LARP

LQ Test Results and Next Steps

1st HiLumi LHC/LARP Collaboration Meeting
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Outline

- Introduction
- LQS01 and LQS02 test results
- Field quality study of LQS magnets
- LQ coil test in a mirror structure
- Next steps
- Conclusion

Introduction

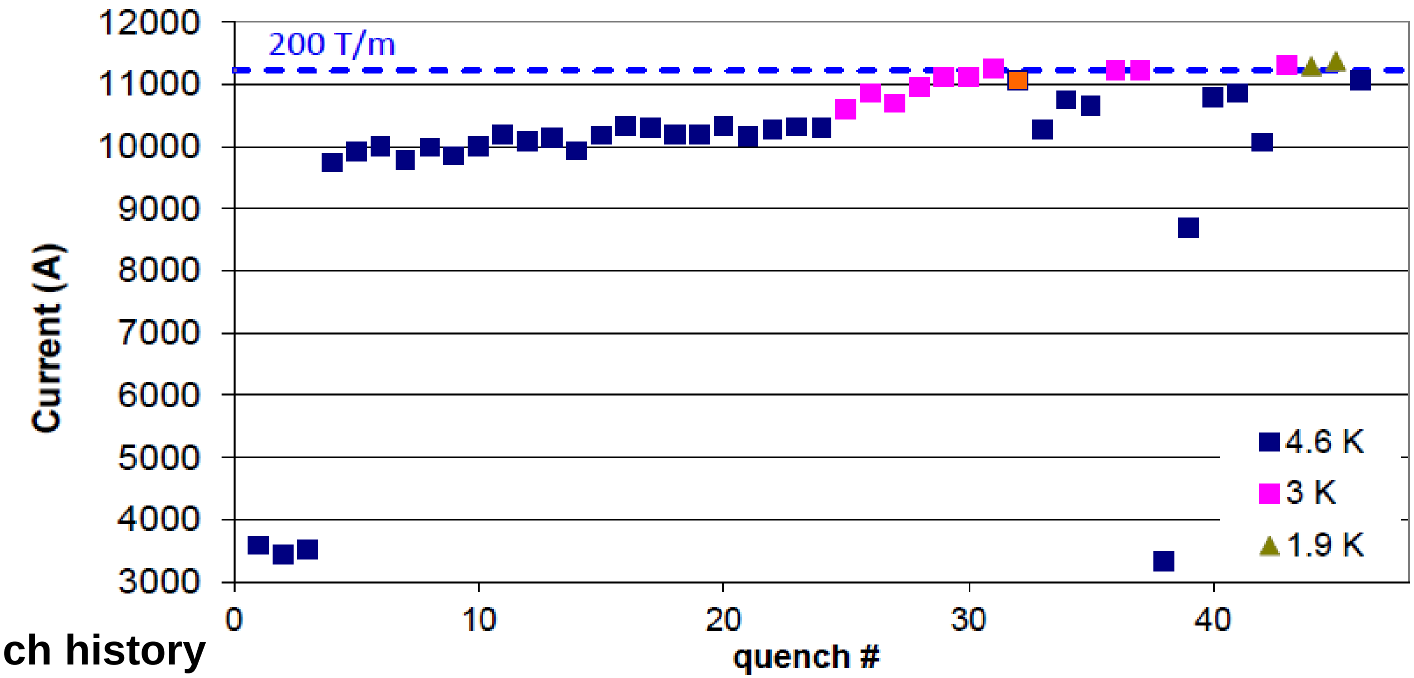
- LQ project is an important part of the LARP magnet program for LHC luminosity upgrade
  - Demonstrate scale-up of Nb_3Sn technology
  - Target field gradient of 200 T/m
  - Demonstrate predictable and reproducible performance
- LQS01, the first 3.7-m long Nb_3Sn quadrupole with a shell-based structure, reached 200 T/m field gradient in December 2009
  - Later on the same target field gradient was exceeded in LQS01b and LQS02
- Presently assessing reproducibility, training memory, accelerator quality features
  - LQS01b, subjected to a full thermal cycle, reached the previous quench plateau of 222 T/m at 4.6 K in 2 quenches

Introduction

- LQ coils are made of 27-strand Rutherford cable with 0.7-mm diameter Nb_3Sn strand based on the “Restack Rod Process” (RRP) of various sub-element design
  - Coils #1-5 (RRP 54/61) Practice coils
  - Coils #6-9 (RRP 54/61) Tested in LQS01a/b
  - Coils #10-13 (RRP 54/61) Tested in LQS02
  - Coil #14 (RRP 114/127) Tested in a mirror structure (LQM01)
  - Coils #15-19 (RRP 108/127) To be tested (LQS03)
- LQ coils were fabricated at BNL and FNAL, instrumented and assembled in a magnet structure at LBNL and then tested at FNAL
- LQS01 test readiness review was held in October 2009, LQS02 test readiness review - in October 2010 and LQS03 test readiness review is expected in January 2012

LQS01 Test at Fermilab

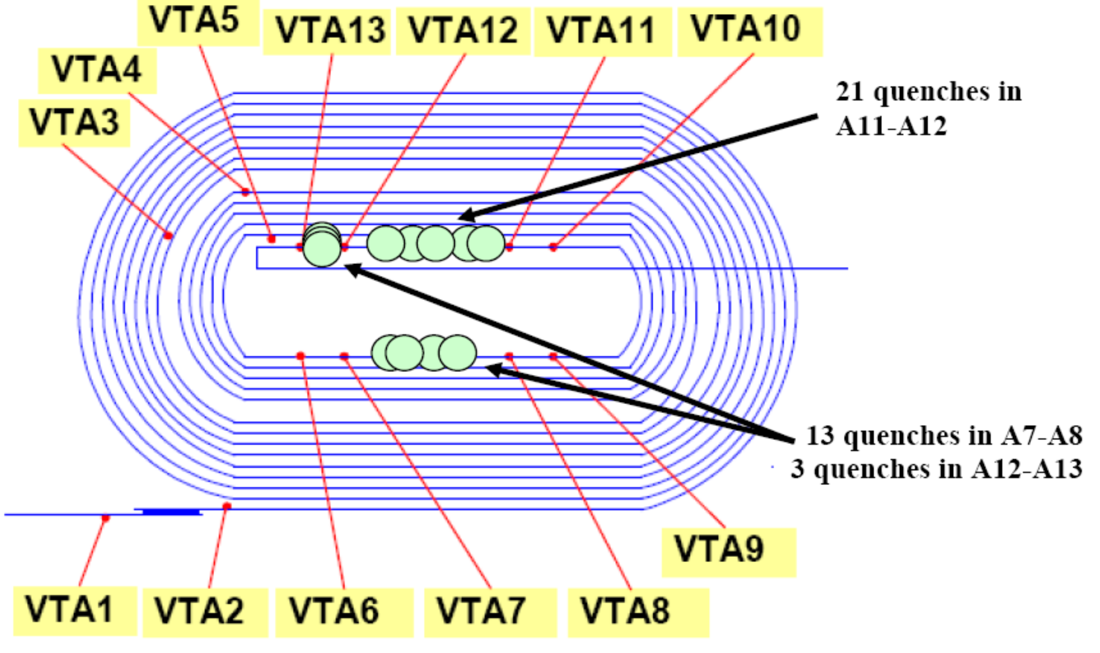
- LQS01a was tested at Fermilab in Nov.–Dec. 2009. Quench training was stopped at 202 T/m in order to avoid coil damage at high currents
  - Most of the pole gauges showed a “stress plateau” during current ramps
  - Large discrepancy was observed between measured and expected azimuthal coil pre-load



