Long Quadrupole

G. Ambrosio
Fermilab

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2nd Joint HiLumi LHC/LARP Annual Meeting
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Frascati

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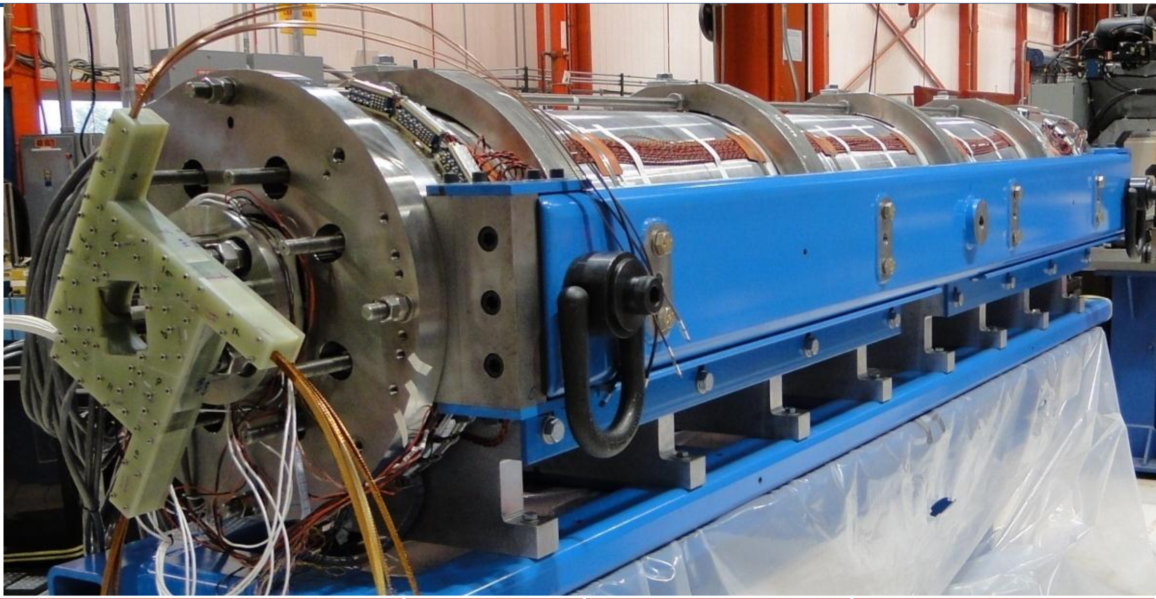
High Luminosity LHC

U.S. LARP

Long Nb_3Sn Quadrupole†



Main Features:

Aperture: 90 mm

Magnet length: 3.7 m

Target:

Gradient: 200 T/m

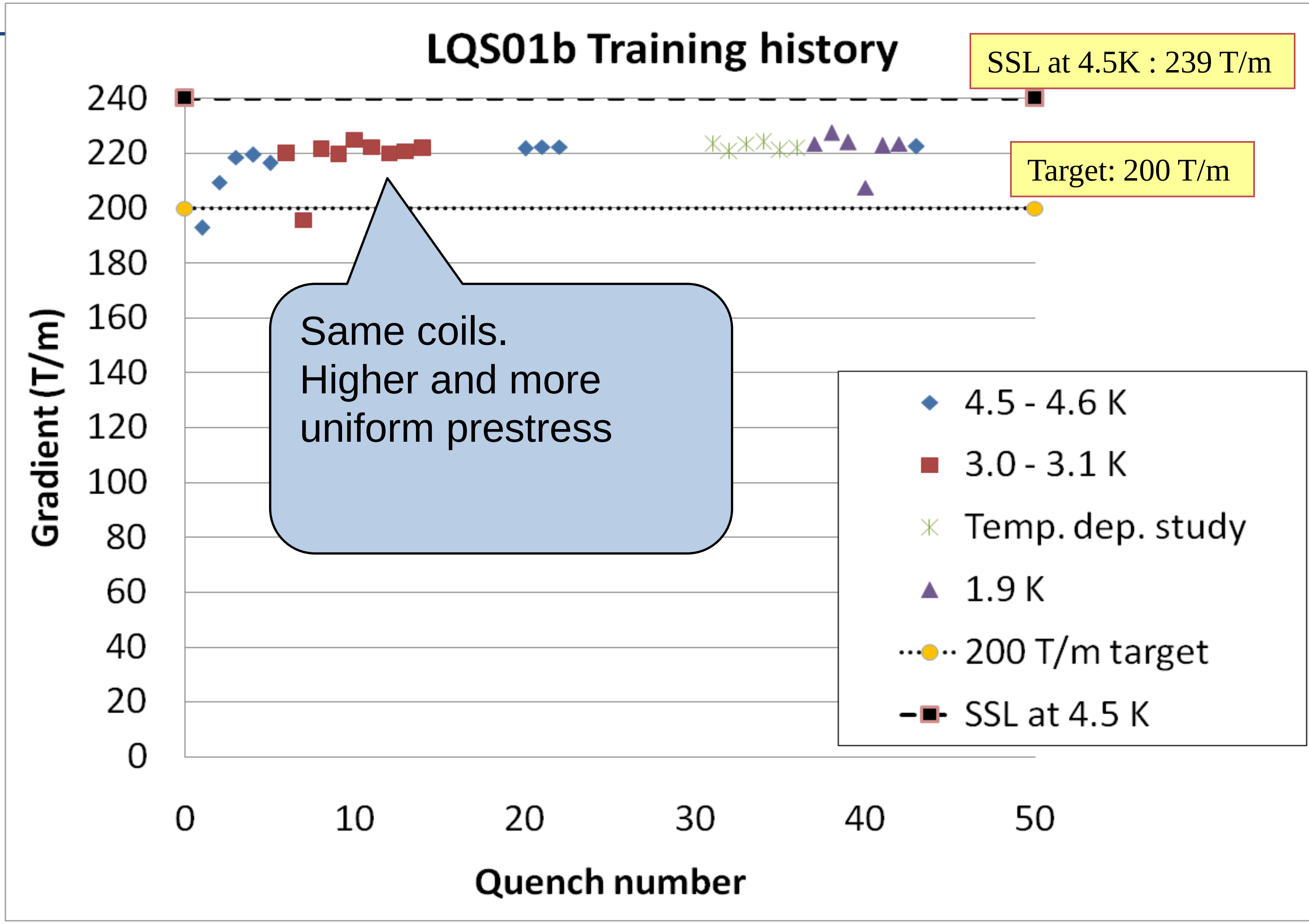
Goal:

Demonstrate Nb_3Sn magnet scale up

Parameter at ssl		LQS01/02	LQS03
Strand type		RRP 54/61	RRP 108/127
Jc at 4.2K 12T	A/mm^2	2670	2660
Copper	%	46%	55%
SSL Current 4.6K/1.9K	kA	13.7/15.2	12.9/14.4
SSL Gradient 4.6K/1.9K	T/m	239/263	227/250

