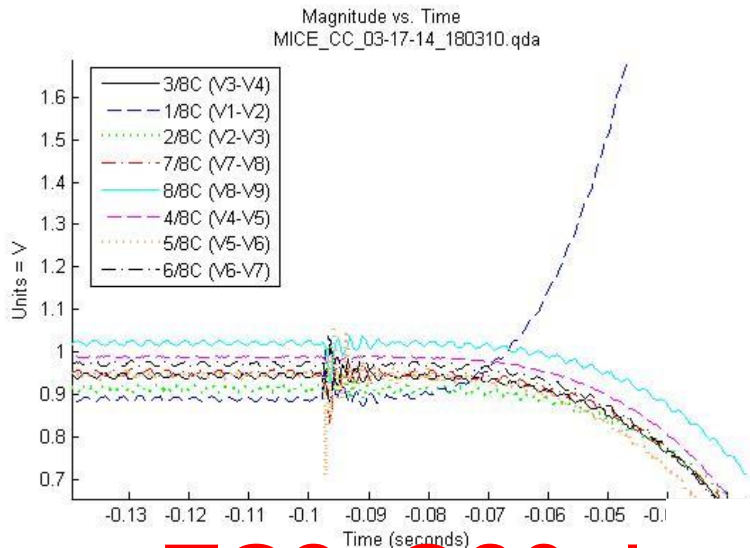
"soak test" performed for 2.5 hours at 175 A



150A Field Profile On Solenoid



Typical Coil 1 Quench



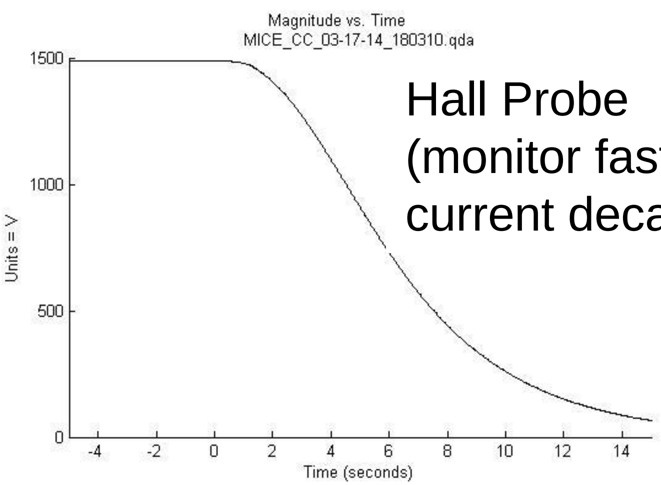
Quench Developments are all VERY SIMILAR

Variable delay between time of disturbance and start of quench propagation depends upon:

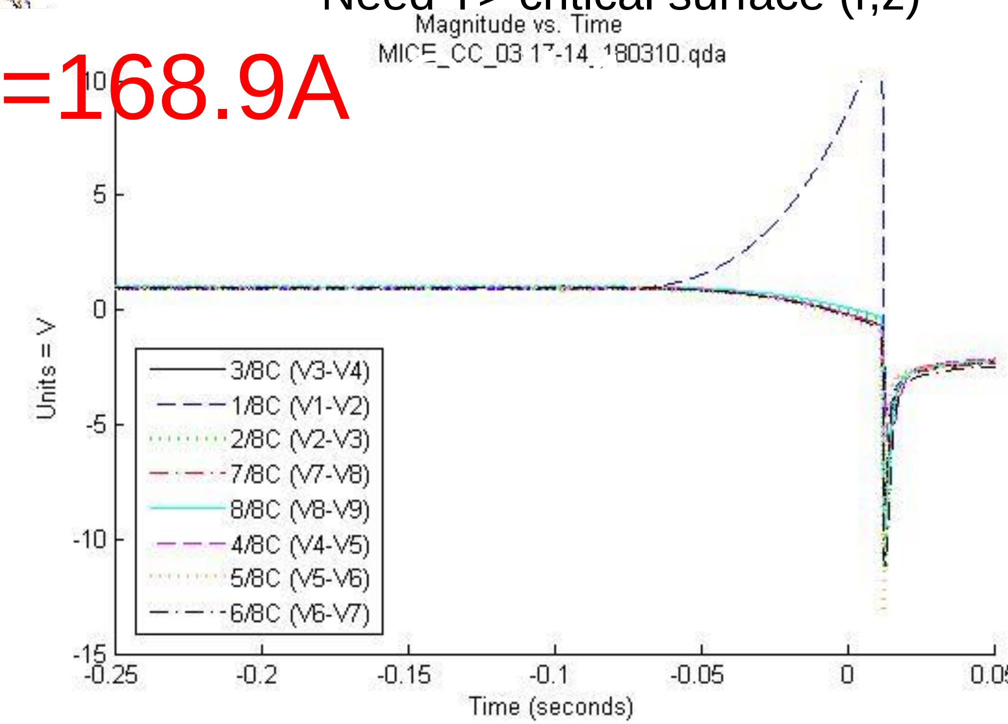
1) Energy deposited >MQE
2) Distance from high field region

Need T> critical surface (r,z)

TC3 Q26 Iq=168.9A

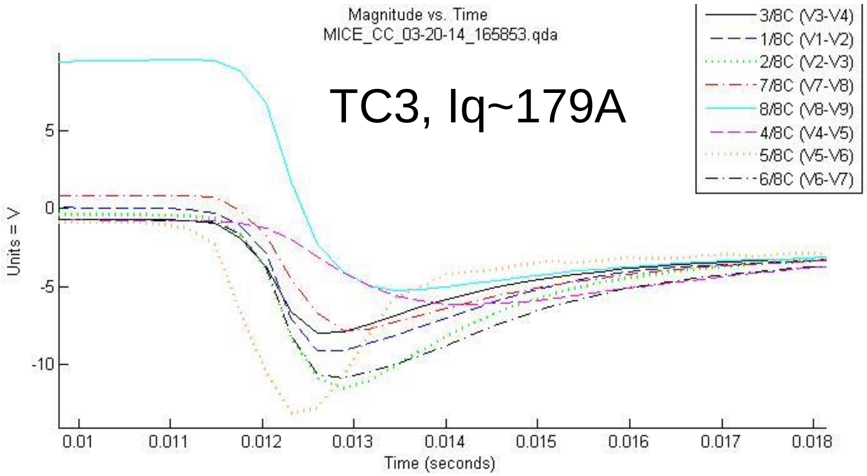


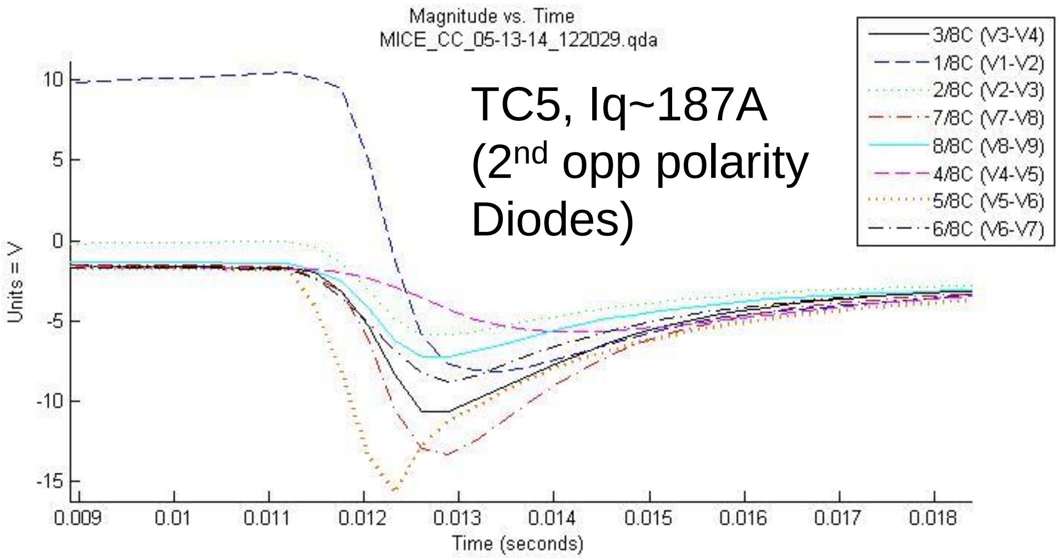
Hall Probe (monitor fast current decay)



