Design and Test of the 1st Nb_3Sn Long Quadrupole by LARP

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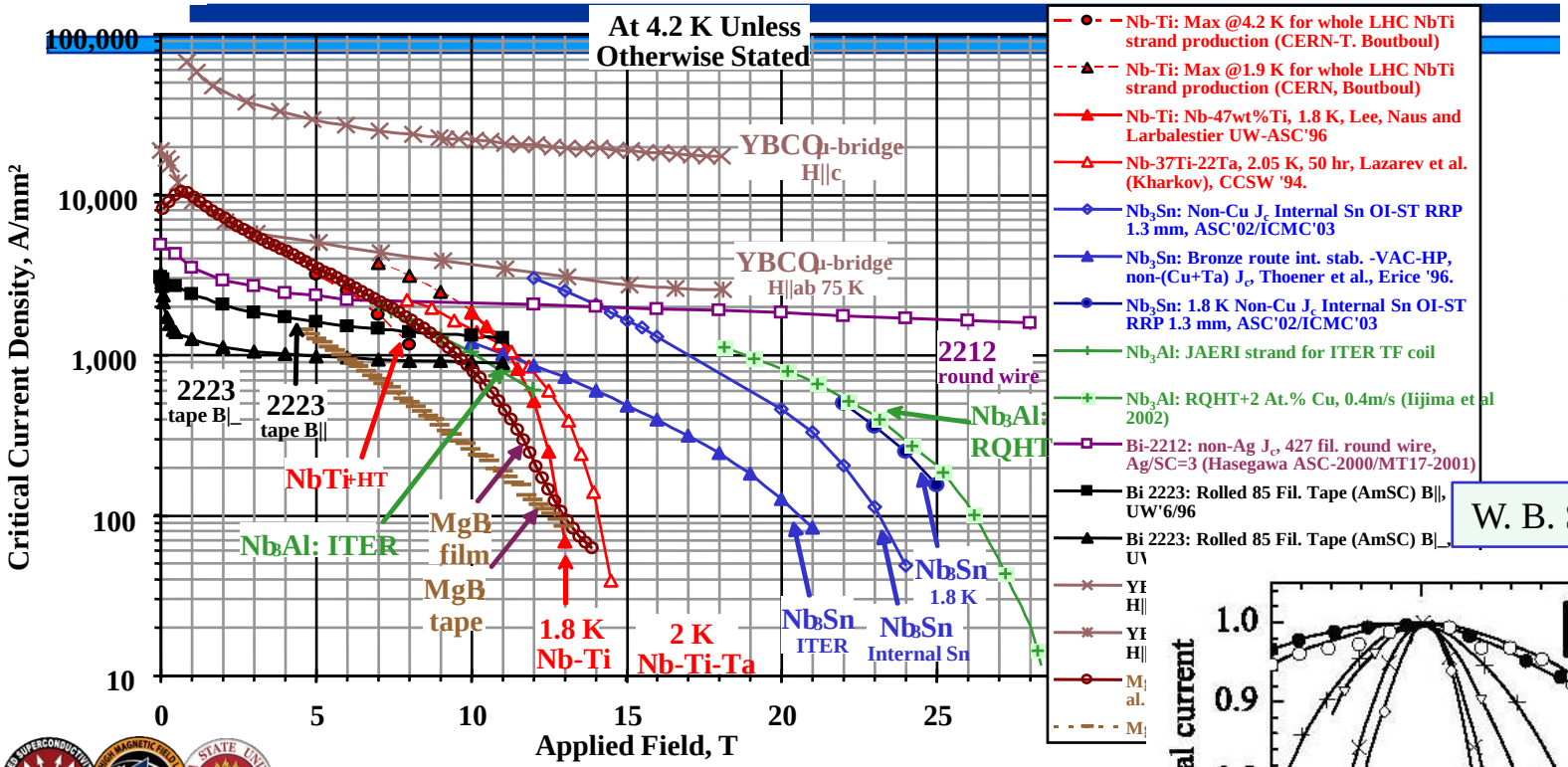
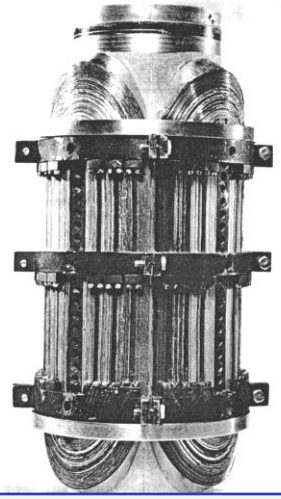
Fermilab

Acknowledgement: 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

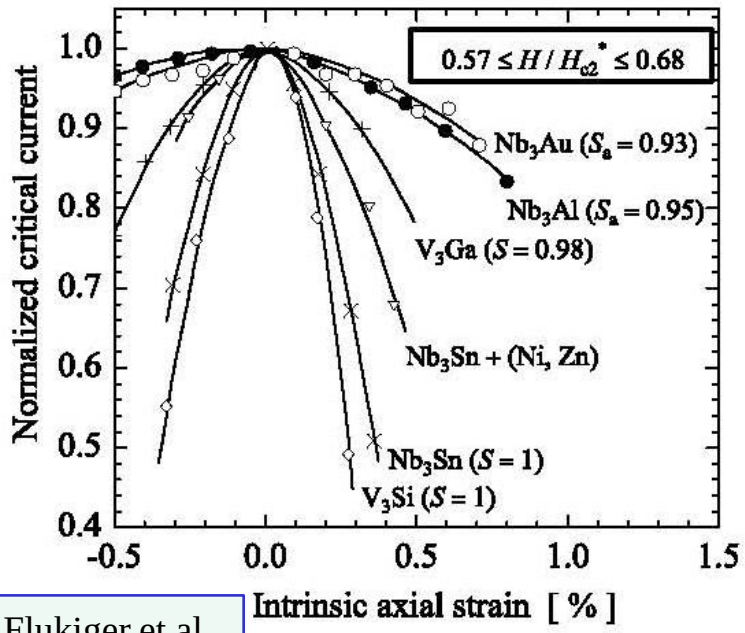
Post NbTi Candidates



http://www.magnet.fsu.edu/magnettechnology/research/asc/plots.ht



W. B. Sampson, MT-2 1967



R. Flukiger et al.,

- **Nb_3Sn is the only candidate in the mid-term (~10 years)**
- **Development started in the '60s …**
- **But it is brittle and strain sensitive!**

