LQS01a Test Results

LARP Collaboration Meeting 14

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Outline

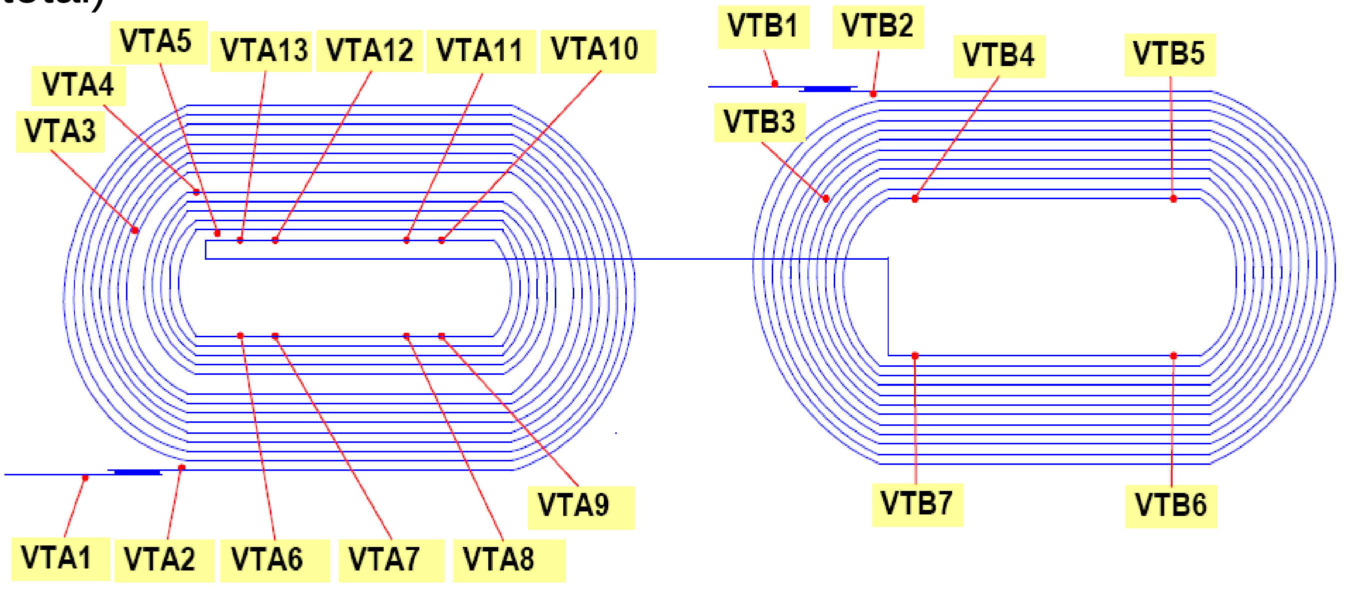
- Introduction
- Quench History
- Quench Locations
- Ramp Rate and Temperature Dependence Study
- Magnetic Measurements
- Summary
- Active Ground Fault Monitoring System
- LQS01b Test Plan

Introduction

- The first long Nb_3Sn quadrupole with a shell-based structure - LQS01a - was tested at Fermilab (Nov. – Dec. 2009) and 200 T/m field gradient was reached
- Magnet training was interrupted to avoid coil damage at high currents
- Most of the test was performed at 4.5 and 3 K (2 quenches at 1.9 K)
- Various system upgrades were implemented at the Fermilab's Vertical Magnet Test Facility (VMTF) in preparation to LQS01a test
  - Quench detection system with current dependent thresholds
  - Magnet protection and Strain gauge readout system
  - Active Ground Fault Detection System to be implemented at VMTF before LQS01b test
  - Upgrade details were presented at LARP CM12 at LBNL, April 2009
- LQS01a test readiness review at Fermilab - October 2009

LQS01a coil instrumentation

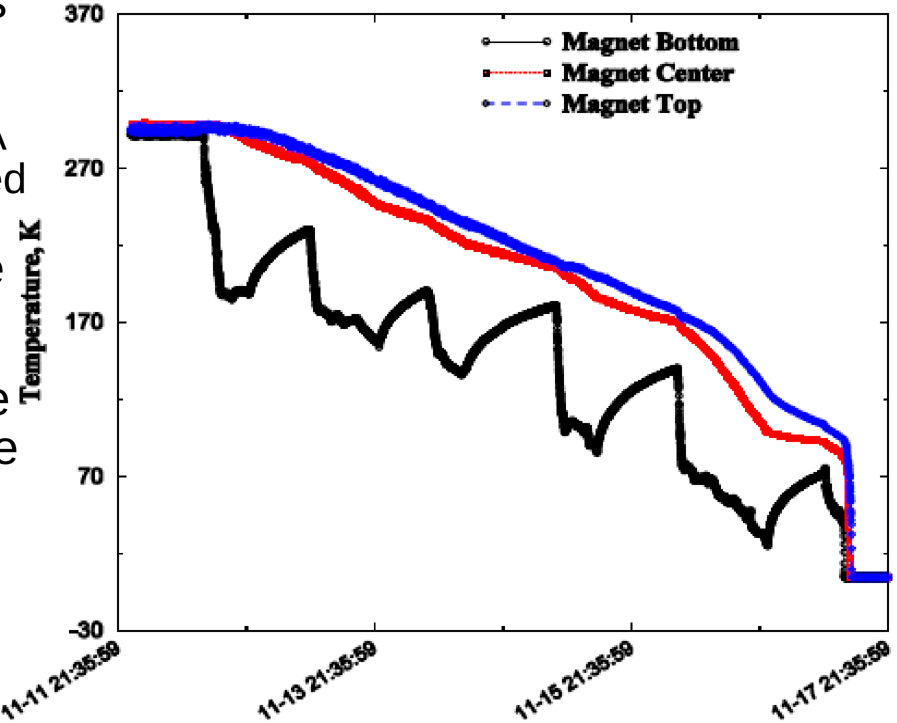
- LQ coils were made of 27-strand Rutherford cable with 0.7-mm Nb_3Sn RRP strand of 54/61 design
- Voltage tap system covers the inner and outer coil layers (20 segments per coil in total)



