US LHC Accelerator Research Program

bnl - fnal- lbnl - slac

Nb_3Sn Magnet Development for LHC Luminosity Upgrade

Peter Wanderer
Head, LARP Magnet System

WAMSDO 2008 – May 19-23 – at CERN

OUTLINE

- LARP Magnet Goals
- Materials
- Racetrack magnet – long, shell (LRS)
- Technology Quads (TQ → TQC, TQS)
  - Support structures: collar and shell
- Long Quads (LQ → LQC, LQS)
- High Gradient/Aperture (HQ)
- QA – slot-compatible with NbTi Phase 1 quads
- QB – Phase 2 quad

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Collaborators (on org chart)

L0: S. Peggs → E. Prebys

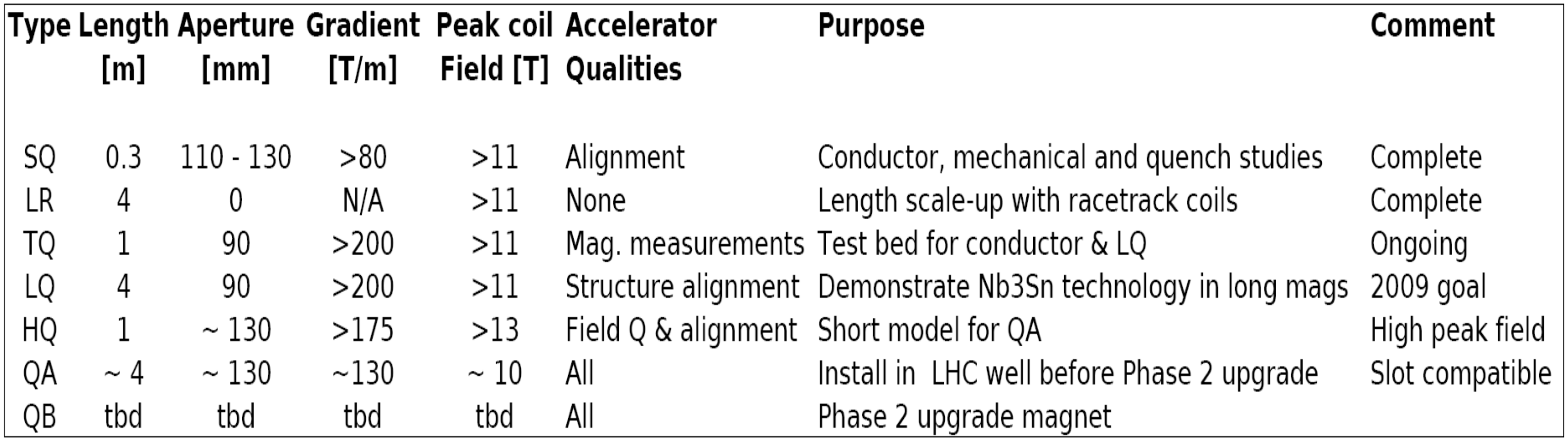
  Joint IR Study: A. Zlobin

L1: P. Wanderer (magnet) + T. Markiewicz (accelerator)

L2:

- G. Sabbi – Model Quadrupoles
  - R. Bossert, S. Caspi, P. Ferracin
- G. Ambrosio – Long Quadrupoles
  - H. Helice, P. Ferracin, F. Nobrega, J. Schmalzle
- A. Ghosh – Materials
  - E. Barzi, D. Dietderich

LARP Magnet Sequence Table & Goals



Type	Length [m]	Aperture [mm]	Gradient [T/m]	Peak coil Field [T]	Accelerator Qualities	Purpose	Comment
SQ	0.3	110 - 130	>80	>11	Alignment	Conductor, mechanical and quench studies	Complete
LR	4	0	N/A	>11	None	Length scale-up with racetrack coils	Complete
TQ	1	90	>200	>11	Mag. measurements	Test bed for conductor & LQ	Ongoing
LQ	4	90	>200	>11	Structure alignment	Demonstrate Nb3Sn technology in long mags	2009 goal
HQ	1	~ 130	>175	>13	Field Q & alignment	Short model for QA	High peak field
QA	~ 4	~ 130	~130	~ 10	All	Install in LHC well before Phase 2 upgrade	Slot compatible
QB	tbd	tbd	tbd	tbd	All	Phase 2 upgrade magnet	

GOALS

LQ (3.6 m, 90 mm) reaches 200 T/m by end of CY2009

Fully qualify Nb_3Sn magnets for use in the LHC

Supply Nb_3Sn magnets for Phase 2 upgrade

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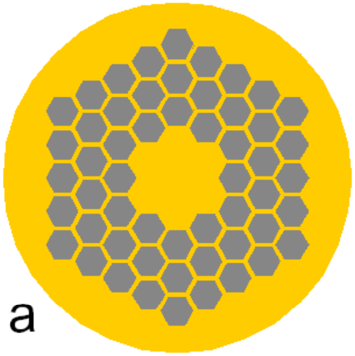
Materials Topics

- Strand
  - Status
  - Production summary
  - R&D (Jc, strain, stability, reaction schedule)

- Cable (impregnated)
  - J_c vs. stress
  - Mechanical properties
  - Dynamic Effects / Interstrand resistance R_I / Sintering
  - Radiation damage, thermal model (with Joint IR Study - JIRS)
  - Temperature margin

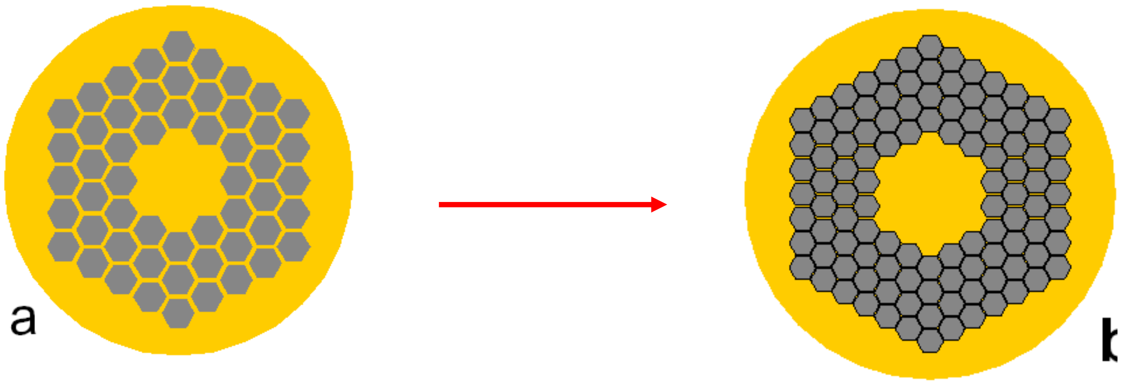
RRP 54/61 (Oxford)

- Development of RRP 54/61 high J_c strand by Oxford, replacing MJR as the standard material
  - funded by DOE Conductor Development Program
  - Lab 'base' programs help with strand & magnets
  - Collaboration with CERN: cable and magnet tests
- Oxford 54/61 reaction schedule (max. J_c) modified to increase stability with modest reduction of J_c



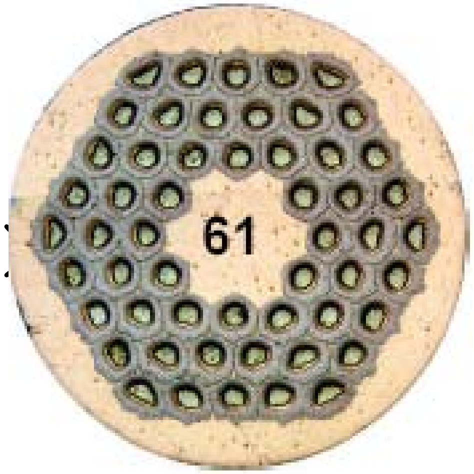
RRP 108/127

- Magnet apertures > 90 mm → need for larger-diameter strand with no increase in filament diameter → more rods: 54/61 → 108/127
  - 108/127 reaction schedule optimization underway
  - Coils using 108/127 to be made this year