LQS01a quench history

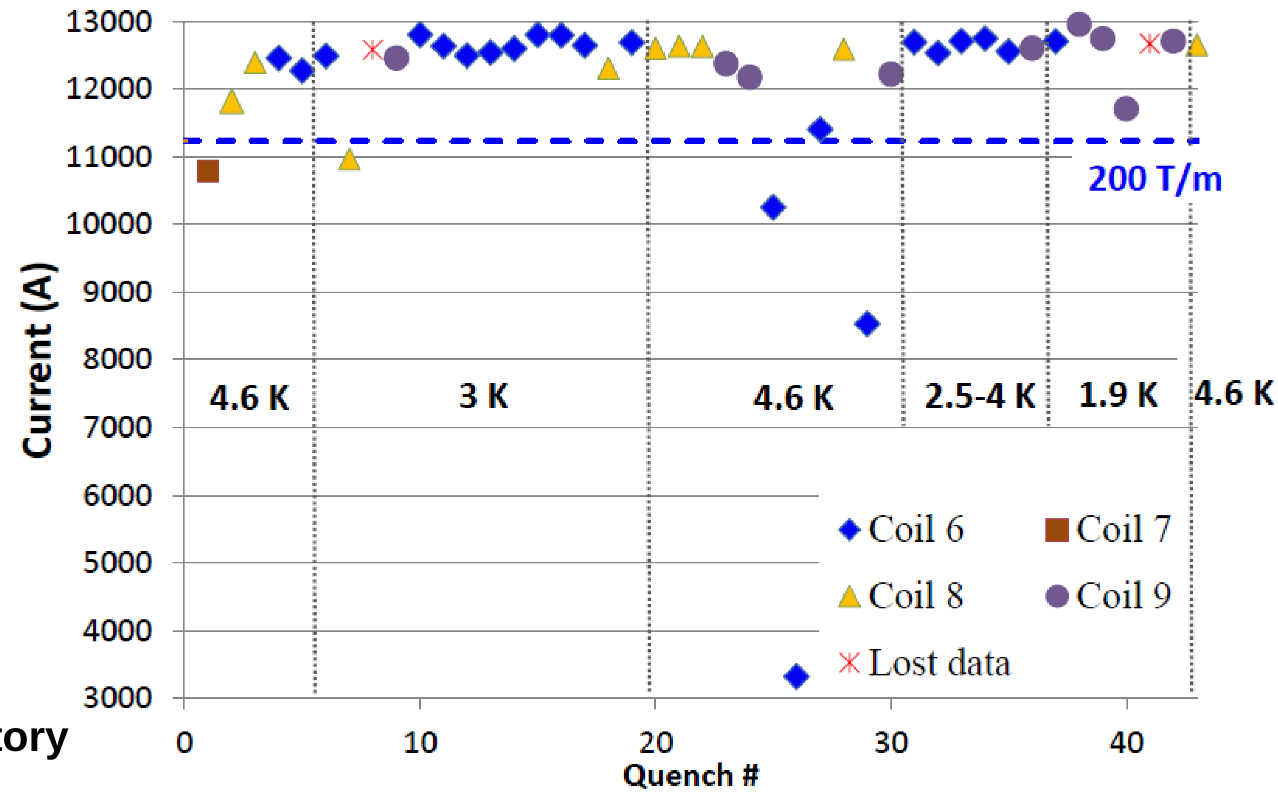
LQS01 Quench Locations

- All training quenches developed in the pole turn segments - no preferred longitudinal location was observed
- High ramp rate quenches developed in the mid-plane segments
- All coils participated in training



LQS01 Test at Fermilab

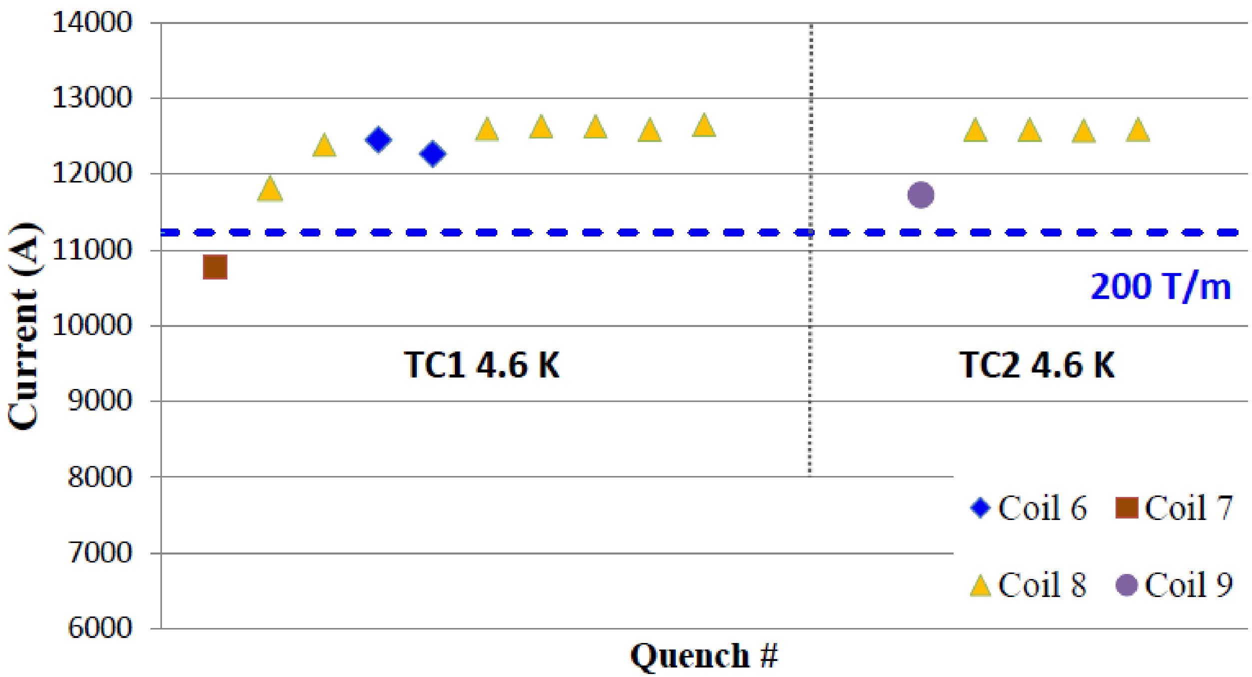
- LQS01b, a reassembly of LQS01a with more uniform and higher pre-stress, was tested in July 2010
  - Reached 222 T/m at 4.6 K



LQS01b quench history

LQS01b 2nd Thermal Cycle

- LQS01b retested after a full thermal cycle
  - The magnet was warmed up to 300 K and then cooled down to 4.6 K
  - Only one training quench was observed in TC2 at 208 T/m

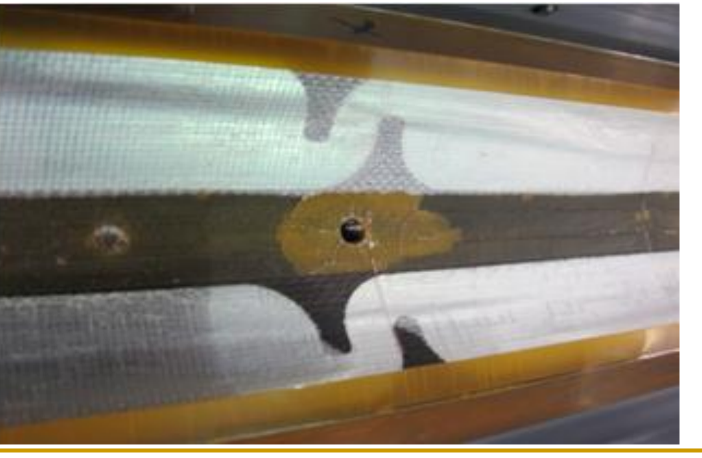


- LQS01 test results were reported at ASC-2010 (***IEEE Trans. on Applied Supercond.*** **Vol. 21, no. 3, p. 1858-1862, June 2011**)

LQS02 Test at Fermilab

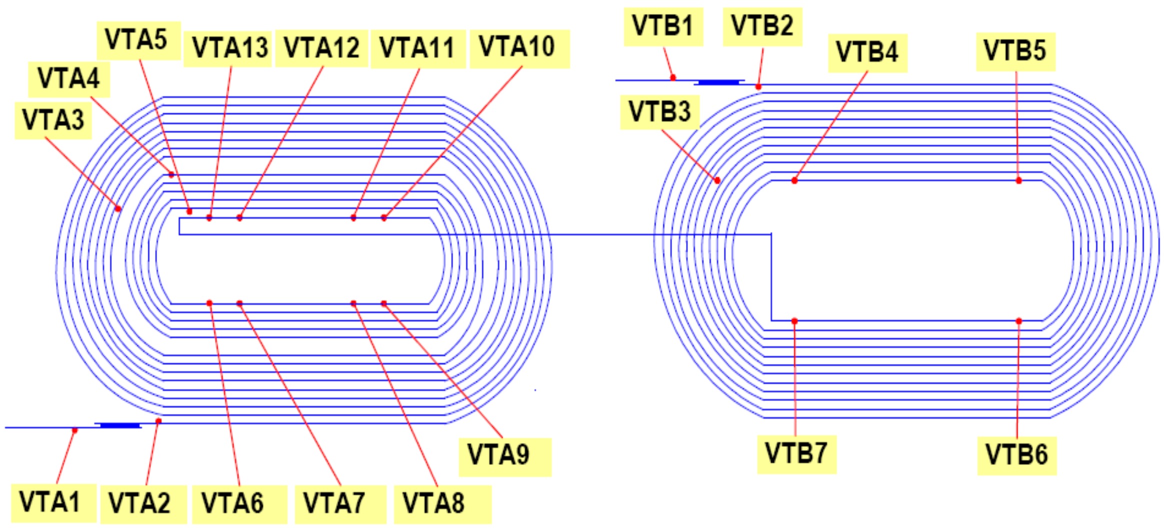
- One of the main goals of LQS02 test was to reproduce LQS01b performance
- 4 new coils were made with the same conductor and design of the LQS01 coils
- Only in coil 13 the inner layer insulation was reinforced to prevent de-bonding of the protection heaters observed after the test in LQS01
- Three different materials applied each one covering 1/3 of the coil length:
  - *S2 glass* 127 μm thick
  - 2 layers of *Nomex* 51 μm thick each
  - 1 layer of ceramic cloth 152 μm thick

