LARP Collaboration Meeting 15

SLAC, Nov. 1-3, 2010

Long Quadrupole

Giorgio Ambrosio

Fermilab

Many people contributed to this work,
most of all the Long Quadrupole Task Leaders:
Fred Nobrega (FNAL) – Coils
Jesse Schmalzle (BNL) – Coils
Paolo Ferracin (LBNL) – Structure
Helene Felice (LBNL) – Instrumentation and QP
Guram Chlachidize (FNAL) – Test preparation and test

Long Nb_3Sn Quadrupole†

Main Features:

- **Aperture:** **90 mm**
- **magnet length:** **3.7 m**

Target:

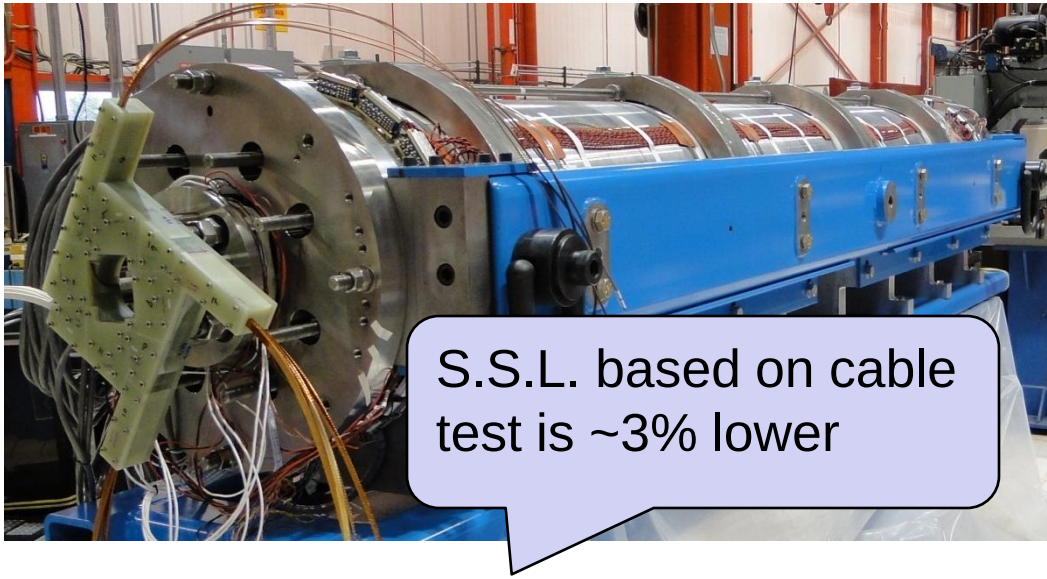
- **Gradient:** **200+ T/m**

Goal:

- **Demonstrate Nb_3Sn magnet scale up:**
  - Long shell-type coils
  - Long shell-based structure (bladder & keys)

LQS01a was tested in Nov-Dec 2009

LQS01b (same coils) test in progress



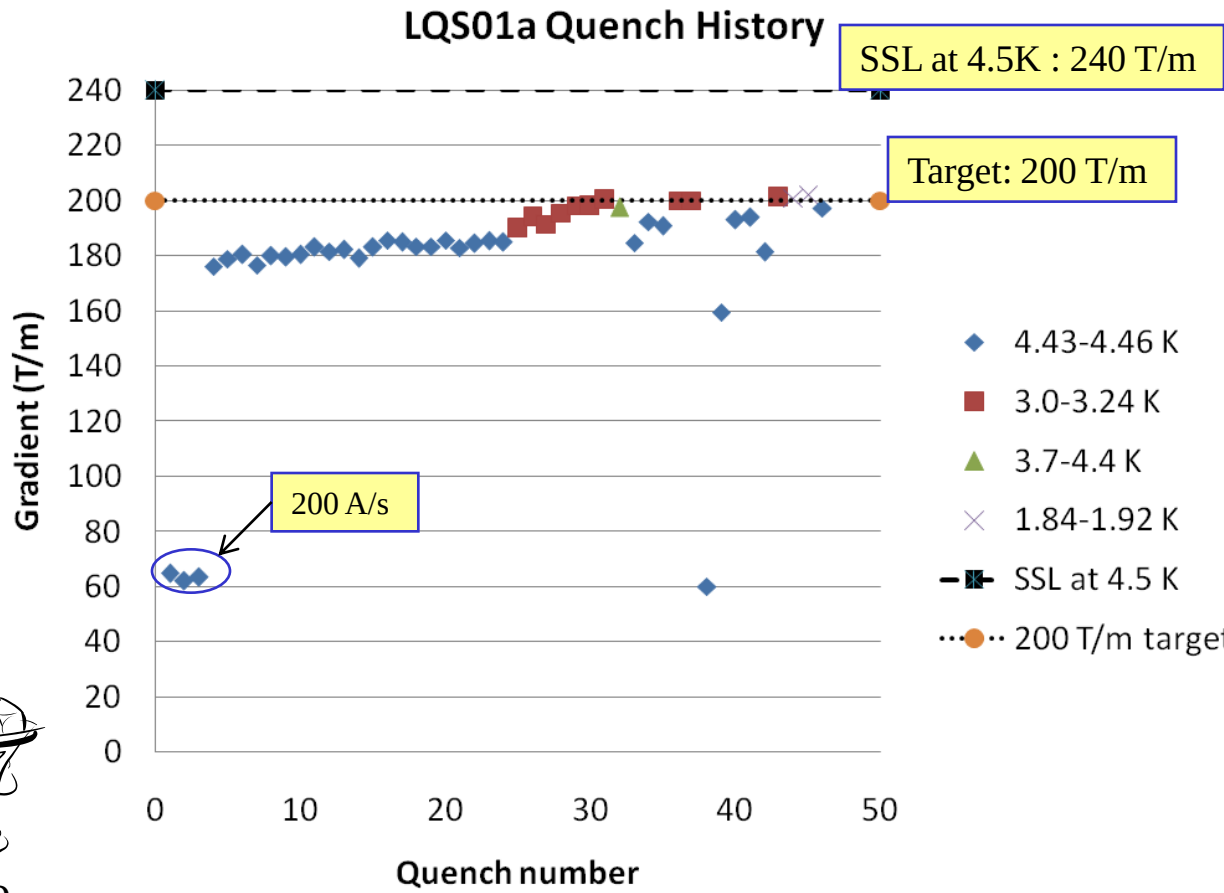
LQS01 S.S.L.	4.5 K
Current	13.7 kA
Gradient	240 T/m
Peak Field	12.25 T
Stored Energy	460 kJ/m

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

LQS01a Quench History

- **Slow start**
  - First quenches at high ramp rate (200 A/s)
  - Slow training at 4.5K
    - Due to low pre-load on pole turns
- **Faster training at 3 K**
  - **Reached 200 T/m**

- **Stopped training**
  - to avoid coil damage and to achieve better performance with optimal pre-stress



Test report available online at:
https://plone4.fnal.gov/P1/USLARP/MagnetRD/longquad/report/TD-10-001_LQS01_test_summary.pdf

LQS01b (same coils of LQS01a)