US LARP Program

*" The **US LHC Accelerator Research Program** enables U.S. accelerator specialists to take an active and important role in the LHC accelerator during its commissioning and operations, and to be a major collaborator in LHC performance upgrades (…)"*
(mission statement)

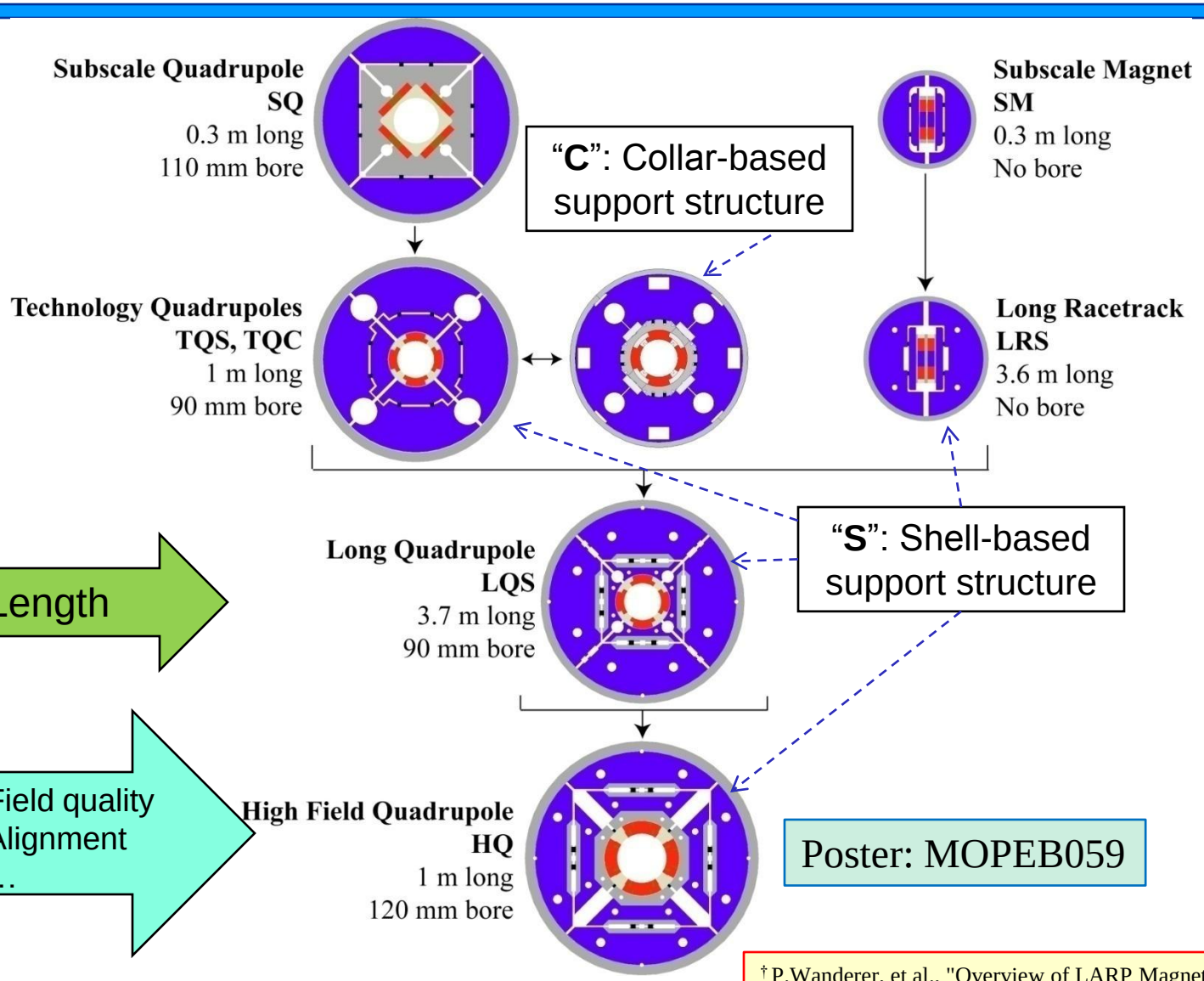
- **Magnet R&D (FNAL, BNL, LBNL) Goal:**

  Demonstrate that Nb_3Sn is a viable option for LHC Luminosity Upgrade

➔ **2005 milestone by DOE, CERN, LARP:**

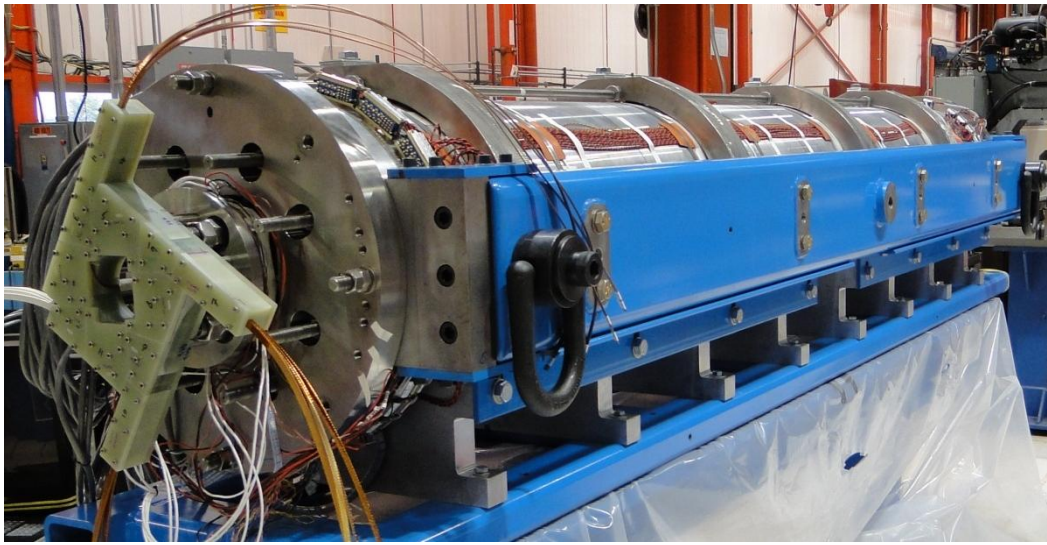
- 90 mm aperture, 4 m long Quadrupole
- Gradient = 200 T/m
- by the end of 2009

LARP R&D plan†



† P.Wanderer, et al., "Overview of LARP Magnet R&D," *Applied Superconductivity, IEEE Trans. on* , vol.19, no.3, pp.1208-1211, June 2009