Diode Performance

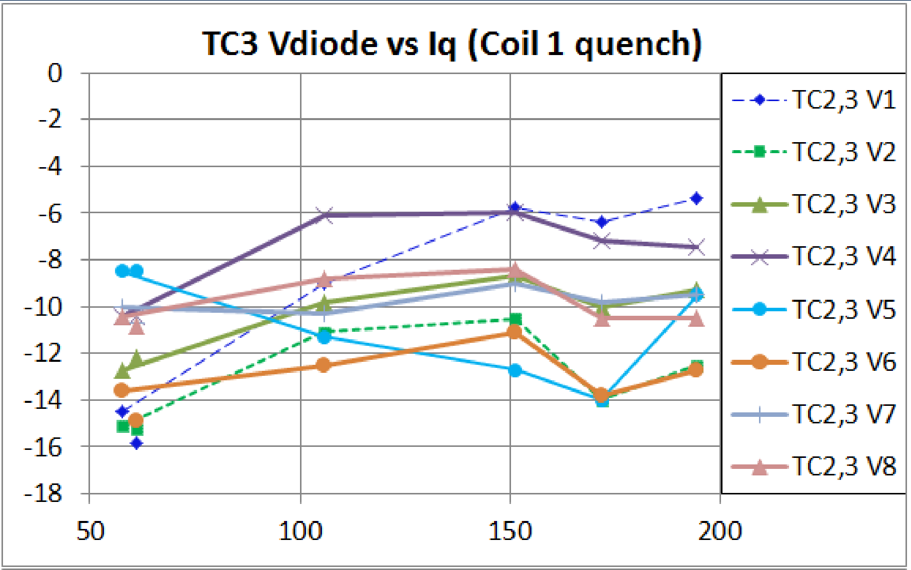
- Diode turn-on voltages

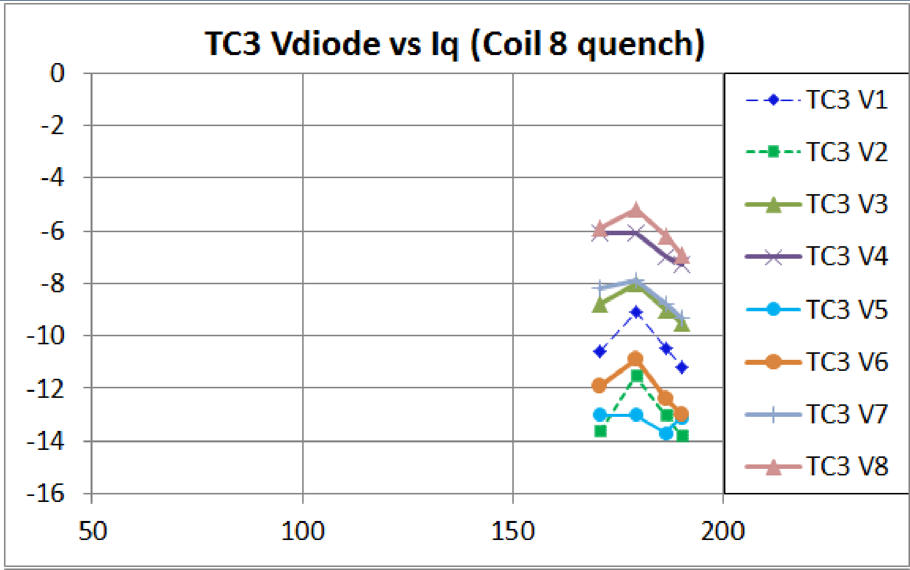


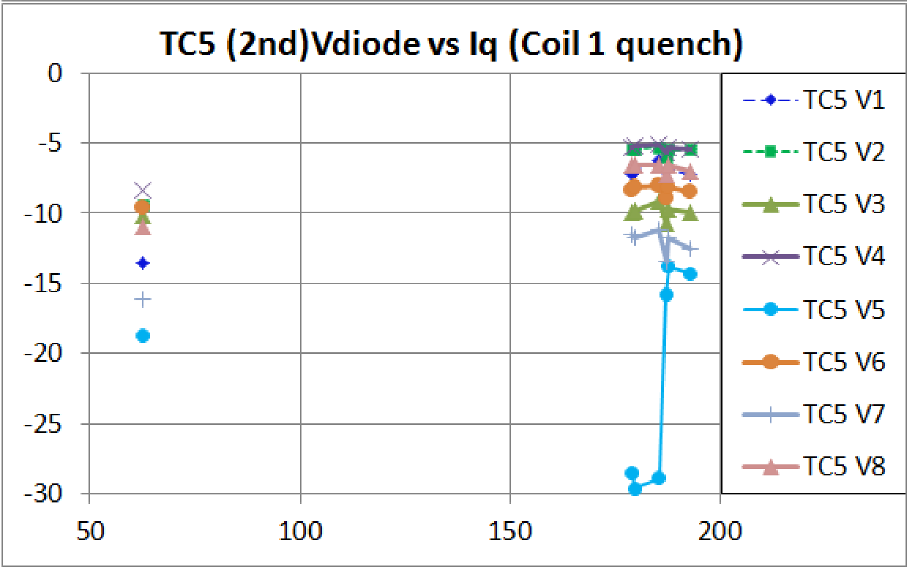


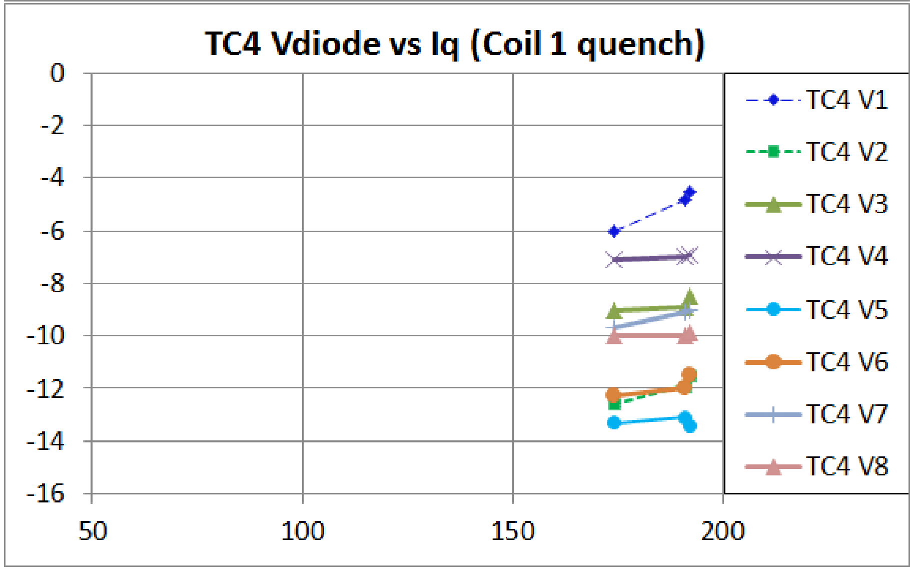
Lab tests (Barzi, Turrioni at FNAL) showed T, field-dependence (B⊥, B||), 4-25 volts growing with B⊥