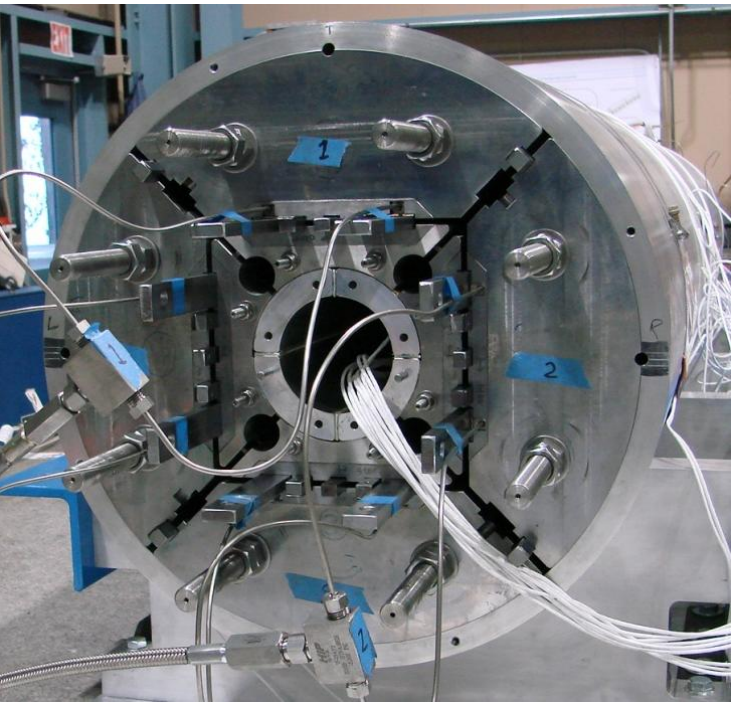
- **More uniform prestress distribution in the coils**