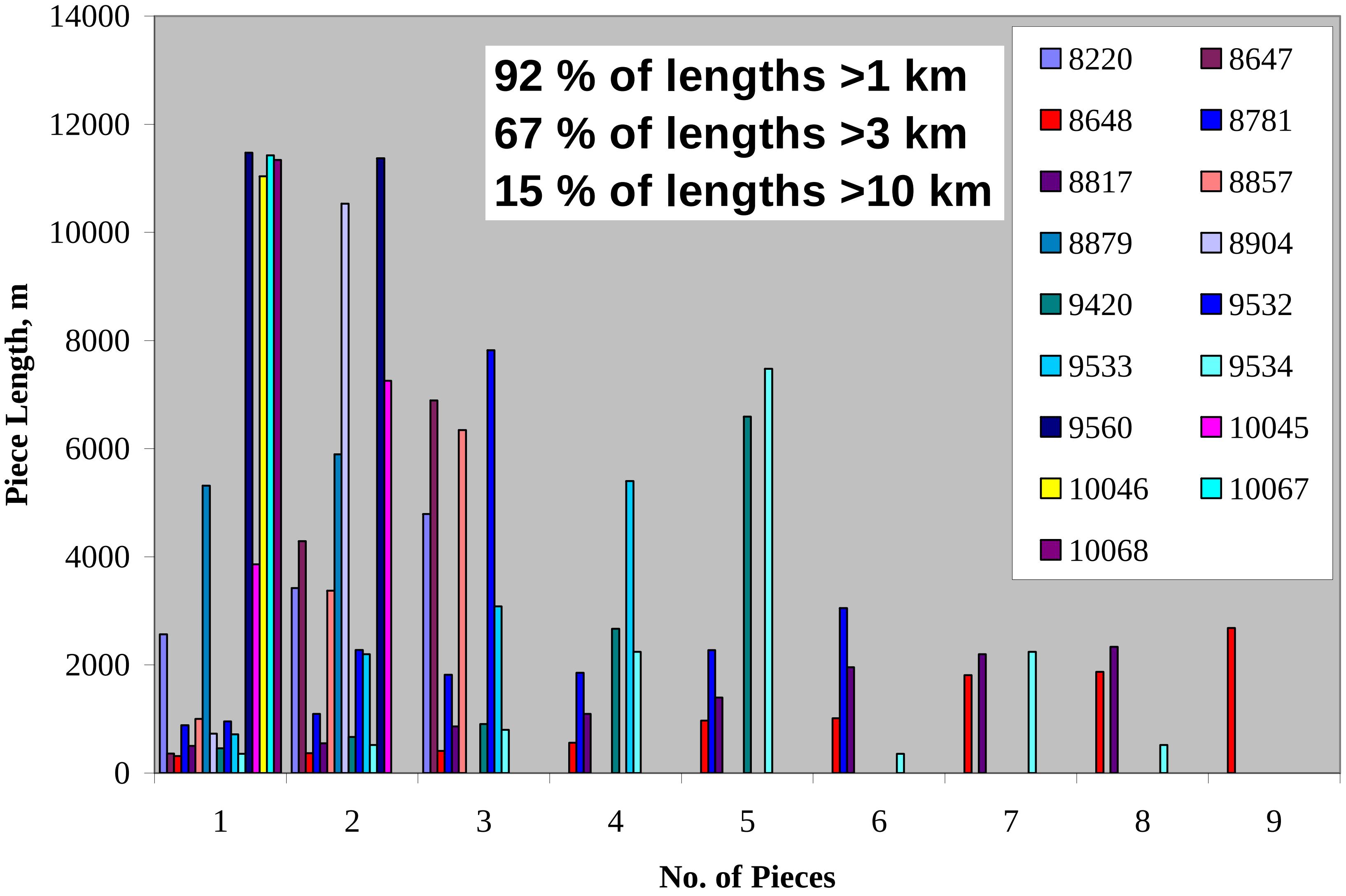


Conductor Production Summary

- RRP 54/61, 0.7 mm strand (LRS, TQ, LQ)
  - 688 kg (17 billets) produced for the LARP magnets ⇨1 billet yields ~ 40 kg
  - LRS (3ULs-100 kg), TQ (6 ULs-40 kg), LQ (6 ULs-150 kg) (UL ⇨cable length for 1 coil
  - Long piece lengths
  - Present strand inventory is 282 kg
- RRP 108/127 (with increased spacing)– 180 kg has been processed
  - 37 kg at 0.7 mm
  - 30 kg at 0.8 mm
  - 114 kg at 1.07 mm
- RRP 54/61 with increased spacing – 90kg
  - Wire diameter ~ 0.8 – 1.0 mm
  - To be used for HQ magnets



RRP 54/61 Piece Lengths

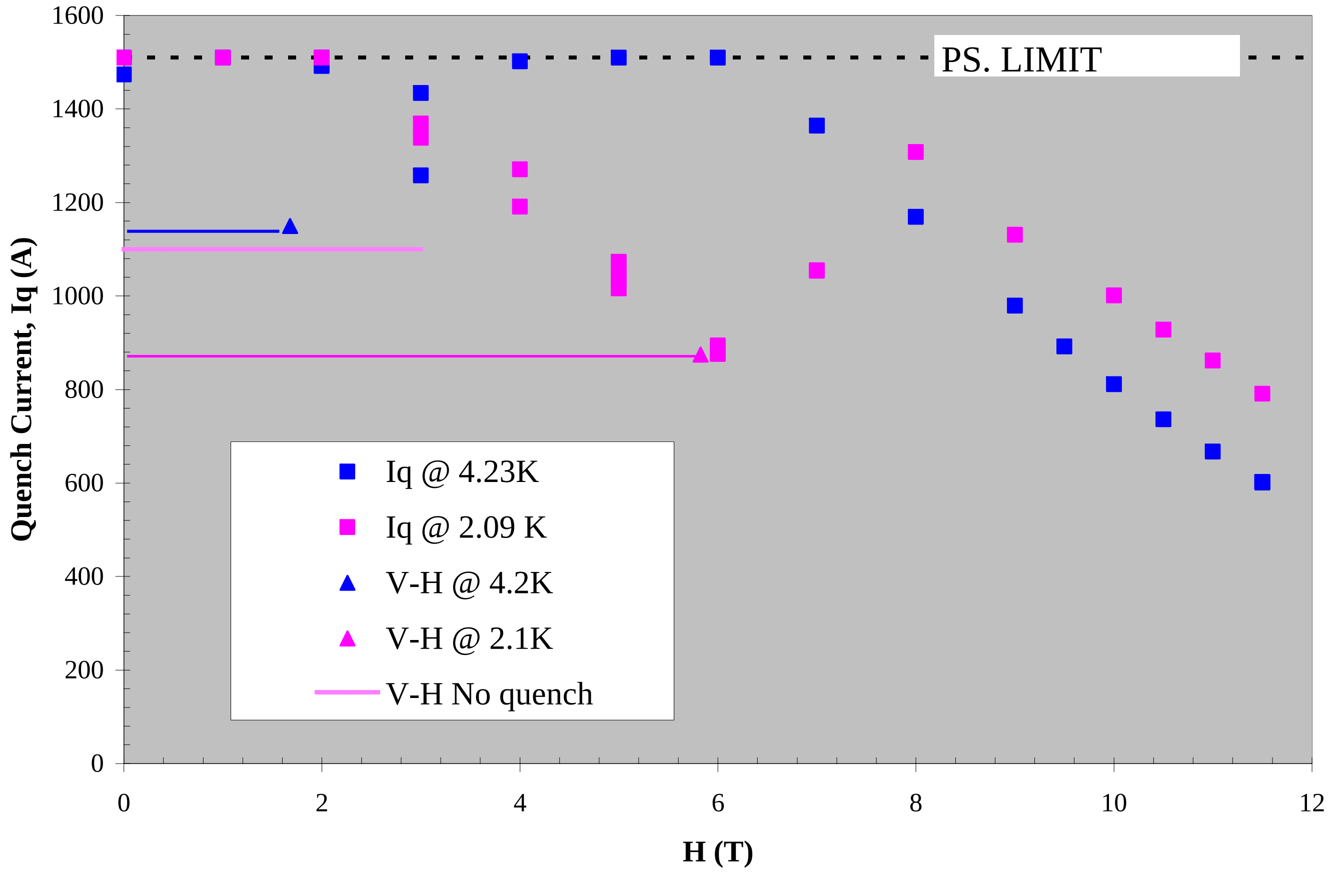


92 % of lengths >1 km
67 % of lengths >3 km
15 % of lengths >10 km

Strand R&D Underway

- J_c vs. strain for 54/61: measurement at NIST (Colorado)
  - Results expected mid-June
- J_c & stability vs. reaction schedule for 108/127
  - Results this summer
- Instability larger at 2K than at 4.2K
  - Strand data
  - Magnet data

RRP 54/61, Jc ~ 2550 A/mm2, RRR ~ 310



At 4.2 K,

I(TQ) < 500 A

54/61 RRP Strand and Magnets, 4.2 K and 1.9 K

- RRP unstable above a threshold current I_{th}
  - Low field: 2.09 K and 4.2 K
  - Medium field: 2.09 K

- Increasing RRR (Cu conductivity) ⇒ increased I_{th}
- Increase RRR by adjusting Nb_3Sn heat treatment (HT)

- **RRP(LARP HT) in TQ, I_{th} > 2 X I_{TQ} at 4.2 K,2.1 K**

- *Should* assure that TQ not affected by instabilities at 4.2 K or 1.9 K → I_q (1.9 K) not higher than I_q (4.2 K) is a puzzle which is under investigation.

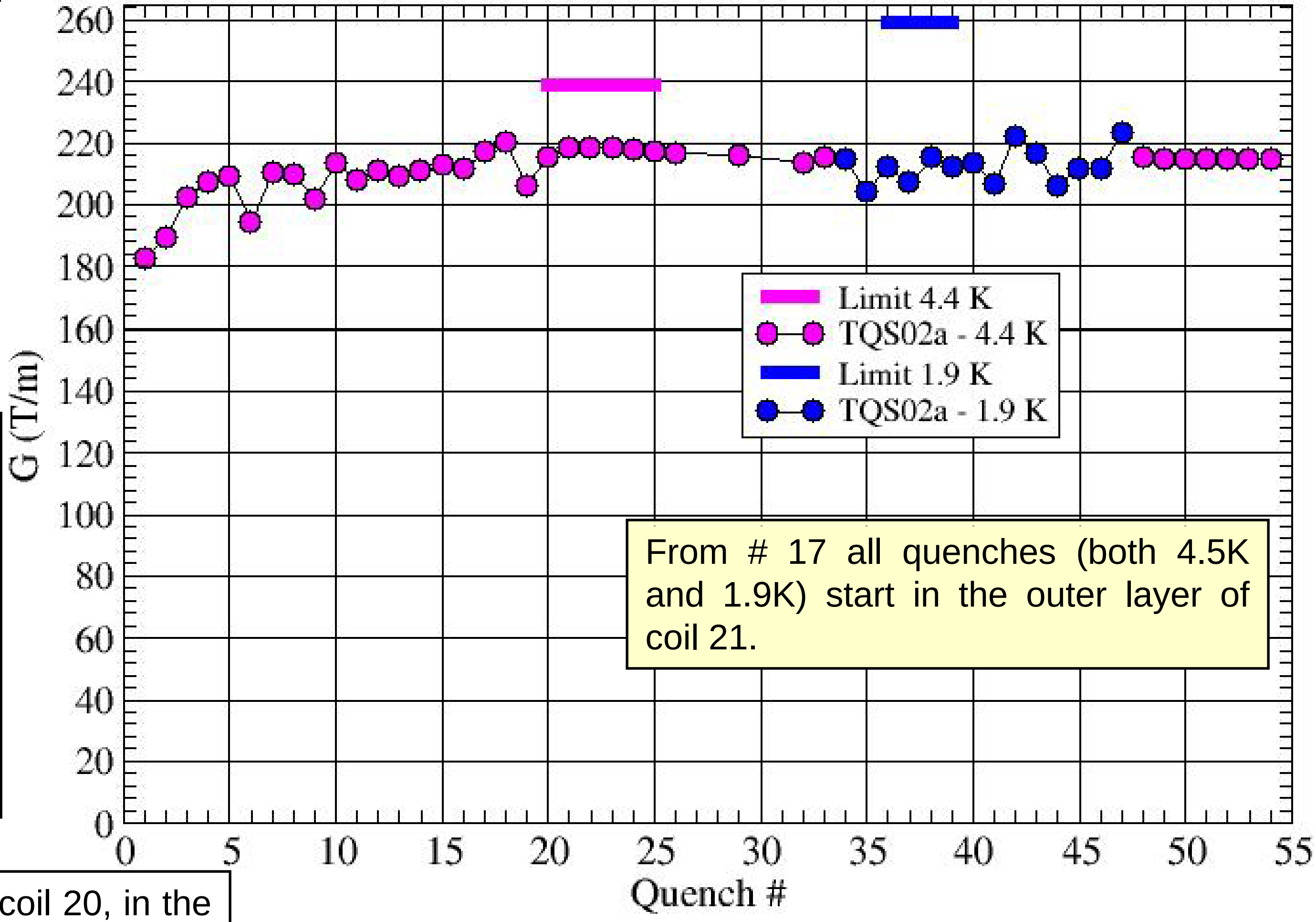
TQS02a Training

TQS02a

180 to 220 T/m, 20 quenches

Plateau coil 21 layer 2

No gain at 1.9 K



From # 17 all quenches (both 4.5K and 1.9K) start in the outer layer of coil 21.