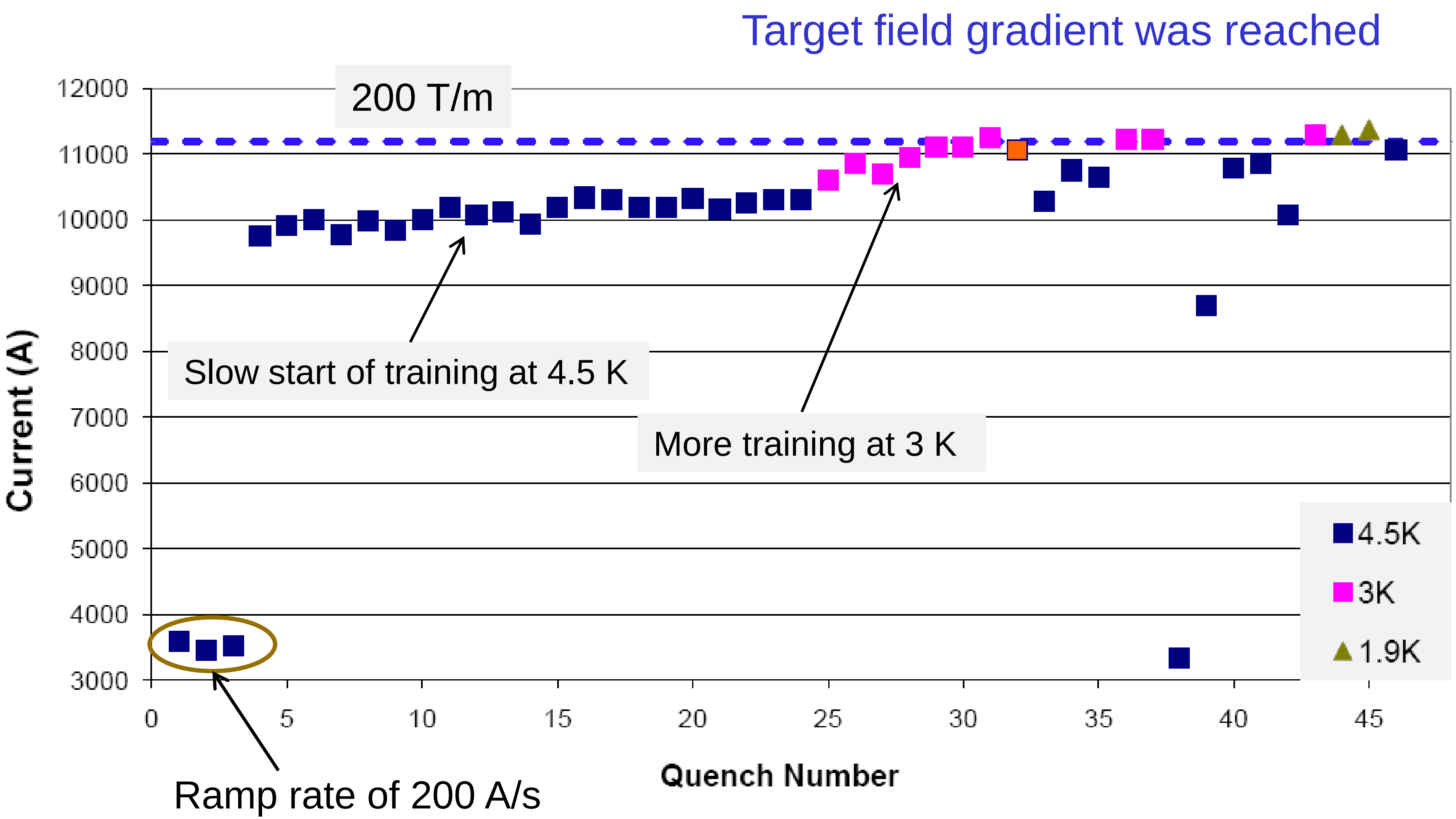
- Protection heaters were installed on both the outer and inner coil layers
- Details on coil instrumentation and protection heaters will be presented by Helene Felice