Diode Performance





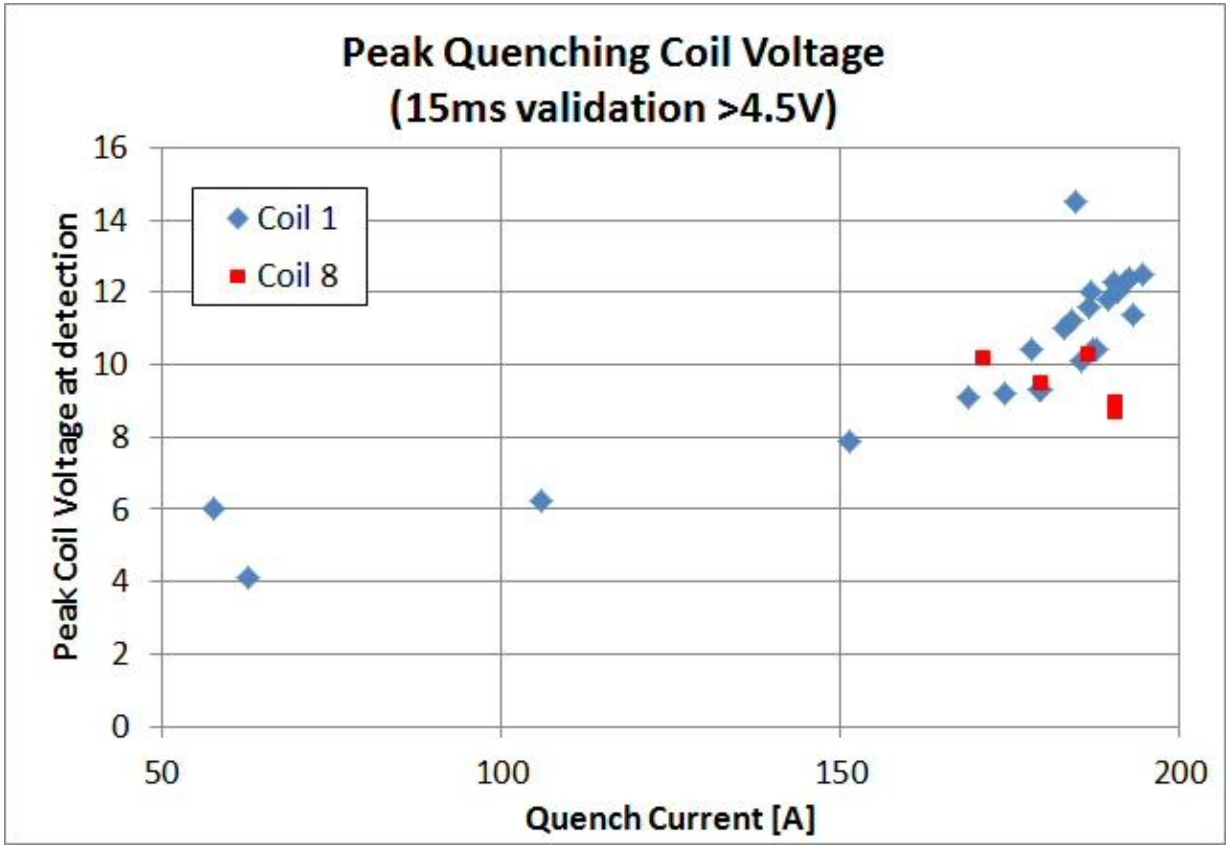




Diode Performance

- Turn-on Voltages ~5-15V, appear to decrease slightly with field (Coil1 ~ 5V)

We never saw diodes conduct due to coil resistive voltage ??



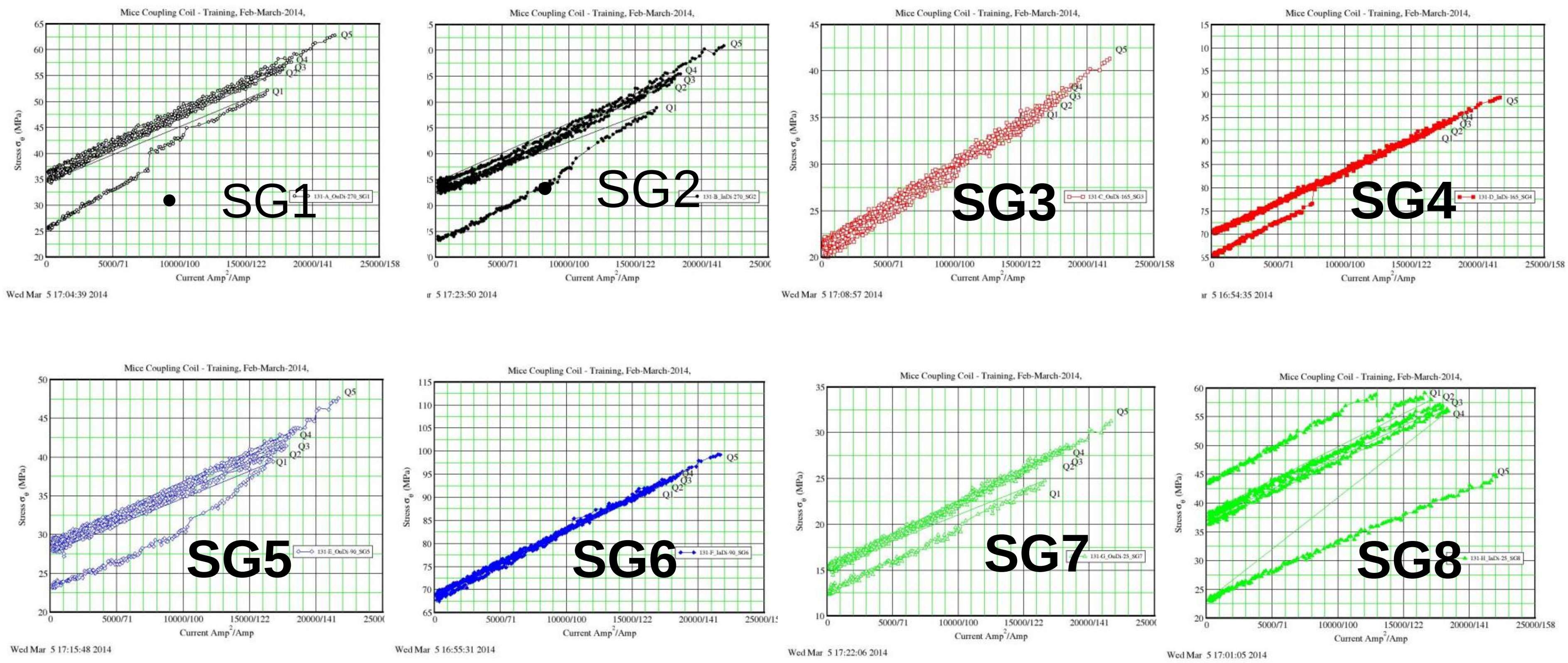
Conclusion

- Marathon Test of 1st MICE Coupling Coil is complete
  - The entire team is exhausted and relieved!
- Coil Reached 194.5 A (goal was 214A) with slow but steady training
  - mostly coil 1(highest field and forces) & 8
  - limited by temperature in negative lead region
  - Looking at the thermal intercepts, etc.
- Quench memory is very good after Thermal Cycles to room temperature
  - Iq >174A after each of 2 TCs
- 2.5 Hour “soak test” performed at 175 A
- Still much analysis to do – modeling of quench and peak coil temperature (MIITS)
  - Being done at LBNL