Quench 1: inner layer pole turn, ramp and multi-turn
Quench 2-3: outer layer multi-turn followed by return end.
Quench 4: inner layer pole turn and multi-turn segment inside wedge.
Quench 5-6: outer layer multi-turn followed by pole turn.

Quench 8 to 16, inner layer of coil 20, in the turns inside the wedge.

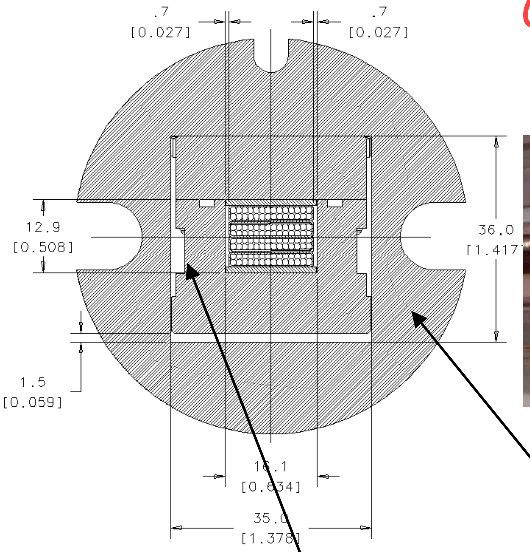
Cable – J_c - status and plans

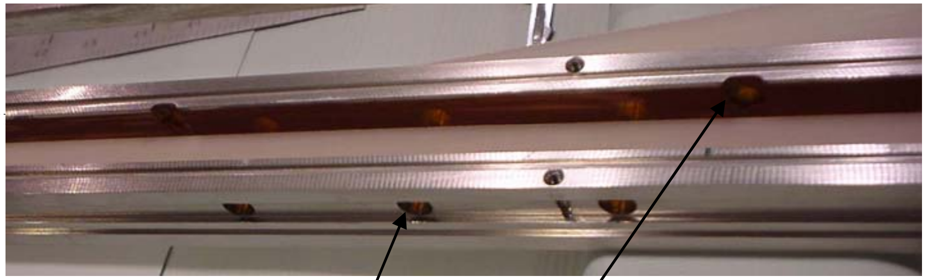
- J_c dependence on strain assumed same for RRP as MJR
- J_c limit of cable in magnet not corrected for strain
- Strain of impregnated cable not well defined.
- J_c limit of cable estimated from tests of several strands extracted from the cable before reaction.

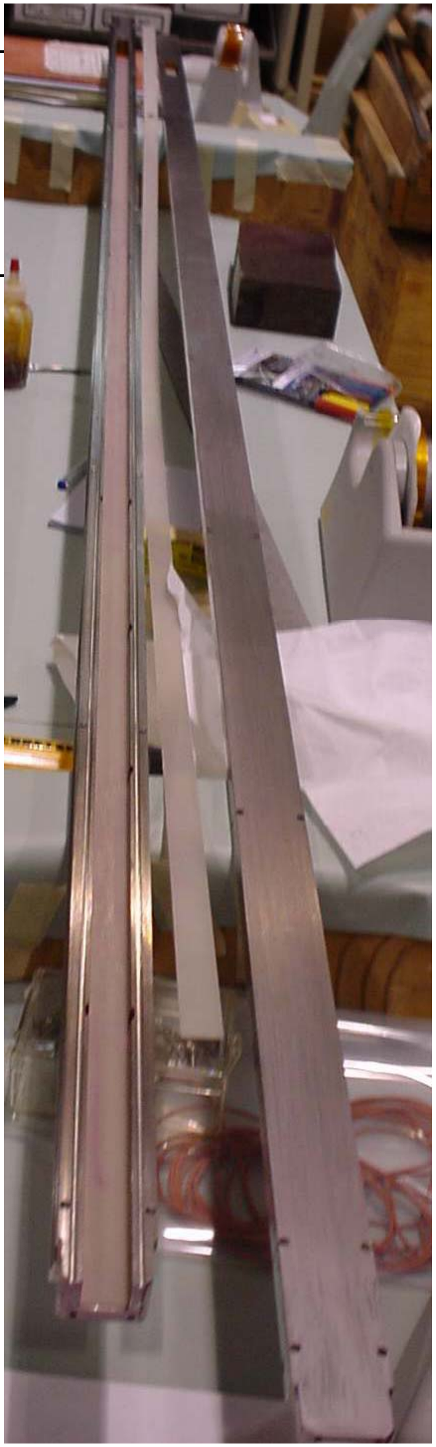
- J_c vs. stress – two tests planned:
  - Load ⊥ plane of impregnated cable
  - FRESCA – 4.5 K, 1.9 K – sample must be warm to change the stress – this fall
  - NHMFL (Florida) – 4.5 K – stress can be changed while sample cold – not before Oct. 1

Sample Holder for test at CERN

Goal: Measure J_c, Stability of LQ cable

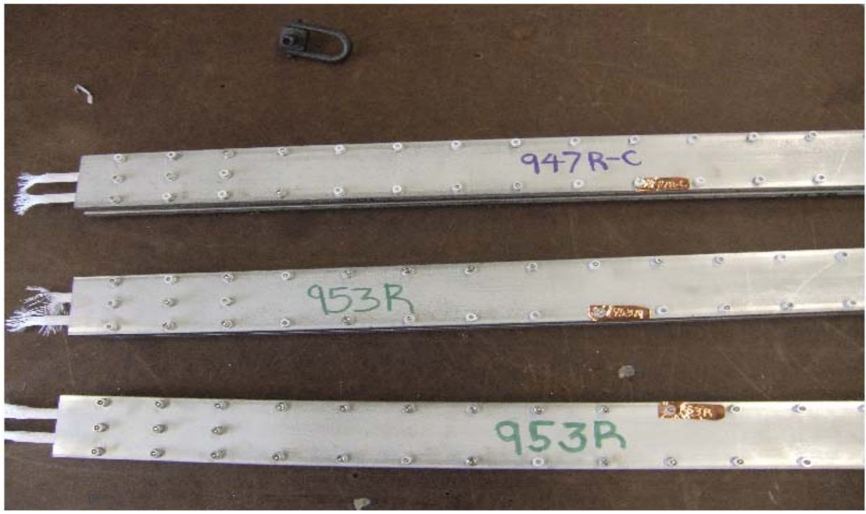




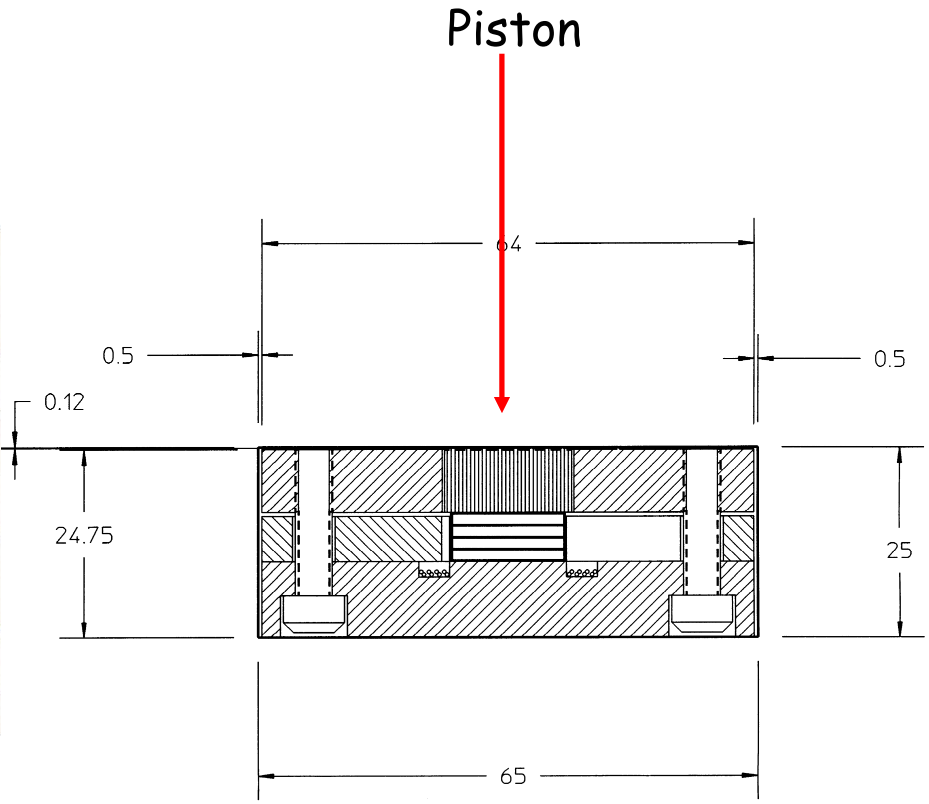


Designed to fit FRESCA collars
Two cables protected by two "dummy" cables
Vacuum impregnation in situ
Pre-stress by adding a Kapton layer after impregnation
He channels and holes for splice cooling
Notches for voltage taps

Testing at NHMFL (Florida)



Test cables ready for reaction



Cable test fixture

Cable – Mechanical Properties

- "Representative" coil finite-element models for warm, cold, 240 T/m
  - Compressive stress < 150 MPa
  - Shear stress between turns < ± 30 MPa
- Coil properties, available data
  - Compression ok at least to 180 MPa at (room temp)
  - Shear stress between turns – failure ~ 25 MPa (room temp)
  - Fiberglass+binder+epoxy good to ~ 100 MPa (77 K), dropped to ~ 30 MPa after 20 MGy irradiation
  - Ref: FNAL Technical Div. Note TD-08-001, Ambrosio, Bossert, Ferracin
- Additional data from tests in FRESCA, NHMFL, etc.