LQS01 IL heaters show signs of de-lamination



LQS02 Test at Fermilab

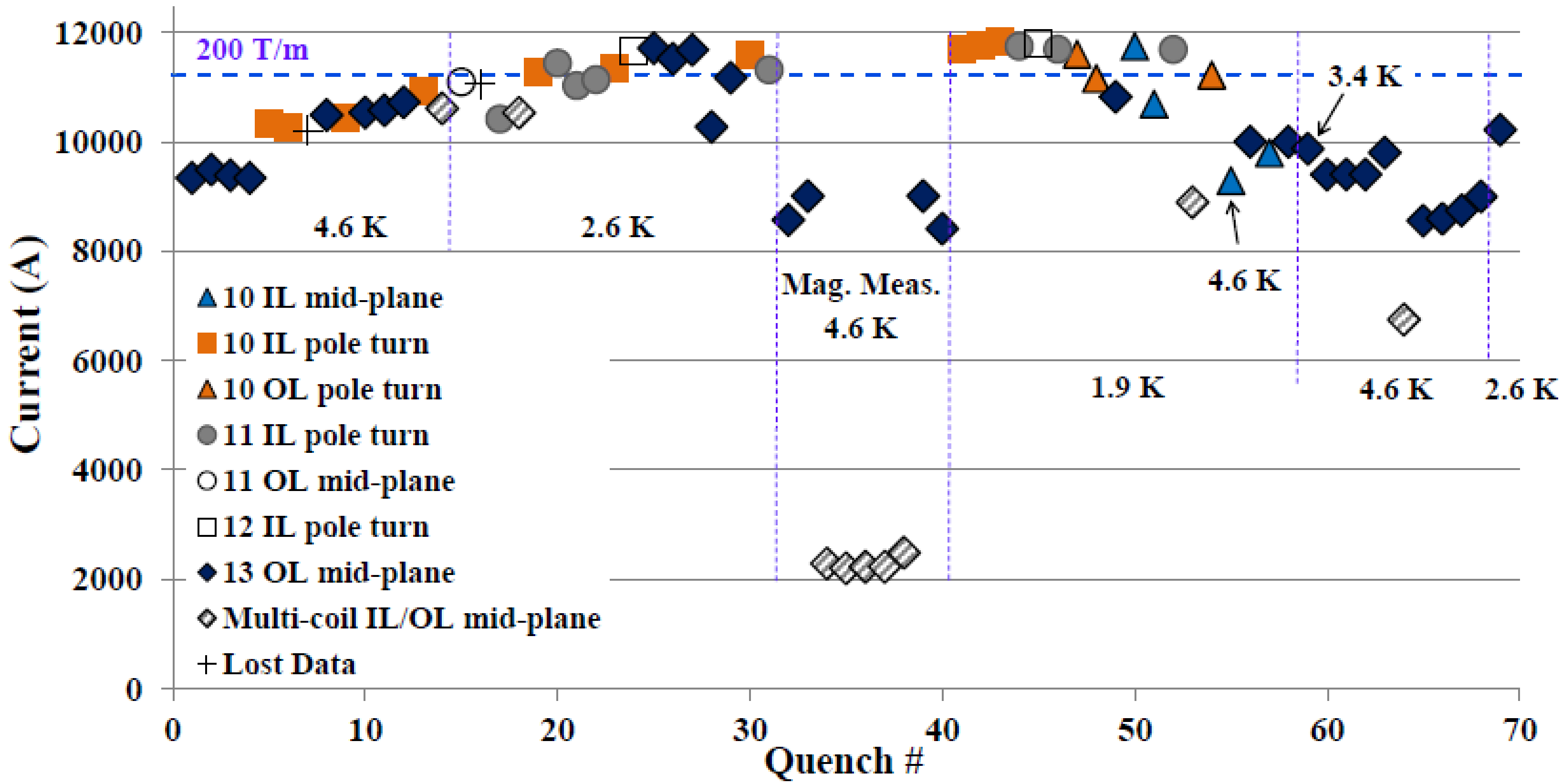
- SSL was computed based on extracted witness sample test results
  - LQS02 SSL estimate w/o additional strain: 13.8 kA or 240 T/m at 4.6 K
  - Compare to 13.75 kA for LQS01 SSL at 4.6 K
- Azimuthal compression of the coil's pole reached -133 ± 28 MPa in LQS02, similar to -130 ± 30 MPa in LQS01b
- LQS02 was tested at Fermilab in July-August 2011