- BACKUP SLIDES

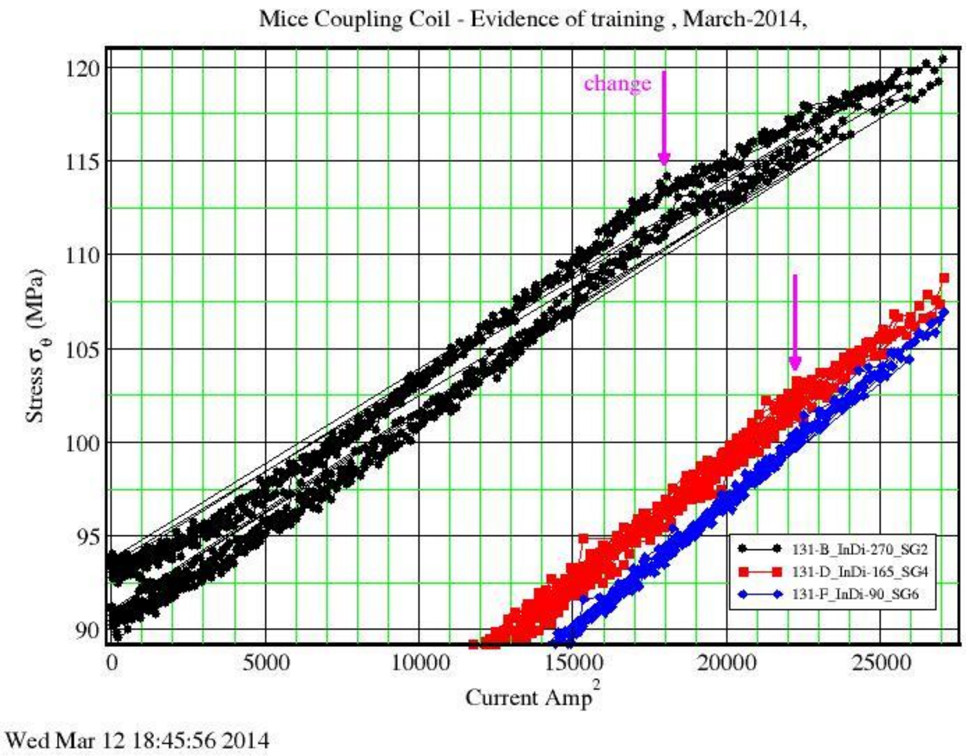
Strain Gauges

- “Ratcheting” stress redistribution during early ramps (1-5 shown)



Strain Gauges

- Expect linear behavior with I^2
  - Some “unloading” possibly seen on the inner bobbin gauges



Cooling Tube Leak (LBNL)

- Cooling Tube Vacuum Leak found during checkout
- Solution: a bypass pipe branch

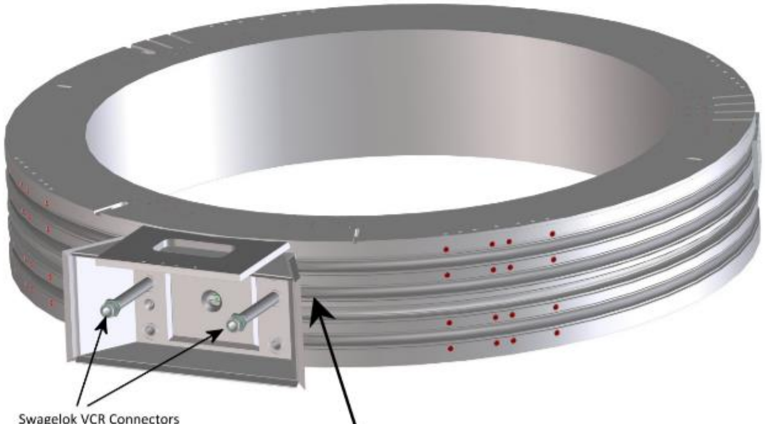
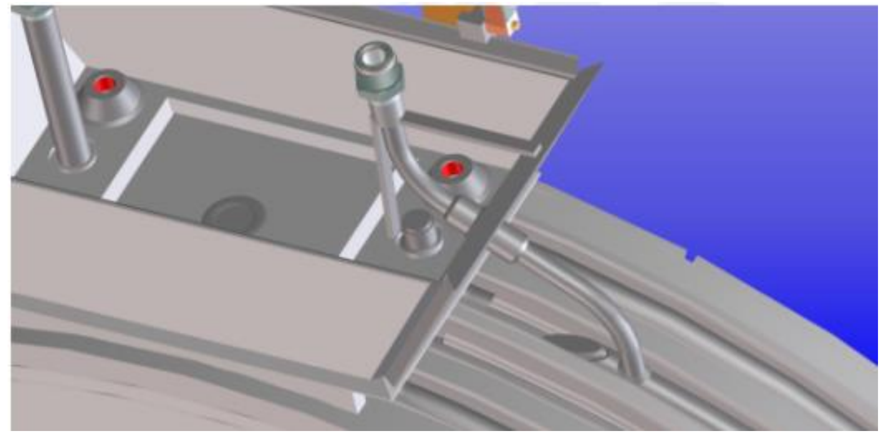
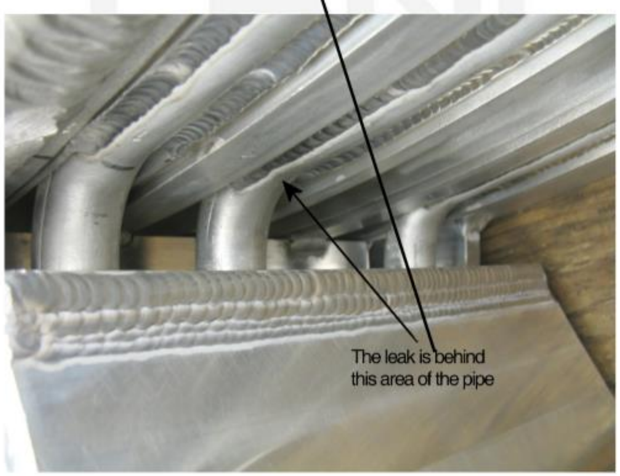


Figure 1 CAD model image of magnet showing approximate location of vacuum leak.