Cool down and first quenches

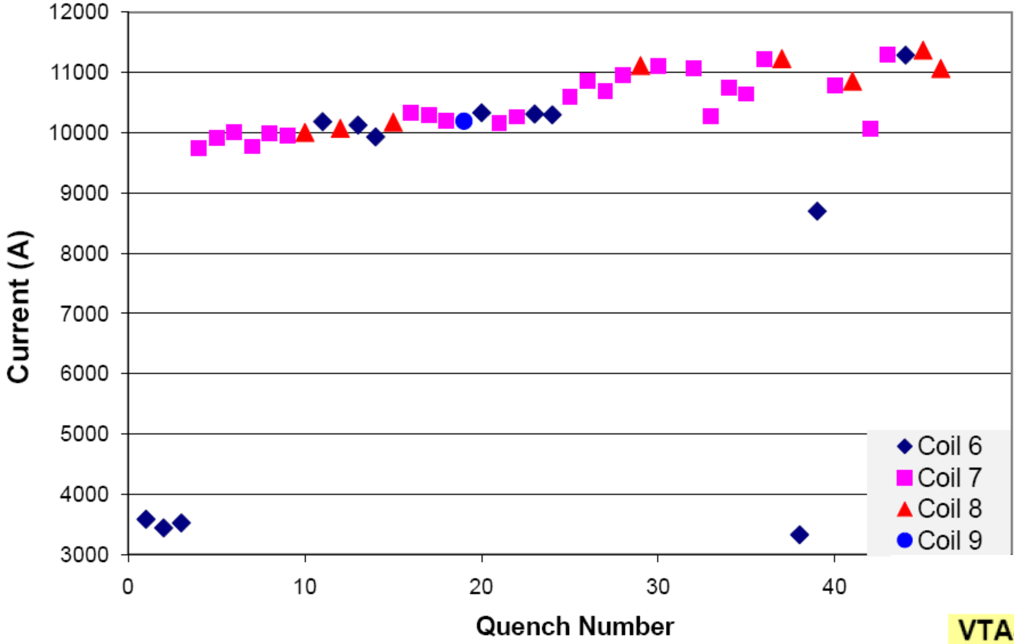
- Helium only cool down - no pre-cool with Nitrogen gas
- 5 calendar days of cool down from 300 to 4.5 K with 150 K constrain on temperature gradient along the magnet length. 6-7 days required for warm-up back to room temperature
- Large voltage spikes at low currents
  - Consistent with other coils made of RRP 54/61 strand
  - Spikes up to 4 V at currents 1.5-2 kA
  - Quench detection thresholds adjusted
- Less and smaller voltage spikes are observed at high ramp rates
- Few high ramp rate quenches at the beginning until the optimal ramp rate settings were found
  - 200 A/s to 3 kA,
  - 50 A/s to 5 kA,
  - 20 A/s to 9 kA and
  - 10 A/s to quench