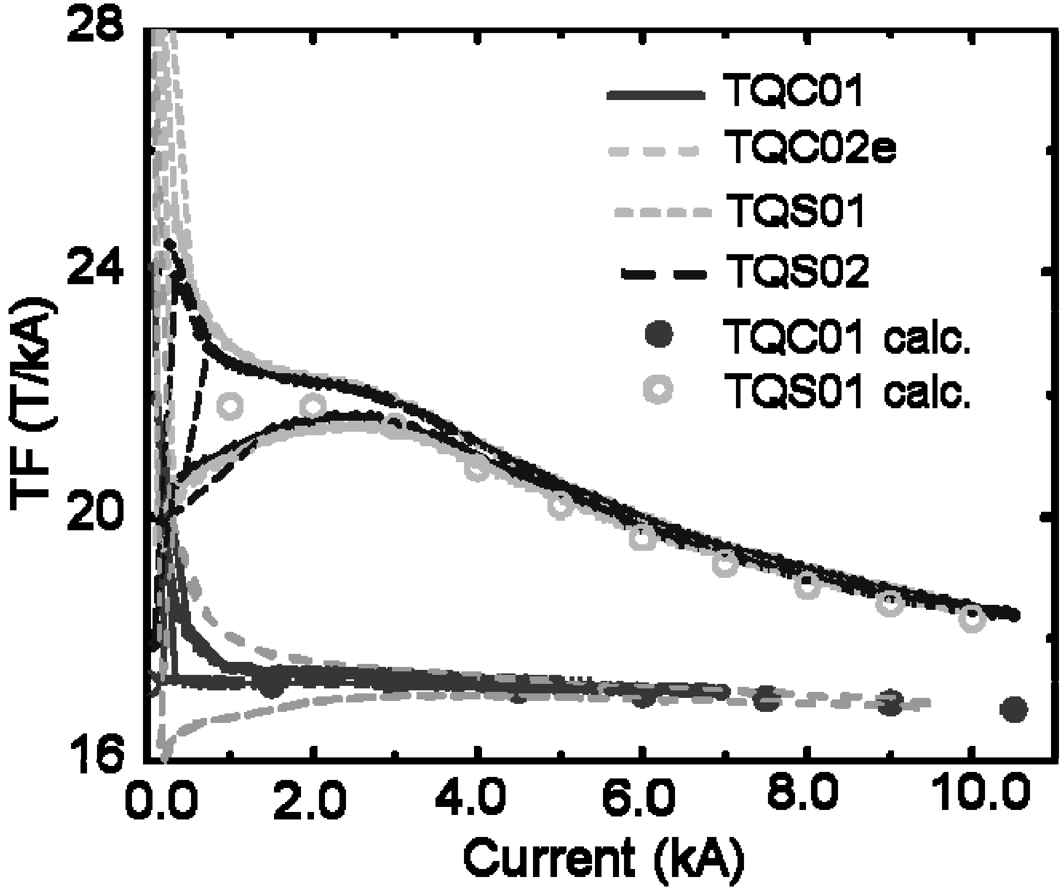
Cable – Dynamic Effects

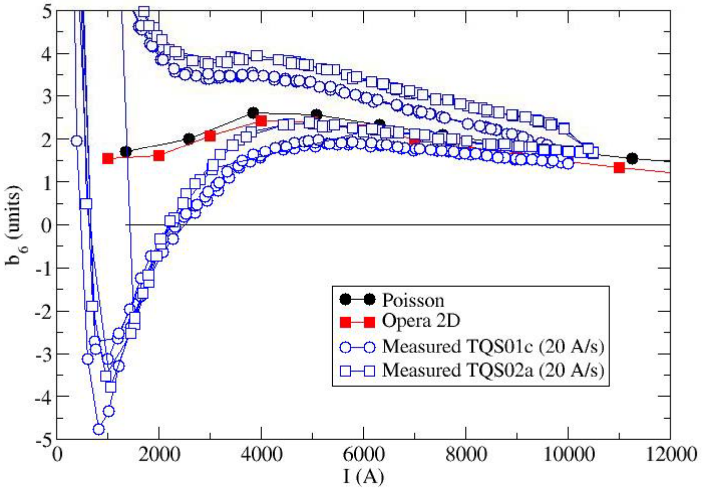
- Allowed harmonics during injection "front porch"
  - "snapback" seen at start and end of front porch
  - NO drift while the current is constant

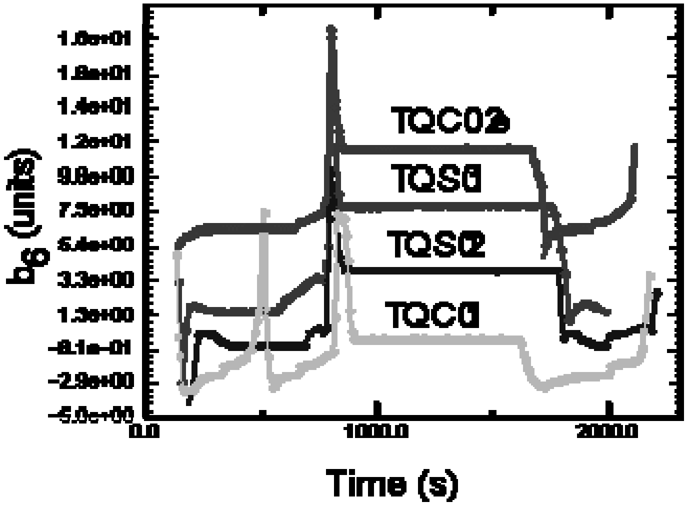
- Gradient, harmonics during the ramp
  - dG/(dI/dt) linear in dI/dt, dG/G ~ 1% at LHC ramp rate
  - Significant magnet-to-magnet variation
  - Presume caused by variations in interstrand resistivity R_I due to sintering of the strands during the reaction

- Add "core" (25μm ss between top and bottom of cable)
  - R_I will increase significantly $\Rightarrow$ should test in a TQ
  - Current-sharing will be reduced

TQS and TQC – measured field



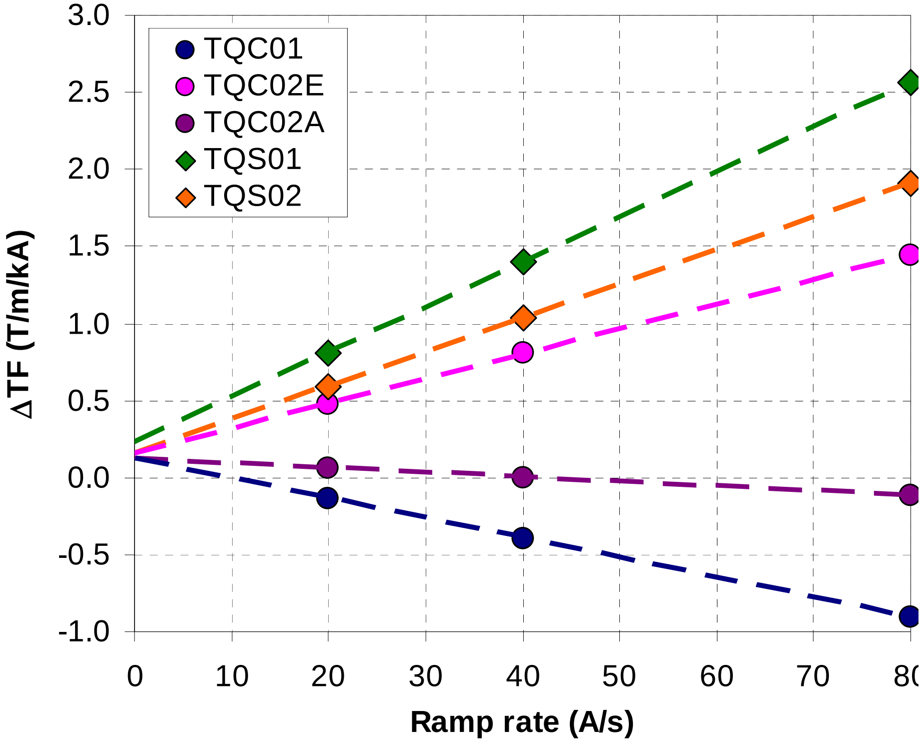




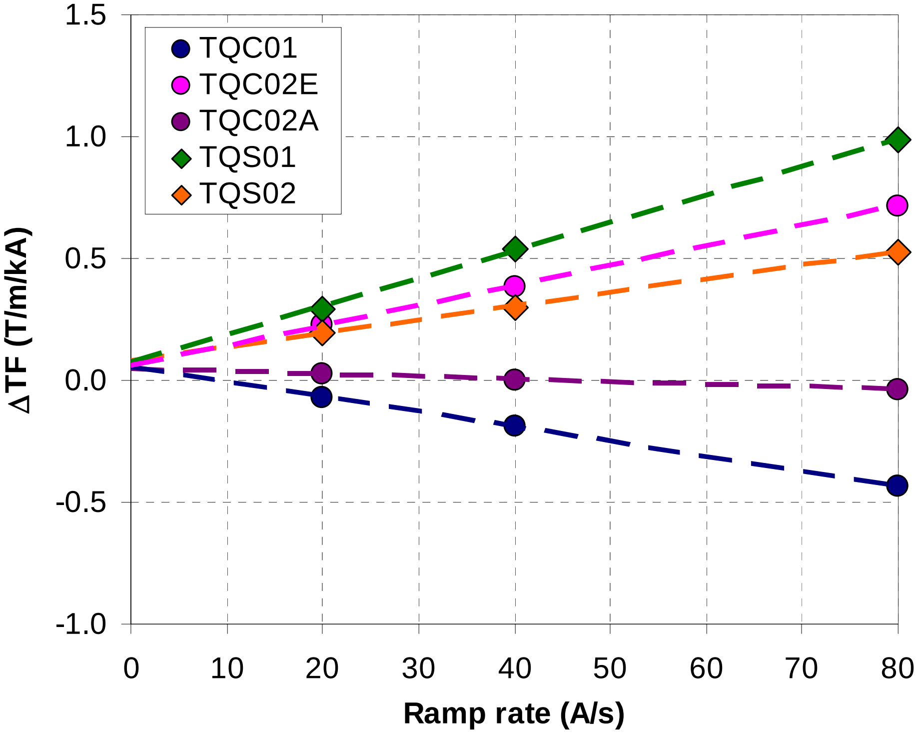
Ramp-rate dependence: TF = G/I

Different interstrand resistance in coils is most likely responsible for ramp rate dependence of the transfer function (TF). LHC ramp ~ 10A/s

45 T/m



90 T/m



Cable – Thermal, Radiation

- Radiation damage and thermal model – continue Joint IR Studies (JIRS) work (beam optics, radiation effects)

- Measure thermal margin of magnet
    - An important advantage of Nb_3Sn compared to NbTi
    - Complex topic, especially at 1.9 K