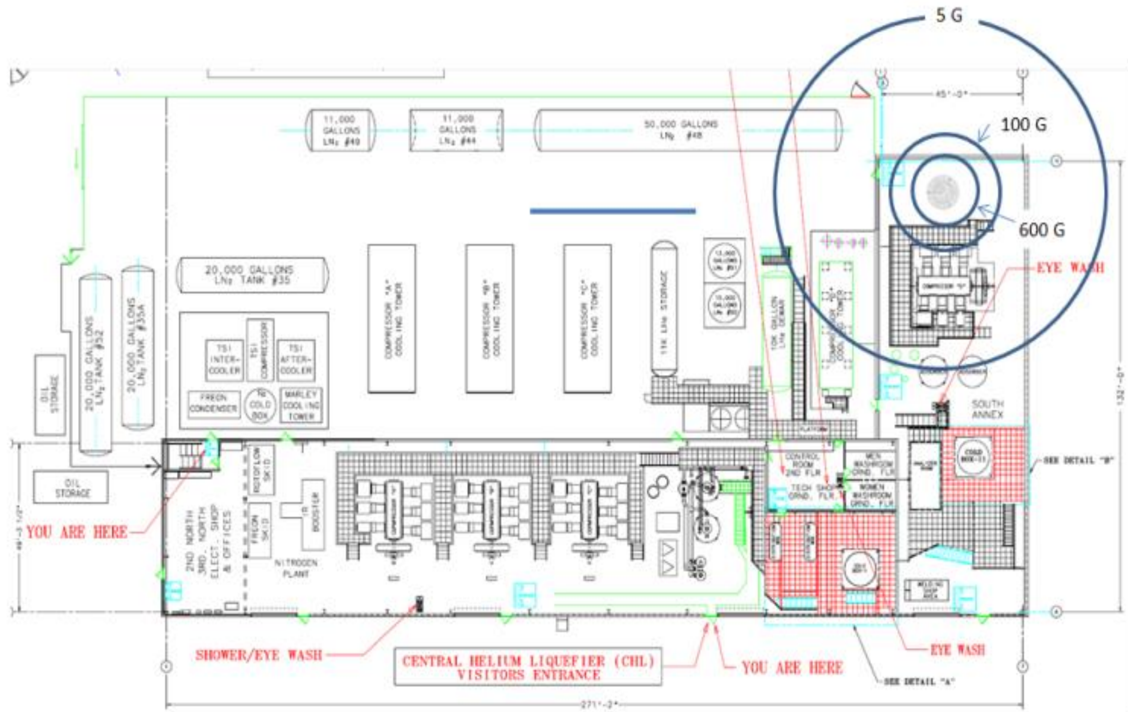


STF Documentation

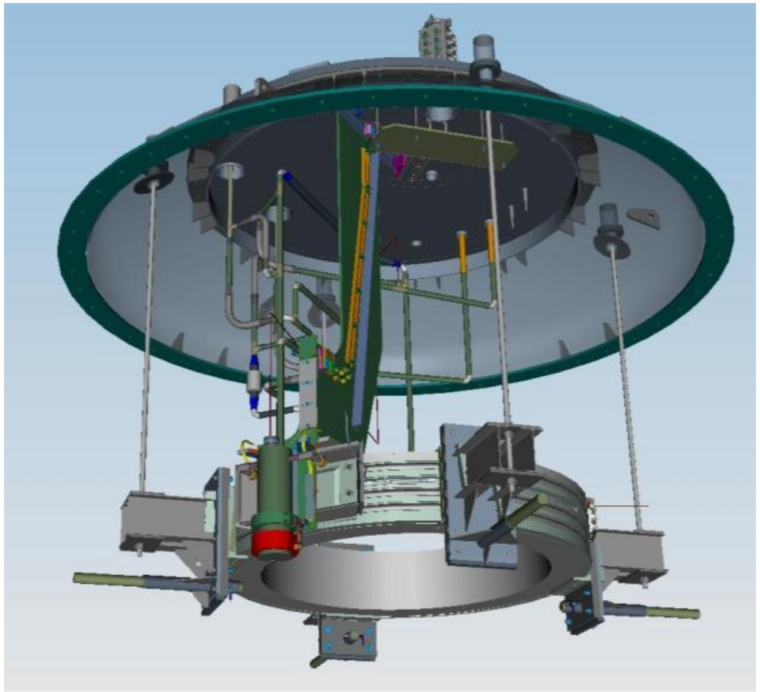
- Project Web Site
  - http://tiweb.fnal.gov/website/controller/2184
- Follows FNAL Engineering Manual and T&I Department Engineering Work Process Guidelines
  - http://tiweb.fnal.gov/website/controller/540
- Subject to several engineering and safety reviews
- New test facility site: CHL building
  - Required close collaboration between TD-T&I and AD-Cryo
  - Liquid helium to test stand provided by AD-Cryo and CHL infrastructure
- Provisions for large fringe magnetic field operation under high magnetic field safety hazards

Test Cryostat

- The Test Cryostat was brought to Fermilab from the NHMFL in Florida and installed in the CHL building, South Annex
- Unnecessary internals were removed, and both the vacuum vessel and the top plate were leak checked and passed

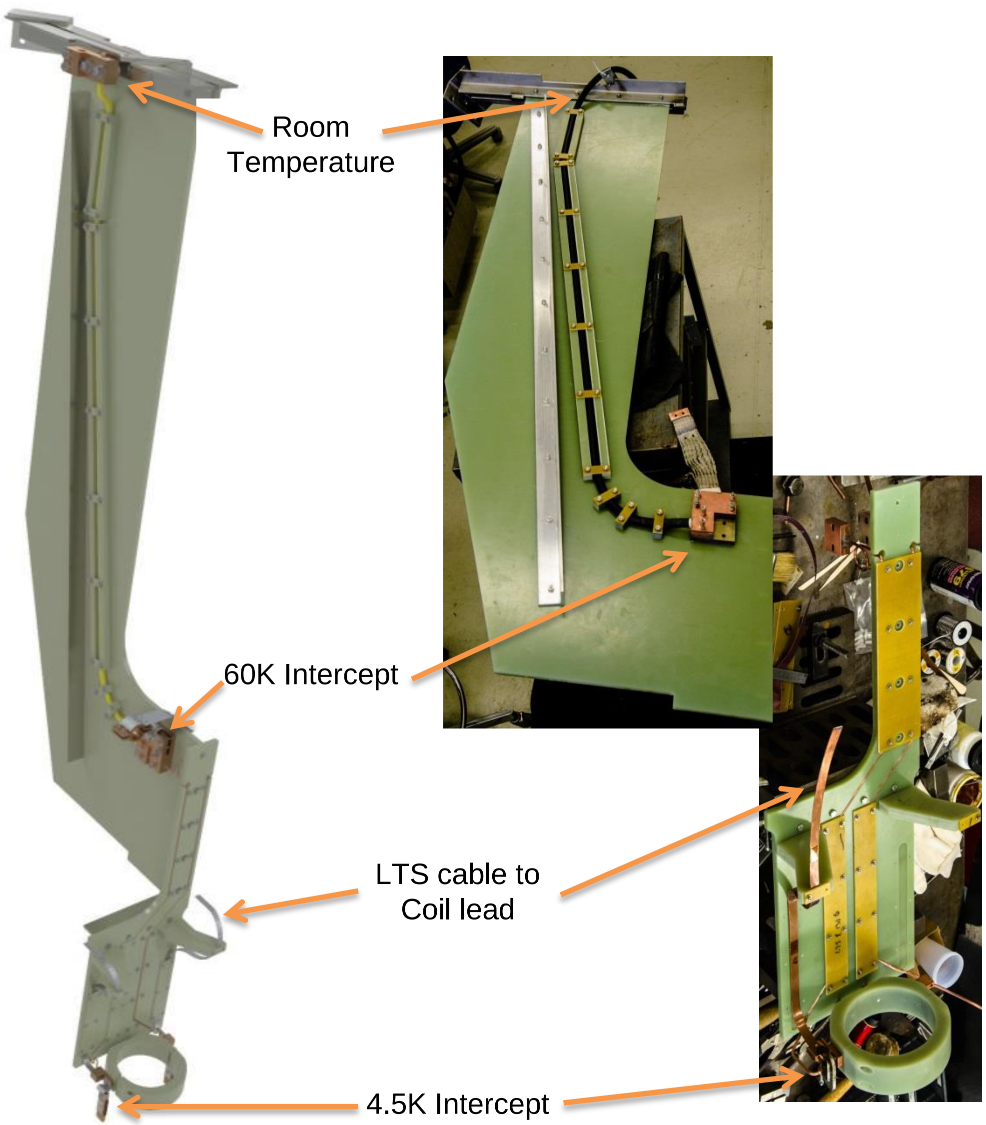


Top Plate Insert



- New Dished Head
- Mechanical Supports
- Cryo Piping
- Current Leads
- Valves, Instrumentation
- Pressure Test
- Leak Check
- Hipot