LQS01a Quench History



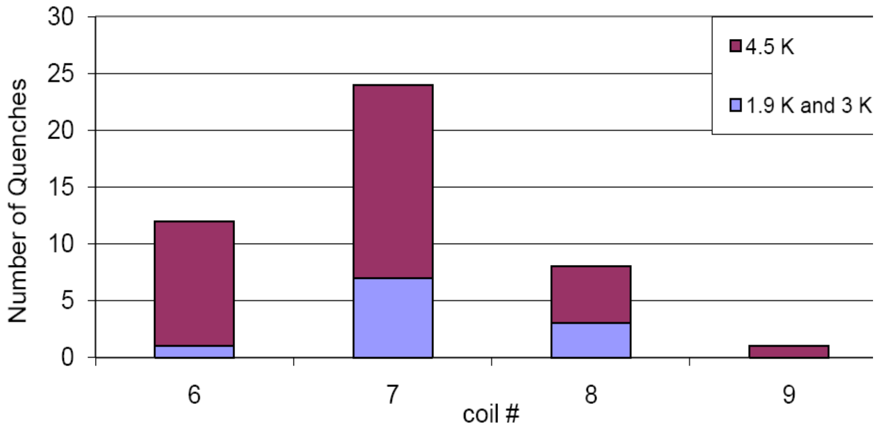
LQS01a Quench Locations

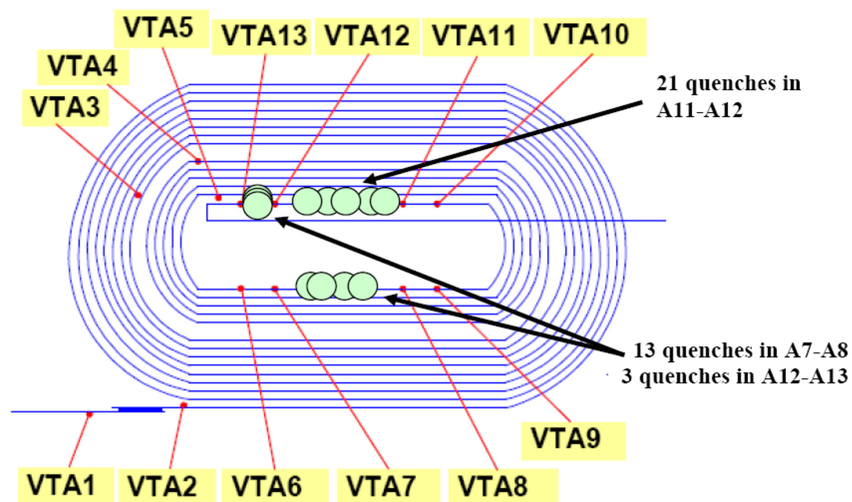


All training quenches developed in pole turns
- No preferred longitudinal location was observed