Long 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)

LQS01 was tested in Nov-Dec 2009 →

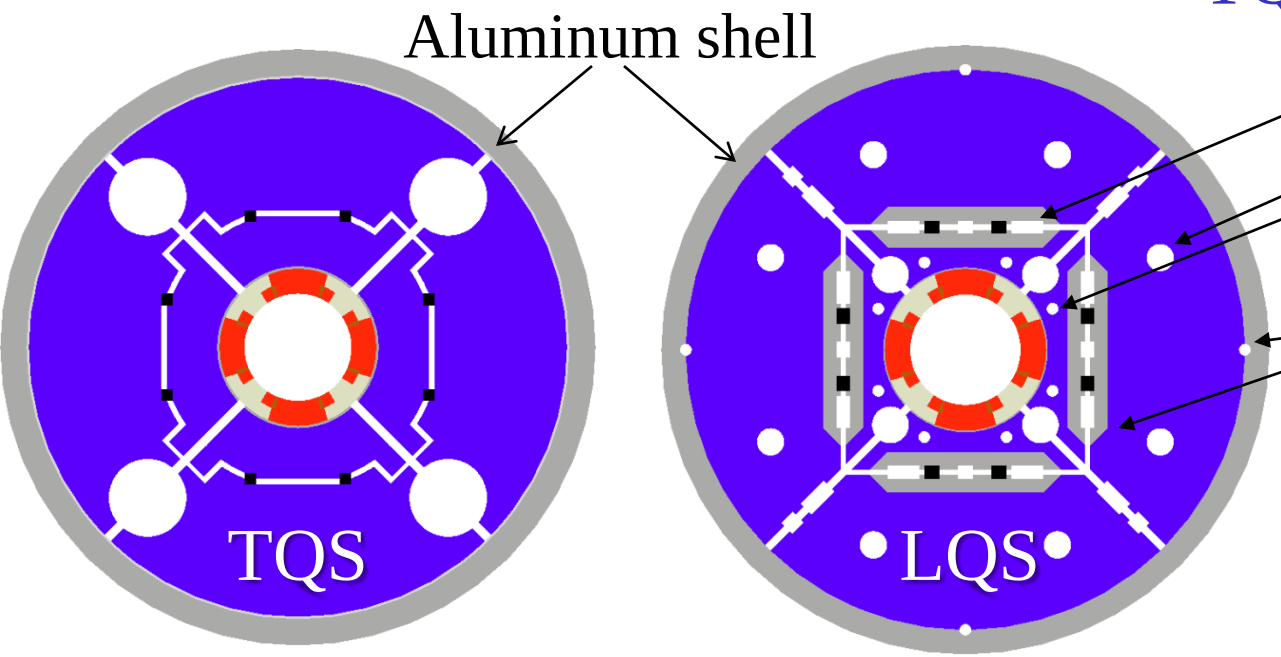
LQS01b test start in June

LQS01 SSL	4.3 K
Current	13.9 kA
Gradient	242 T/m
Peak Field	12.4 T
Stored Energy	473 kJ/m

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

LQ Structure†

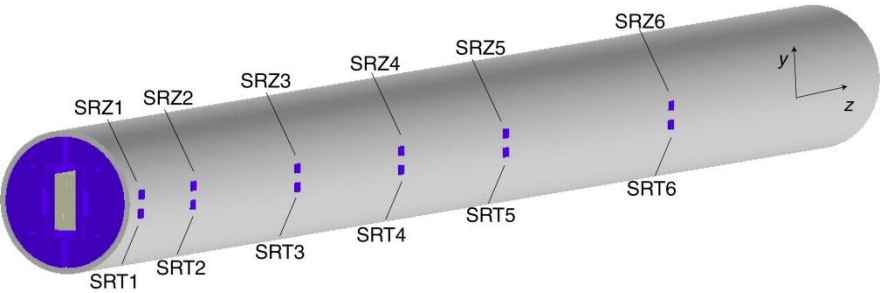
- **LQS is based on TQS (1m model)**

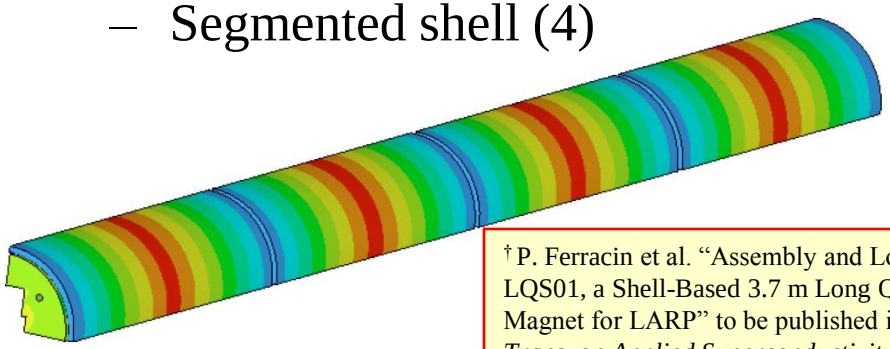


TQS Modifications:

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

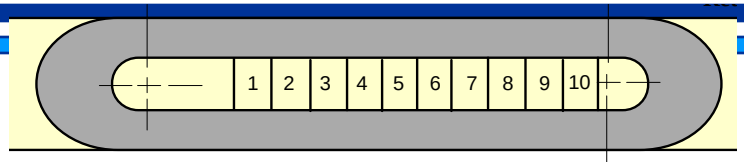
- **and LRS (4m racetrack)**
  - Segmented shell (4)



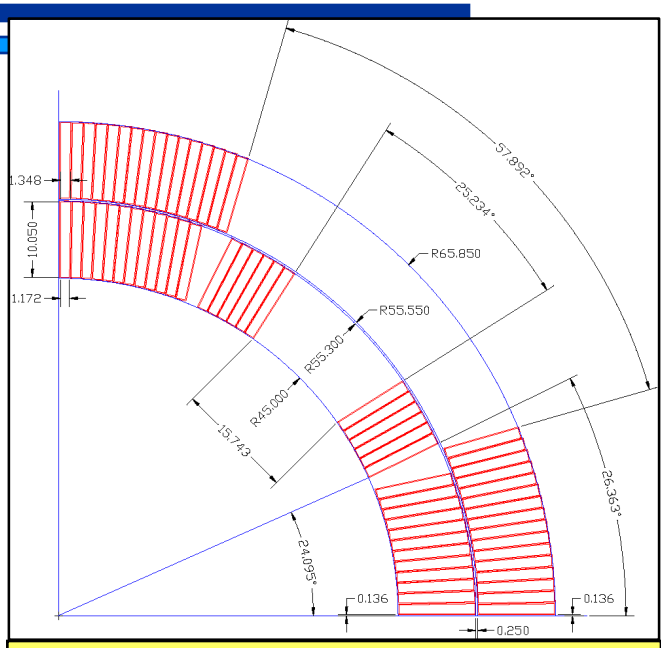


† P. Ferracin et al. "Assembly and Loading of LQS01, a Shell-Based 3.7 m Long Quadrupole Magnet for LARP" to be published in *IEEE Trans. on Applied Superconductivity.*