Current Leads

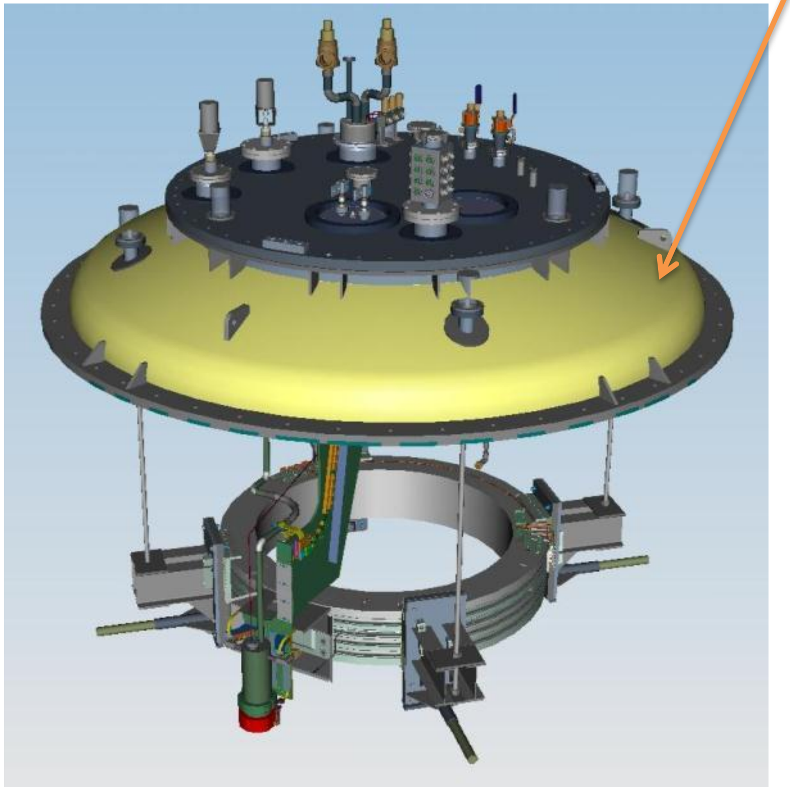


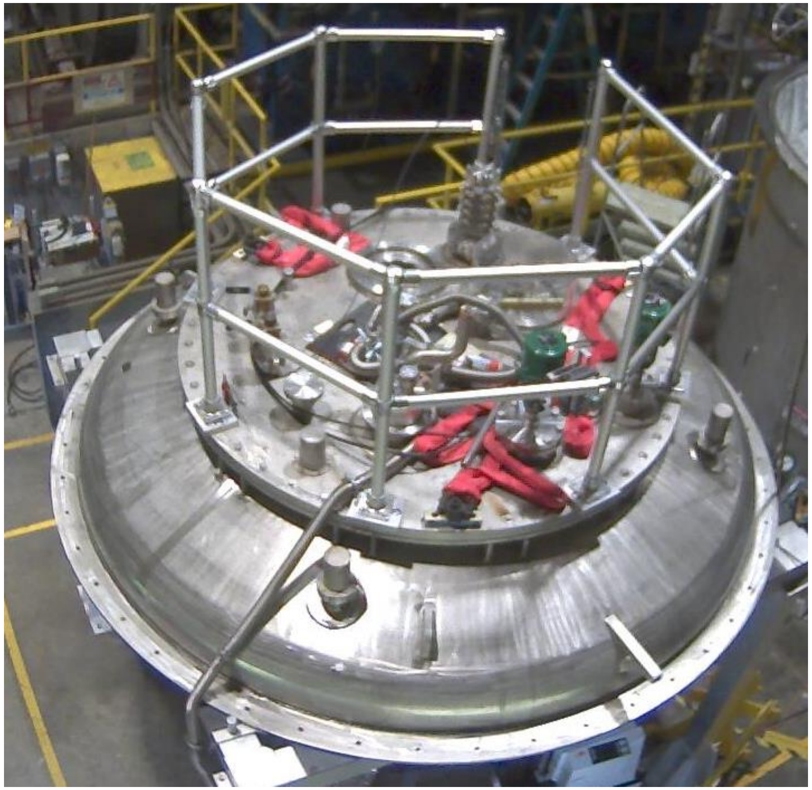
- Conduction-cooled, optimized for 220A
- Two thermal intercepts: 60K (thermal strap to 4.5K GHe return pipe) and 4.5K (Wang NMR intercept to 4.5K boiling He reservoir)
- Low Temperature Superconductor (LTS) section between 4.5K intercept and coil leads
- G-10 mechanical support for magnetic forces

Top Plate

- Valves and Instruments, Instrumentation Tree, U-Tubes Connections, Power Connections, etc.

New Dished Head





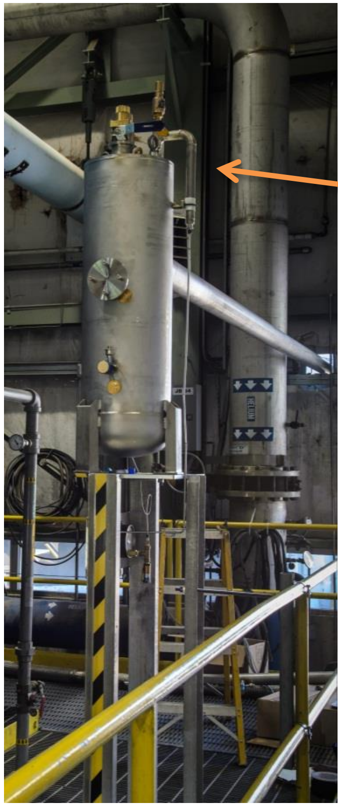
Cryogenic System

- Liquid Helium and Helium gas recovery provided by the Central Helium Liquefier (unused after the Tevatron shutdown in September 2011)
- Up to 10 g/s of liquid helium at 4.5K supply to the Coupling Coil cooling tube from a nearby CHL 10,000 Gallon liquid helium Dewar
- Helium inlet temperature during cooldown/warmup controlled inside test cryostat to maintain a maximum cold mass gradient of 50K
- The return helium warmed up to room temperature before sending back to the CHL facility for recovery
- No venting to atmosphere expected during a quench (small LHe inventory in the cooling tube)

CHL Distribution System

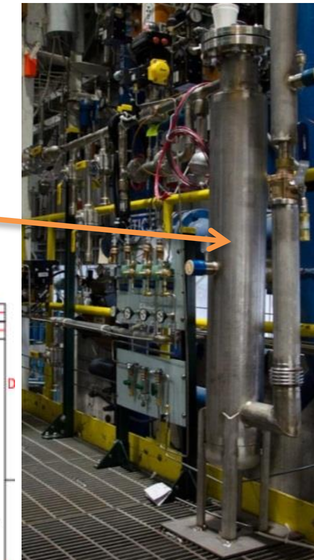
- Liquid Helium (LHe)Transfer Line from 10,000 Gallon LHe dewar to Bayonet Can