High ramp rate quenches developed in mid-plane segments

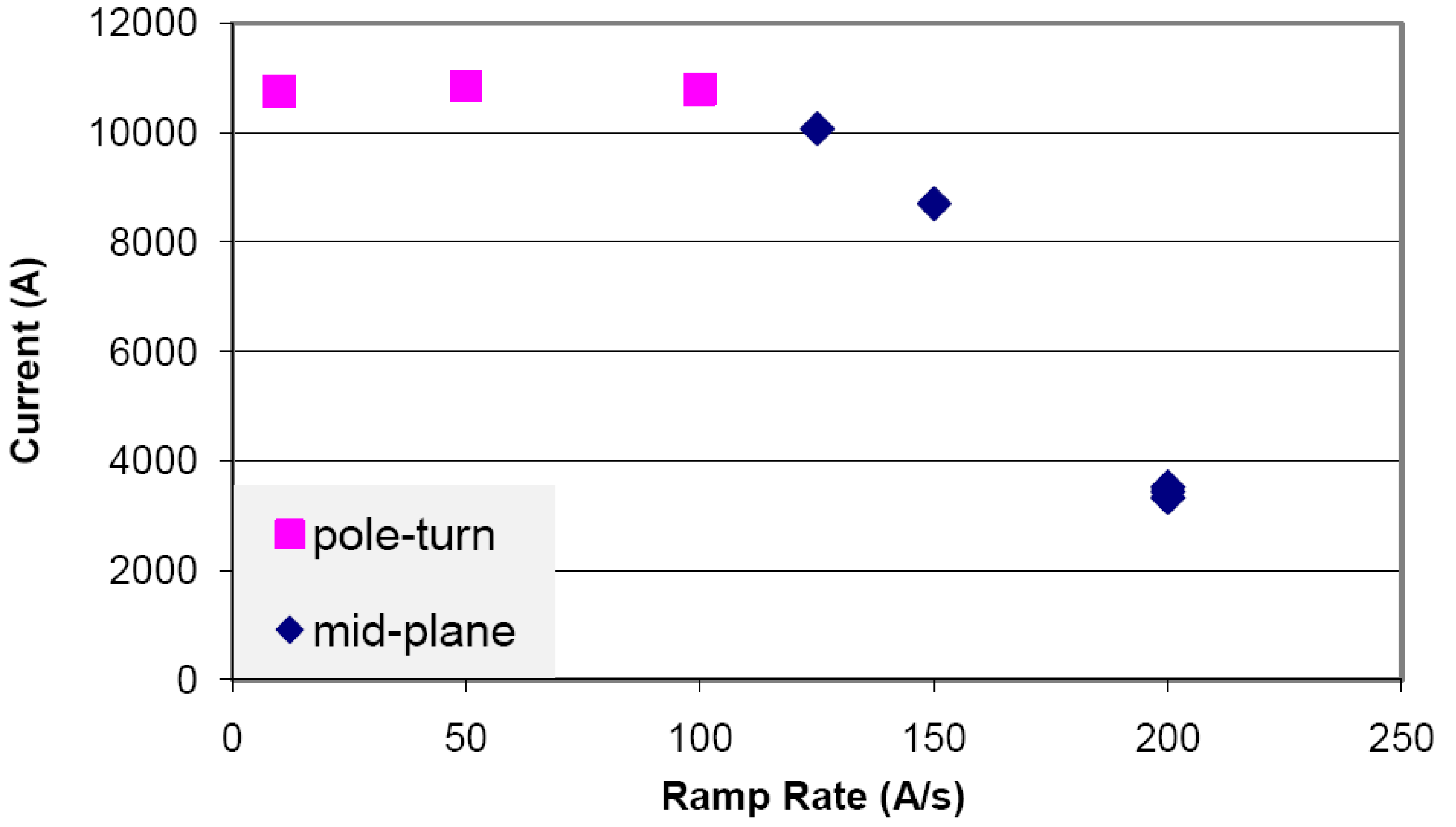
All coils were quenching





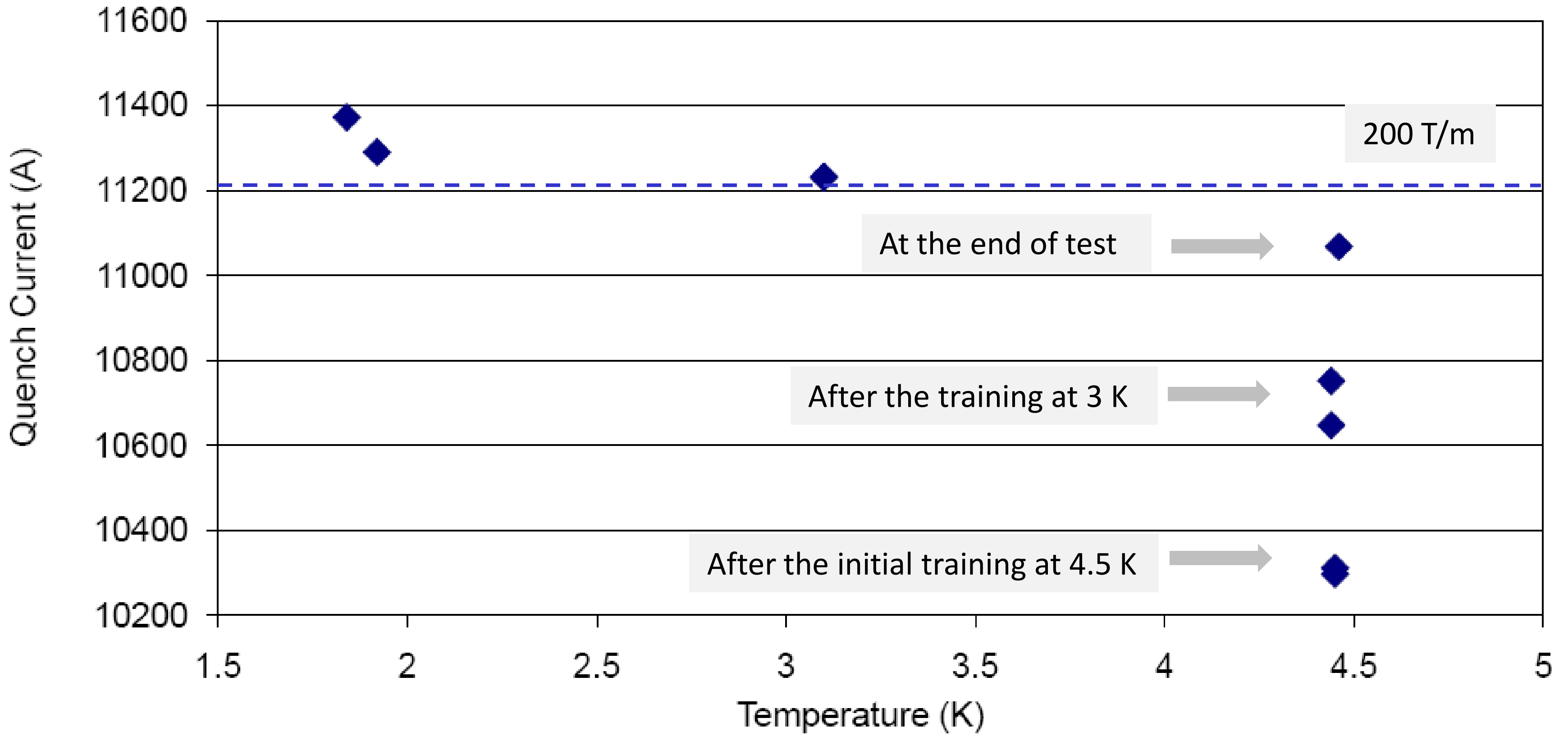
LQS01a Ramp Rate Dependence

Ramp rate study was performed at 4.5 K after the short training at 3 K



LQS01a Temperature Dependence

- Ramp rate of 10 A/s used for the temperature dependence study
- Quenches at 4.5 K are shown after the initial training, after the training at 3 K and at the end of test