Voltage tap system in LQ

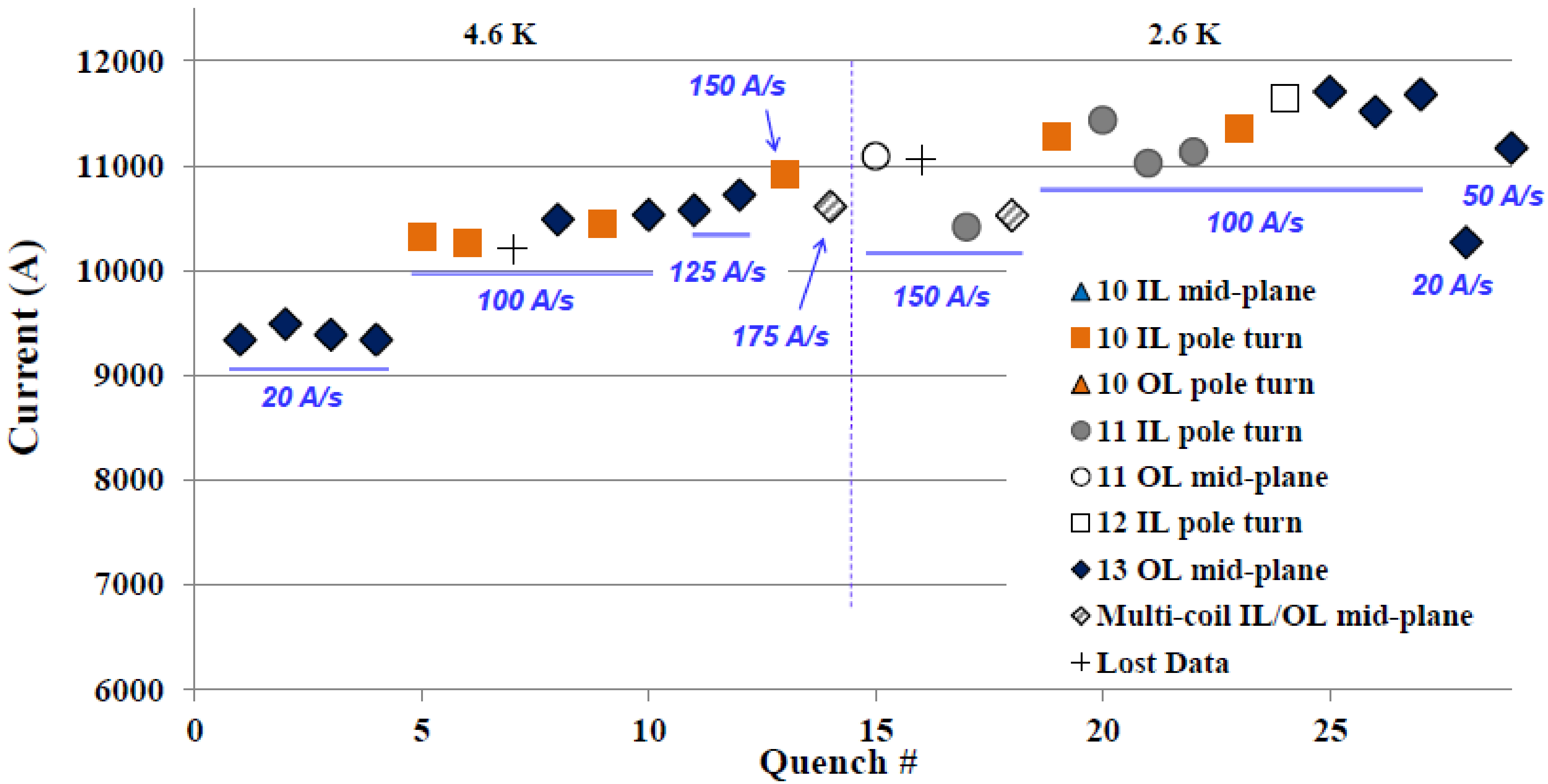
LQS02 Quench History

- Coil 13 was limiting the LQS02 quench performance



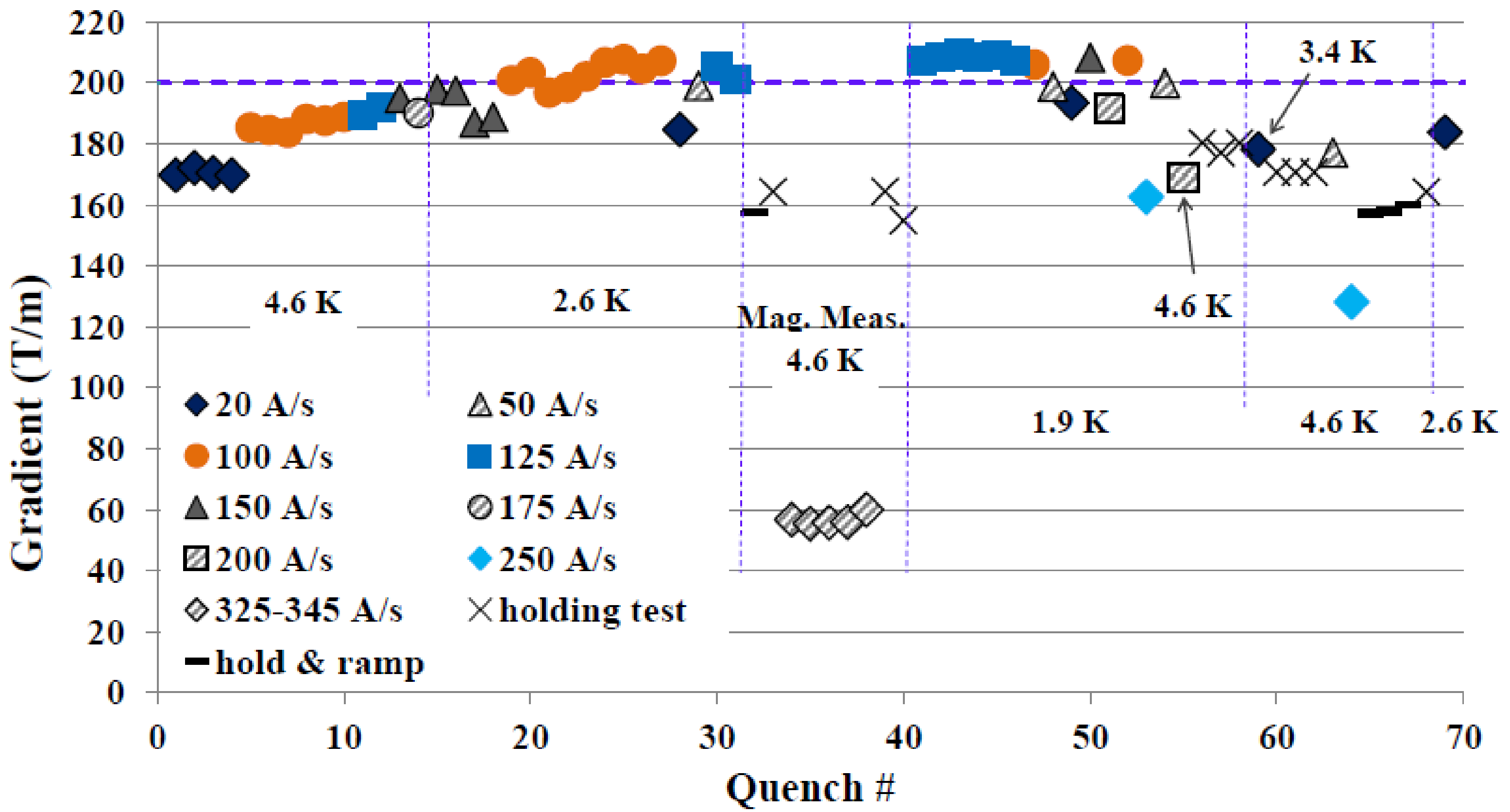
First training quenches

- Higher quench currents reached by increasing the ramp rate at 4.6 K
- Slow training for 100 A/s ramp rate at 2.6 K



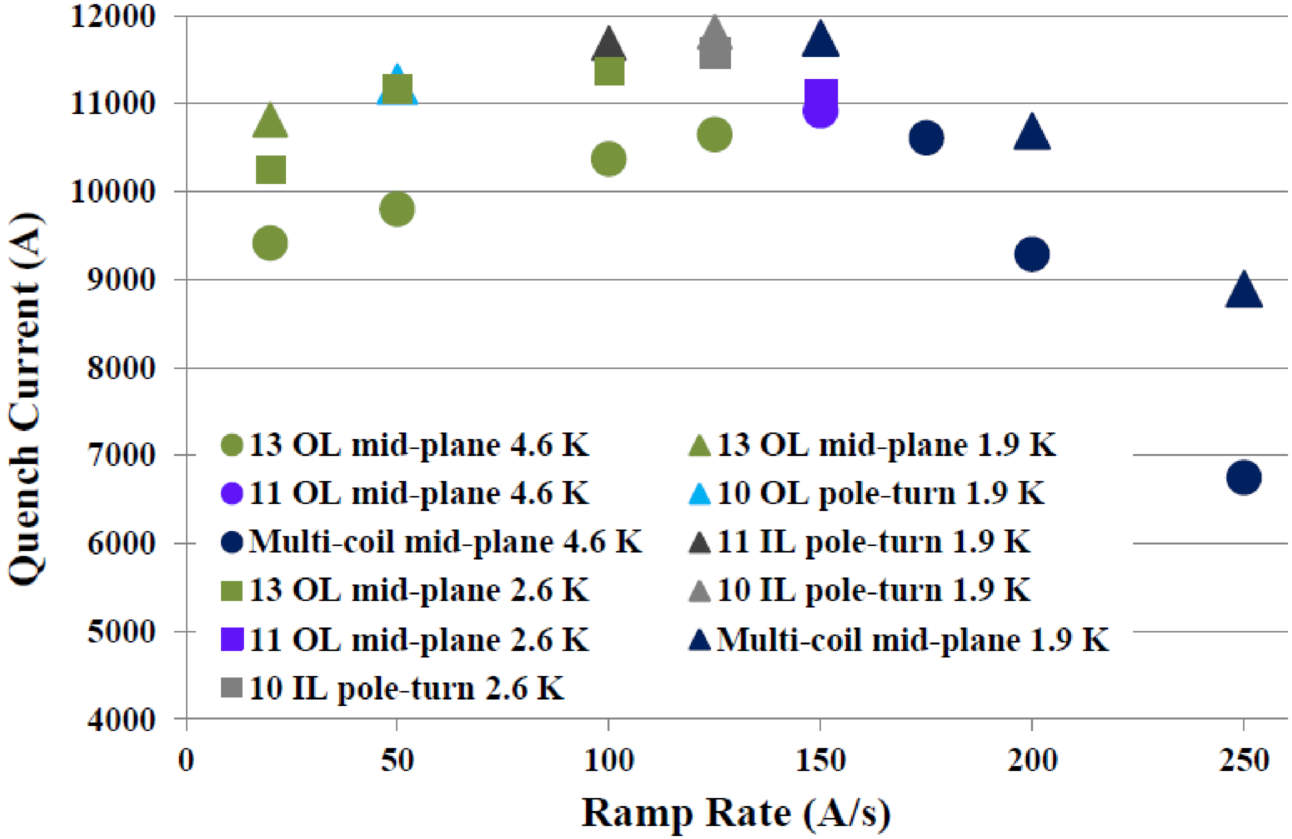
LQS02 Quench History

- Exceeded 200 T/m at 1.9 K and 2.6 K (only for ramp rates of 100-150 A/s) but failed to reproduce LQS01b performance



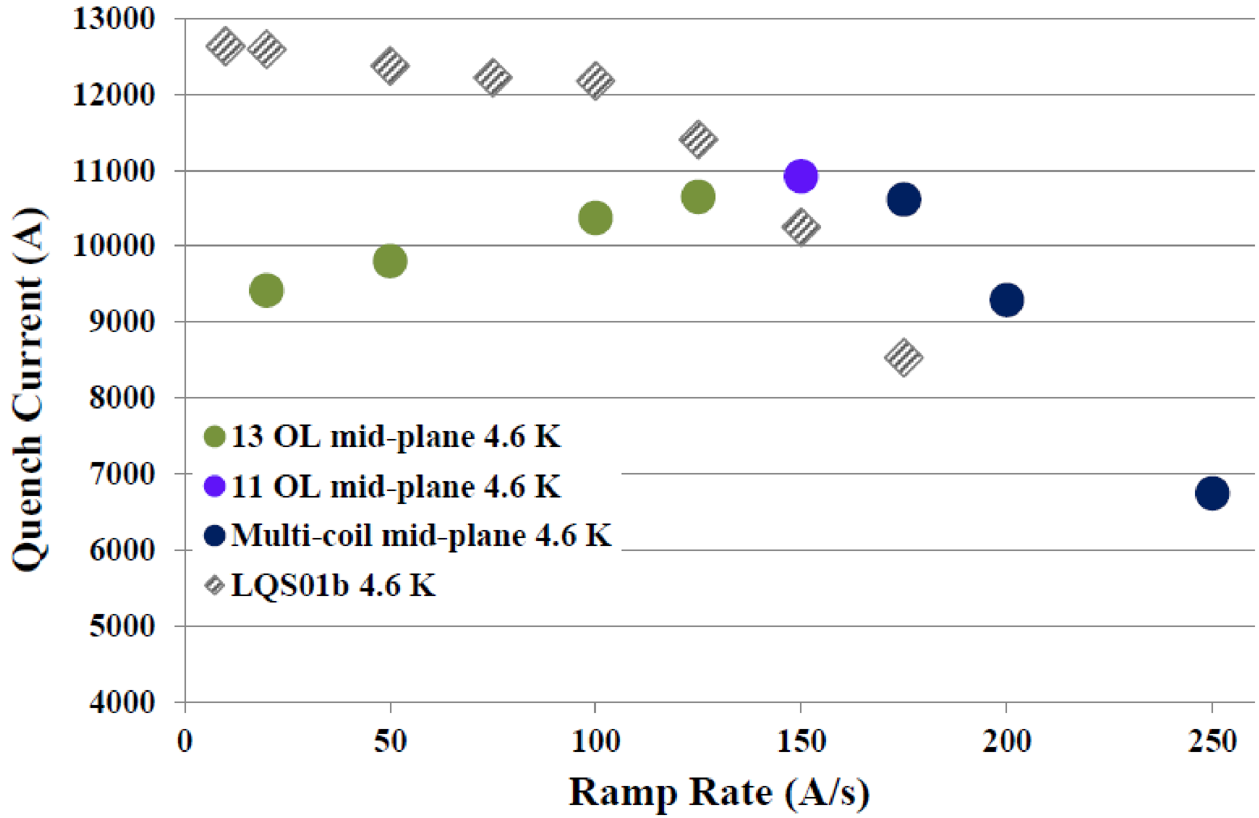
LQS02 Ramp Rate Dependence

- Ramp rate dependence was studied at 1.9 K, 2.6 K and 4.6 K
- Low ramp rate quenches developed in the OL mid-plane block of coil 13