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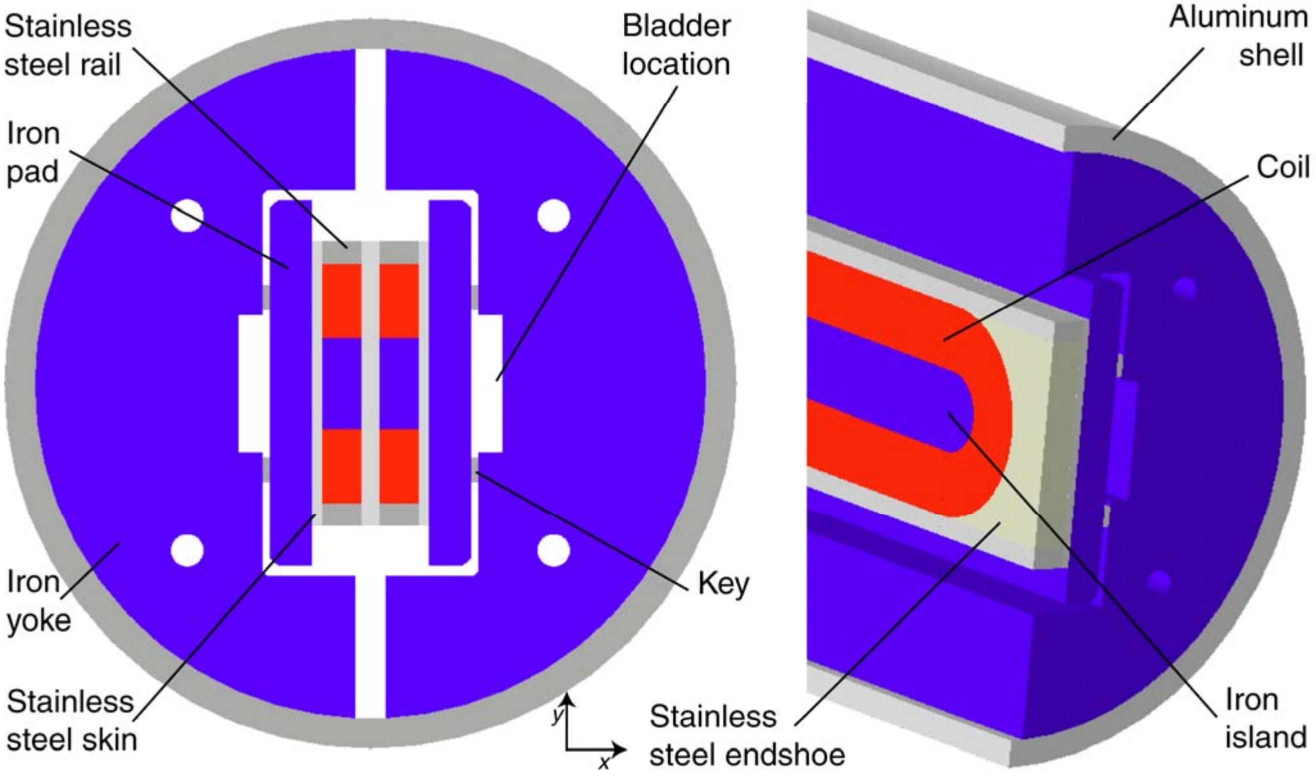
Racetracks

- Coils
  - 0.3 m: “long sample test” (short sample length = 1m)
  - 3.6 m: quick, cheap test for length effects (1 m → 3.6 m) in coil manufacture

- Support structures
  - Significant Lorentz forces along only one axis → relatively quick, cheap
  - 3.6 m shell structure: test for length effects (aluminum shell coefficient thermal expansion ~ 2X iron yoke CTE)

LRS – 3.6 m racetrack coil, shell structure

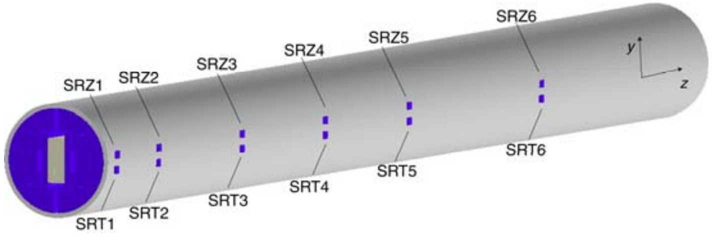


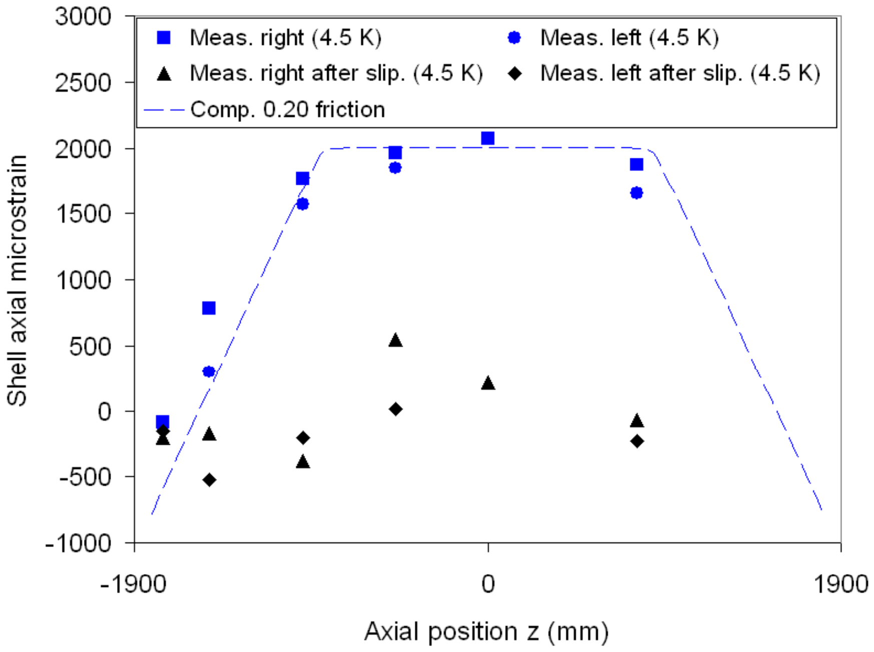
LRS01 – one-piece support structure → sudden large changes in strain due to axial slippage of yoke and shell

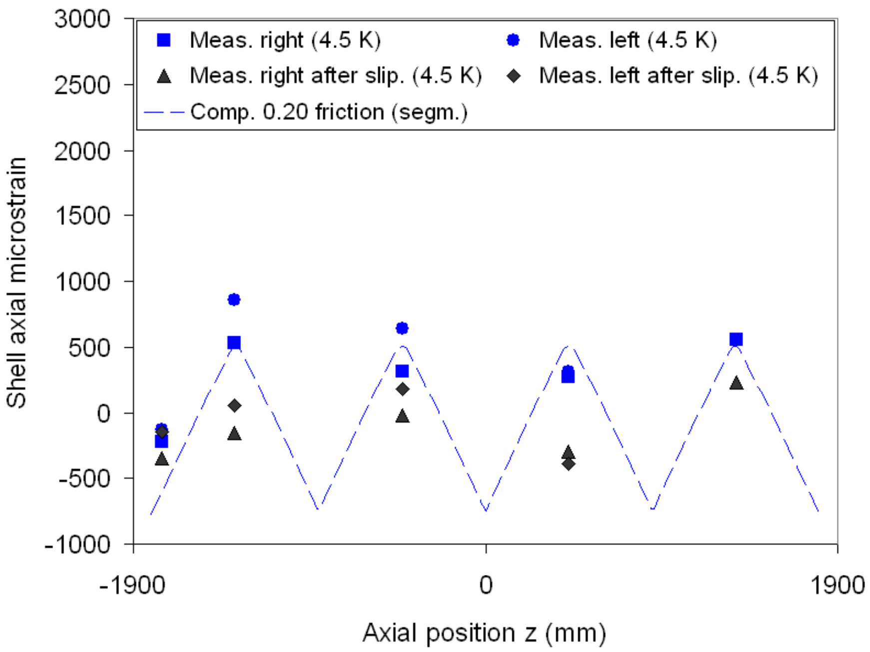
LRS02 – segmented shell, ~ 1m sections → minor changes in strain

3D mechanical analysis
Full length or segmented shell: axial strain

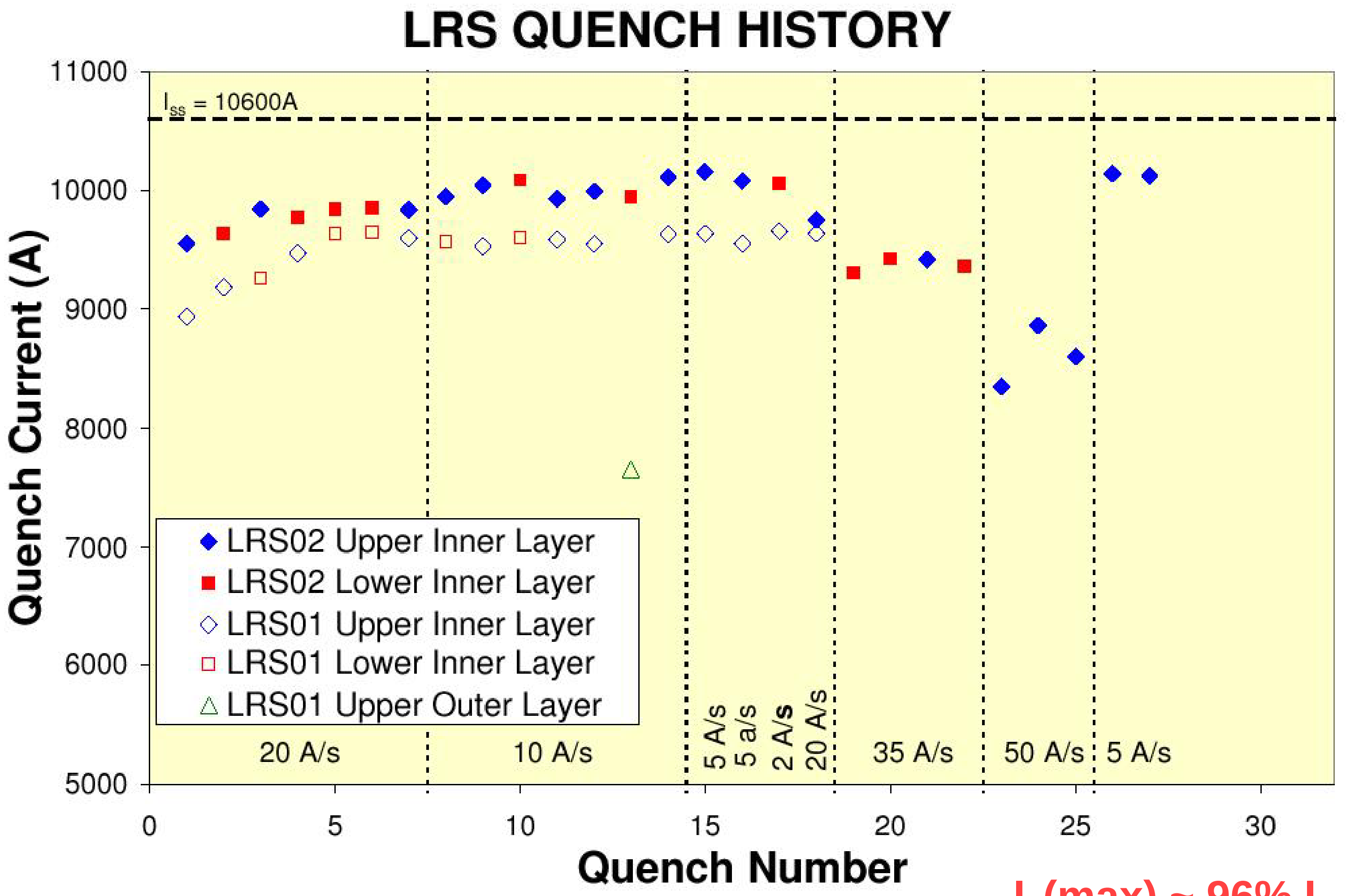
- LRS01
  - High axial strain meas. in LRS01
  - Slippage shell-yoke
- LRS02 (with segmented shell)
  - Reduced axial strain