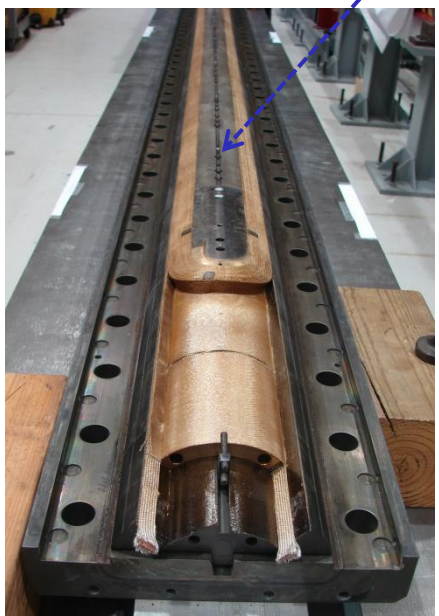
LQ Coils†



- **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:

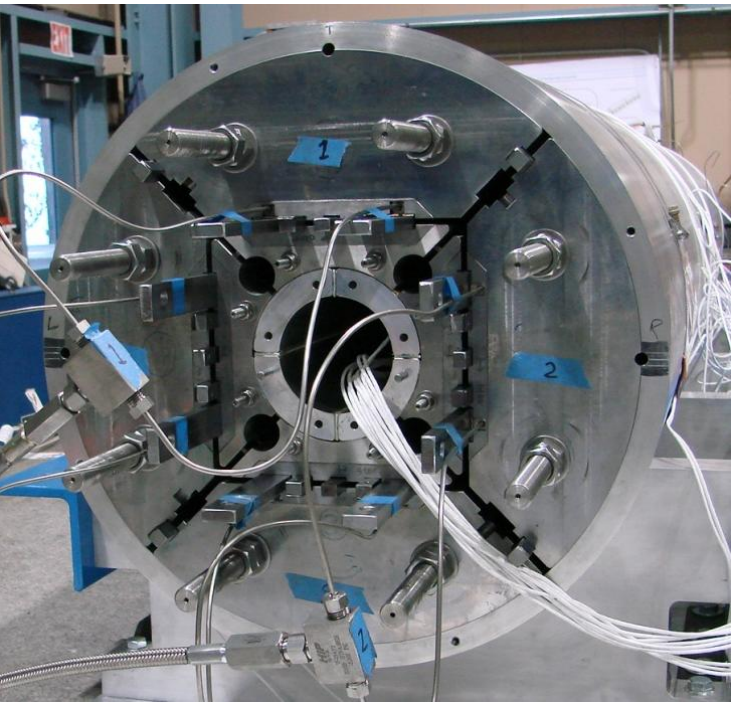
- 5 practice coils (Cu and Nb_3Sn)
- coils #6-#9 ➔ LQS01
- coils #10-#13 ➔ LQS02

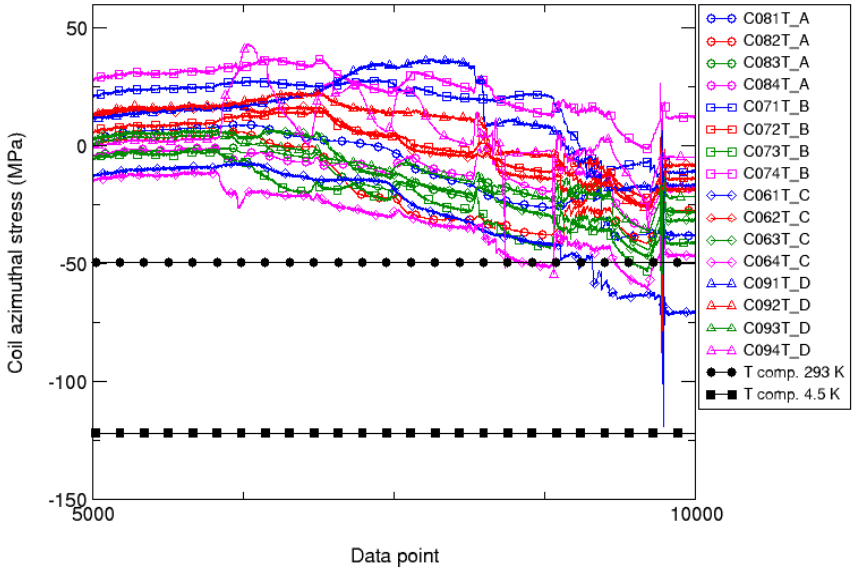
Note: coils #6-#9 had 3 severe discrepancies

† G. Ambrosio et al. "Final Development and Test Preparation of the First 3.7 m Long Nb3Sn Quadrupole by LARP" to be published in *IEEE Trans. on Applied Superconductivity.*

LQS01 Load & Cooldown

- **Pre-load**
  - Target stress on shell
  - Target stress on roads
  - Lower stress on coils ID
- **Cooldown**
  - Shell: close to target stress
  - Rods: close to target stress
  - Coil ID: ~ ½ target stress