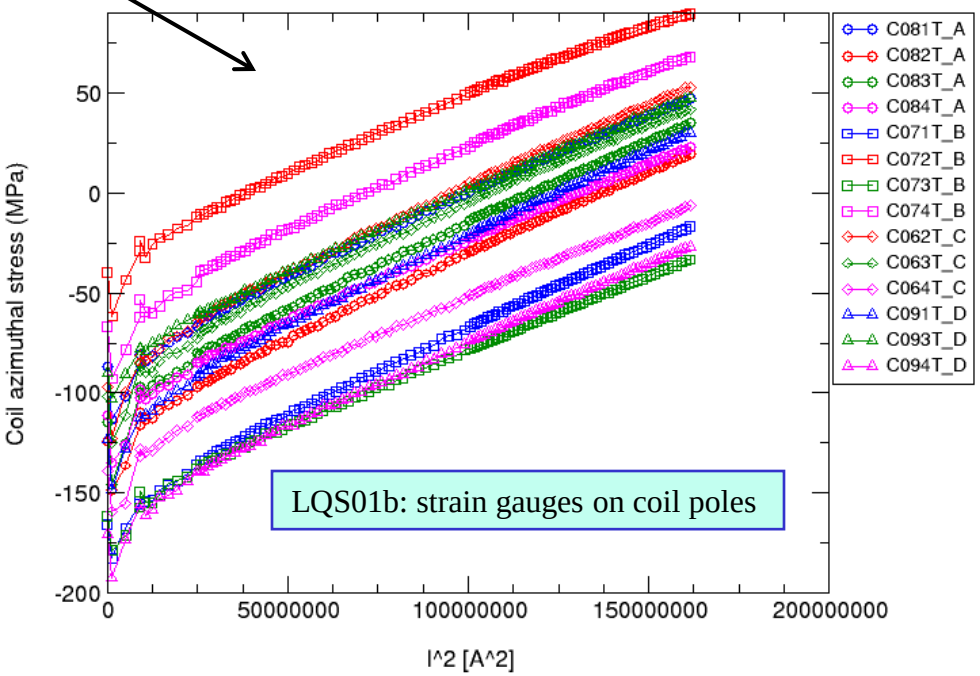
  By using thinner coil-pad shims

- **Higher preload based on short models (TQS03 a/b/c)**

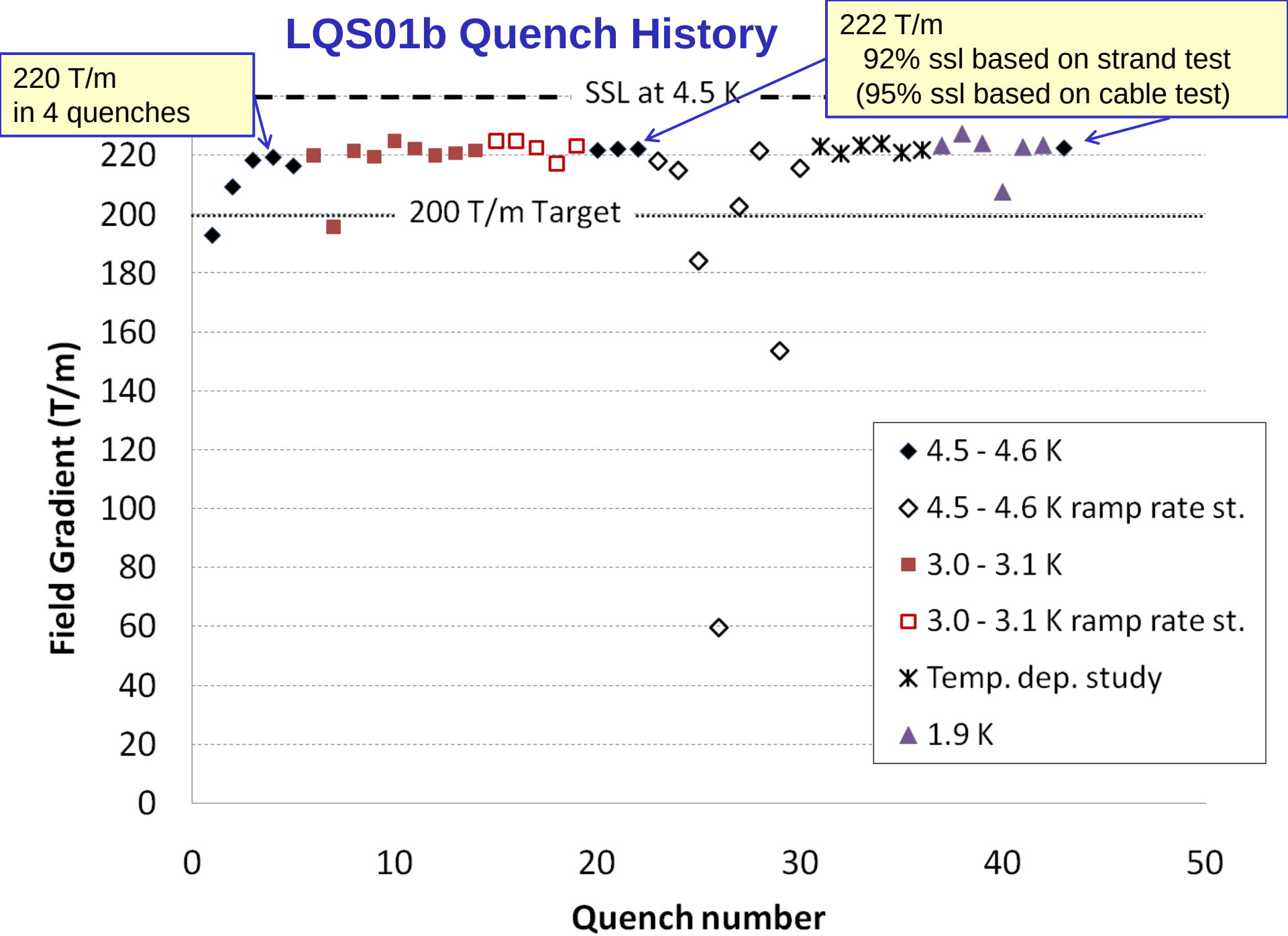
  ➔ Peak load: 190 MPa +/- 30

  ➔ No coil-pole separation in LQS01b





LQS01b Quench History

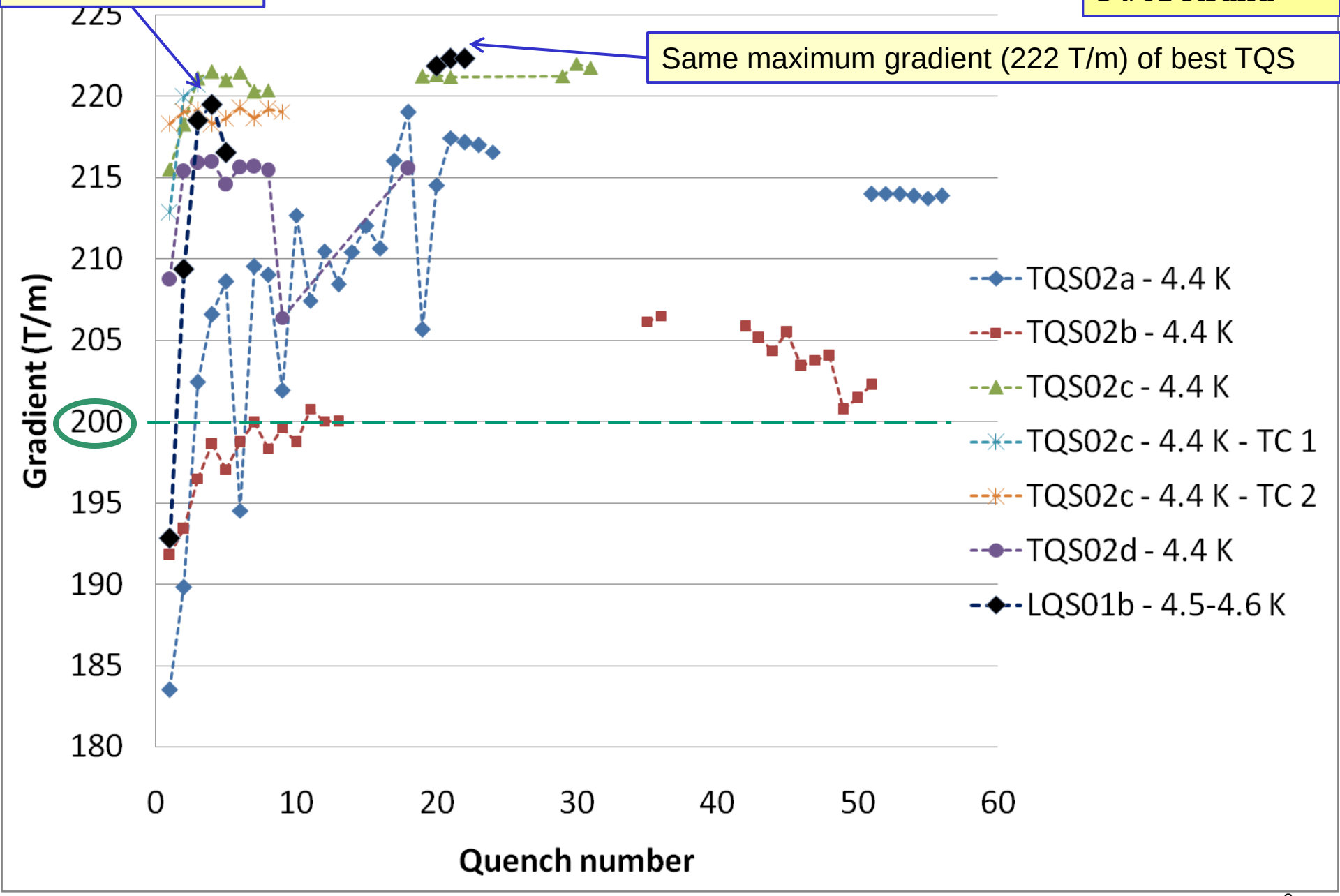


Fast training as in best TQS

LQS01b and TQS02a/b/c/d gradient at 4.4 K

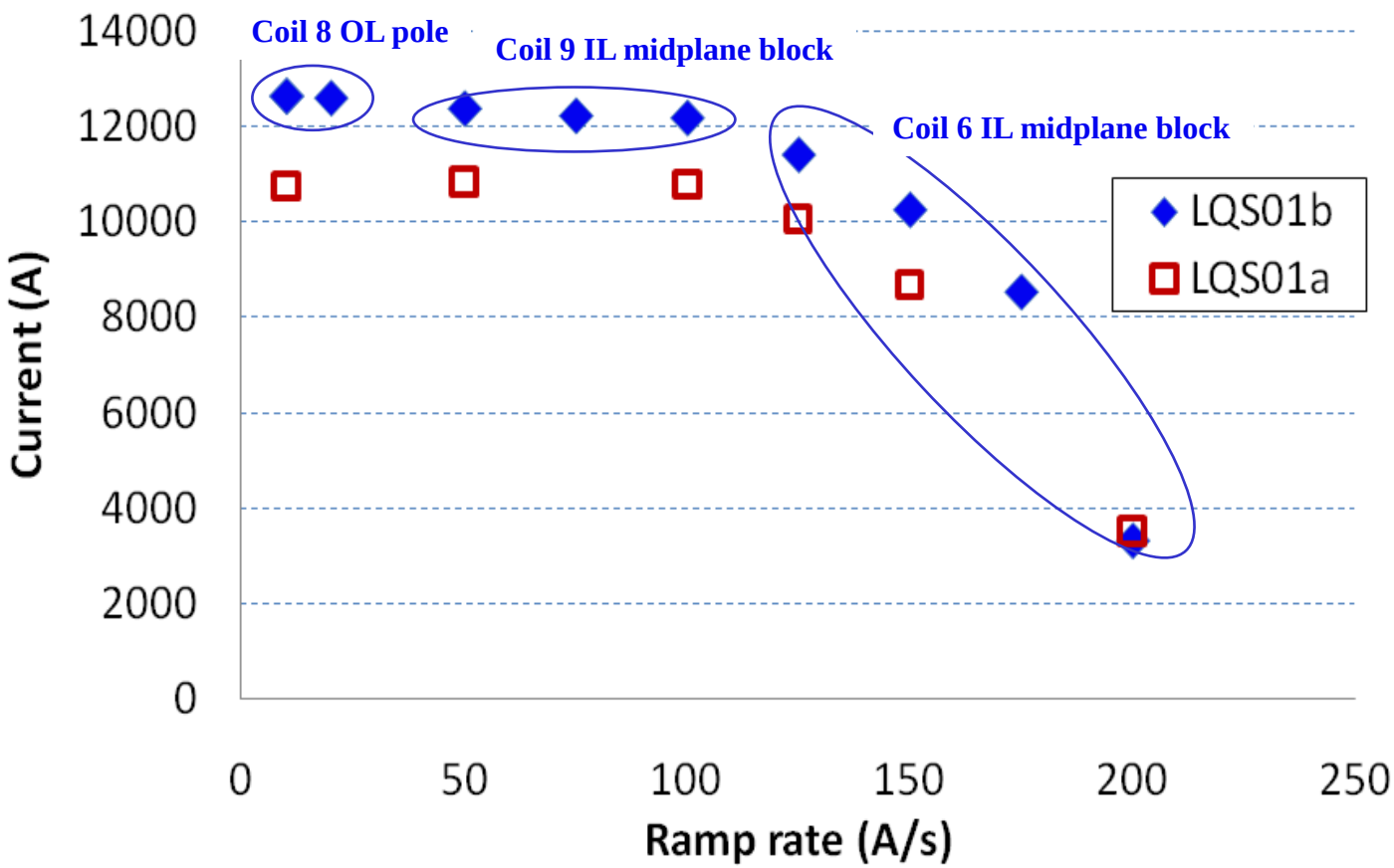
All with RRP 54/61 strand