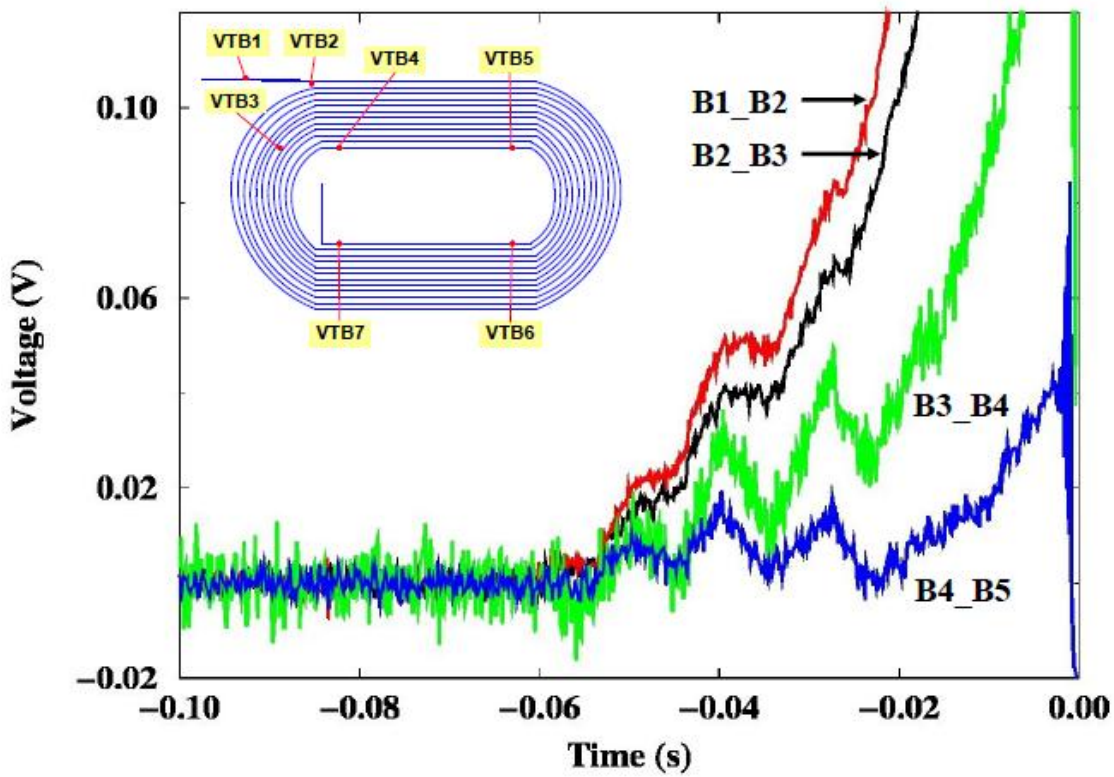
Ramp Rate Dependence: LQS01b vs. LQS02

- LQS01 and LQS02 magnets with the same conductor and coil design show very different ramp rate dependence
- Not mechanical limitation at low ramp rates in LQS02



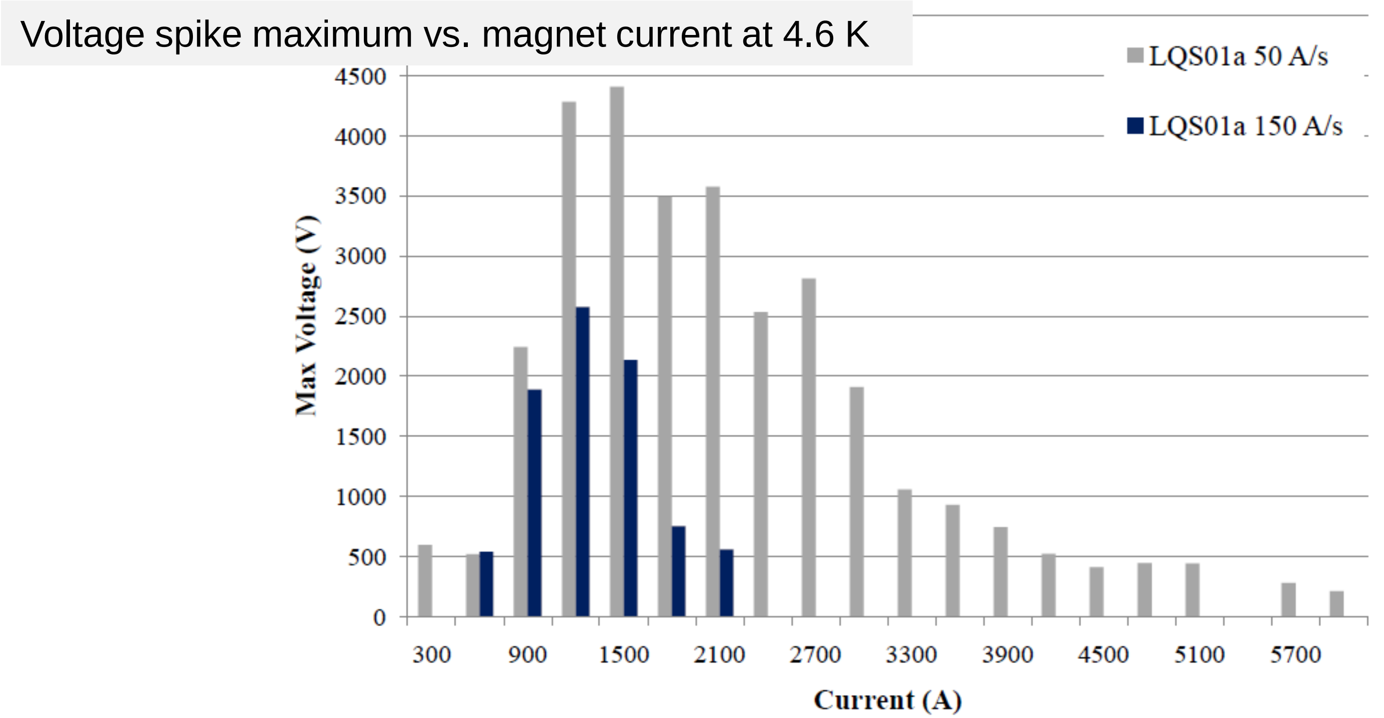
LQS02 quenches in coil 13

- All quenches in coil 13 OL mid-plane area showed similar pattern
  - Simultaneous start in several segments
  - Voltage spikes at the beginning of quench could be indication of decreased conductor stability



Voltage Spikes in LQ magnets

- The voltage spike detection system (VSDS) captures half-coil signals at 100 kHz sampling rate
- Different ramp rates result in the different voltage spike distribution. Current dependent thresholds were derived from the spike data analysis

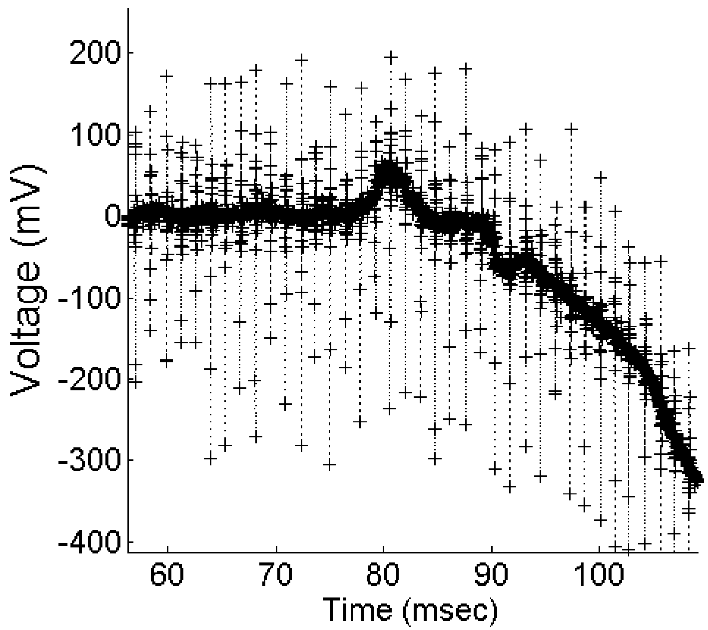


- Large spike activity observed in LQS01/02 at low currents 1000-1500 A

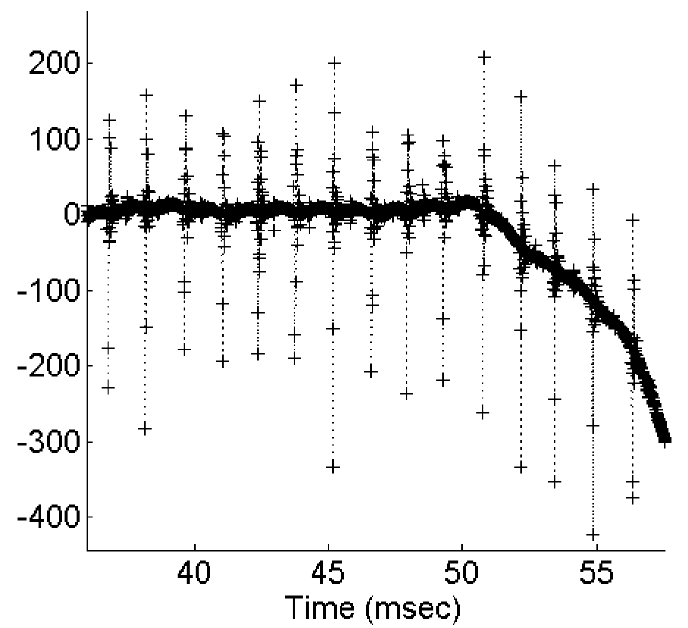
LQS02 quench patterns at high currents

- Quench patterns in coil 13 OL mid-plane block (left) and coil 10 pole-turn block (right)