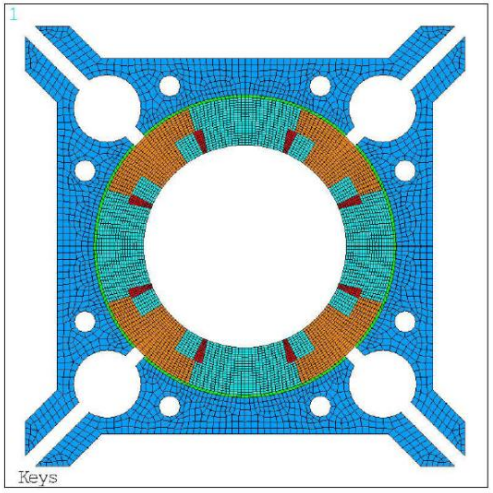


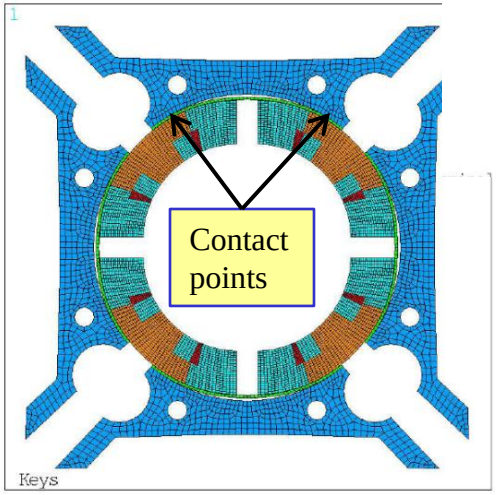
Azimuthal stress (MPa) in the coil poles during cool-down:
values measured (colored markers)
and computed (black markers) from a 3D finite element model

Coil-Pad Mismatch

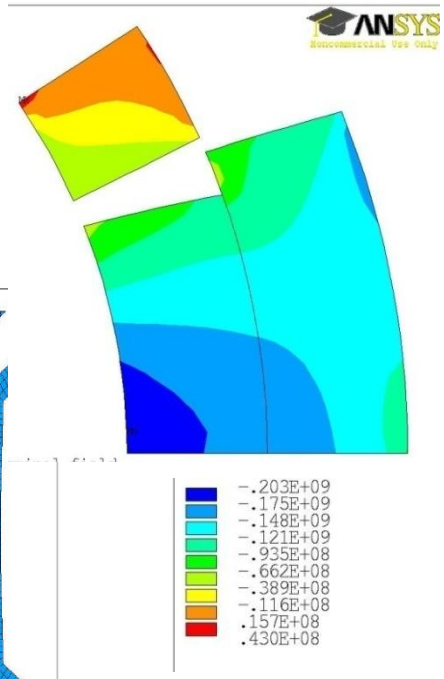
- **FEM model with azimuthally oversized coils (120 μm)**
  - ➔bending due to coil-pad mismatch
  - ➔Lower stress in the pole
    Consistent w measurement
  - ➔Higher stress on midplane
    Risk of damage above 200 T/m

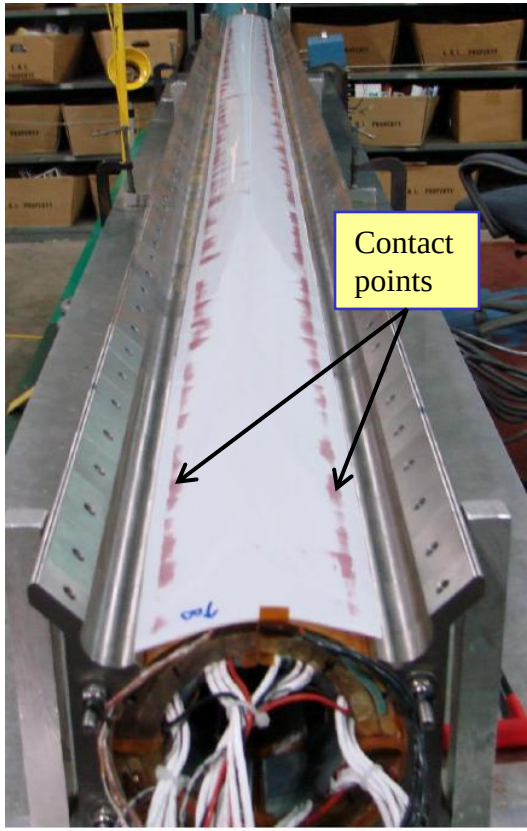
- **Verified during disassembly**
  - Tested with pressure sensitive paper





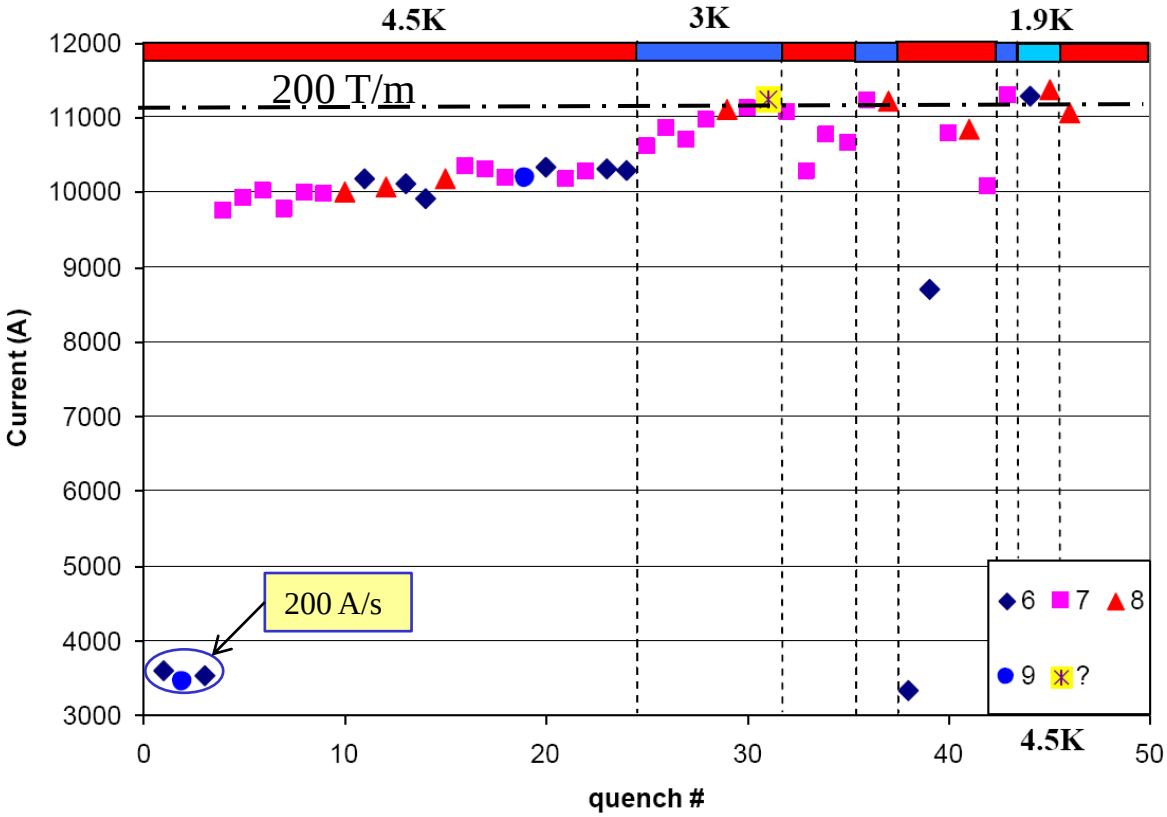
Displ. scaling: 50





LQS01 Quench History

- **Slow start**
  - First quenches at high ramp rate (200 A/s)
    - Trying to avoid QPS trips due to voltage spikes
  - 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 before reassembly