Same maximum gradient (222 T/m) of best TQS



Ramp Rate at 4.5 K

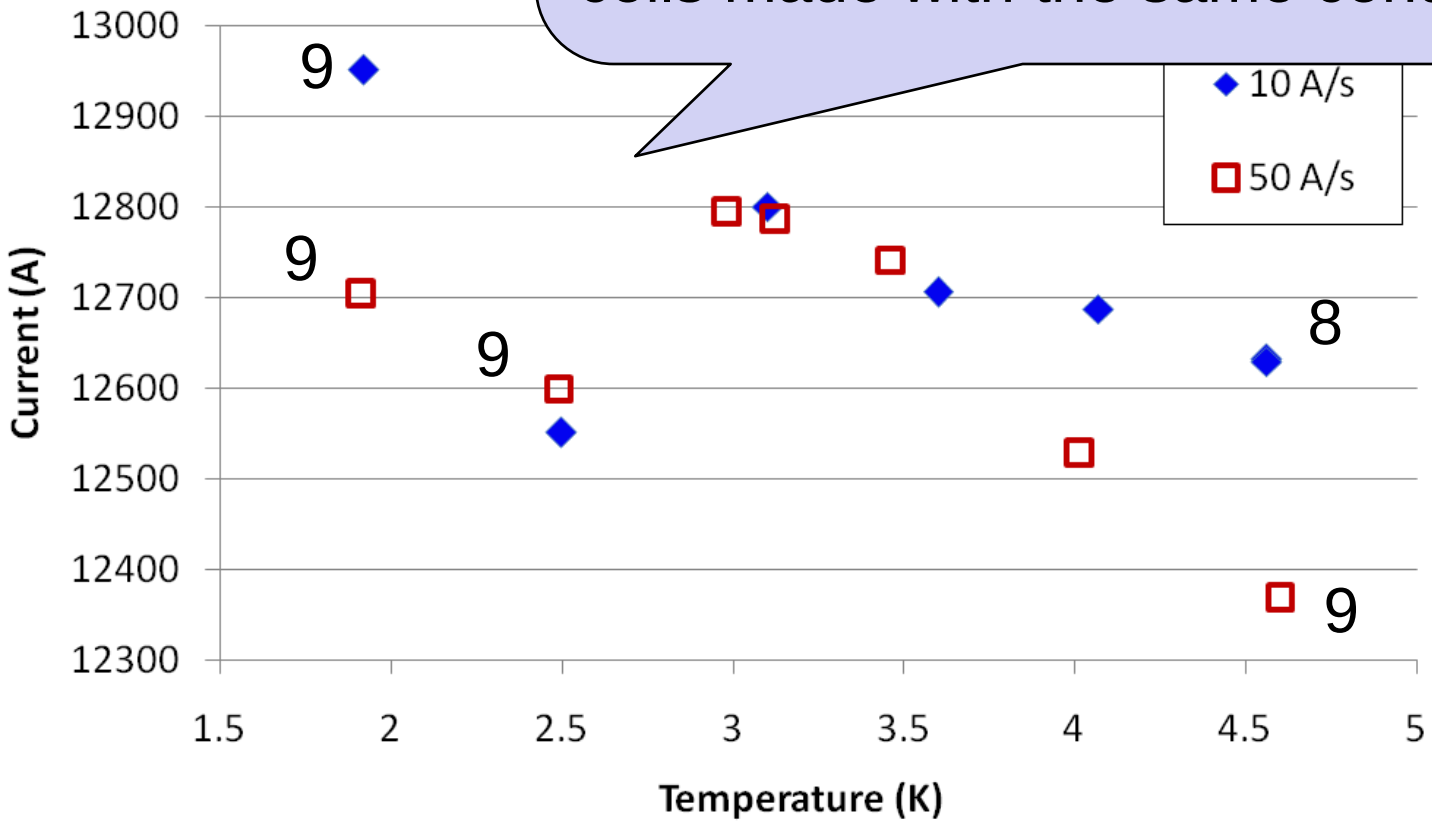
- **Different coil at different ramp rate:**



Tempera

The limited stability of the conductor (RRP 54/61) limits the performance below 4.5 K,
as seen in TQS,TQC and single TQ coils made with the same conductor.

- **Different coil at diff**



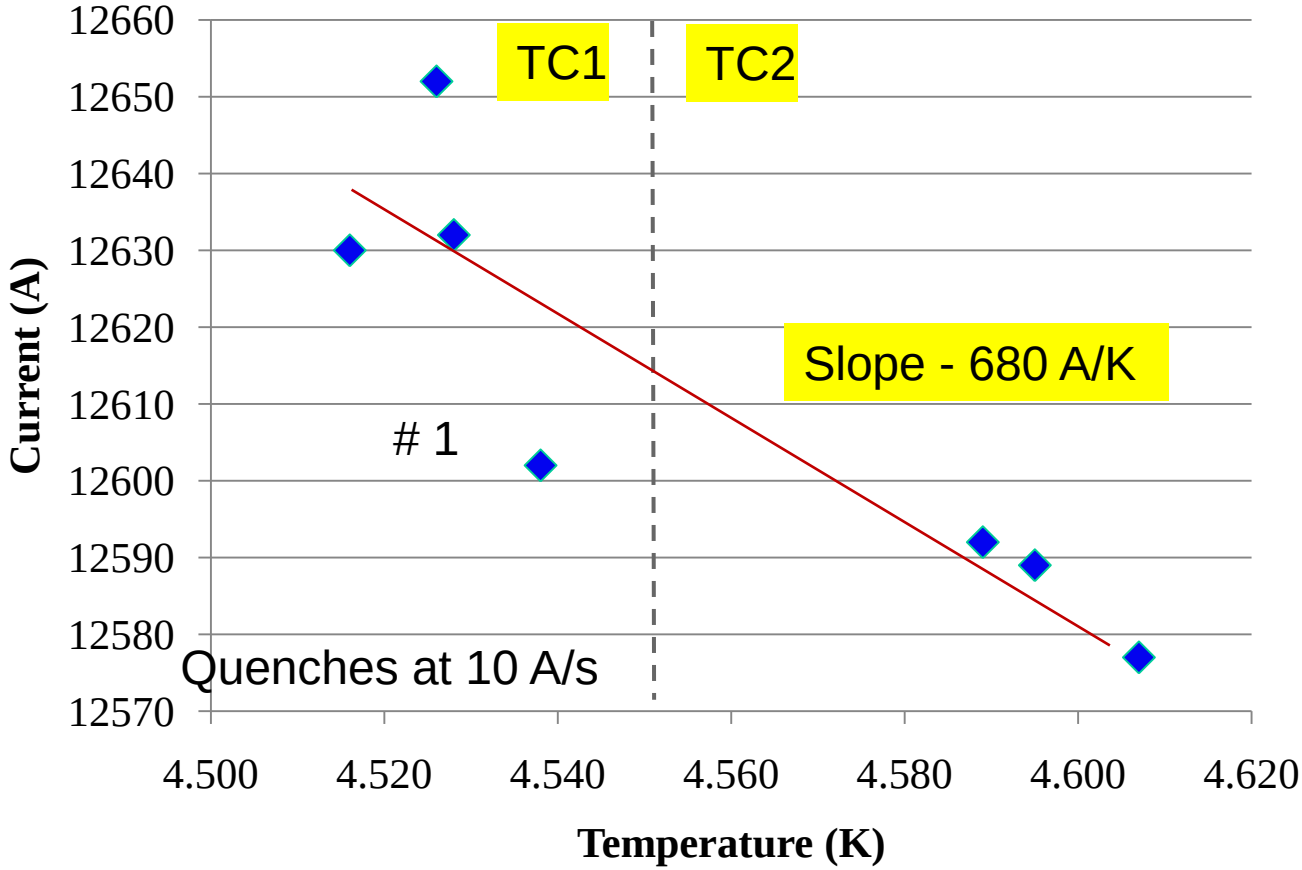
Numbers show coil where quench started; default is Coil 6