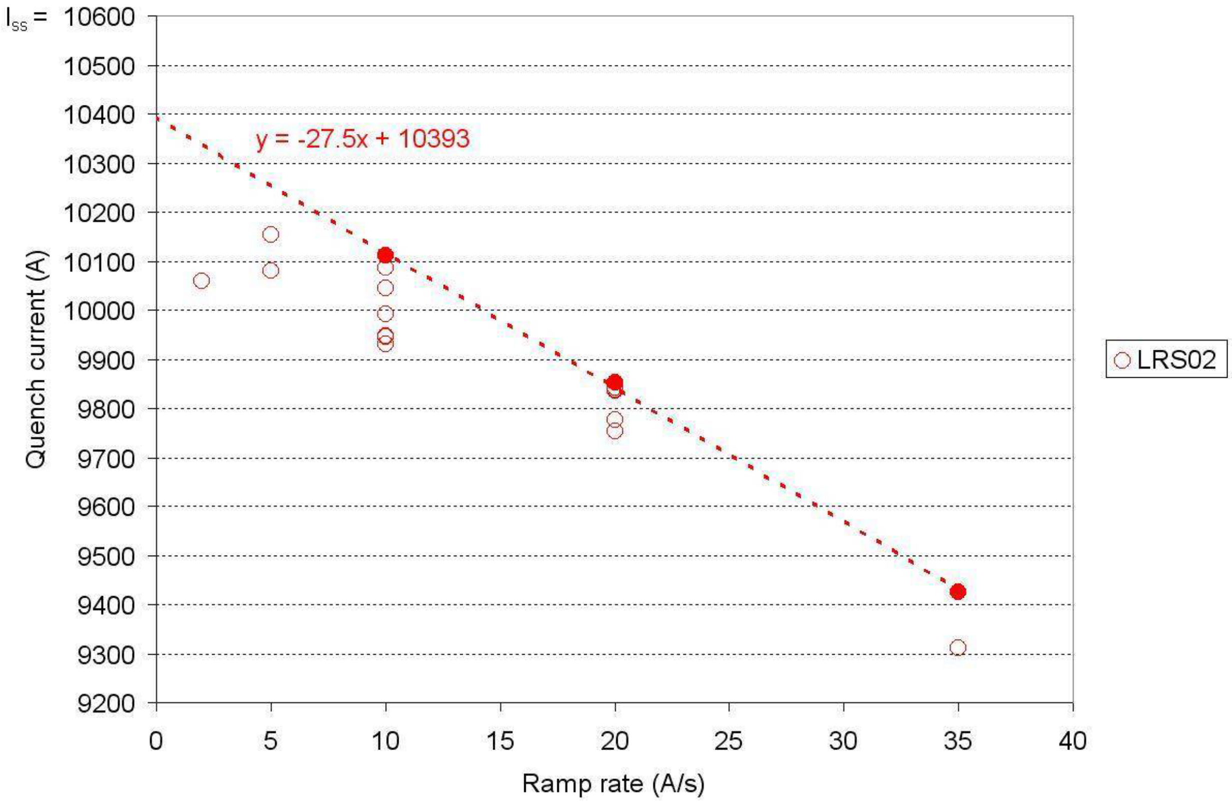


LRS02 = LRS01 coils + segmented shell



I_q(max) ~ 96% I_{ss}

LRS02 I_q vs. dI/dt



Result ⇒ I_{ss} is within few % of magnet limit + thermal margin (est.)

LRS01, LRS02 quench summary

- Nominal conductor limit = 10.6 kA
  - Uncertainly of several percent (4.5 K)

- LRS01: max I_q = 9663 A, 11 T (91% of conductor limit)
- LRS02: max I_q = 10154 A, 11.5 T (96% …)

- Extrapolate I_q vs. dI/dt to DC → 10.3 kA – 10. 4 kA
  - Use highest I_q at each dI/dt
  - Consistent (within uncertainties, which are larger than for NbTi) with conductor limit → data could be used to calculate thermal margin at 4.5 K.

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Technology Quadrupoles

Technology Quadrupoles (TQ)

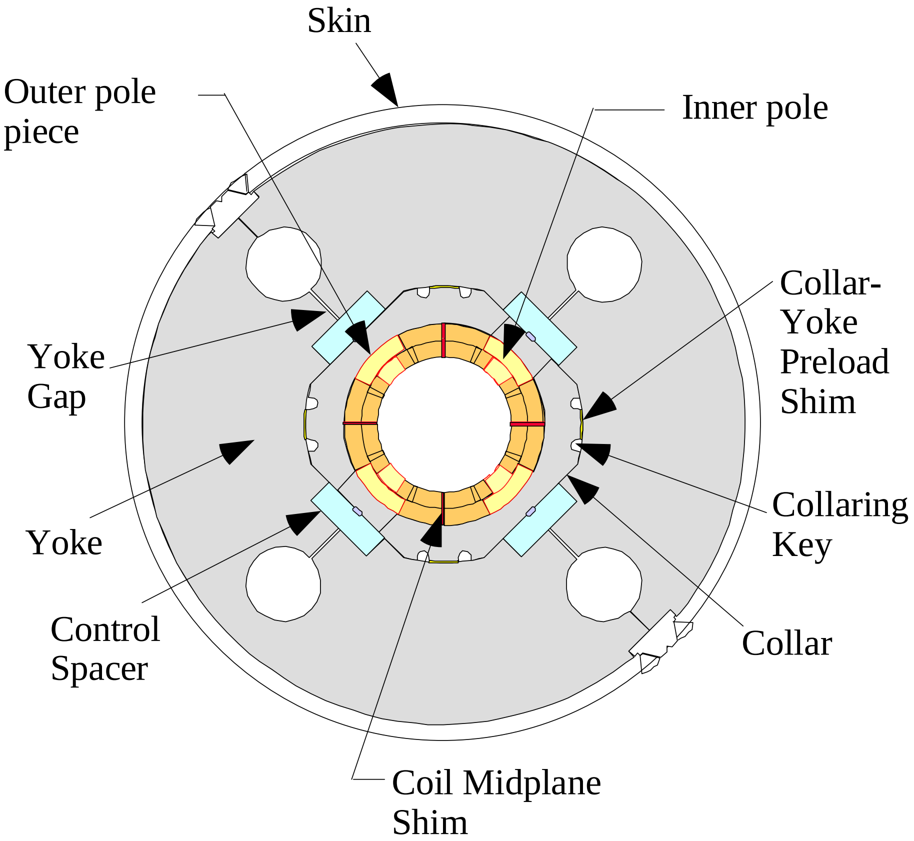
- 1 m long, 90 mm aperture
- Coils made jointly by Fermilab and LBNL

Support structure options:

- TQC: "collar" support
- TQS: "shell" support

Remark: "short sample" current based on extracted strands – should be cable test

TQC Mechanical Structure



Final preload at assembly:

Azimuthal preload via keys that lock collars, welding of ss shell.

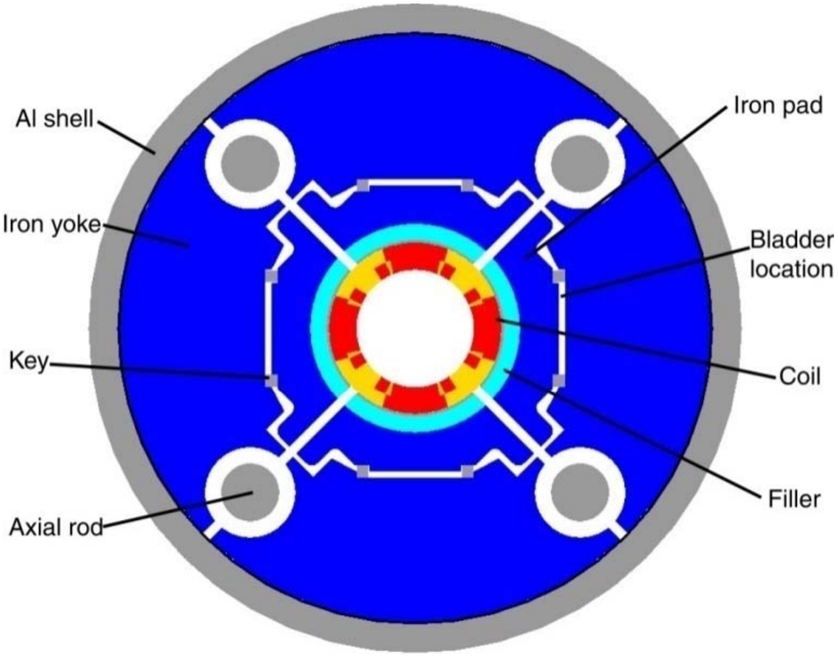
Axial preload: coil ends in (light) contact with structure

TQS Mechanical Structure

Low preload at assembly, final preload during cooldown:

Azimuthal preload via inflatable/removable bladders and keys, between “pad” and yoke, inside aluminum shell.

Axial preload via rods, low ⇒ high during cooldown



TQ program (much more in next talks)

- Nine tested so far – details in the following talks
- Reliably achieve 200 T/m
- Baseline measurements of field quality, quench hot spot temperatures and voltages, quench protection heaters, etc.

- Future TQ's – quick turn-around, relative low cost
  - Test new conductor (e.g., 108/127 [underway], cable with core)
  - Mechanical structure variants
  - Test with 4 good coils → reach gradients > 95% I_{ss}
  - Multiple thermal cycles
  - 1.9 K test at Fermilab or CERN – collaboration LARP + CERN

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Long Quadrupole

Main Features:

Aperture: 90 mm

magnet length: 3.8 m **(coil length: 3.4 m)**

Goal:

Gradient: 200+ T/m

[Cold mass designs look ahead to alignment.]