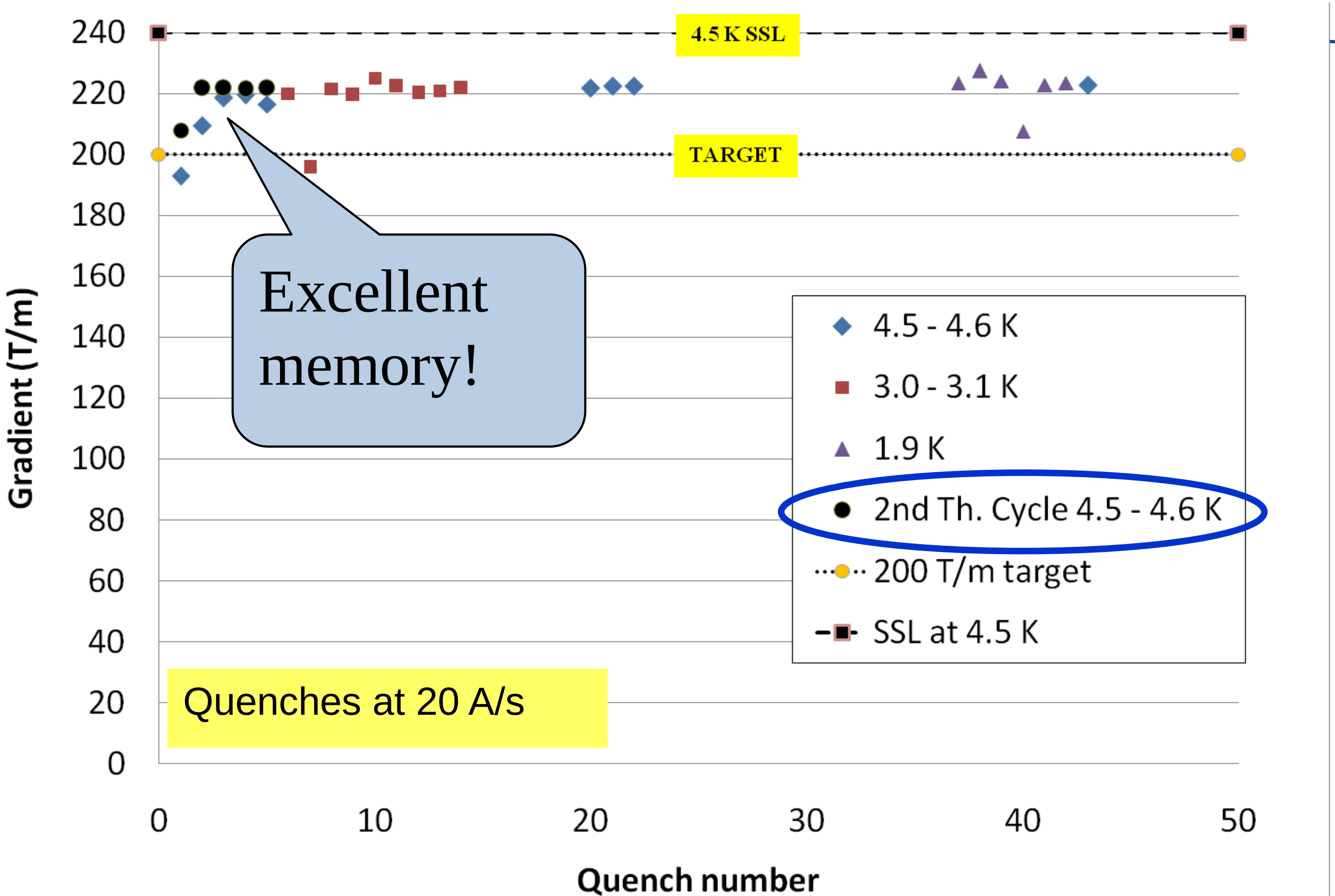
† LQ Design Report available online at:
https://plone4.fnal.gov/P1/USLARP/MagnetRD/longquad/LQ_DR.pdf

LQS01a/b



G. Ambrosio et al. “Test Results of the First 3.7 m Long Nb3Sn Quadrupole by LARP and Future Plans” *IEEE Trans. on Applied Supercond.*, Vol. 21, no. 3, pp. 1058-1062, June 2011

LQS01b 2nd Thermal Cycle



G. Ambrosio, et al., "Progress in the Long Quadrupole R&D by LARP", *IEEE Trans. Appl. Supercond.*, vol. 22, No. 3, June 2012

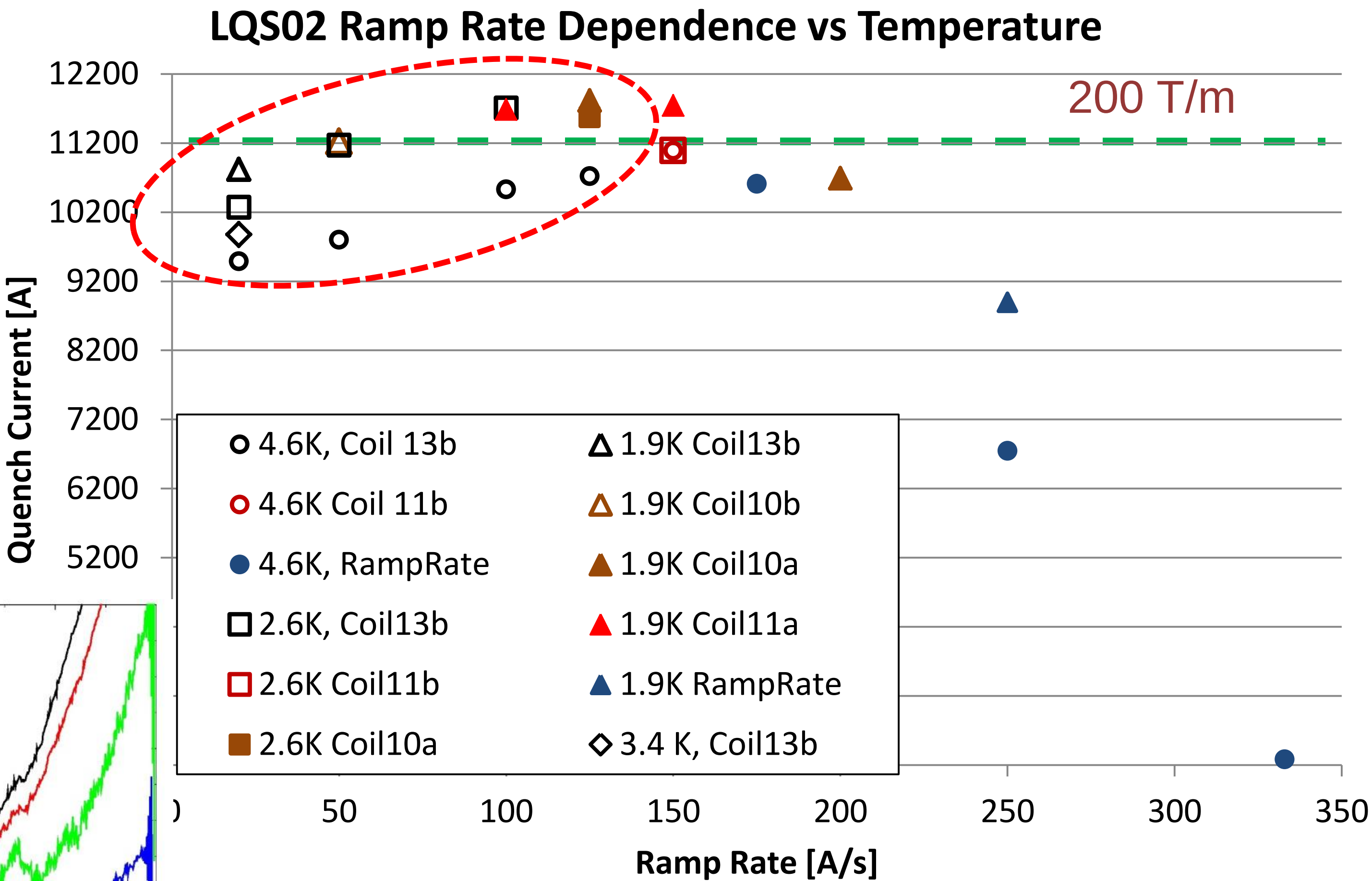
LQS02

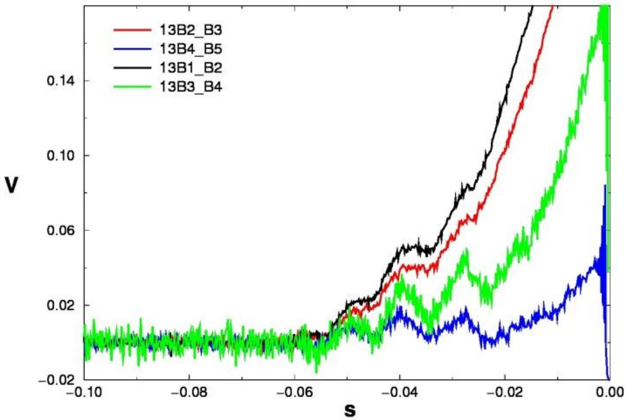
"Reverse ramp-rate dependence"

➔ ~180 T/m

Caused by:

"Enhanced instability"





G. Ambrosio, et al., "Progress in the Long Quadrupole R&D by LARP", *IEEE Trans. Appl. Supercond.*, vol. 22, No. 3, June 2012