Limit at 4.5 K

- Voltage taps: Coil #8, outer layer, pole turn
- Quench antenna: ~ central part of straight section (No max field)
- Temperature dependence in small temperature range:

Computed ΔI/ΔT:
- 850 A/K

Possible degradation in Coil #8 outer layer pole turn

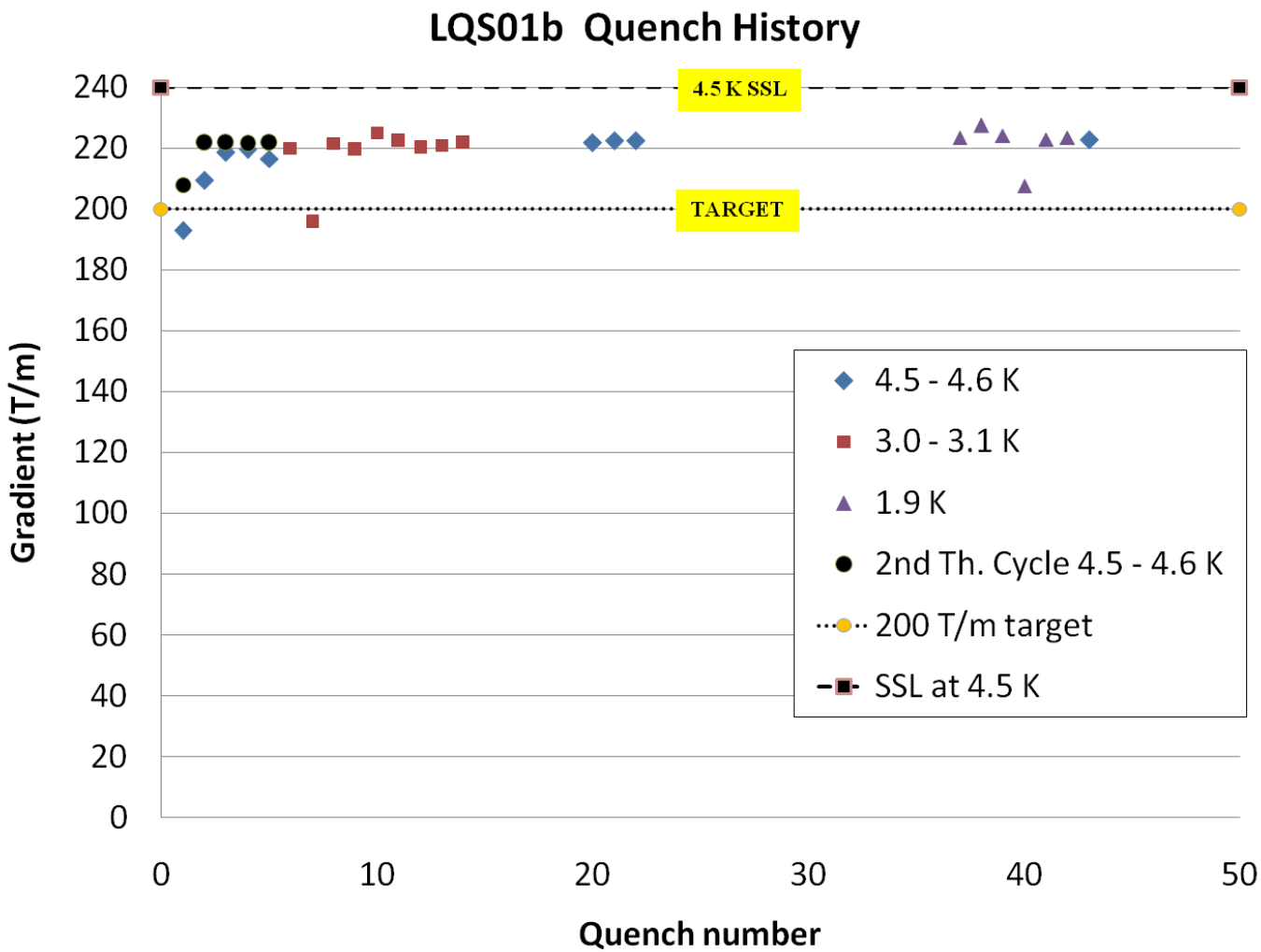


Test After Thermal Cycle

- **Good memory after thermal cycle with limited ΔT:**

–ΔT max 100 K

- Thermal cycle with unrestricted ΔT planned for LQS02



Magnetic Measurement

- **The reference radius is presently limited by the probe radius**
  - New probes with larger radius, and warm bore with larger apertures are under development
  - Features to be discussed tomorrow in WG B3
- **The Long Quadrupole, as the Technological Quadrupoles (TQ), doesn't have alignment features**
  - neither during coil fabrication
  - nor during magnet assembly
- **The HQ has alignment features and aims at testing field quality in Nb_3Sn magnets**

Magnetic Measurement

Magnetic measurement at 4.5K:

- Some are a few units different w.r.t. computed
- Similar to short models †
- Normal octupole (b_4) may have been affected by small differences in impregnation molds
  - Two molds used

b_n a_n	TQS CALC.	TQS MEASURED 01	TQS MEASURED 02	LQS CALC.	LQS MEASURED
b_3	-	-1.46	2.98	-	3.43
b_4	-	-0.52	1.31	-	6.20
b_5	-	3.06	-1.45	-	-0.16
b_6	5.00	5.40	6.23	8.45	10.43
b_7	-	0.07	0.05	-	-0.10
b_8	-	-0.11	-0.13	-	-0.58
b_9	-	0.02	0.10	-	-0.14
B_{10}	0.04	0.02	-0.05	-0.03	-0.32
a_3	-	4.41	0.66	-	2.11
a_4	-	-1.99	0.82	-	1.34
a_5	-	0.71	-1.50	-	0.48
a_6	-	-0.37	0.12	-	-0.37
a_7	-	-0.11	-0.01	-	-0.30
a_8	-	-0.18	-0.10	-	-0.09
a_9	-	-0.02	0.02	-	-0.55
A_{10}	-	0.00	-0.08	-	0.24

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

† 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

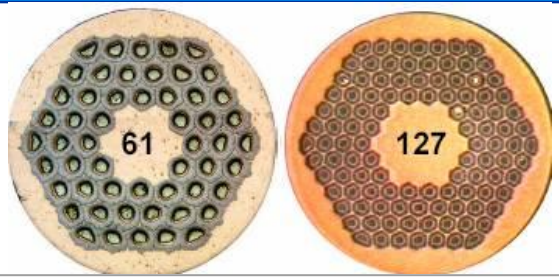
Voltage Spikes

- **Large voltage spikes**
  - Due to flux jumps
    - Seen in TQ magnets using RRP 54/61
  - Larger than in TQs