Timeframe:

Performance and reproducibility by the end of 2009

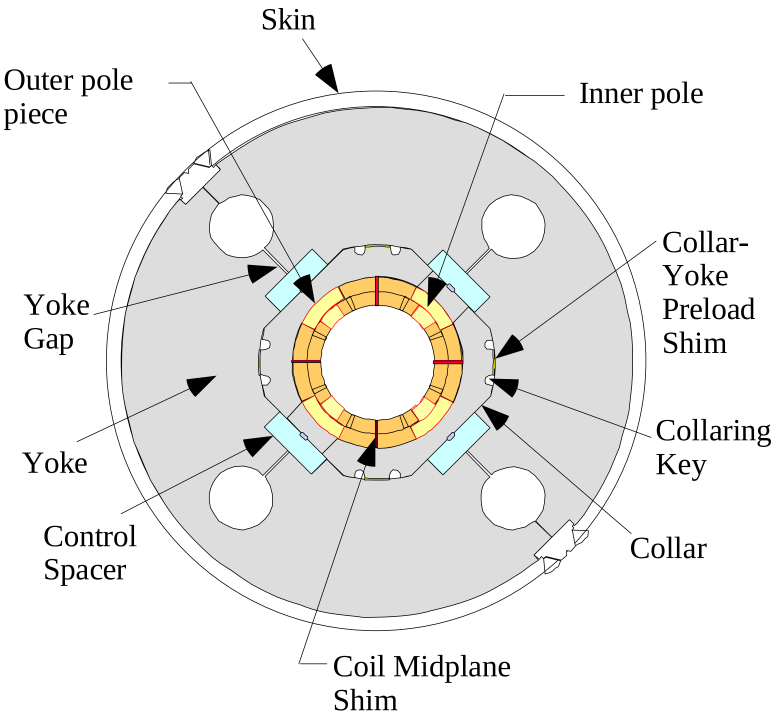
Testing 3 LQs

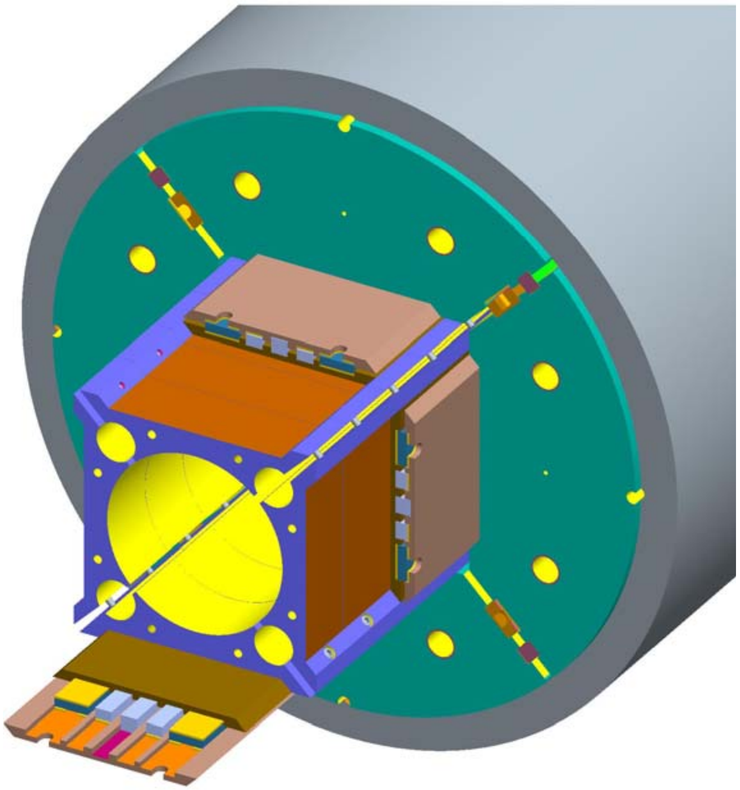
Mechanical Design - I

LQ Magnet Structure Review

Nov 28-29, 2007 at BNL

LQC = Long TQC - LQS based on TQS





Mechanical Design - II

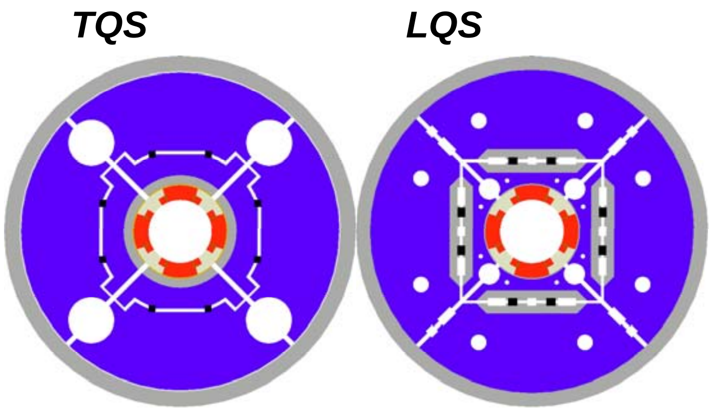
Scale up issues:

- TQC models didn't exceed 200 T/m
- Collaring long coils

- TQS structure needs modifications for long magnets
  - Segmented shell
- Improvements introduced based on TQS test results

Plan:

- Procure in FY08 both shell and collar long structures
  - Provides options & back up
- LQ01 with shell-based structure
  - Best performance, shorter assembly, easier to replace coils
- LQ02 with collar-based structure
  - Reusing LQ01 coils (done w TQs)
- LQ03 with structure depending on previous results



Risk mitigation

→ larger probability of success within end of FY09

Large set of expertise and data for the structure of the LHC IR prototype (QB)

All 3 labs are strongly involved with this plan

→ the best intellectual contribution & high internal scrutiny

Fabrication and test plans

- Coils are being fabricated at FNAL and BNL
  - 2 practice coils at FNAL, 1 at BNL
  - 4 coils by the end of FY08
    - 3 at FNAL, 1 at BNL
  - Start spare coils in Q4 (some work held in contingency)
- Shell structure: design, procurement & test at LBNL
  - Ready by the end of FY08
    - Test of 1m model at LN & assembly w dummy coils
  - LQS01 assembly at LBNL
- Collar structure: procurement at FNAL
  - Some parts held in contingency

LQ01 tested in Feb of 2009 at FNAL

LQ02 tested in July of 2009 at FNAL

LQ03 tested at the end of 2009 at FNAL

Coil Fabrication

Coil design:

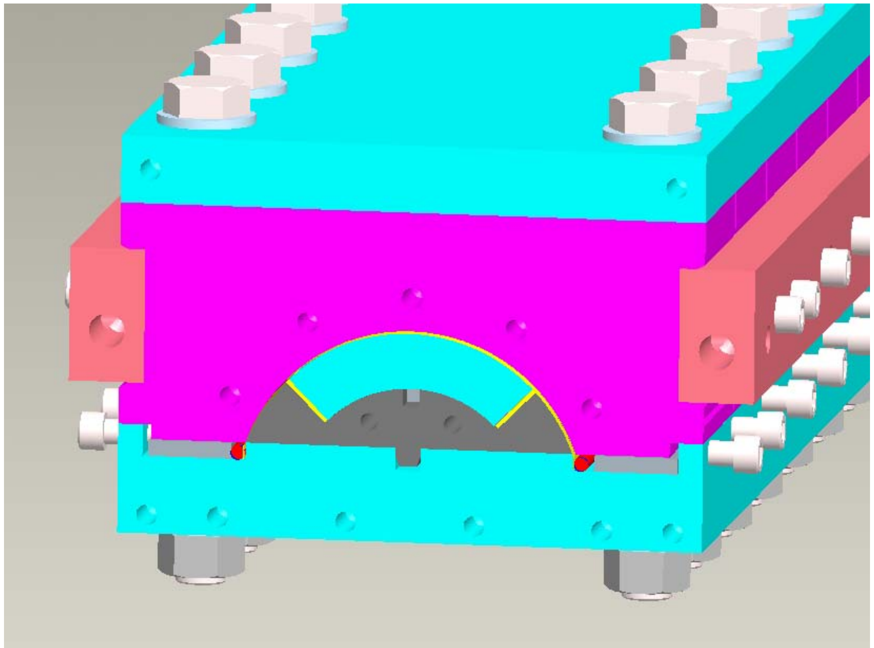
- LQ coils = TQ coils w minor modifications

React&Impr fixture change:

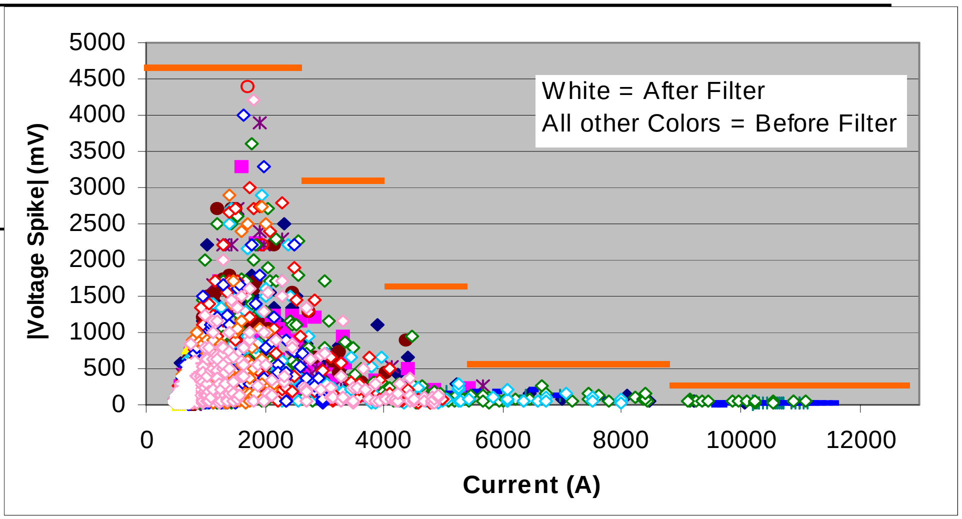
- From 2-in-1 used for TQ coils to single coil fixtures for LQ
  - More symmetric coils (+)
  - New parts, new procedures (-)

Scale-up challenges:

- Reaction
  - Different CTE
  - Friction
- Impregnation
- Handling



Magnet tests



Preparation for test

- Adaptive QP threshold
- Symmetric grounding
- Handling and support of LQs at VMTF
  - Good collaboration with LBNL

Test all LQ magnets

- Test at 4.2 and 2.0 K
- Magnetic measurement, ramp rate dependence, RRR…
  - Magnetic measurement only ½ length
- Thermal cycles to check “training memory”

Quench Protection

Goal:

MIITs < **7.5** ←→ Temp ~ **380 K** (adiabatic approx)