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

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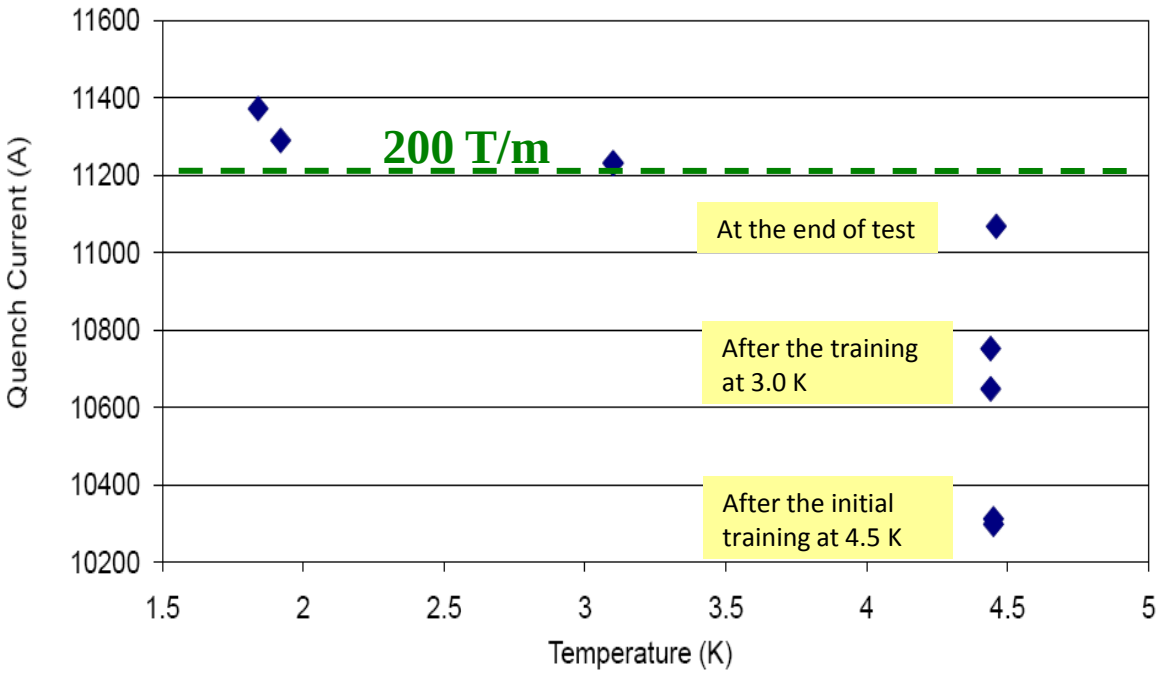

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Voltage Spikes

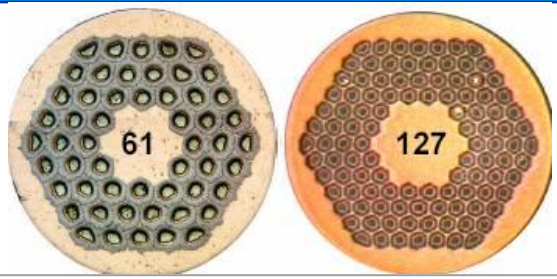
- **Large voltage spikes**
  - Due to flux jumps
    - Seen in TQ magnets using RRP 54/61
  - Larger than in TQs