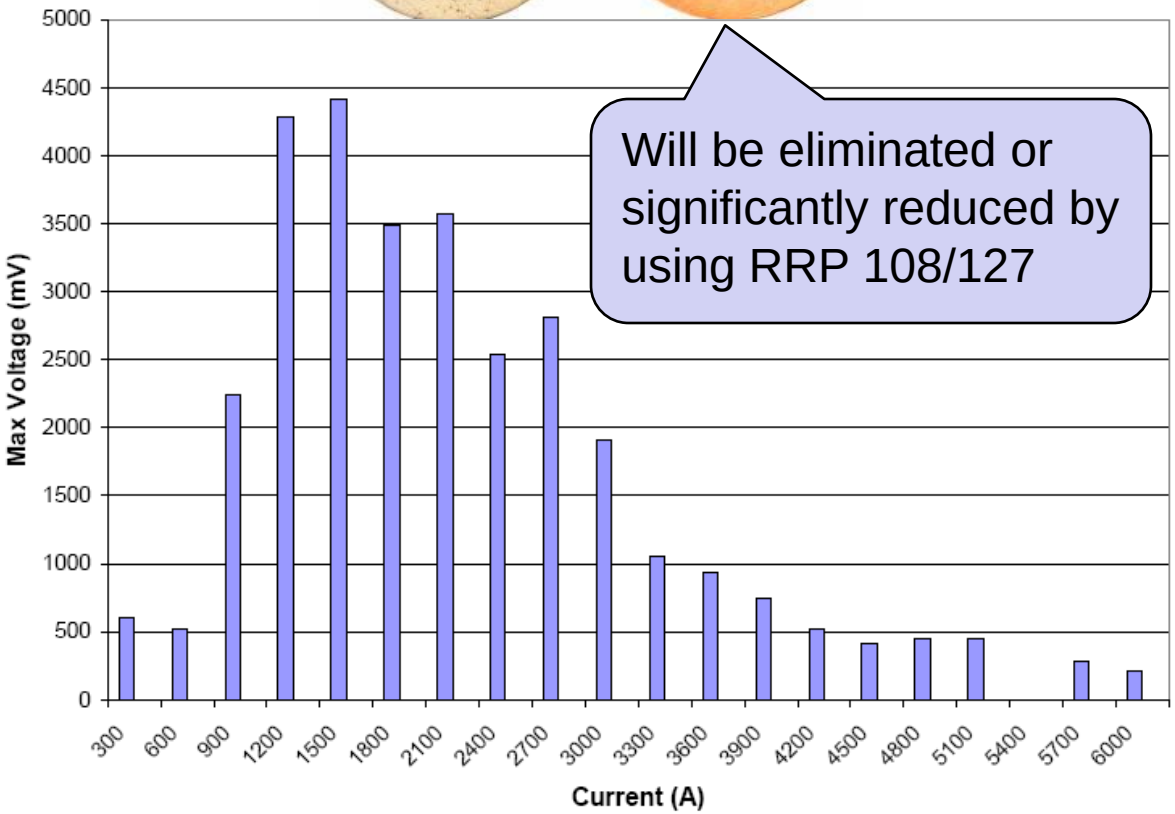
  ➔Variable quench detection threshold

  ➔Variable ramp-rate during training
    - 200 A/s ➔ 3 kA
    - 50 A/s ➔ 5 kA
    - 20 A/s ➔ 9 kA
    - 10 A/s ➔ quench

RRP 54/61 by OST



RRP 108/127 by OST

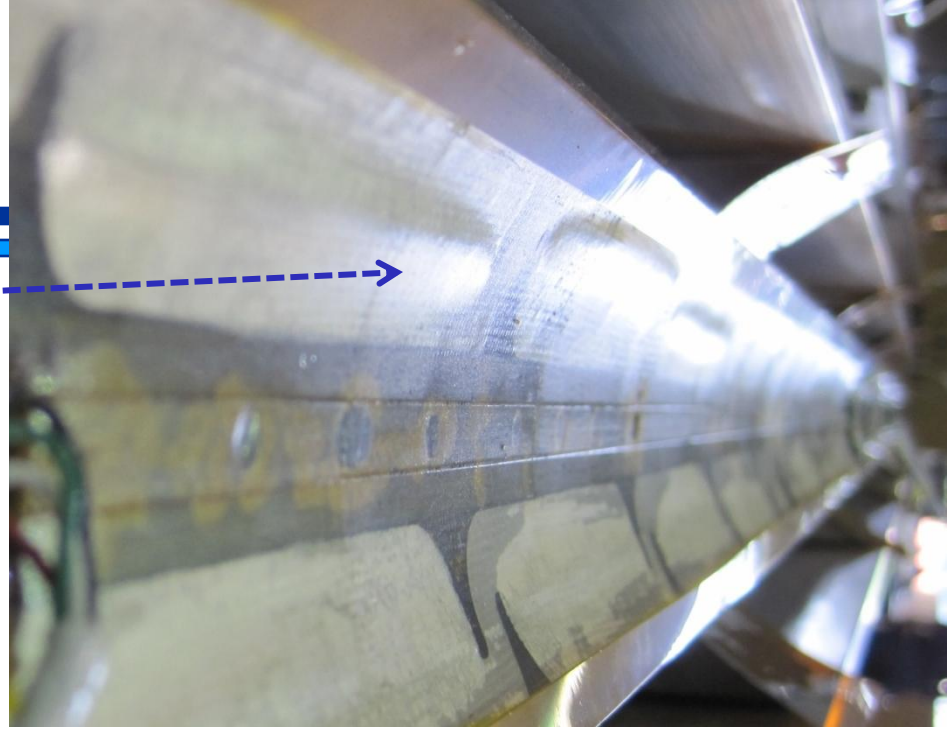


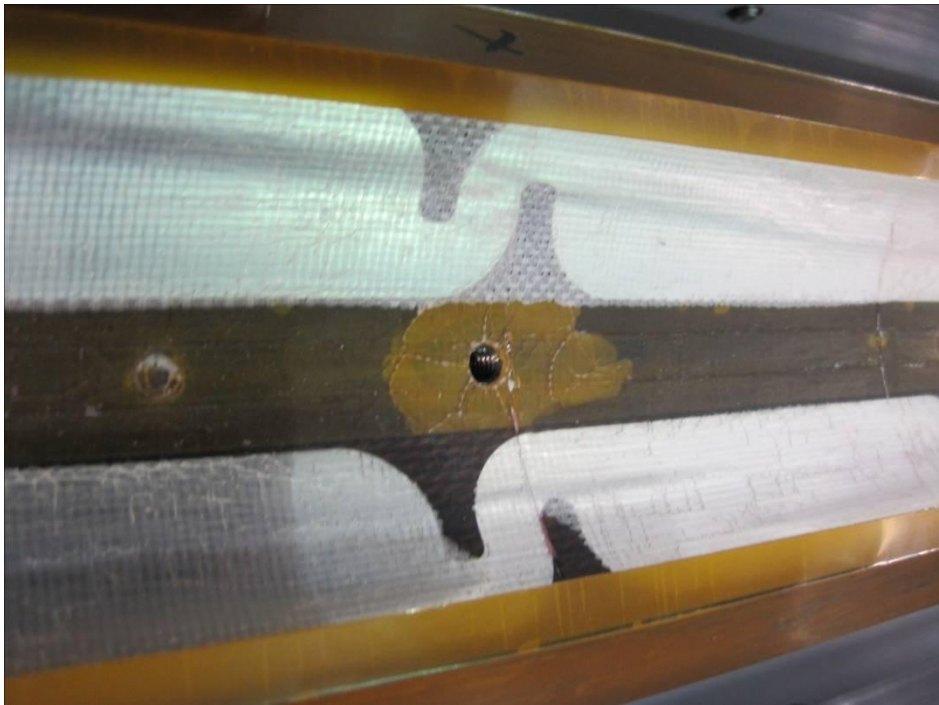
Will be eliminated or significantly reduced by using RRP 108/127