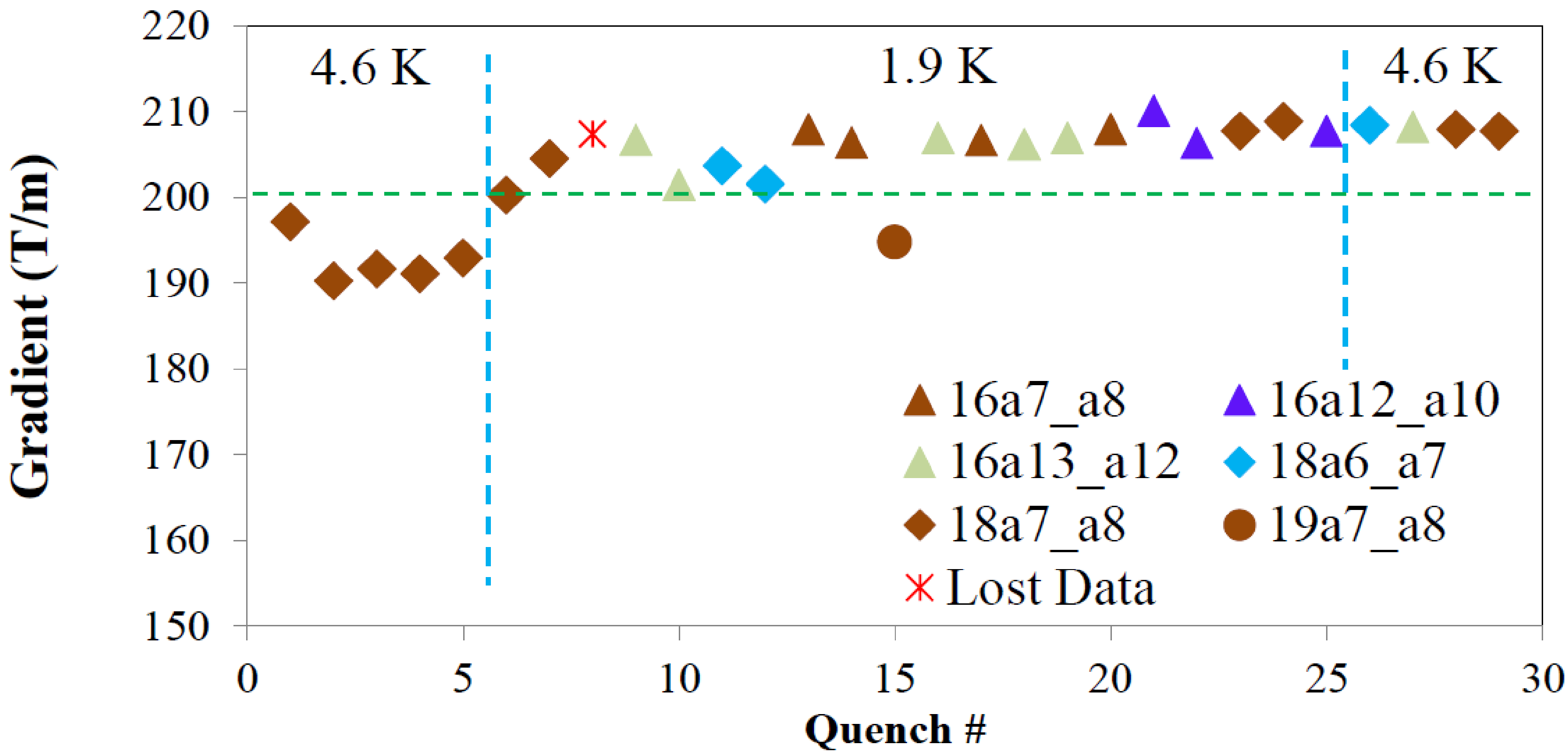
LQS03

Parameter at ssl		LQS01/02	LQS03	TQS03
Strand type		RRP 54/61	RRP 108/127	RRP 108/127
Jc at 4.2K 12T (with SF)	A/mm^2	2670	2660	2790
Copper	%	46%	55%	54%
RRR of extracted strands*		>150	70-150	150-190
SSL Current 4.6K/1.9K	kA	13.7/15.2	12.9/14.4	13/14.5
SSL Gradient 4.6K/1.9K	T/m	239/263	227/250	231/254

* RRR = 50 in kinks of one LQS03 extracted strand

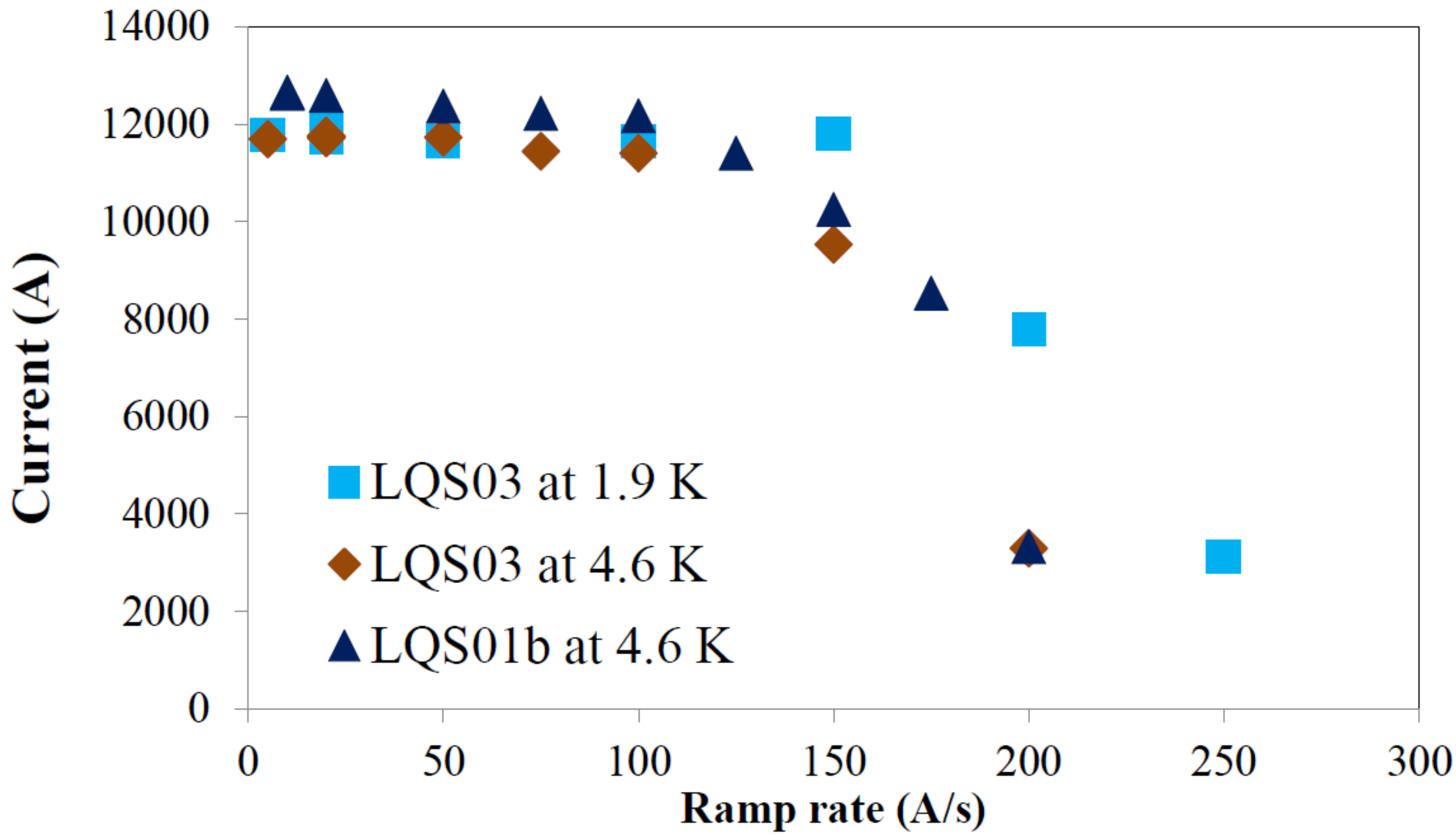
- Test Highlights:
  - 1st quench at 4.6 K reached 197 T/m (86% ssl)
  - 1st quench at 1.9 K exceeded 200 T/m (6th quench overall)
  - Temperature margin at 200 T/m ~3 K in peak field area