➔Variable quench detection threshold

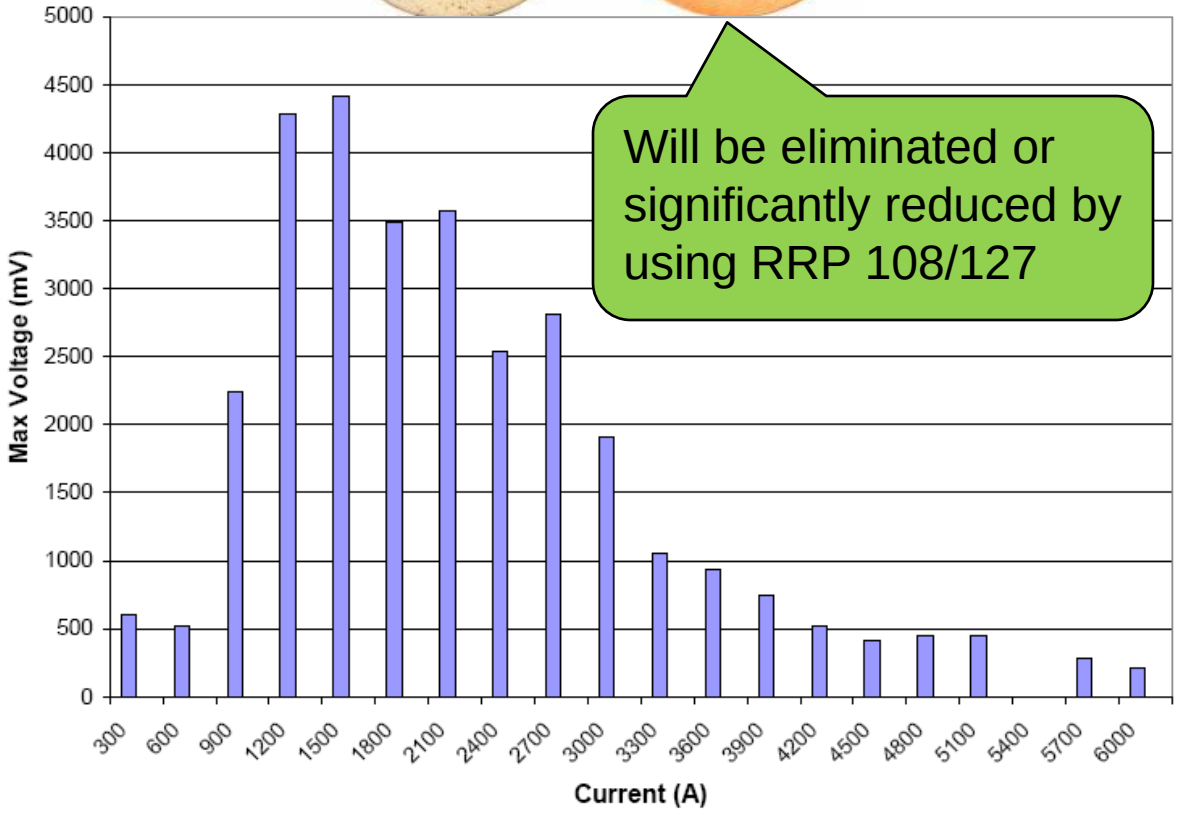
➔Variable ramp-rate during training

- 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



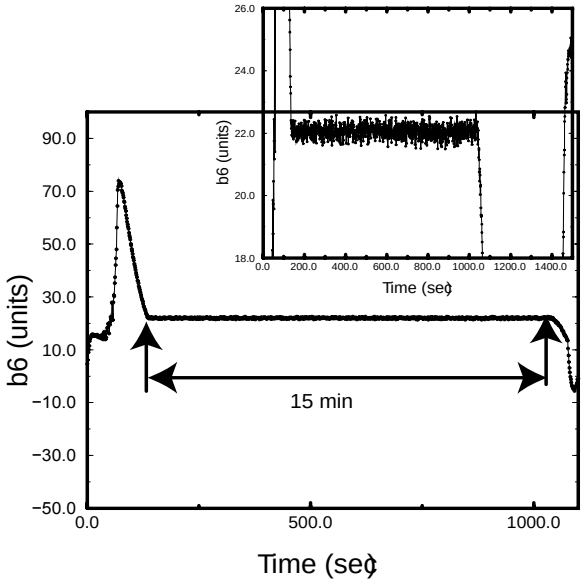
Maximum Voltage Spike amplitude at 4.5 K with 50 A/s ramp rate

Magnetic Measurement

- **Magnetic measurement at 4.5K:**
  - Harmonics:
    - Some are a few units differenf wrt computed
    - Similar to short models (TQ) †
    - A few harmonics, slightly worse, may have been affected by assembly
  - Dynamic effects
    - No decay and snapback
- **Will repeat and expand on LQS01b**

#	100 T/m (5.3 kA)		179 T/m (10 kA)	
	Computed	Measured	Computed	Measured
b_3		2.29		2.61
b_4		6.73		6.93
b_5		0.17		-0.08
b_6	9.8	9.89	6.1	7.47
b_7		-0.06		-0.11
b_8		-0.98		-0.38
b_9		0.19		0.13
b_10	-0.04	0.35	-0.02	-0.47
a_3		2.28		2.28
a_4		1.94		2.11
a_5		-0.51		-0.65
a_6		-0.12		-0.29
a_7		0.29		0.14
a_8		0.08		0.06
a_9		-1.09		-0.16
a_10		0.37		0.12

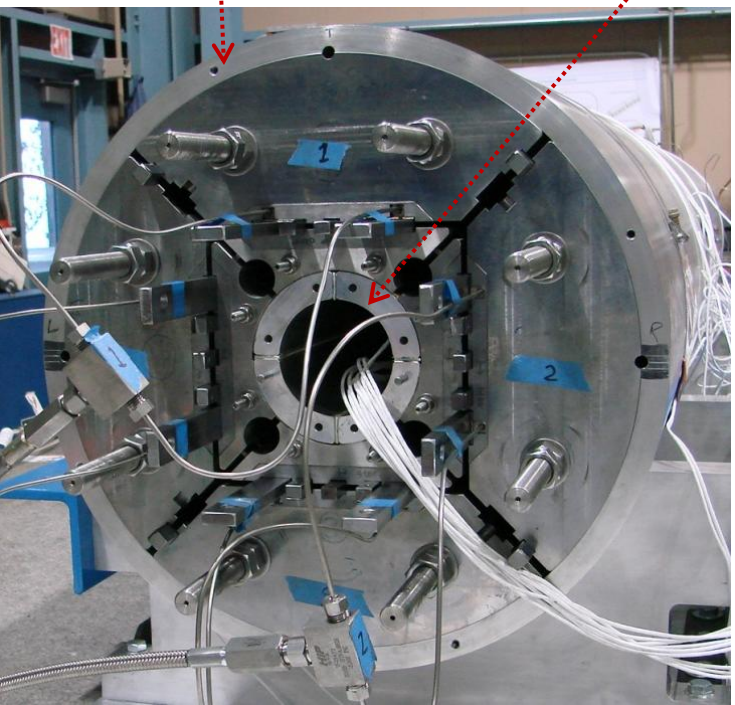
Geometrical harmonics at 100 and 179 T/m field gradient. Results are presented at 22.5 mm reference radius, *which corresponds to the official radius adopted for LHC (17 mm) corrected for the increase in the magnet aperture from 70 to 90 mm.*
An 81.8 cm long tangential probe was used.

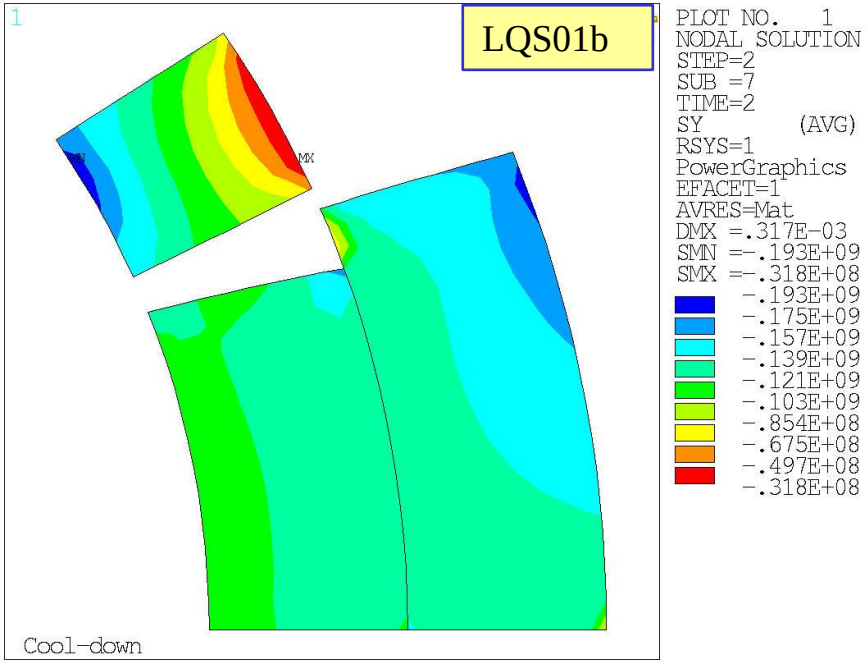


† G. Velev, et al., "Field Quality Measurements and Analysis of the LARP Technology Quafrupole Models", IEEE Trans. On Applied Supercond. , vol.18, no.2, pp.184-187, June 2008