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

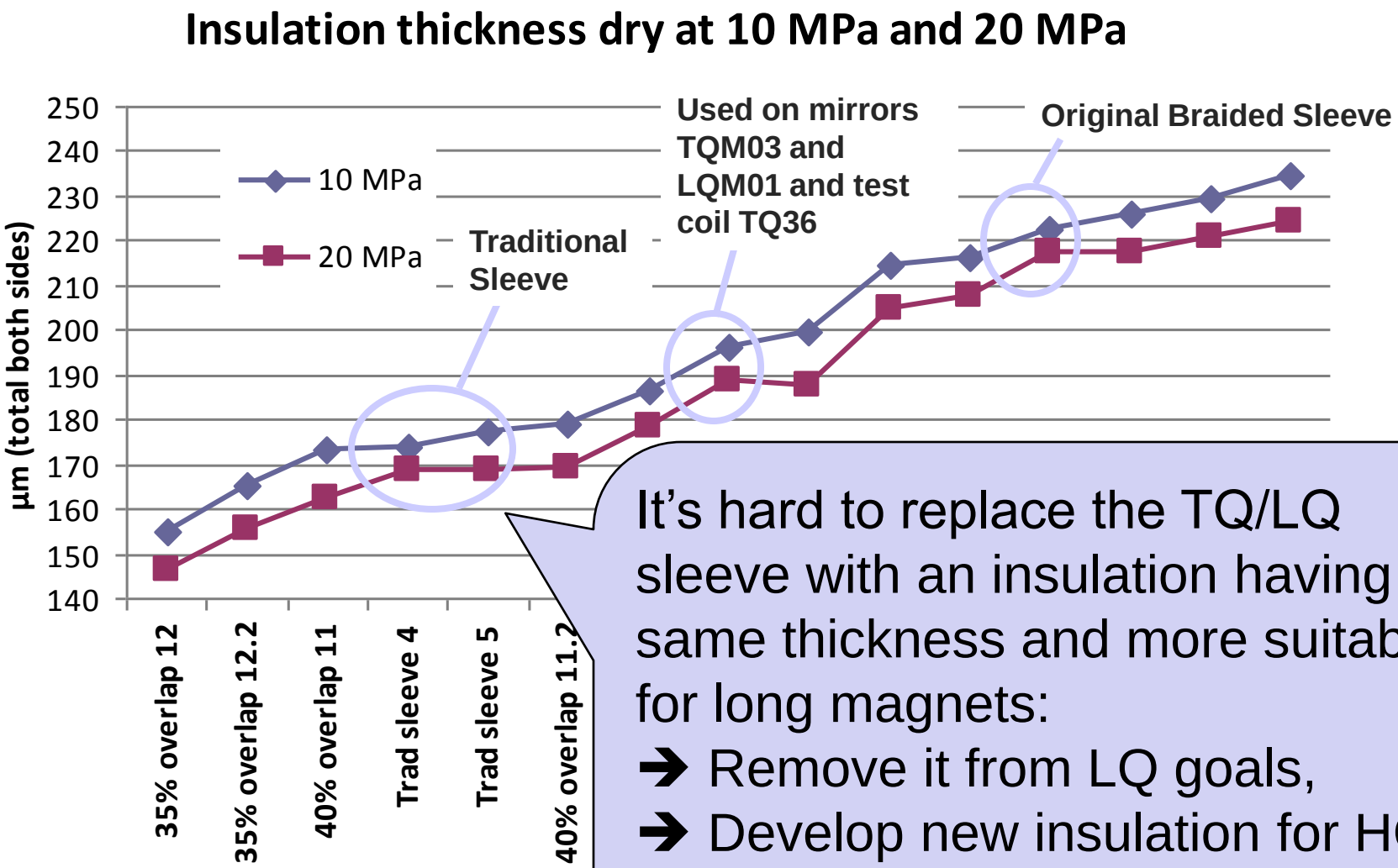
Coils after Test

- **Some "bubbles" on coils inner layer**
  - Coil-insulation separation
- **Possible causes:**
  - Superfluid helium and heat during quench
    - Seen in TQ coils
  - Heat from heaters on inner layer
    - Only in LQ coils
- **Plans:**
  - Strengthen insulation (#13),
  - Change heater location,
  - Add support on coil ID





New Insulation Development



It's hard to replace the TQ/LQ sleeve with an insulation having the same thickness and more suitable for long magnets:

➔ Remove it from LQ goals,

➔ Develop new insulation for HQ

➔ Demonstrate it in LHQ

LQS01b Preliminary Observations

- **LQS01b reached the best performance of all TQS02!**
  - With the first four LQ-production coils; three of which had "severe" discrepancies

  ➔ We know how to make and fix long Nb_3Sn coils

  - Al-shell-based structure is providing support (up to 227 T/m and 92% of ssl) with no signs of limitation

  ➔ Segmented shell structure can be used for long Nb_3Sn magnets with shell-type coils

  - Quench protection keeps hot-spot temperature below 260 K

  ➔ We have tools (computation & instrumentation) for protecting long Nb_3Sn magnets above 2.2K

  - Good memory with DT-restricted thermal cycle

  ➔ Very promising for use in particle accelertors

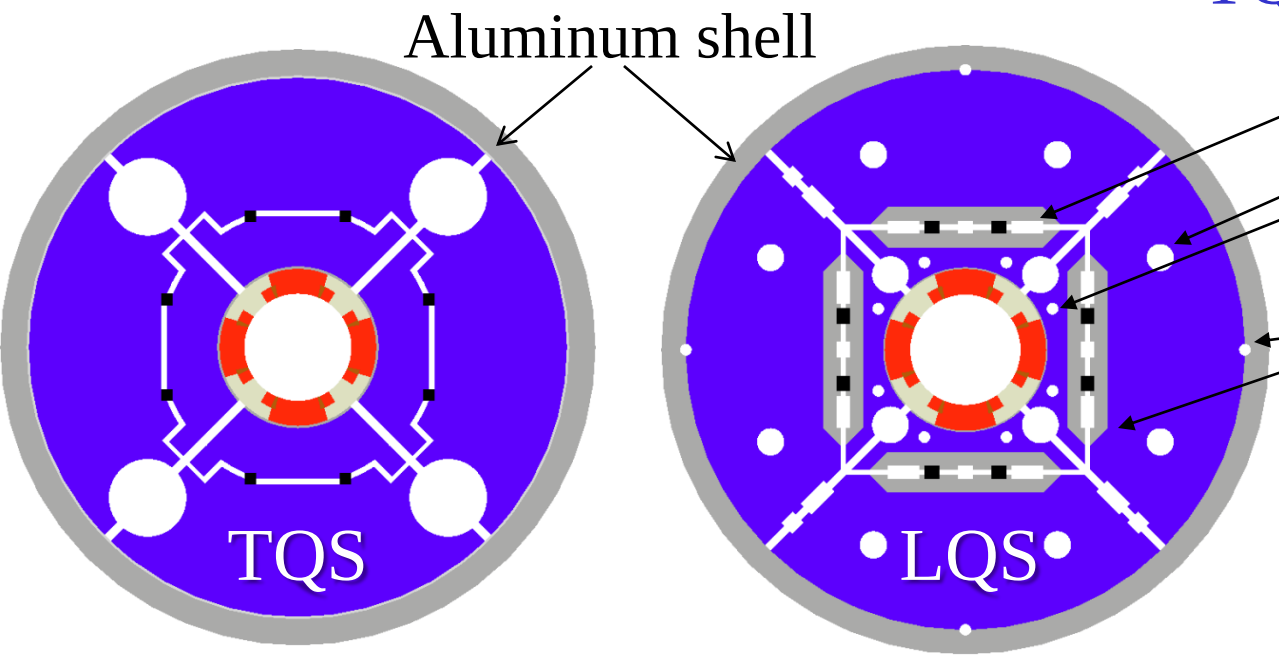
LQS02 Readiness Review (*October 26, 2010)*
➔ OK to use coils #10-13
➔ Slightly smaller pre-stress than in LQS01b