LQS03 Training History



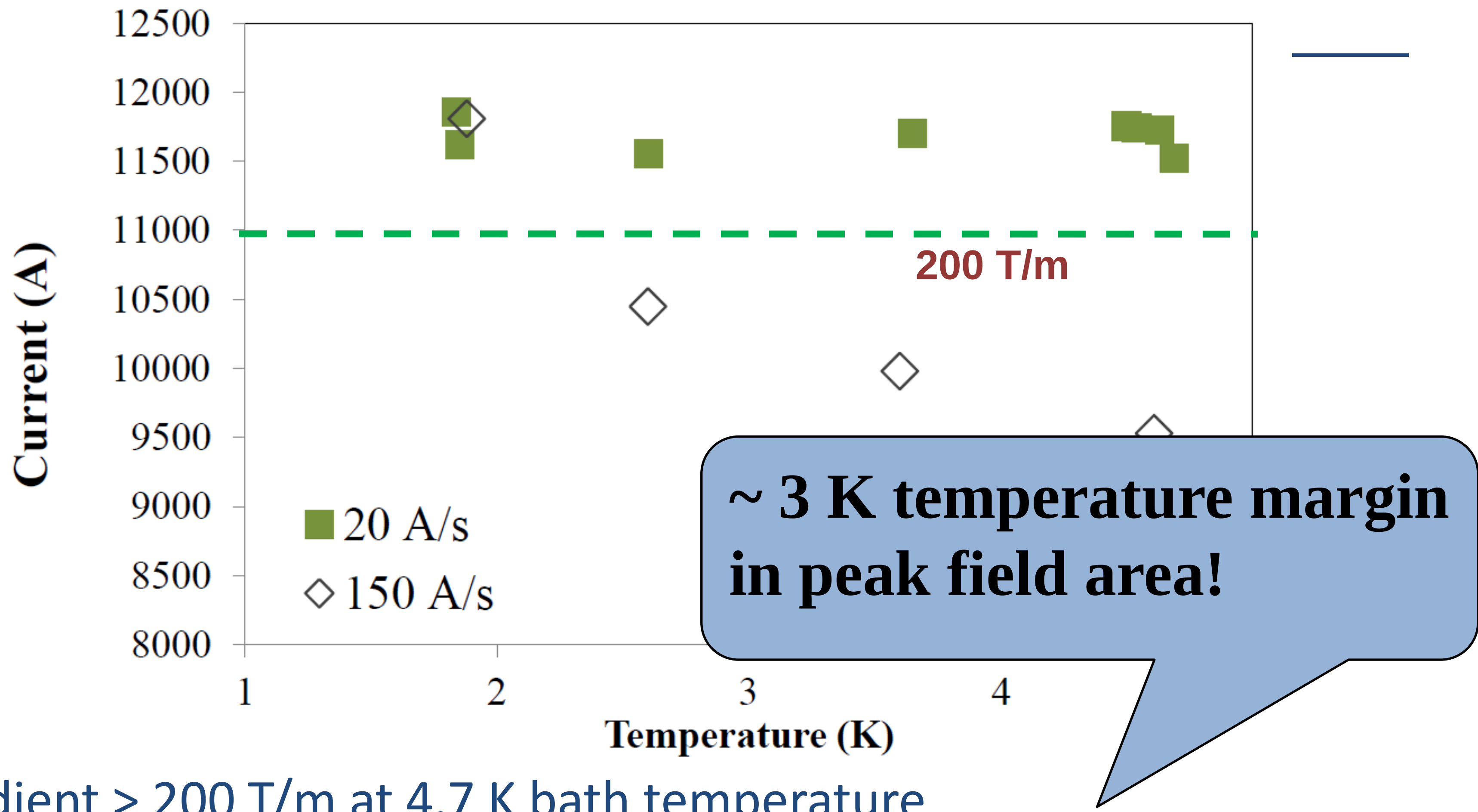
- Training quenches: 50 A/s to 9 kA, 20 A/s to quench
- All quenches started in the pole turn of the inner layer
  - Always in the straight section

LQS03 Ramp-Rate Dependence



- Current limitation in the range 11.5-11.8 kA
  - pole turn quenches (coil #16 and 18, several segments)

LQS03 Temperature Dependence



- Gradient > 200 T/m at 4.7 K bath temperature
- Gradient > 200 T/m at 4.6 K with 100 A/s current ramp
- Holding current at 200 T/m and 4.6 K for 40 minutes

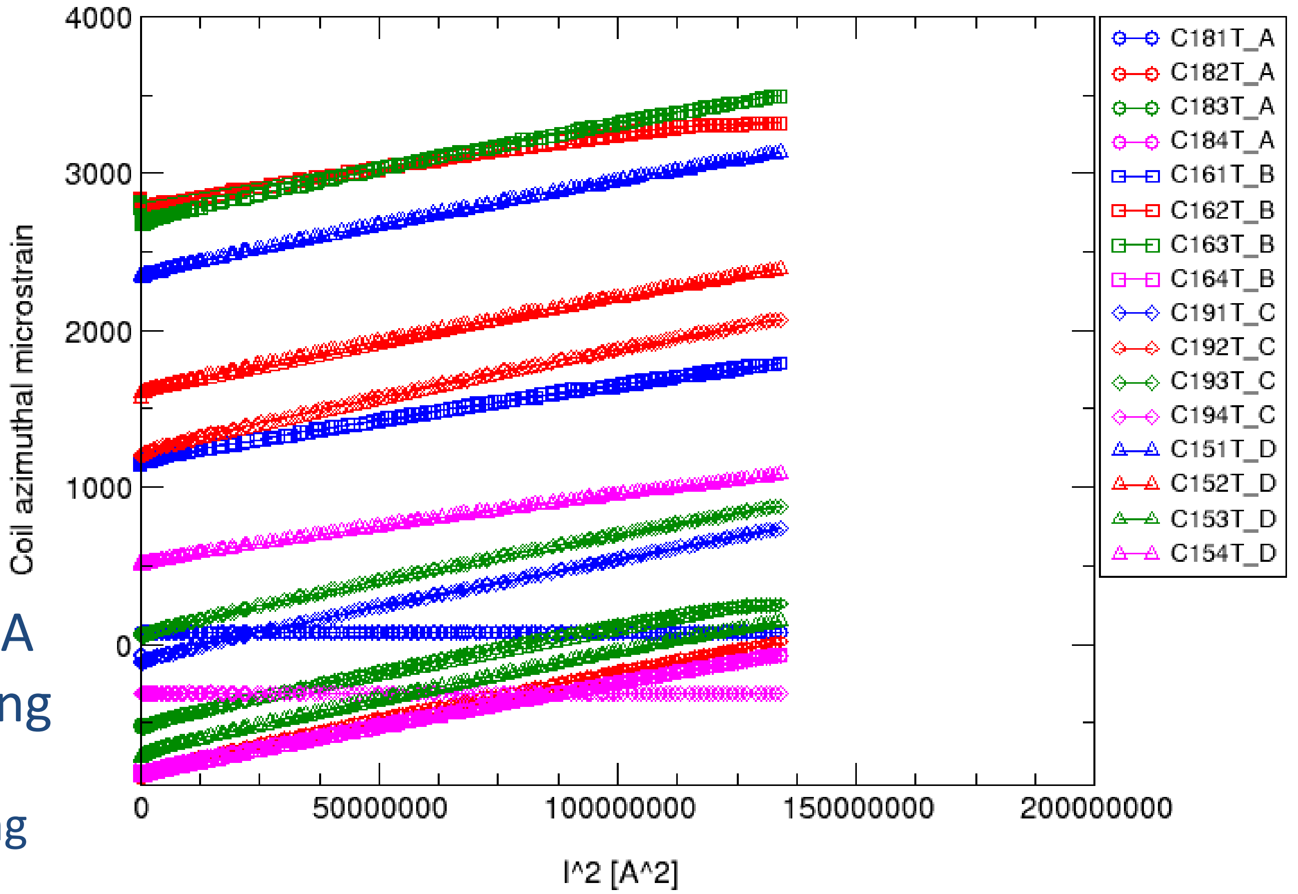
LQS03 Mechanical Behavior

Strain gauges on structure:

- As expected
- Same prestress as LQS02 (target)

Strain gauges on coils:

- 2 lost
- 1 unloading at 10.6 kA
- large spread of starting points
  - Calibration lost during cool down?
  - Issues with thermal compensation?



More details in next talk

LQS03 Preliminary Analysis

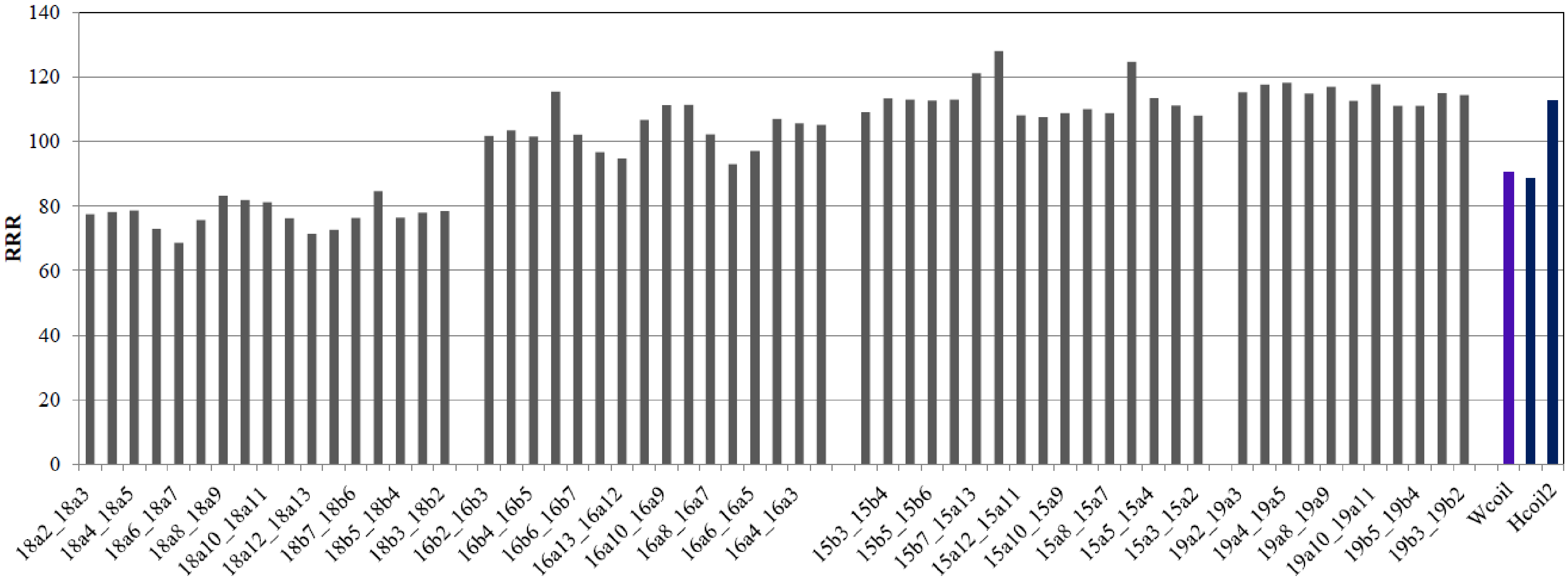
- Current limitation independent of temperature
  - 11.5-11.8 kA
- Quench onset moving through several segments of 2 coils
- No signs of precursors at quench start
- One strain gauge showed unloading at 10.6 kA
  - Current of quenches #2-#5
- ➔ possible cause: quenches due to start of unloading