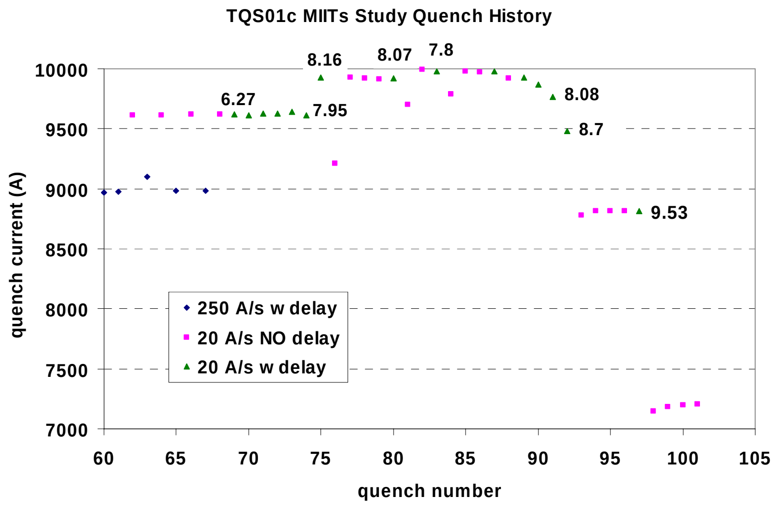
Quench protection param. (4.5 K) – conservative hypothesis

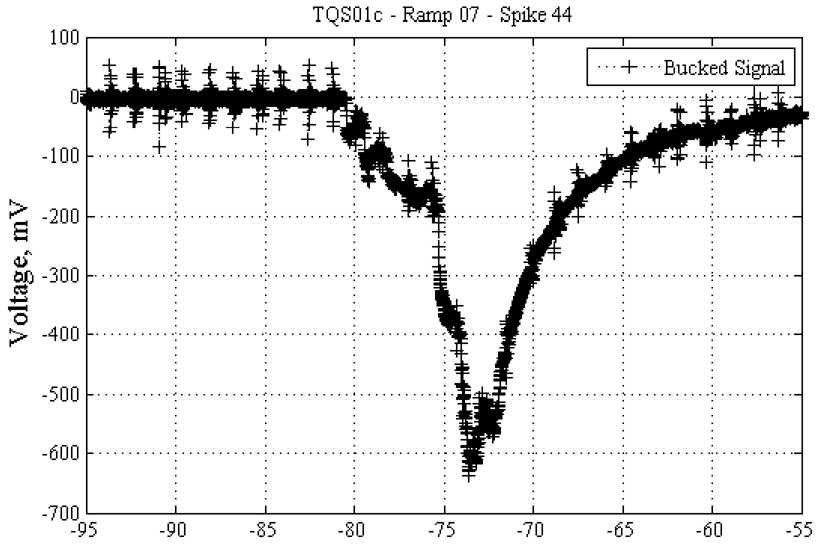
Dump resistance: **60 mΩ** (extract ~1/3 of the energy; V_{leads} ~ 800 V)

100% heater coverage (→ heaters also on the inner layer)

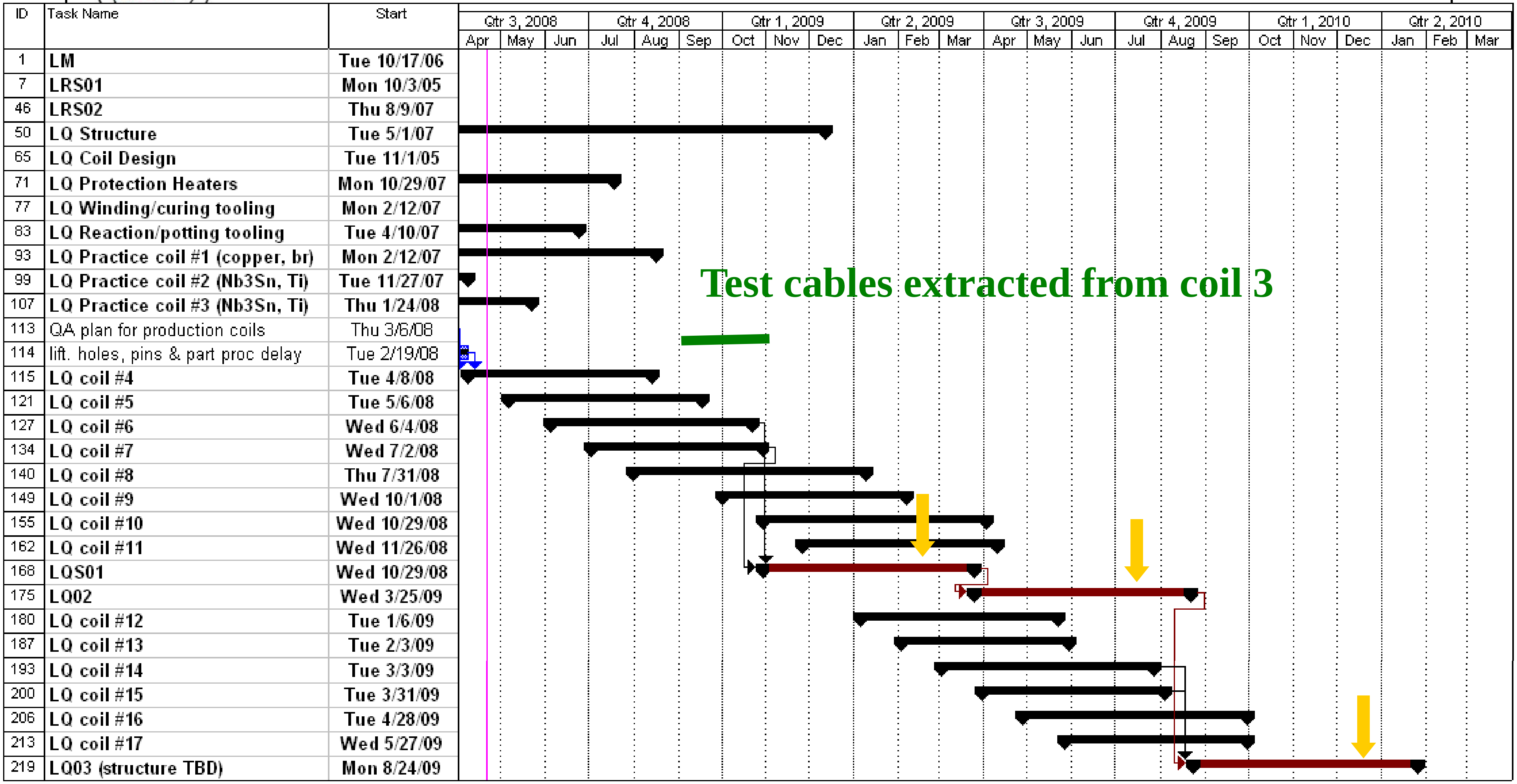
Detection time: **~5 ms** based on TQs with I > 80% ssl

Heater delay time: **12 ms** based on TQs with I > 80% ssl





Schedule



ID	Task Name	Start
1	**LM**	**Tue 10/17/06**
7	**LRS01**	**Mon 10/3/05**
46	**LRS02**	**Thu 8/9/07**
50	**LQ Structure**	**Tue 5/1/07**
65	**LQ Coil Design**	**Tue 11/1/05**
71	**LQ Protection Heaters**	**Mon 10/29/07**
77	**LQ Winding/curing tooling**	**Mon 2/12/07**
83	**LQ Reaction/potting tooling**	**Tue 4/10/07**
93	**LQ Practice coil #1 (copper, br)**	**Mon 2/12/07**
99	**LQ Practice coil #2 (Nb3Sn, Ti)**	**Tue 11/27/07**
107	**LQ Practice coil #3 (Nb3Sn, Ti)**	**Thu 1/24/08**
113	QA plan for production coils	Thu 3/6/08
114	lift. holes, pins & part proc delay	Tue 2/19/08
115	**LQ coil #4**	**Tue 4/8/08**
121	**LQ coil #5**	**Tue 5/6/08**
127	**LQ coil #6**	**Wed 6/4/08**
134	**LQ coil #7**	**Wed 7/2/08**
140	**LQ coil #8**	**Thu 7/31/08**
149	**LQ coil #9**	**Wed 10/1/08**
155	**LQ coil #10**	**Wed 10/29/08**
162	**LQ coil #11**	**Wed 11/26/08**
168	**LQS01**	**Wed 10/29/08**
175	**LQ02**	**Wed 3/25/09**
180	**LQ coil #12**	**Tue 1/6/09**
187	**LQ coil #13**	**Tue 2/3/09**
193	**LQ coil #14**	**Tue 3/3/09**
200	**LQ coil #15**	**Tue 3/31/09**
206	**LQ coil #16**	**Tue 4/28/09**
213	**LQ coil #17**	**Wed 5/27/09**
219	**LQ03 (structure TBD)**	**Mon 8/24/09**

Test cables extracted from coil 3

This is the plan in case we need to make coils with new conductor for LQ03

If we will be able to use LQ01 spare coils ➔ LQ03 assembly could start in Apr. 09

“Projectized” task

LARP is a collaboration with a program

LQ project-like features:

- Plan: Task sheets with milestones, budget for each milestones, and commitment (technical, not financial) by task leader and supporting lab to do the job
- Budget: LQ had priority in the use of mid-year contingency;
  - Budget so that no core-program support needed
- QA plan: implementing LQ QA plan

OUTLINE

- LARP Magnet Goals
- Materials
- Racetrack magnet – long, shell (LRS)
- Technology Quads (TQ → TQC, TQS)
  - Support structures: collar and shell
- Long Quads (LQ → LQC, LQS)
- **High Gradient/Aperture (HQ)**
- **QA – slot-compatible with NbTi Phase 1 quads**
- **QB – Phase 2 quad**

LARP Magnet Goals

- LQ (3.6 m, 90 mm) reaches 200 T/m by end of CY2009
  - goal does not include field quality or alignment
- Fully qualify Nb_3Sn magnets for use in the LHC
  - HQ – details next talks – 1m - leads to QA
  - QA: fully qualified
- Supply Nb_3Sn magnets for Phase 2 upgrade
  - QB

Summary

- 1 m quads reach 200 T/m reliably
  - Quench performance at 1.9 K not understood
  - Dynamic effects in cable must be reduced

- 3.6 m racetrack reached 11.5 T field on coil with segmented shell support structure

- 3.8 m quads
  - Coil reaction tooling being debugged
  - Schedule includes tests of shell and collar support structures
  - Schedule shows three magnets tested by end of CY2009

BACKUP

54/61 RRP Stability (simplified)

Background Field	4.2 K	1.9 K
~ 2 T	Y	Y
~ 6 T	N	Y
~ 12 T	N	N