Coil 13 OL mid-plane, 10.5 k A

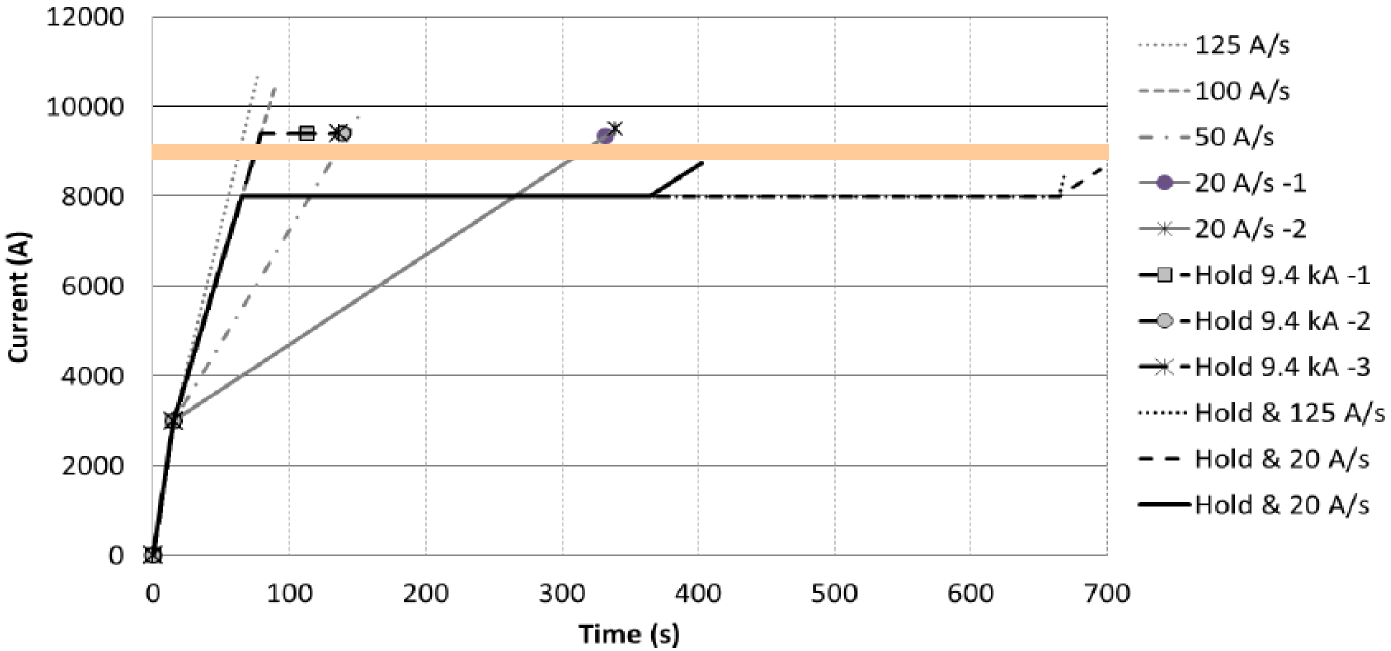


Coil 10 IL pole-turn, Quench at 10.5 k A



More checks on conductor stability in LQS02

- “Unknown conductor damage” could be a reason for enhanced instability
  - Forcing current in a fewer number of strands
- Holding quenches: the magnet current increased to 9.4 kA and then held till a quench occurred after 34 s, 57 s and 60 s



- All segments have RRR larger than 200, resistance of NbTi-Nb_3Sn splices in coil 13 found acceptable 0.8-1 nOhm

Field quality measurements in LQ magnets

- Rotating coil system with 0.1-m or 0.8-m long and 4-cm diameter tangential probes was used for “cold” magnetic measurements
- Room temperature measurements performed before and after the cold test
  - Magnet in a horizontal position
  - 0.48-m long and 6-cm diameter mole-type rotating probe
  - Measurement current at ±10 A
- 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 90% of quench current at plateau
  - Eddy current loops with the ramp rates 20 A/s, 40 A/s, 80 A/s
  - Measurement of dynamic effects (accelerator profile)
  - Stair step measurements from 1.5 kA to 9-10 kA
- Reference radius at 2.25 cm

Calculated and measured harmonics at 45 T/m

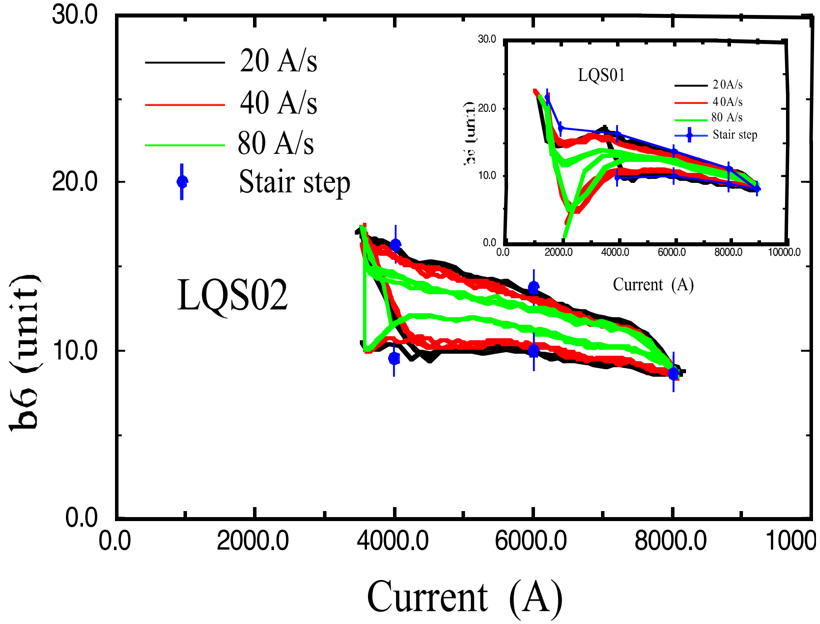
- Good agreement between the measured and calculated harmonics w/o coil alignment feature in LQ magnets

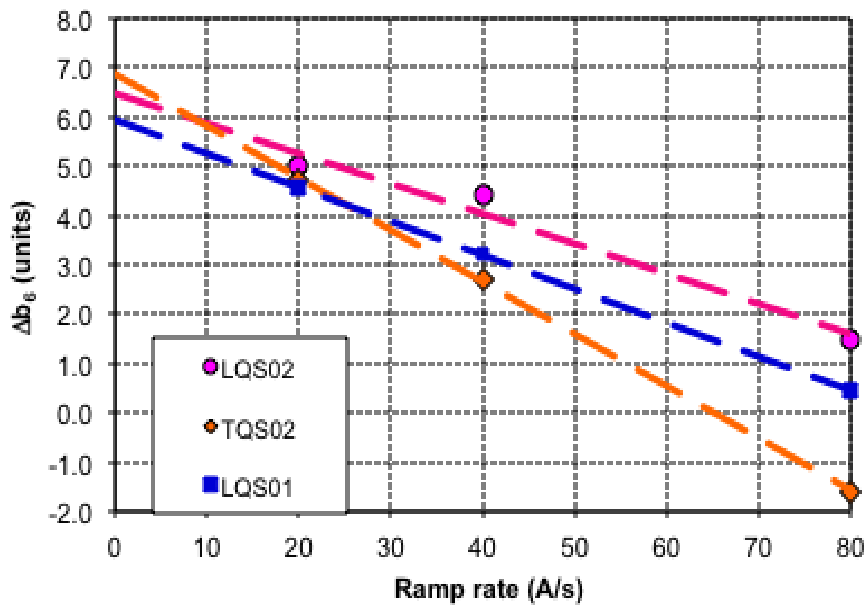
b_n a_n	CALCULATED	MEASURED		CALCULATED	MEASURED	
		TQS01	TQS02		LQS01	LQS02
b_3	-	-1.46	2.98	-	3.43	-14.0
b_4	-	-0.52	1.31	-	6.20	2.64
b_5	-	3.06	-1.45	-	-0.16	-3.16
b_6	5.00	5.40	6.23	8.45	10.43	8.44
b_7	-	0.07	0.05	-	-0.10	0.54
b_8	-	-0.11	-0.13	-	-0.58	-1.28
b_9	-	0.02	0.10	-	-0.14	-0.13
b_{10}	0.04	0.02	-0.05	-0.03	-0.32	-1.13
a_3	-	4.41	0.66	-	2.11	-0.74
a_4	-	-1.99	0.82	-	1.34	0.68
a_5	-	0.71	-1.50	-	0.48	0.48
a_6	-	-0.37	0.12	-	-0.37	0.06
a_7	-	-0.11	-0.01	-	-0.30	0.61
a_8	-	-0.18	-0.10	-	-0.09	0.35
a_9	-	-0.02	0.02	-	-0.55	-1.68
a_{10}	-	0.00	-0.08	-	0.24	0.31