- **But TQS03 showed more unloading and nonetheless trained up to 238 T/m**
- **➔ possible effect of low RRR (50) on MQE**
- **➔ possible contribution of self-field instability with low RRR**

E. Takala, et al., "Perturbation Sensitivity of the Magneto-thermal Instability",
ASC 2012: 4MF-02

LQS03 RRR measurements

Coil 18 Coil 16 Coil 15 Coil 19



High Luminosity LHC U.S. LARP

Conclusions

- LQS03:
  - reached 200 T/m at 1st 1.9 K quench
  - Demonstrated ~ 3 K temperature margin in peak field
  - Was current limited slightly above 200 T/m
    - Possible causes: low RRR and prestress
    - Disassembly and reassembly in the plans
- LQ R&D so far:
  - Reached 200 T/m in 4 tests out of 4
    - One magnet, LQS02, was limited (~180 T/m) by one coil
  - 11 coils, out of 12 tested, met requirements
  - Demonstrated very good training memory

My conclusions:

- small filaments provide resilience against issues
- ideal conductor has small filaments and high RRR
- in case of trade-off it is better to have small filaments than high RRR:
  - low RRR is detected early
  - in LQS03 did not prevent reaching target

- Stran
  - LQ
    -
  - LQ
  - LQS02 was l ... T/m by an unknown issue decreasing s... ity threshold in a coil
  - LQS03 used 108/127
    - f_d ~45 um; RRR: 70-150
  - LQS03 exceeded target despite low RRR and possible prestress/mechanical issue

Conclusions for MQXF - II

- Coil design and fabrication technology
  - Bubbles and heater failures on inner layer
  - → No protection heaters on inner layer of MQXF
    - Unless we develop a new design/technology
  - Some heater-coil voltage breakdowns (< 1 kV) on outer layer
  - →Additional Kapton layers between heaters and coil OD

PLAN: test these and other HQ features in LHQ coils

- Structure is the subject of next talk…

Thanks

Back up slides

US LHC Accelerator Research Program

BNL - FNAL - LBNL - SLAC

Test Results and Analysis of LQS03 Third Long Nb_3Sn Quadrupole by LARP

Giorgio Ambrosio

Fermilab

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Long Quadrupole Task Leaders:

Fred Nobrega (FNAL) – Coils

Jesse Schmalzle (BNL) – Coils

Helene Felice (LBNL) – Structure

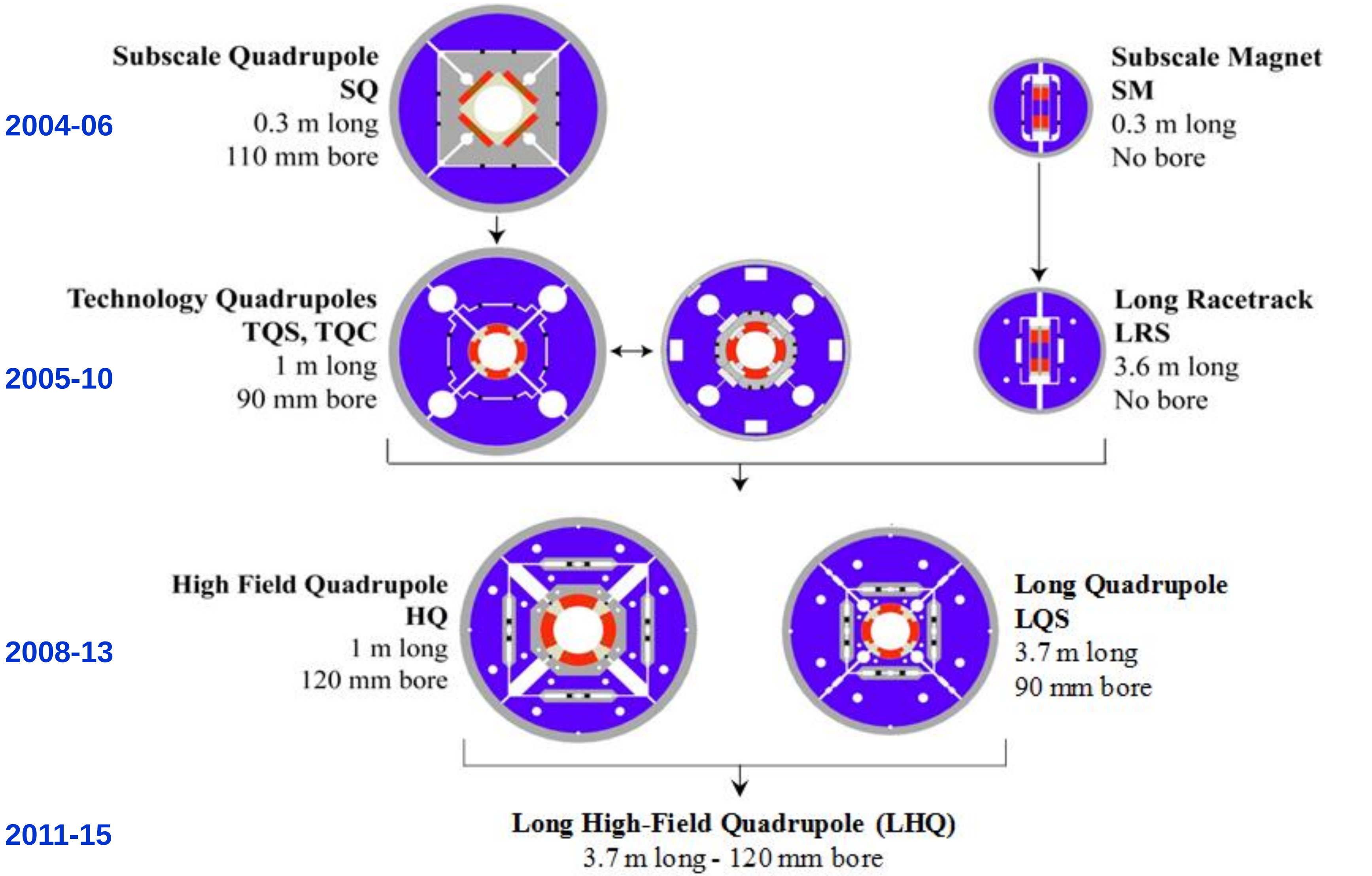
Maxim Marchevsky (LBNL) – Instrumentation and QP

Guram Chlachidize (FNAL) – Test preparation and test

Acknowledgement:

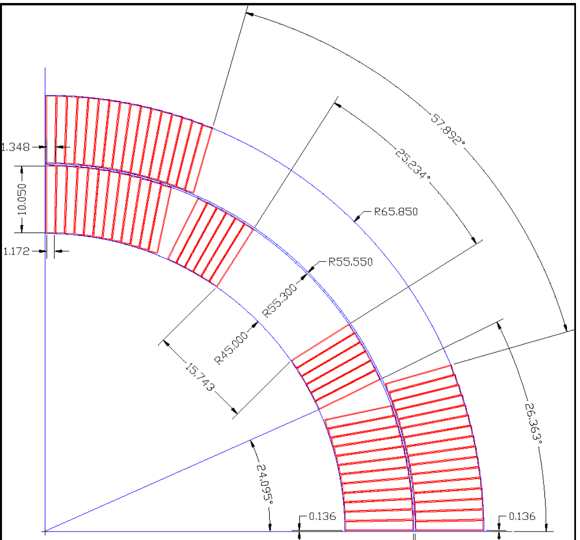
U.S. DEPARTMENT OF ENERGY | Office of Science