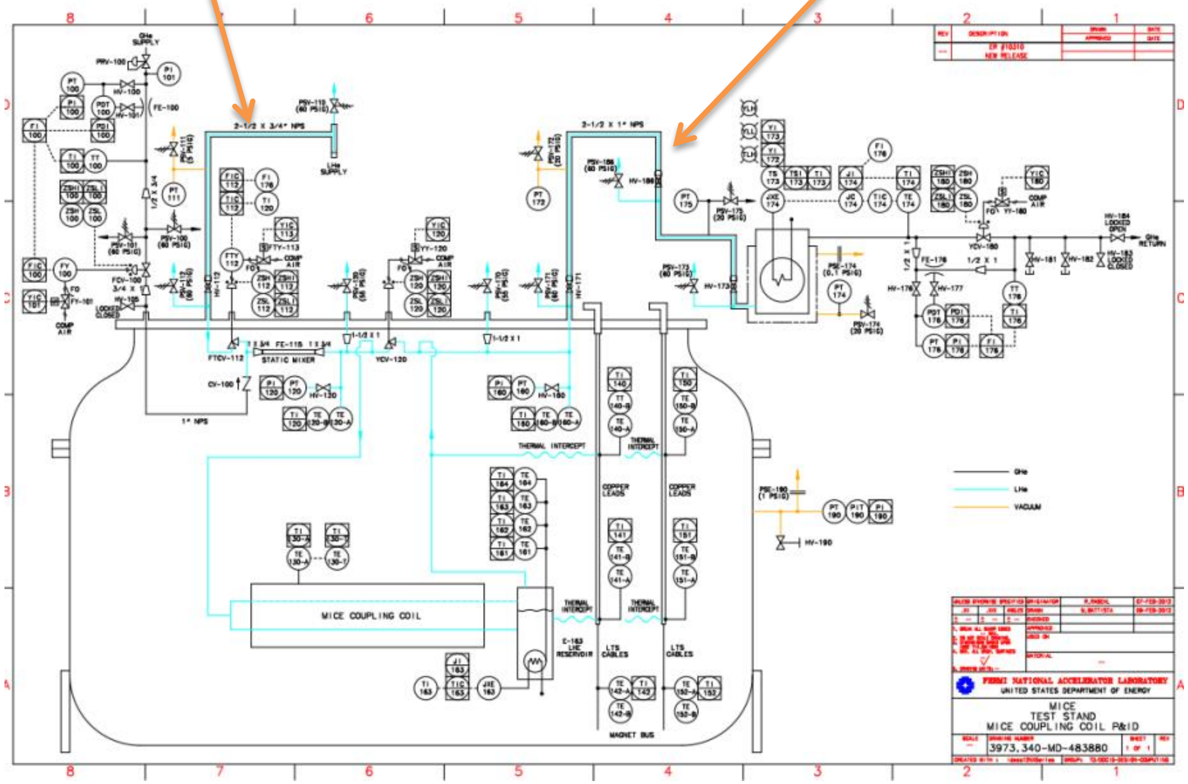
Cryogenic System P&ID



U-Tube to Bayonet Can

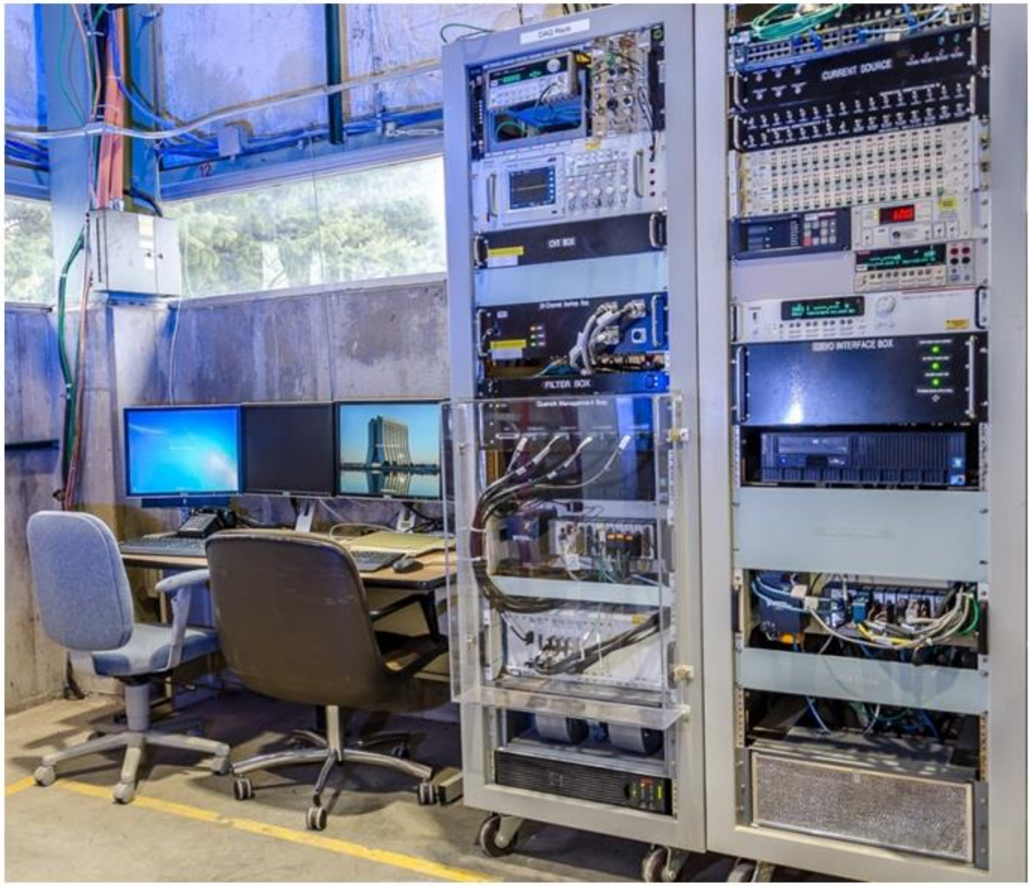
Return Gas to Warmup Heater

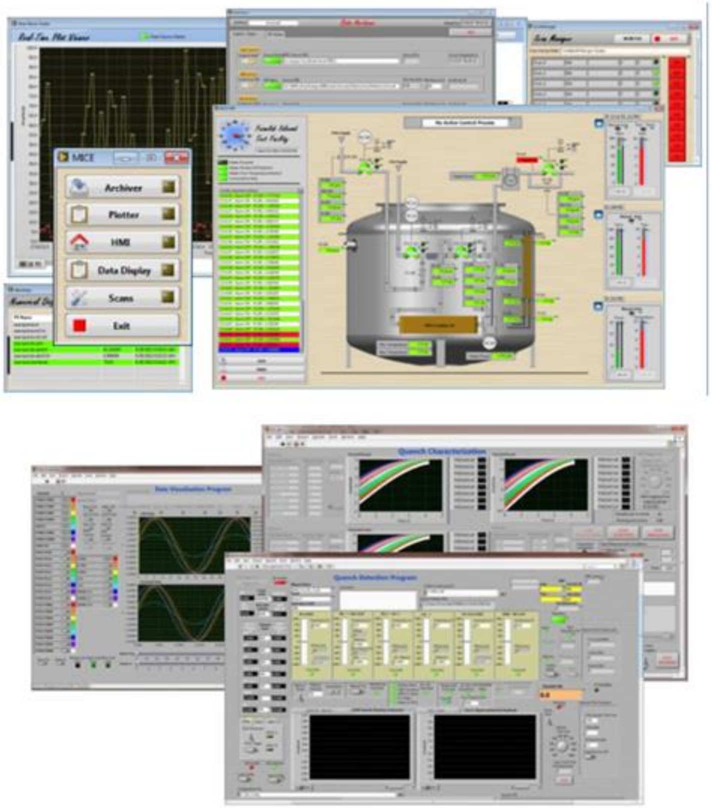




Controls, DAQ, QPS

- Test Stand Instrumentation Racks and Examples of User Interfaces

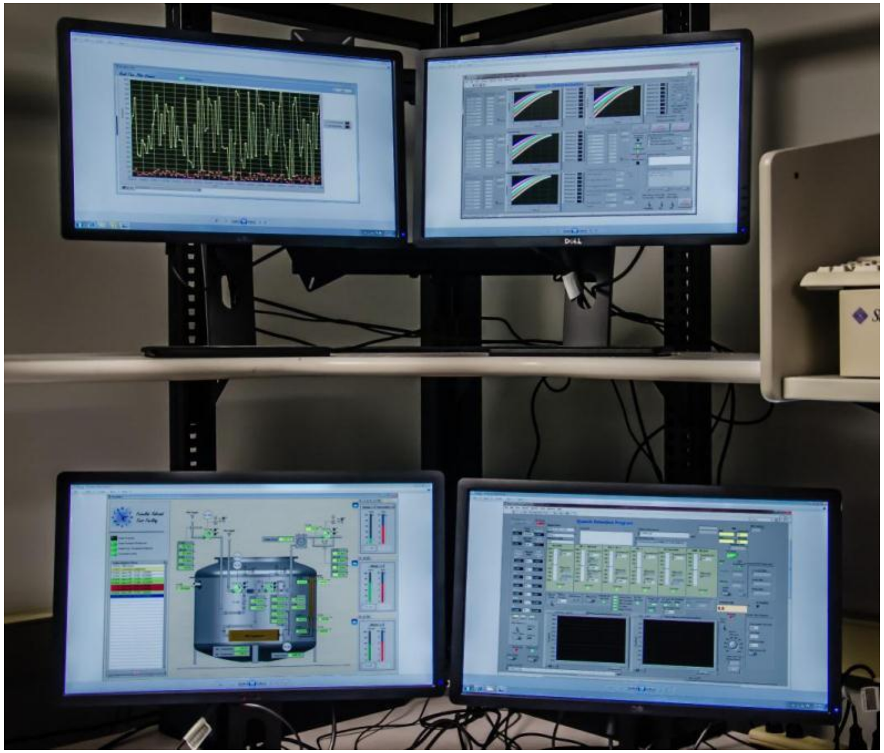




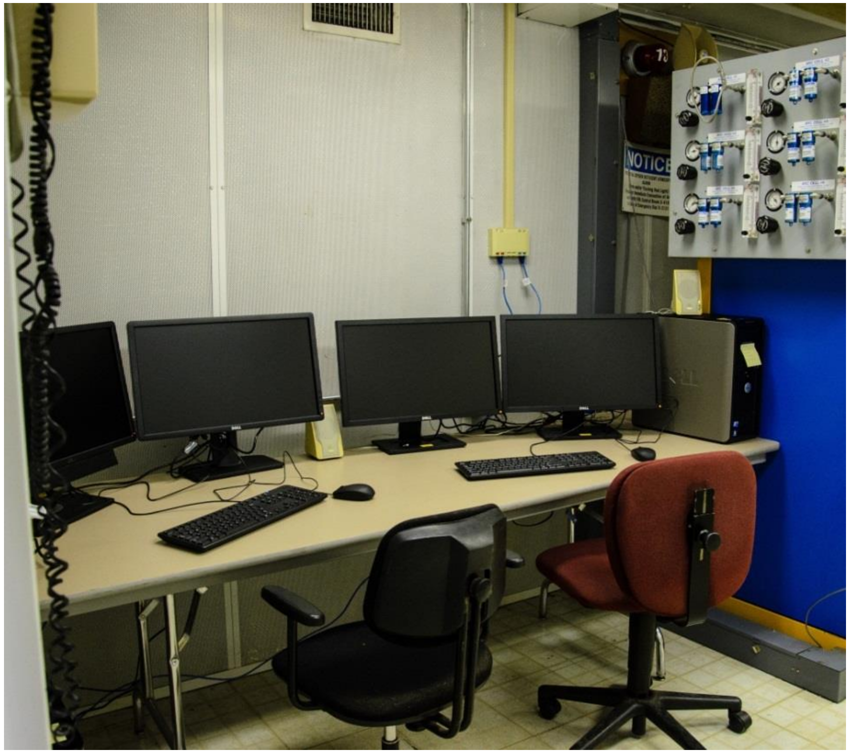
Remote Control Stations

- Local control station cannot be used under high magnetic field because personnel have to evacuate the area for safety reasons
- Two remote control stations installed: one in the CHL building, and another at the IB1 Magnet Test Facility
- E-log and measurement data available on a web interface

Remote Test Stand control station at IB1 Magnet Test Facility Control Room



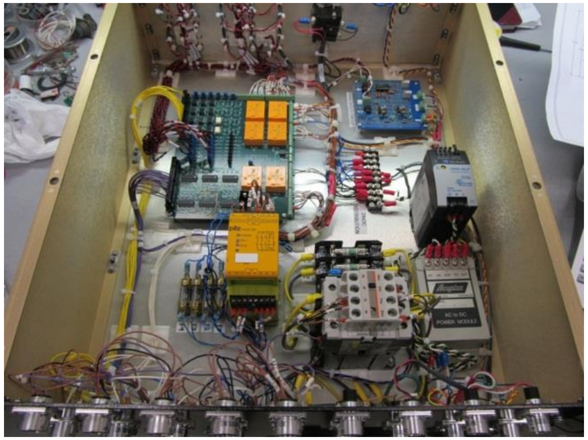
CHL Test Stand Control Room (Climate Controlled, Acoustically Insulated)