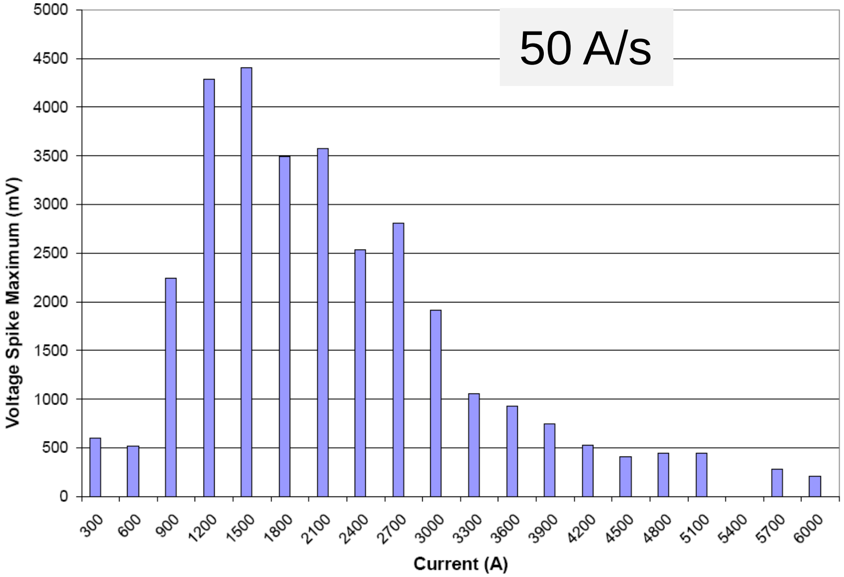


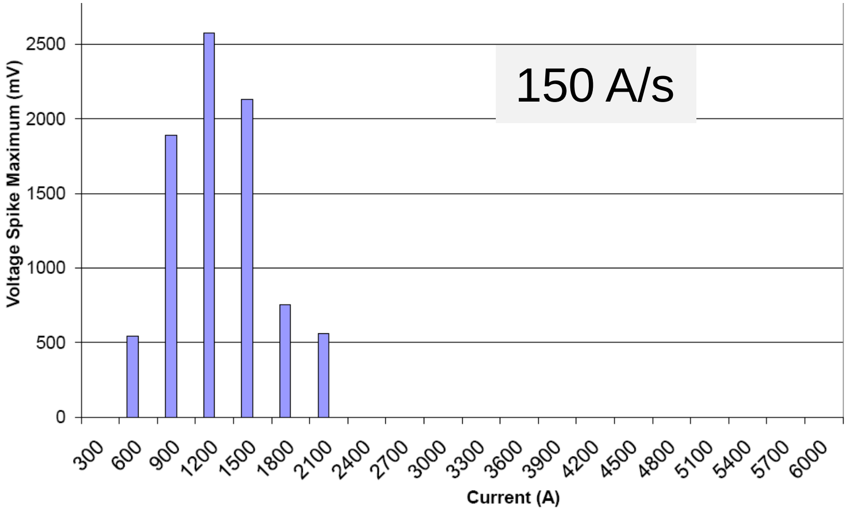
Magnetic Field Measurements

- Magnetic measurements were made at VMTF using a vertical drive rotating coil system with 82-cm long &1.95-cm radius tangential probe. Warm bore was only ~2/3 of the magnet length
- Warm (300 K) measurements before and after the cold test were consistent
- Cold measurements included
  - Pre-quench z-scan at 6.5 kA
  - Z-scans at 12.3 Tm/m (LHC injection, ~ 655 A), 100 Tm/m (5.3 kA) and at 10 kA
  - Eddy current loops with the ramp rates 20 A/s, 40 A/s, 80 A/s
  - Measurement of dynamic effects
  - Stair step measurements from 1.5 kA to 9 kA
- Reference radius at 2.25 cm
- Unallowed harmonics up to 8 units were observed at all currents
- Iron saturation observed for currents above ~6 kA
- No decay or "snapback" was observed in the dodecapole (b6)
- Ramp rate dependence shows little or no eddy current contribution to the b6 hysteresis loop

#	Injection (0.66 kA)	100 T/m (5.3 kA)	10 kA
b_3	3.34	2.29	2.61
b_4	7.72	6.73	6.93
b_5	0.06	0.17	-0.08
b_6	-33.31	9.89	7.47
b_7	0.05	-0.06	-0.11
b_8	-0.28	-0.98	-0.38
b_9	0.08	0.19	0.13
b_10	0.56	0.35	-0.47
a_3	2.03	2.28	2.28
a_4	6.28	1.94	2.11
a_5	-0.50	-0.51	-0.65
a_6	-1.14	-0.12	-0.29
a_7	0.17	0.29	0.14
a_8	0.12	0.08	0.06
a_9	-0.29	-1.09	-0.16
a_10	0.05	0.37	0.12

Voltage Spikes





The voltage spike detection system captures half-coil signals at 100 kHz sampling rate

Different ramp rates result in the different Voltage spike distribution

Quench Detection system with a current dependent threshold allowed to avoid low current trips due to voltage spikes and keep MIITs low during quench training
- 0.6-0.8 V threshold at quench

Current dependent thresholds were derived from the spike data analysis

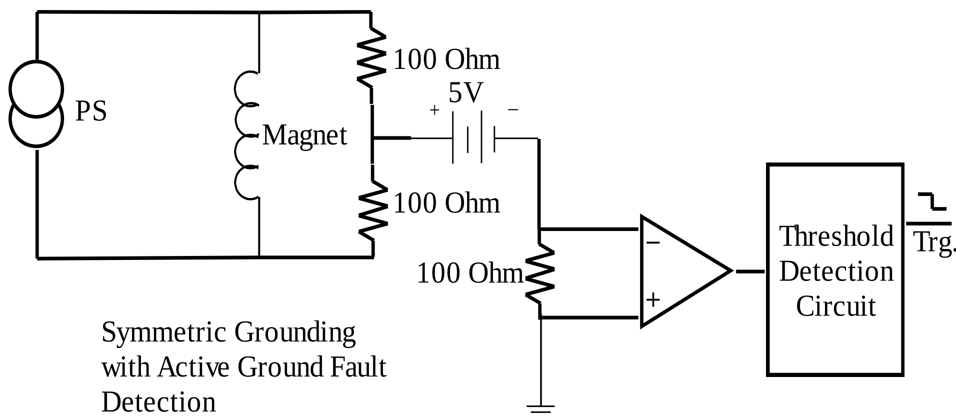
Voltage spike maximum amplitude vs. current at 4.5 K