LARP Magnet Development Chart

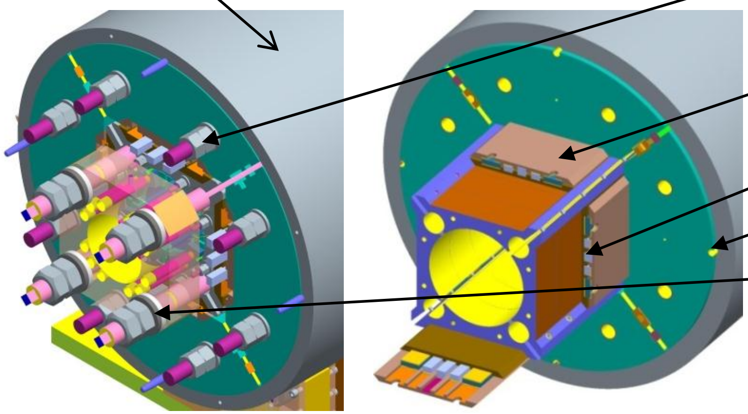


LQ Features

- **LQS is based on TQS (1m model) with modifications for long magnets**

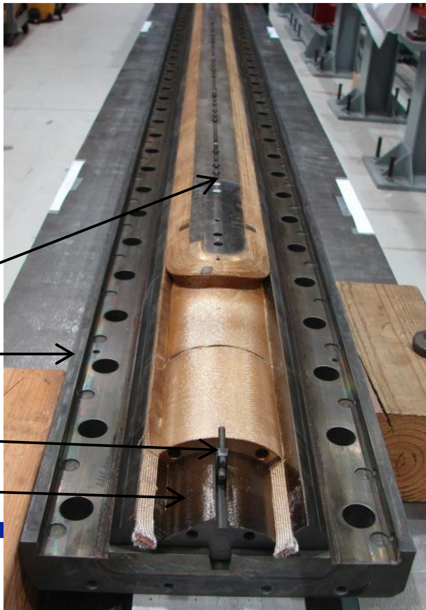


Cross-section of TQ/LQ coil



- **Structure Modifications:**
  - Added tie-rods for yoke & pad laminations
  - Added masters
  - Added alignment features for the structure
  - Rods closer to coils
  - Rods made of SS

- **Coil modifications:**
  - LQ coils = TQ coils with gaps to accommodate different CTE during HT
  - From 2-in-1 (TQ coils) to single coil fixtures (LQ)
  - Bridge between lead-end saddle and pole
  - Mica during heat treatment



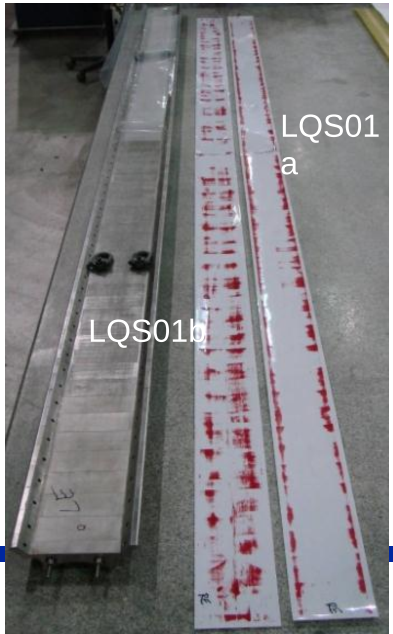
LQS01a - Lessons Learned

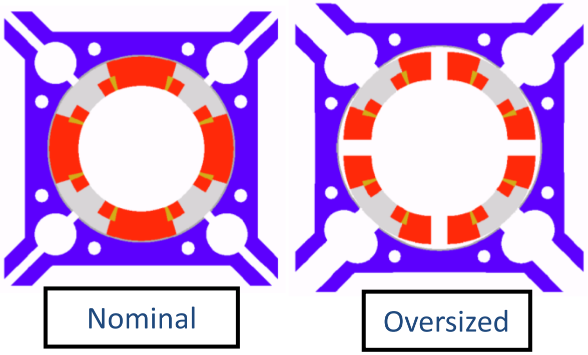
- **Coil oversize not accounted for in structure assembly, caused non optimal prestress**

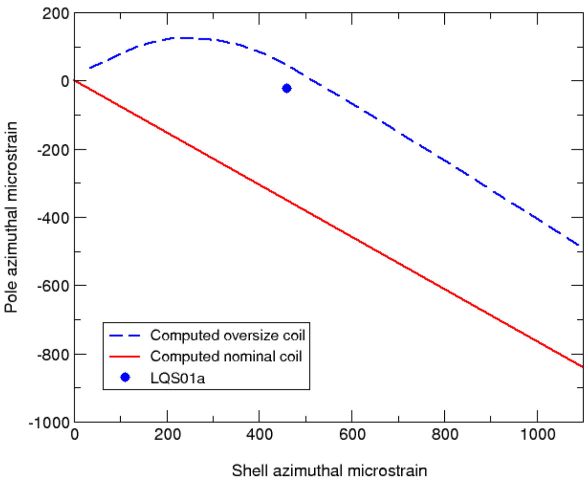
➔ **CMM measurements of all coils**

➔ **Adjustment of coil-structure shims for optimal preload**

➔ **Procedures for checking at warm proper coils-structure matching**

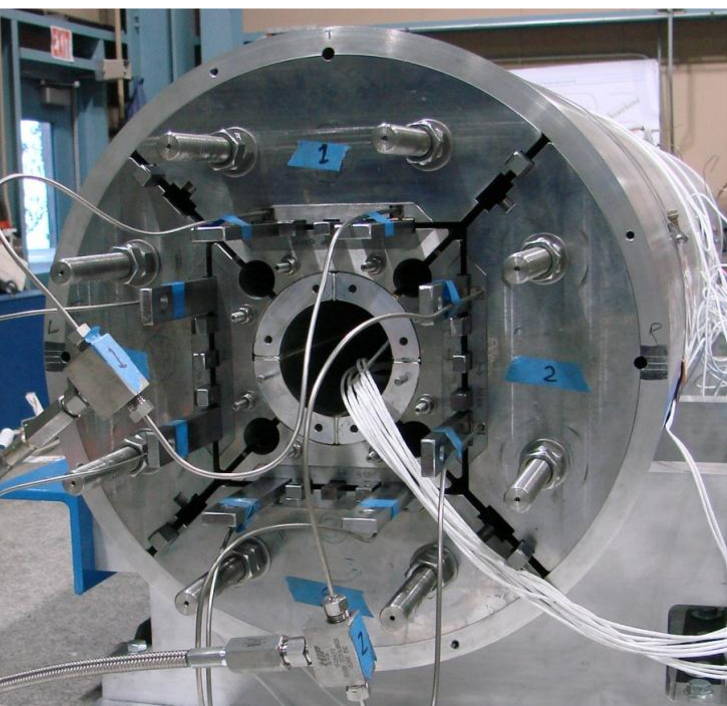


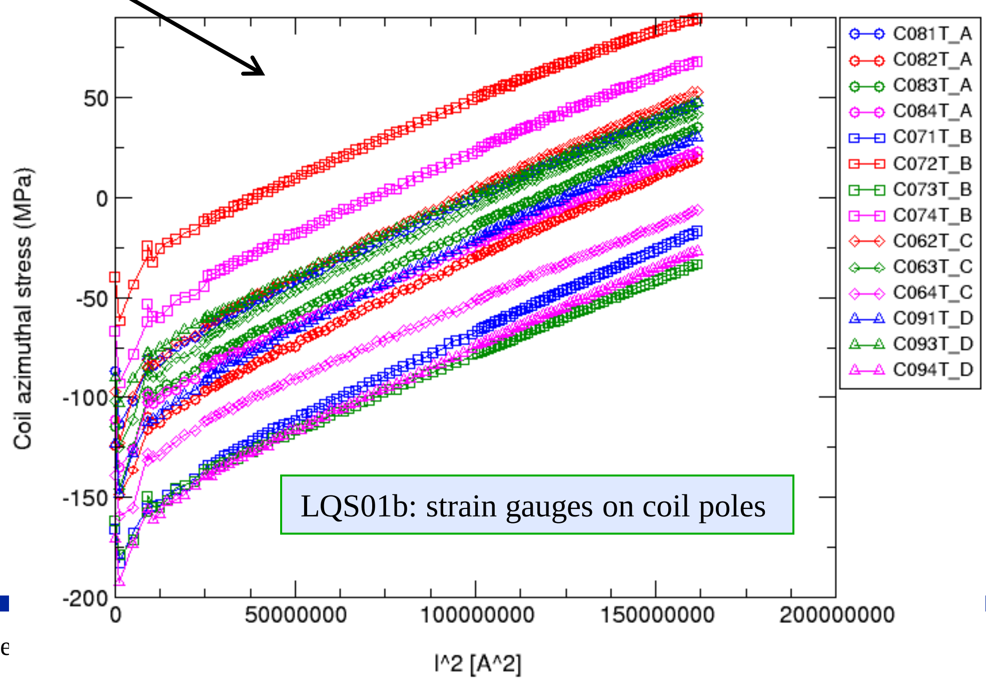




LQS01b (same coils of LQS01a)