George Velev

Eddy Current effects

- Excitation loops executed at 20 A/s, 40 A/s and 80 A/s
- Current loops started at 3.5 kA due to a low current voltage spikes
- LQS01 and LQS02 showed similar hysteresis widths
- Eddy current effects due to low inter-strand resistance



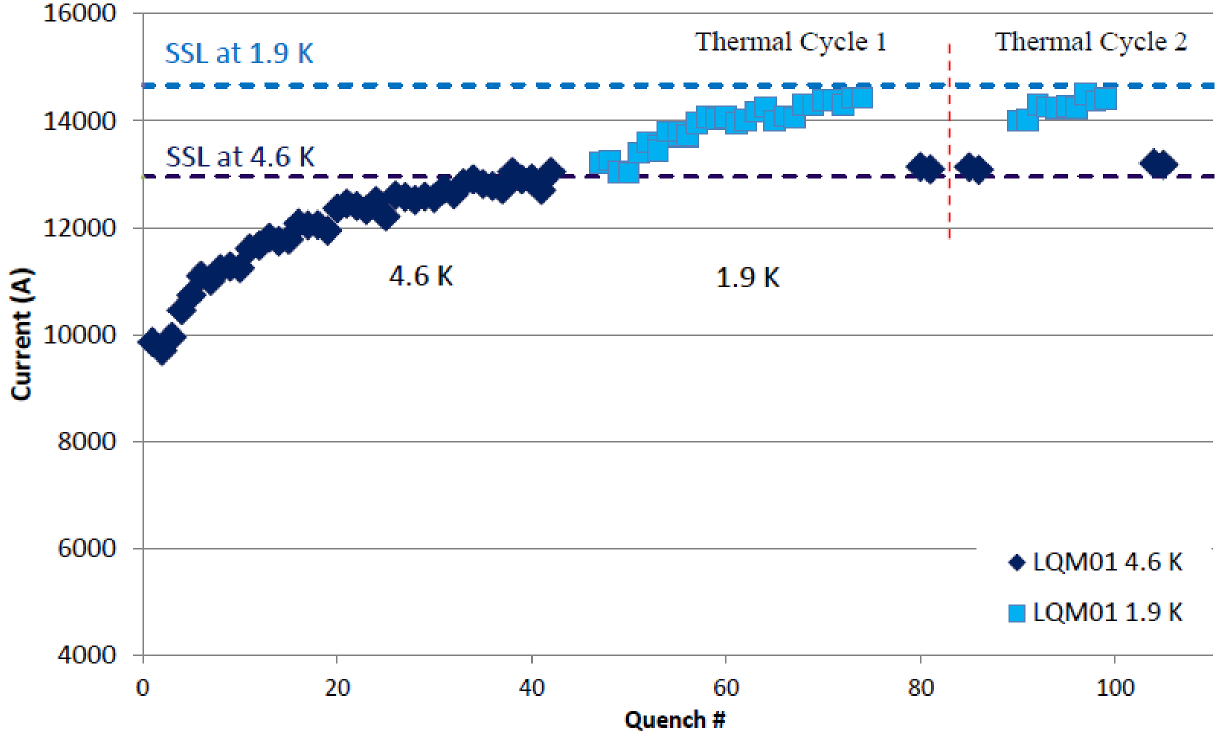


Summary on Field Quality Measurements

- Good agreement was found between calculated and measured harmonics at 45 T/m
  - Except for the normal sextupole of LQS02 at the level of 14 units
  - Coil alignment should help to reduce large multipoles
- Relatively large Eddy current effects due to low inter-strand resistance
  - SS core in cable will help to control these effects
- Iron saturation observed for currents above 5-6 kA
  - SS pads could reduce the observed saturation
- No decay or "snapback" effects were observed
  - More study to be done
- Field quality measurement results presented at ASC-2010 (***IEEE Trans. Appl. Supercond*****., Vol. 21, no. 3, pp. 1688-1691, June 2011)** and MT-22 (***5JO-4, Marselle, 12-16 September 2011***)

LQ coil 14 test in a mirror structure

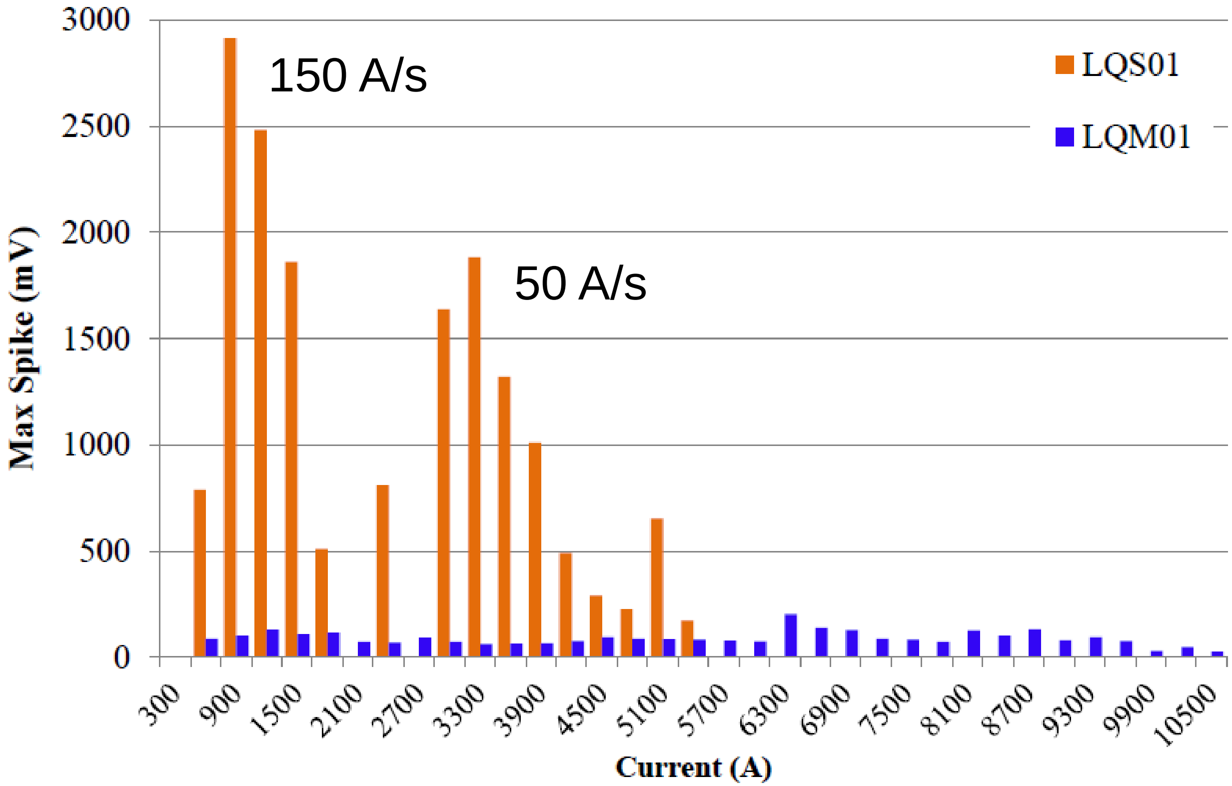
- LQ coil 14 in a mirror structure tested at Fermilab in Feb.-March 2011
  - 0.7 mm Nb_3Sn strand of RRP 114/127 sub-element design
  - Almost same filament size as in RRP 108/127 strand (LQ coils 15-19)
  - E-Glass insulated cable



- Coil 14 reached SSL both at 4.6 K & 1.9 K

Voltage spikes in LQ coil 14

- Coil 14 (RRP 114/127) vs. LQS01a (RRP 54/61)



- LQM01 test results presented at CEC/ICMC 2011 (***C2PoA-02, Washington 13-17 June 2011***)

Next steps

- New coils using Nb_3Sn strands of RRP 108/127 sub-element design will be tested in May 2012
- Check magnet performance after uncontrolled warm-up and cool-down
  - Until now controlled cool-down and warm-up was applied with a maximum top-bottom temperature difference of 150 K
- Demonstrate stable performance especially at lower temperatures, as well as accelerator quality features
  - More field quality measurements
- Transition to the long high-gradient quadrupoles (LHQ)