Summary

- The First LARP Nb_3Sn Long Quadrupole - LQS01a - was successfully tested at Fermilab
- The magnet reached target field gradient of 200 T/m several times at both 3 K and 1.9 K temperatures
- Magnet training was interrupted to avoid coil degradation due to possibly non-optimal pre-stress distribution in the magnet
- The maximum quench current reached in the test was 11372 A (~202 T/m) at 1.9 K. At 4.5 K magnet reached ~11100 A (~197 T/m) or ~ 80% of the predicted short sample limit
- Ramp rate dependence study confirmed that quench training was not completed and there is margin for improving the magnet performance
- Measured RRR for most of segments was above 250, and for the half-coil segments - 290-295

Active Ground Fault Monitoring System

- Active ground fault monitoring system at VMTF was proposed in order to increase sensitivity to the detection of ground faults which would not depend on the location of the fault or the magnet inductance
- An active ground fault detection circuit includes an isolated 5V voltage source connected in series with the ground resistor



Symmetric Grounding with Active Ground Fault Detection

- Voltage drop will develop across the 100-Ohm ground resistor in case of coil-to-ground short
  - System is "always armed"
- Internal review and Failure Modes Analysis completed
- First bench testing was successful, currently implementing the system for testing with a magnet (TQM04)

LQS01b Test Plan

Test Cycle I

Room Temperature preparation and cool down

Magnetic measurements (z-scan) at VMTF

At 4.5 K Operation:

Cold Electrical Checkout

Quench Detection Checkout

Start quench Training, only 2-3 quenches (install Quench Antenna)

Comments:

LQS01a cold test showed fast quench training at 3 K while start of the training at 4.5 K was rather slow. Since LHe consumption during the 3 K training was less than at 4.5 K (with comparable recovery time between quenches) most of the quench training will be done at 3 K.

At 3.0 K

Quench Training

Quench Temperature Dependence

LQS01b Test Plan

At 4.5 K Operation:

- Check quench plateau at 20A/s ramp rate
- Magnetic measurements (6500A)
- Quench Ramp Rate Dependence
- Heater study (low current tests)

At 1.9 K

- Quench Training

Comments:

To avoid possible damage after first few quenches we will do heater to coil hipot to verify proper operation of heaters

- Heater to coil hipot (after first few quenches)
- Quench Ramp Rate Dependence
- Magnetic measurements (90% of max. quench current at 1.9K)
- Outer Coil Conductor Stability Heater test (if required)
- Temperature Dependence Study

At 4.5 K

- Check quench plateau at 20 A/s ramp rate
- Heater study

LQS01b Test Plan

Warm up to 300K

RRR Measurement

Test Cycle II

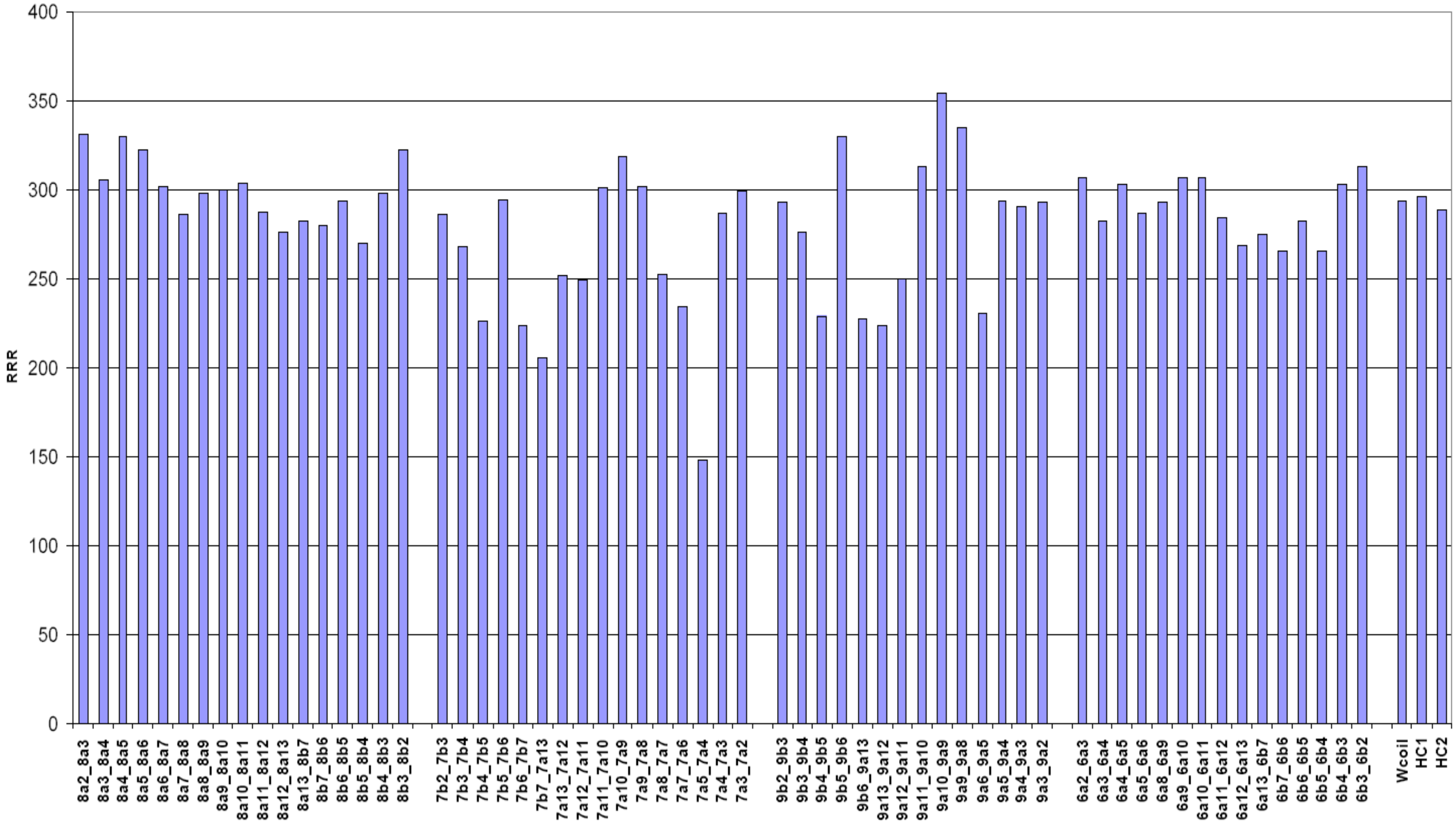
Not finalized, depending on results of the Test Cycle I.