- **More uniform prestress distribution in the coils**
  By using thinner coil-pad shims
- **Higher preload based on short models (TQS03 a/b/c)**
  - ➔ **Peak load: 190 MPa +/- 30**
  - ➔ **No coil-pole separation in LQS01b**





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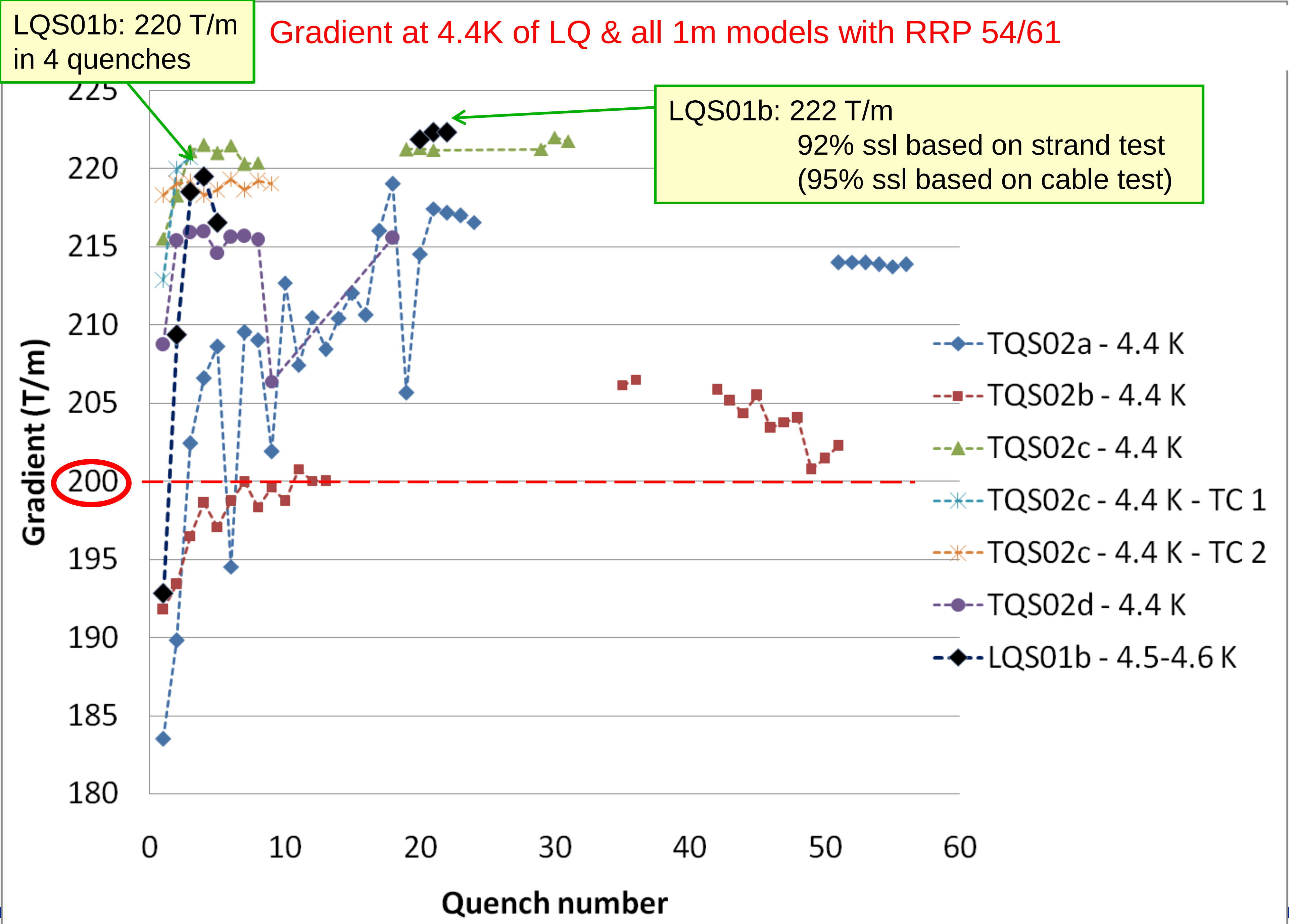
Gradient at 4.4K of LQ & all 1m models with RRP 54/61



LQS01b Magnetic Measurement

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	[illegible]	-0.10	0.54
b_8	-	-0.11	-0.13	[illegible]	[illegible]	-1.28
a_9	-	-0.02	0.02	-	-0.55	-1.68
a_{10}	-	0.00	-0.08	-	0.24	0.31

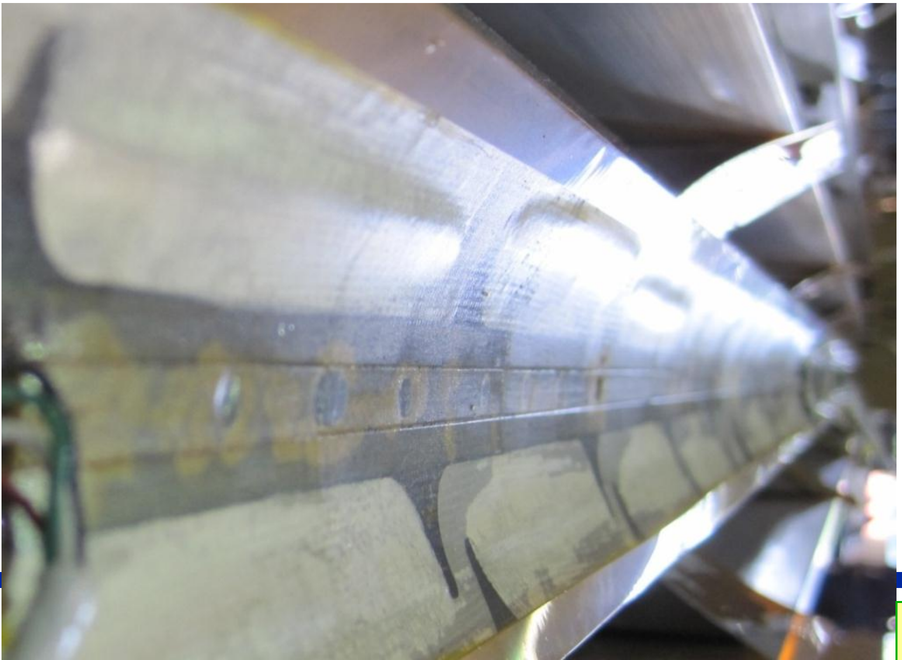
LQ does not have alignment features.
They are in HQ (1m) and will be in LHQ (~4m).
➔ Field quality of long Nb_3Sn magnets will be demonstrated by LHQ

† G. Velev, et al., "Field Quality Measurements and Analysis of the LARP Technology Quadrupole Models", IEEE Trans. On Applied Supercond. , vol.18, no.2, pp.184-187, June 2008

Average harmonics in the TQS and LQS at 45 T/m (~ 2.6 kA) at the ref. radius r_0 of 22.5 mm

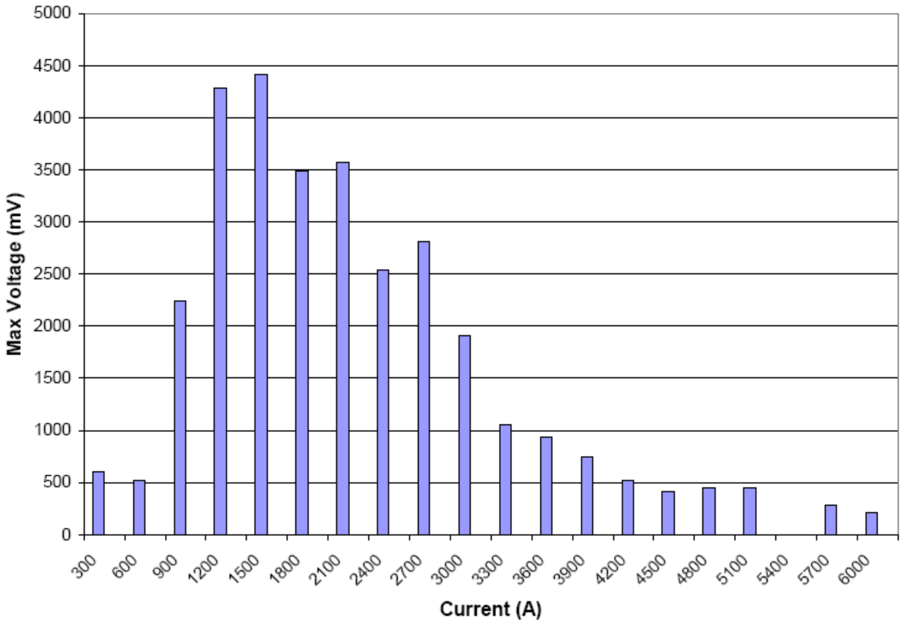
LQS01b To Be Improved

- **Some "bubbles" on coils inner layer**
  - — Coil-insulation separation
- **Plans:**
  - — Strengthen insulation (coil 13)
  - — Change/remove inner layer heaters