LQS01b Loading

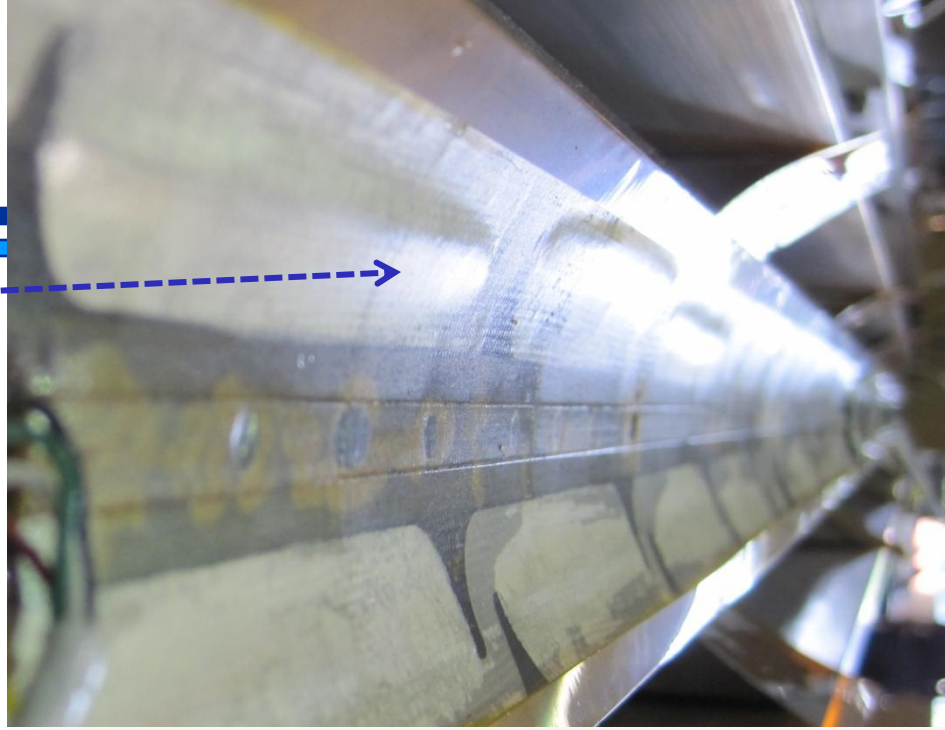
- **New shims give correct ratio between strain in the shell and strain in the coils (same coils of LQS01)**
  - More uniform prestress
- **Higher preload based on short models (TQS03 a/b/c)**
  - Peak load: 190 MPa +/- 30

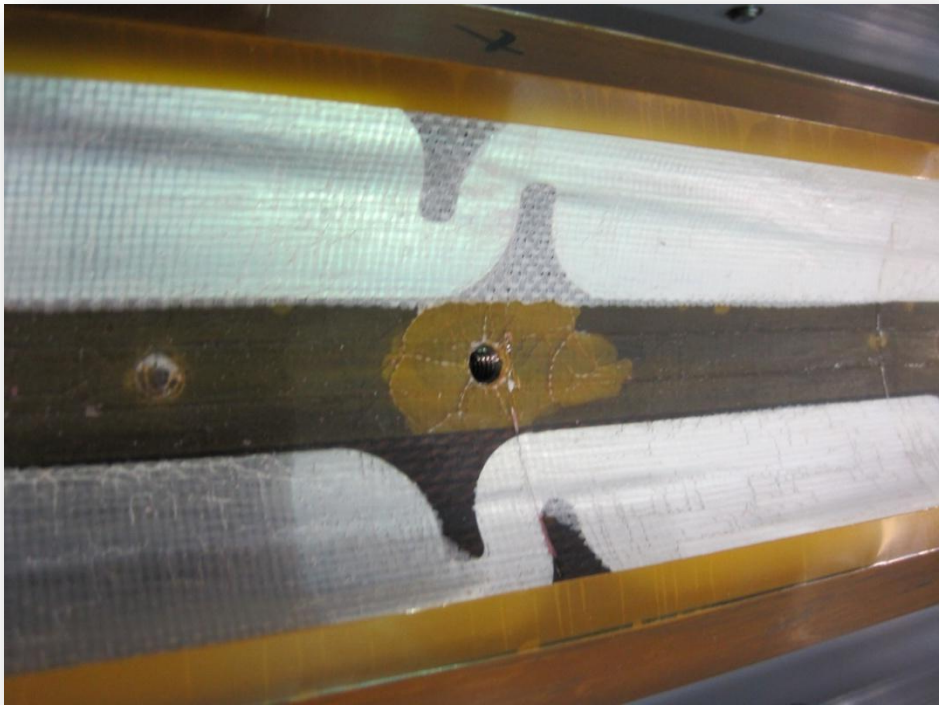




Coils after Test

- **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 or
  - Change heater location





Plans

- **LQS01b with LQS01 coils**
  - GOAL: reproduce TQS02 performance
    - Check uniform preload with new shims
    - Check effects of higher pre-load

Beginning of June

- **LQS02 with 4 new coils (54/61 strand)**
  - GOAL: better training and memory
    - Gradient > 200 T/m with short training
    - Effect of thermal cycle (memory)

November 2010

- **LQS03 with 4 new coils (108/127 strand) and new cable insulation (glass tape)**
  - GOAL: accelerator-quality conductor & insulation
    - Smaller Voltage Spikes
    - Better 1.9 K performance

June 2011

Plus additional reassemblies based on results

Conclusions

- **The first Nb_3Sn Long Quadrupole (LQS01) reached the 200 T/m target**
  - Even if training was not completed
  - Even if coils and assembly had some issues
- **Next LQ models aim at:**
  - Achieving same performance of short models
  - Demonstrating short training & good memory
  - Demonstrating accelerator-quality conductor and cable insulation
- **Need still some R&D:**
  - Protection heaters for inner layer

Are Nb3Sn magnets ready for use in Particle Accelerators?

**Not yet...
but we are MUCH closer!**