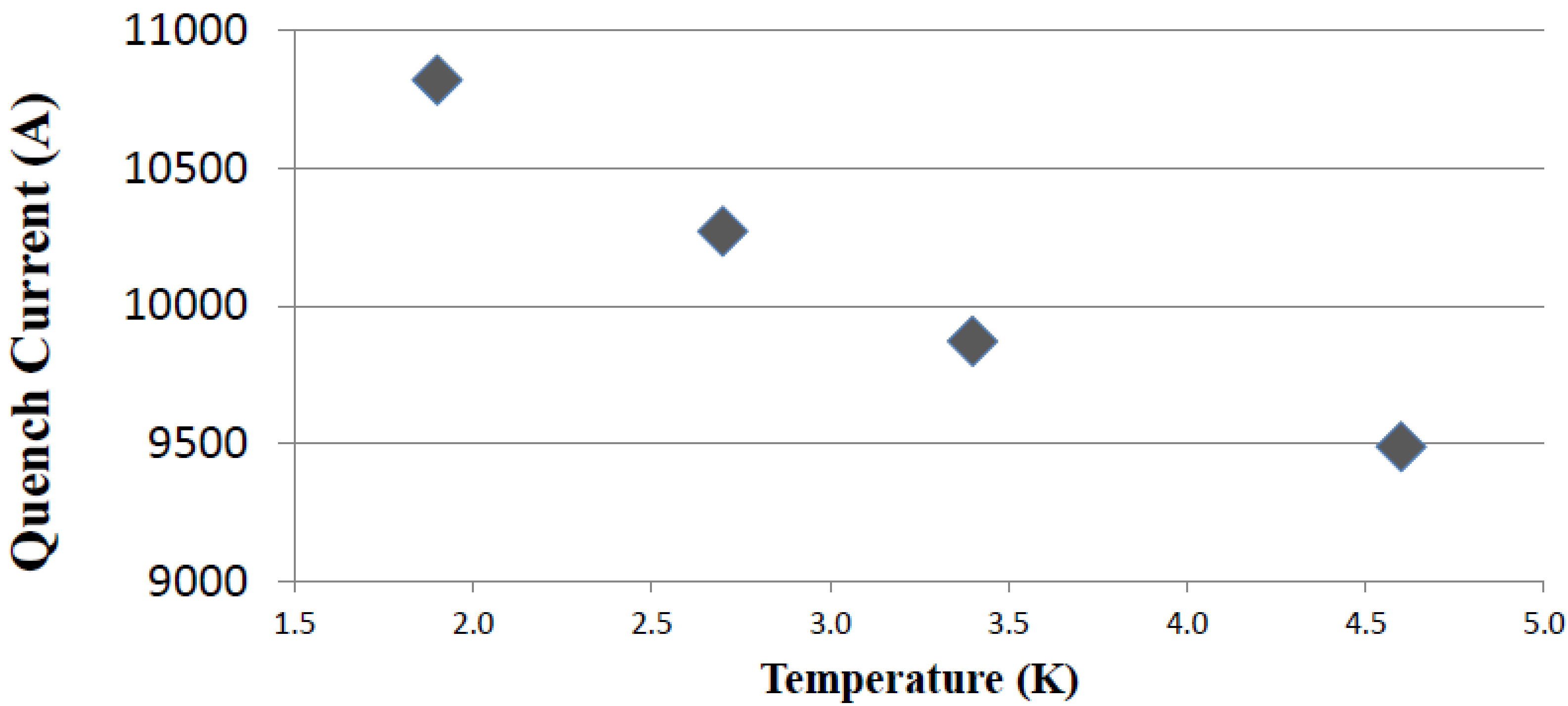
Conclusion

- LQS01, the first 3.7-m long Nb_3Sn quadrupole reached and exceeded its target field gradient of 200 T/m. The magnet showed good training memory after a full thermal cycle
- LQS02 reached 200 T/m at 2.6 K and 1.9 K, but failed to reproduce LQS01 performance
- LQS02 test results indicate an enhanced instability of the conductor
- Inner layer insulation in one of the LQS02 coils was reinforced to prevent de-bonding of the protection heaters
  - Results will be available after disassembly of LQS02
- First LQ coil with a smaller filament size (RRP 114/127) successfully was tested in a mirror structure
  - Stable and predictable performance both at 4.6 K and 1.9 K

Backup Slides

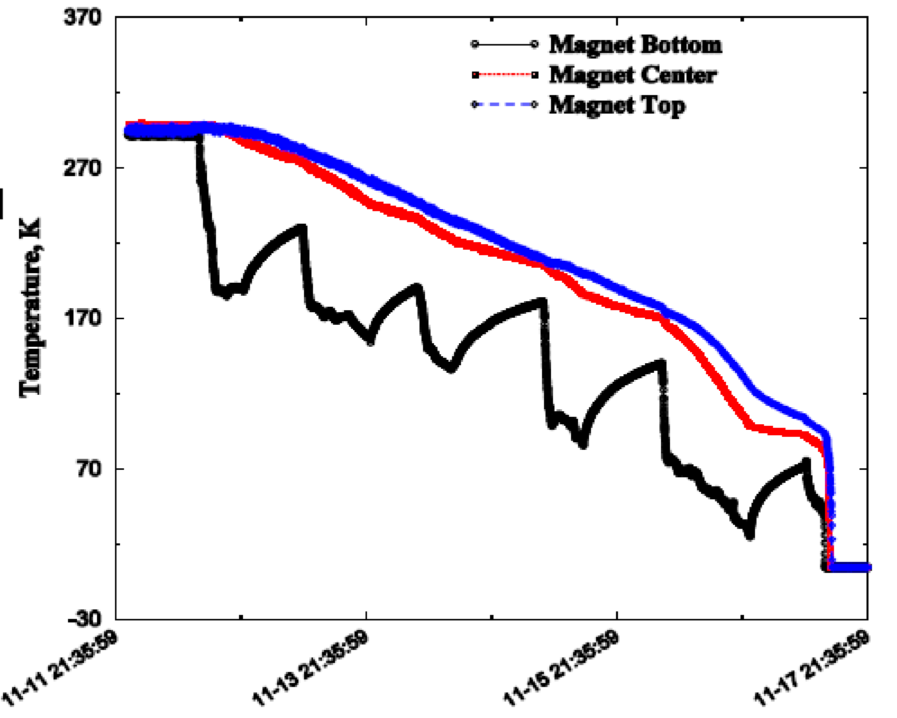
LQS02 Temperature Dependence

- Only quenches at 20 A/s



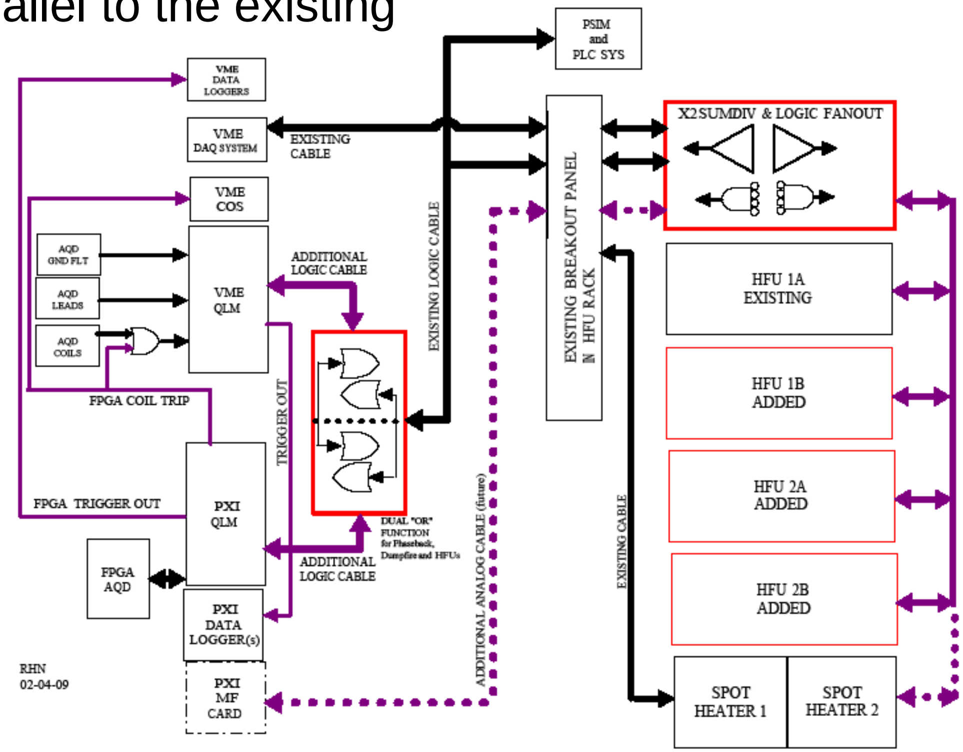
Cool down and first quenches

- 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



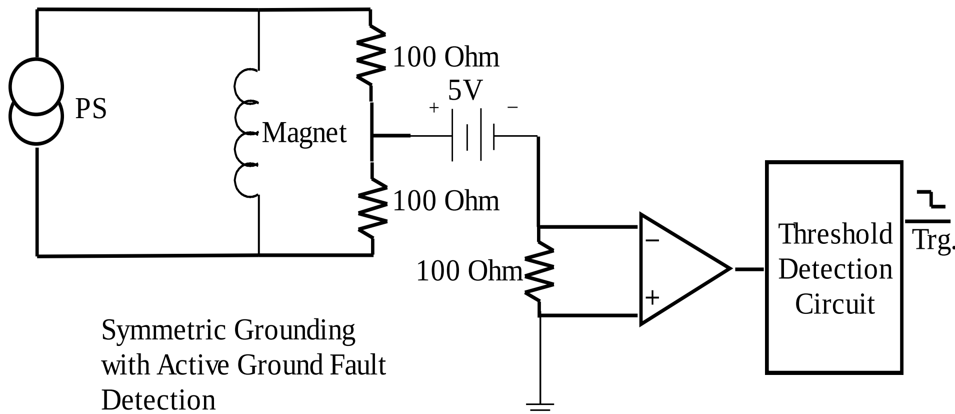
Quench Detection System with Adaptive Thresholds

- 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.



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)