- **Big voltage spikes at low current (flux jumps)**
- **No expected Gradient increase at 1.9 K**

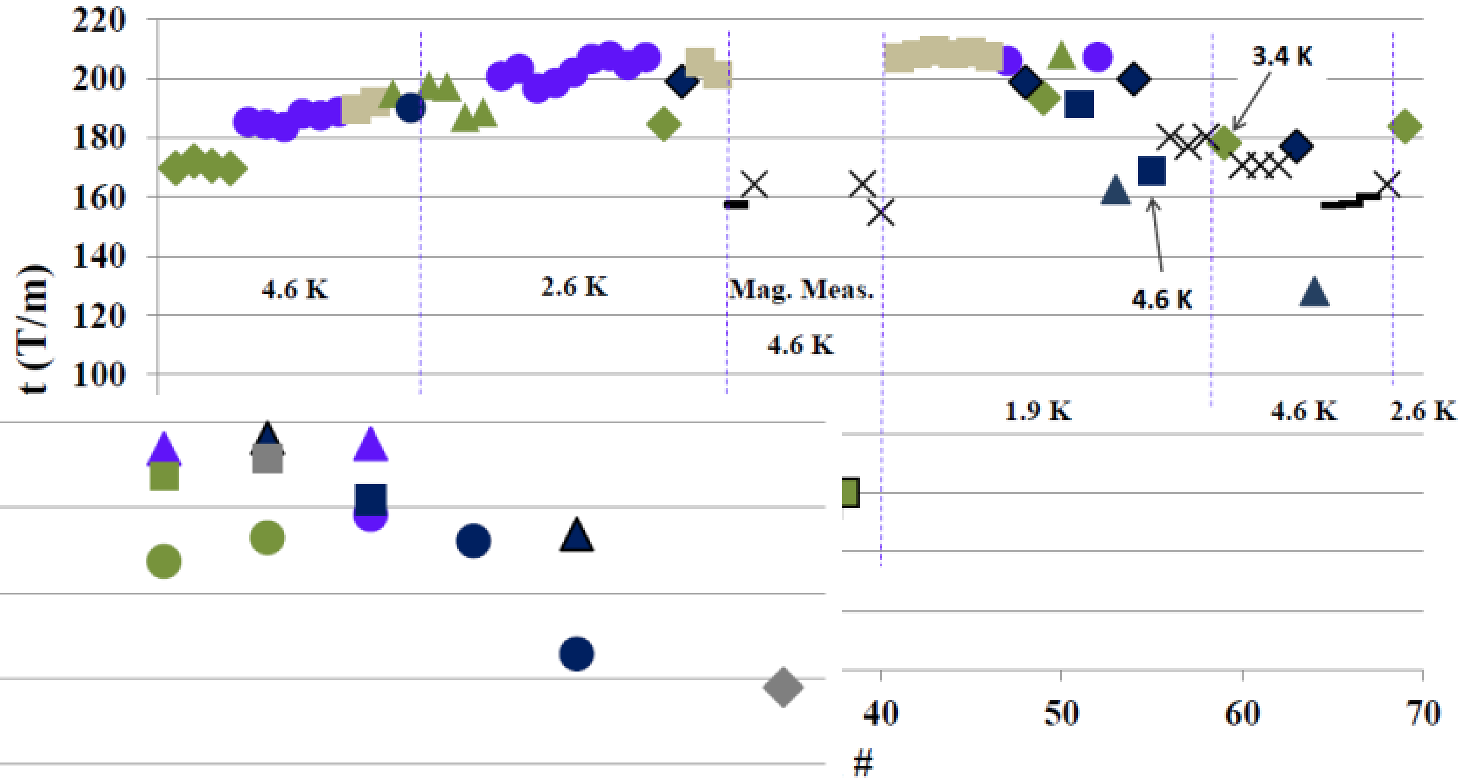
➔ Smaller filament diam. in LQS03 coils 54/61 ➔ 108/127

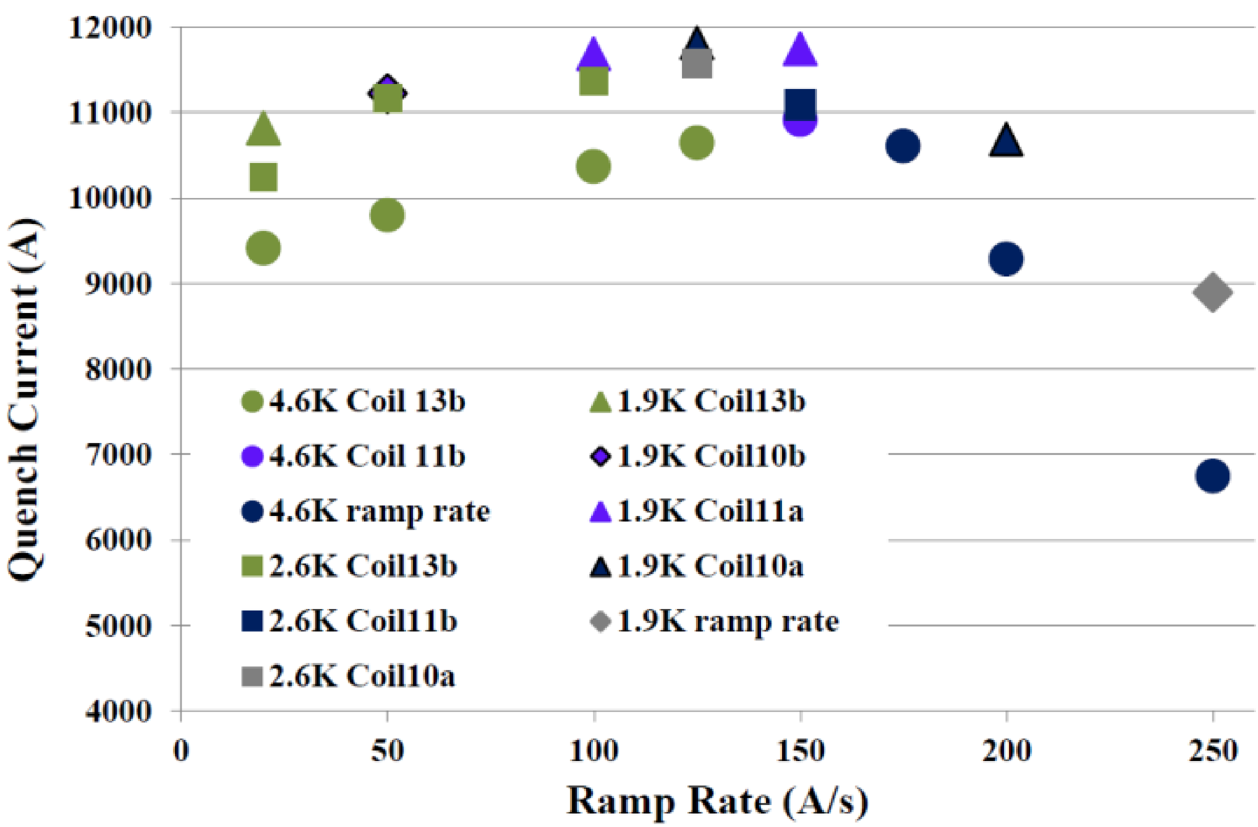


Maximum Voltage Spike amplitude at 4.5 K with 50 A/s ramp rate

LQS02 Quench History

Limited performance





"Reverse ramp-rate dependence"

LQS02 Analysis

- **Holding quenches, Voltage Tap data, Quench Antenna data, and Spike Recording System data confirmed:**
- **The cause is "Enhanced Instability" in one coil**
  - — An unknown "issue" causes a decrease of the stability threshold of the conductor in coil 13 OL.
  - — Possible "issues" are: (i) a local damage or a non-uniform splice forcing more current in a few strands; (ii) a damage of some strands decreasing the local RRR and/or causing filaments merging.