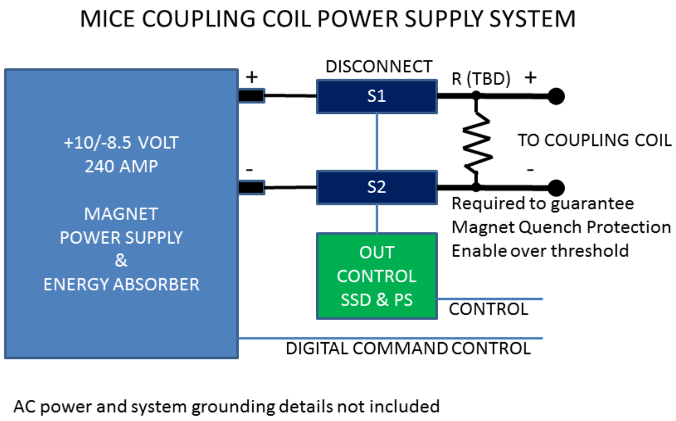


Fermilab

Power System

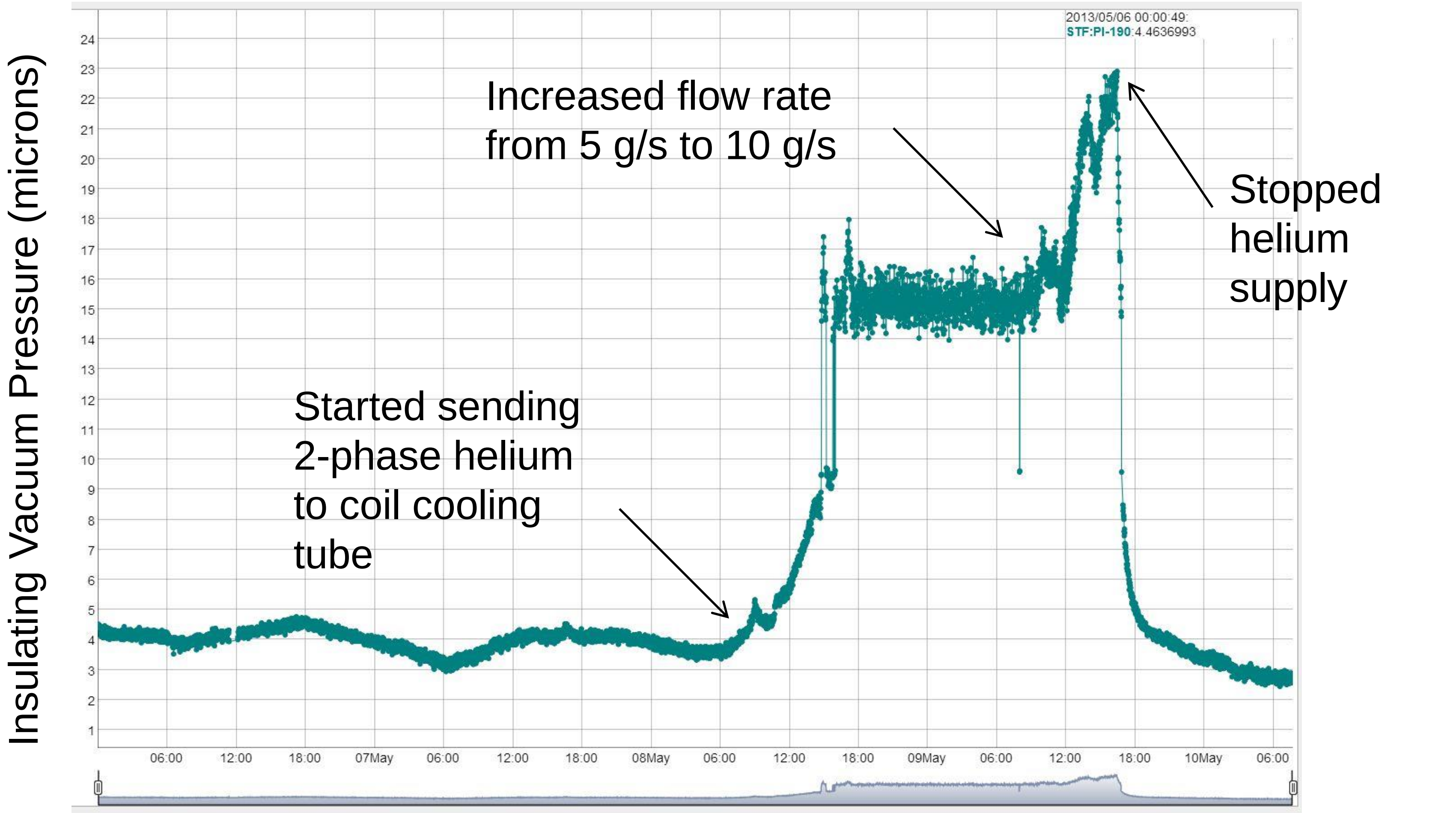
- The Test Facility Power System Rack delivered by LBNL
- Fermilab added personnel Emergency Trip System Box and current readout hardware to the rack





A Cold Leak!

- Insulating vacuum quickly degraded when two-phase helium started flowing to the coil cooling tube
- Cold Mass surface temperatures could not get below 8 – 11K.



Leak Hunting and Repair

- After pressurizing the piping to 80 psig, a leak was found at one of the outlet VCR connections. All other joints did not show signs of a leak.
- Installed flexible hose to mitigate risk of VCR leaks
- A Test Cryostat acceptance test was conducted on July 24, 2013. The cold mass was bypassed and current leads shorted.
  - No Leaks
  - Current ramped successfully to 210A