Fermilab/VMTF is ready for LQS01b test

Backup Slides

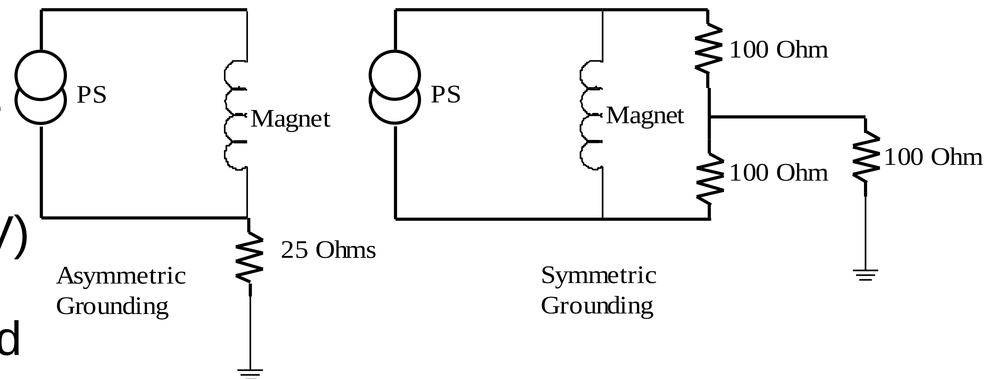
RRR Measurements

In average RRR for most of segments is above 250, and for half-coil segments varies from 290 to 295



Symmetric Coil Grounding

- The 30kA DC power system used for testing magnets in VMTF is grounded at one point on the negative current bus via a 25 Ohm current limiting resistor.
- This "asymmetric" grounding configuration will be changed to a “symmetric” grounding scheme in which both the positive and negative bus will be grounded via two100 Ohm resistors to a center tap, which will be connected to ground through another 100 Ohm current limiting resistor.
- With symmetric grounding the maximum coil to ground voltage will be 500 V (the power system is designed for a max. of 1000 V)



- Symmetric grounding was tested several times and will be implemented on a permanent base in April.

Modified Strain Gauge Readout System

- In order to boost the strain gauge signals in LQS01 magnet we plan to use 4 current sources.
  - 2 *Keithley* current sources were used for 36 strain gauges in LQSD magnet providing a maximum current of 1.25 mA.
- We plan to increase data saving rate by splitting the SG and RTD (temperature) scans
- Reference bridge was built at Fermilab for the calibration and monitoring of the strain gauge readout systems. Measurements with the LBNL portable and Fermilab SG readout systems showed very good agreement with the reference numbers.
  - LQSD SG data were read out with the LBNL portable system before and after the test. During the test we used the Fermilab SG readout system. We will continue the same practice for LQS01 test.
- Modified SG readout system will be tested in June.

Quench Detection System with Adaptive Thresholds

- Proposed solution is to use the FPGA based quench management (QM) system already developed and used to test HINS solenoids at Fermilab.
- New FPGA based will work in parallel to the existing VxWorks based QM system.
- Interfacing an FPGA based quench management system to VMTF has already been tested.
- First full scale test will be done in 2nd half of April – at the end of TQM02 test.