- **LQS02a with new set of 54/61 coils:**
  - Demonstrate reproducibility, test memory after unrestricted thermal cycle
- **LQS02b options:**
  - Change limiting coil of LQS02
  - Test LQS w 4 coils made with the same mold
  - Test use of 4m keys & bladders (for longer magnets)
- **LQS03a/b with 108/127 coils:**
  - Demonstrate better performance below 4.5 K, and smaller voltage spikes
- *Need still some R&D:*
  - Reliable solution for protection heaters on inner layer at 2 K

Extra slides

LQ Structure†

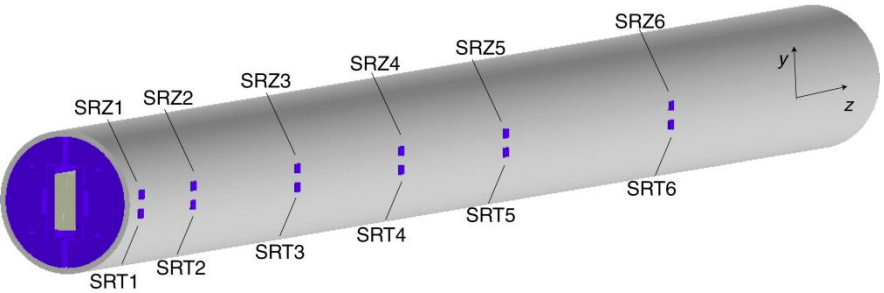
- **LQS is based on TQS (1m model)**

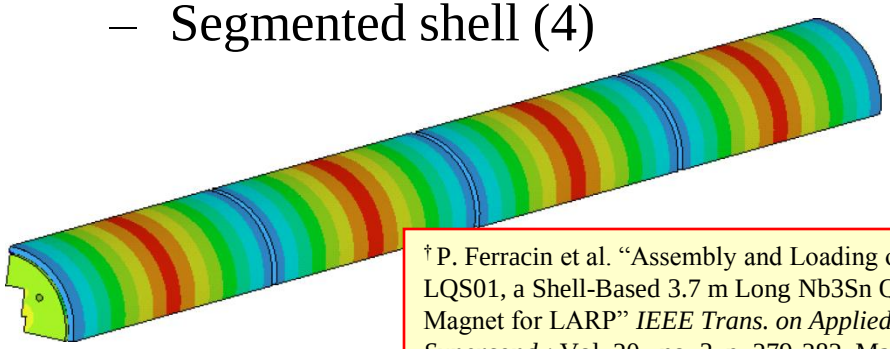


TQS Modifications:

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

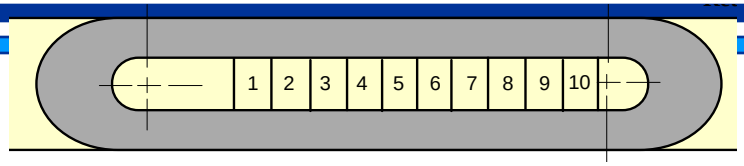
- **and LRS (4m racetrack)**
  - Segmented shell (4)



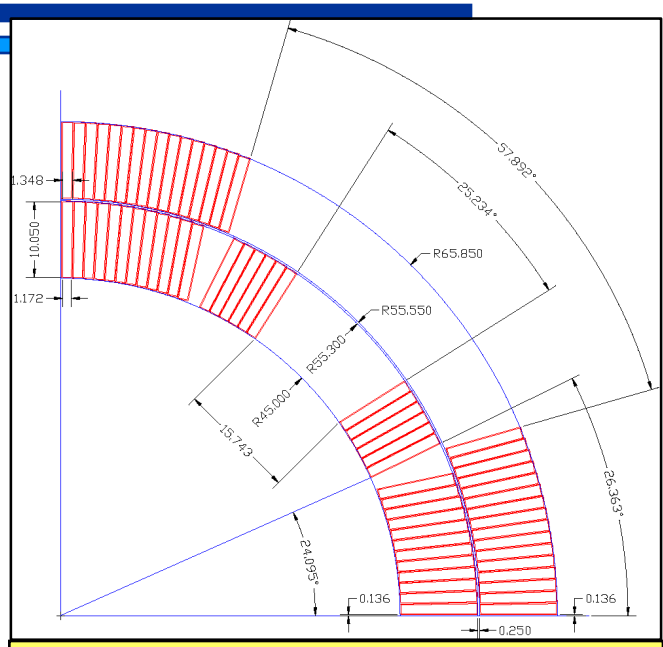


† P. Ferracin et al. "Assembly and Loading of LQS01, a Shell-Based 3.7 m Long Nb3Sn Quadrupole Magnet for LARP" *IEEE Trans. on Applied Supercond.;* Vol. 20, no. 3, p. 279-282, March 2010

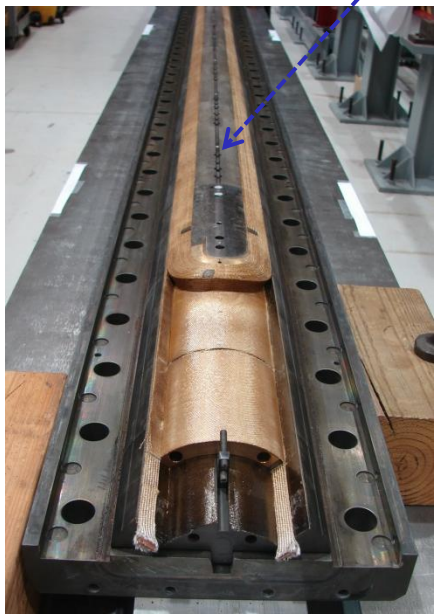
LQ Coils†



- **Coil design:**
  - LQ coils = long TQ02 coils with gaps to accommodate different CTE during HT
- **Fabrication technology:**
  - From 2-in-1 (TQ coils) to single coil fixtures (LQ)
  - Mica during heat treatment
  - Bridge between lead-end saddle and pole



Cross-section of TQ/LQ coil



LQ Coil Fabrication:

- 5 practice coils (Cu and Nb_3Sn)
- coils #6-#9 ➔ LQS01
- coils #10-#13 ➔ LQS02

Note: coils #6-#9 had 3 severe discrepancies

† G. Ambrosio et al. "Final Development and Test Preparation of the First 3.7 m Long Nb3Sn Quadrupole by LARP" *IEEE Trans. on Applied Superconductivity;* Vol. 20, no. 3, p. 283-287, March 2010.