Magnet Development for the LHC Accelerator Research Program (LARP)

2007 Particle Accelerator Conference

June 29, 2006

Gian Luca Sabbi *for the LARP Collaboration*

BNL - FNAL - LBNL - SLAC

LARP Magnet R&D Program

***Goal**: Demonstrate Nb_3Sn technology for the LHC Luminosity Upgrade*

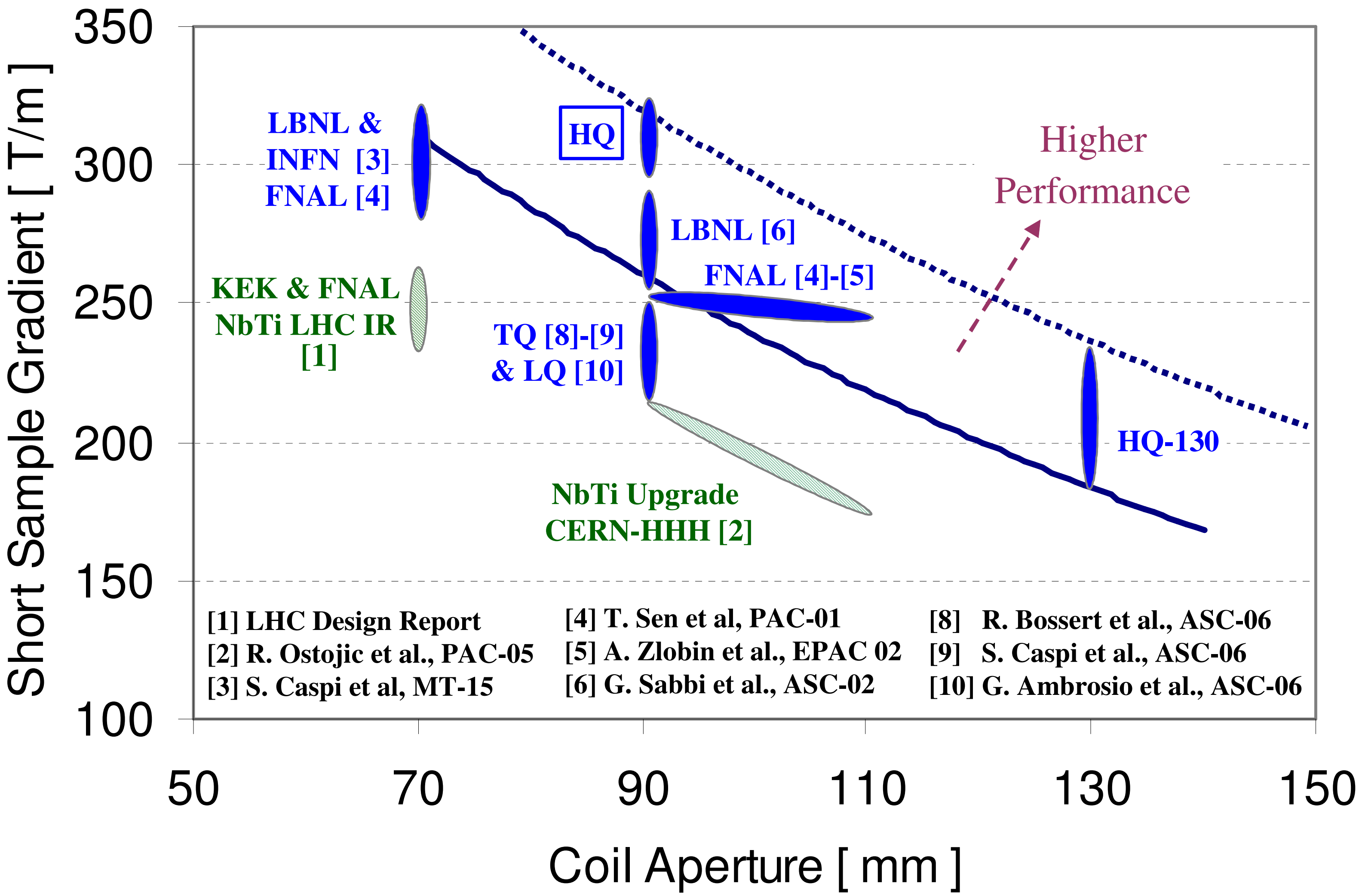
Three main components (models series) based on shell-type coils:

- **TQ (Technology Quads, 2005-07) D = 90 mm, L = 1 m, G_{nom} > 200 T/m**
- **LQ (Long Quadrupoles, 2008-09) D = 90 mm, L = 4 m, G_{nom} > 200 T/m**
- **HQ (High Gradient Quad, 2009-10) D = 90 mm, L = 1 m, G_{nom} > 250 T/m**

In addition, three magnet series based on racetrack coils are used to investigate and resolve fundamental design and technology issues

Oct 25, 2005	Type	Length [m]	Gradient [T/m]	Aperture [mm]	FY05	FY06	FY07	FY08	FY09
MODEL MAGNETS									
Technology Quad (TQ)	cos(2θ)	1	> 200	90		3N+1R	2N+1R		
Long Quad (LQ)	cos(2θ)	4	> 200	90				1N	1N
High Gradient Quad (HQ)	cos(2θ)	1	> 250	90					2N
SUPPORTING R&D			**Peak Field** [T]						
Sub-scale Quad (SQ)	block	0.3	10-11	110	1N+1R	1N+1R	1N+1R	1N	
Short Racetrack (SR)	block	0.3	10-12	N/A		1N	1N	1N	
Long Racetrack (LR)	block	4	10-12	N/A			2N+1R		

Quadrupole Designs for the LHC IR



Technology Quadrupoles (TQ)

LARP

Objectives:

- Optimize/characterize cable design and heat treatment cycle
- Evaluate conductor/cable performance and stability
- Develop and optimize coil fabrication/handling procedures
- Optimize and finalize the coil design for LQ
- Develop/calibrate FEA models (material properties, friction coefficients)
- Compare mechanical design concepts and support structures
- Compare test data with expected (design) values
- Provide experimental feedback for LQ and HQ structure selection

Implementation: two series of models with same coil design:

- TQS models: aluminum shell over iron yoke; axial pre-load
- TQC models: collar & stainless steel shell; axial support

Main parameters:

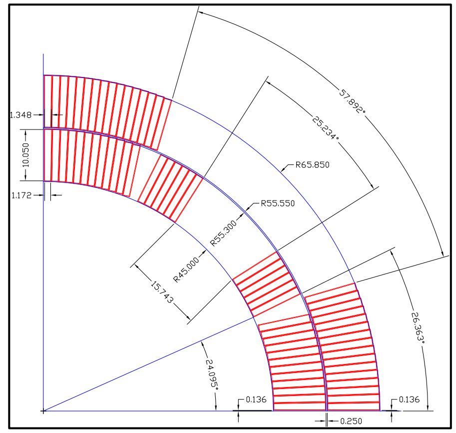
- 1 m length, 90 mm aperture, 11-13 T coil peak field

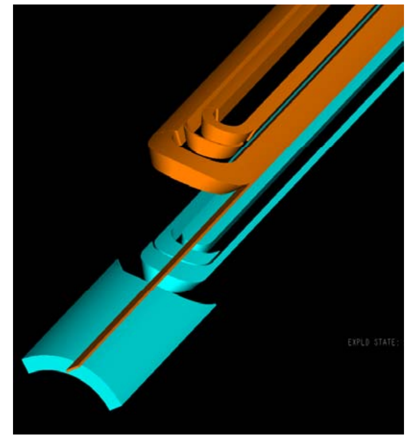
TQ Coil Design and Fabrication

LARP

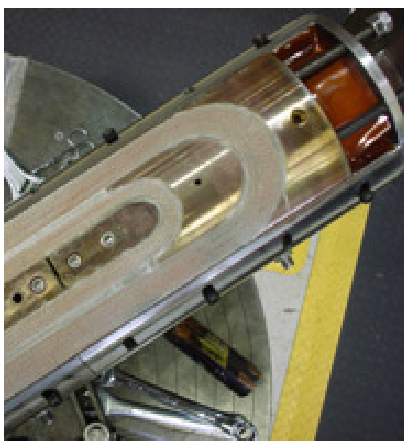
Design features:

- Double-layer, shell-type
- One wedge/octant (inner layer)
- TQ01: OST-MJR strand, 0.7 mm
- TQ02: OST-RRP strand, 0.7 mm
- 27-strand, 10.05 mm width
- Insulation: S-2 glass sleeve

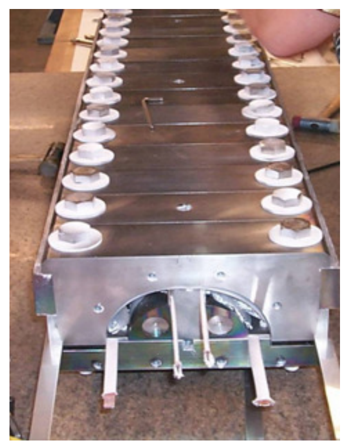




Winding & curing (FNAL - all coils)



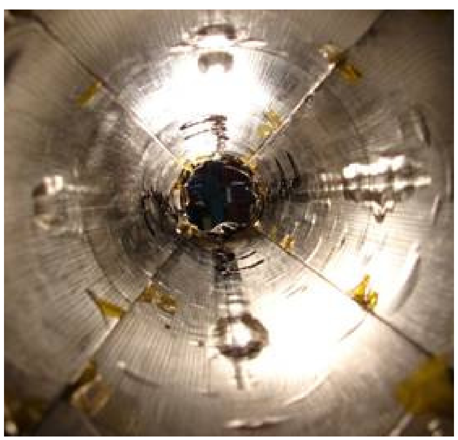
Reaction & potting (LBNL - all coils)



TQ Coil Fabrication Experience

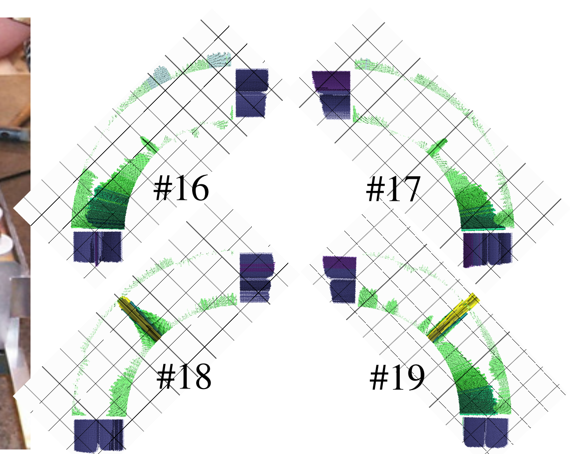
- 23 TQ coils have been fabricated (including 5 practice coils & 2 spare coils)
- Producing high quality coils in a reliable and consistent manner, however:
  - *Some systematic asymmetries related to "2-in-1" reaction/potting*
  - *Some de-bonding in TQC instrumentation traces (minor effect in TQS)*
- All coils are being wound/cured at FNAL and reacted/impregnated at LBNL
  - *Decided based on existing infrastructure and to minimize tooling investment*
  - *Instrumental in developing and maintaining common procedures*
  - *Shipping of coils accomplished without damage or significant delays*

Inner trace after TQC01 test



Reaction/potting tooling

Coil measurements (TQC02)



Titanium poles (TQS02)

TQ Performance References & Range

J_c = 2 kA/mm^2
(12 T, 4.2 K)

MJR strand
First models

Magnet	T_{op} [K]	G_{ss} [T/m]	$B_{ss}^{(body)}$ [T]	I_{ss} [kA]
TQS	4.2	222	11.4	12.5
	1.9	239	12.3	13.6
TQC	4.2	215	11.2	13.0
	1.9	233	12.1	14.1

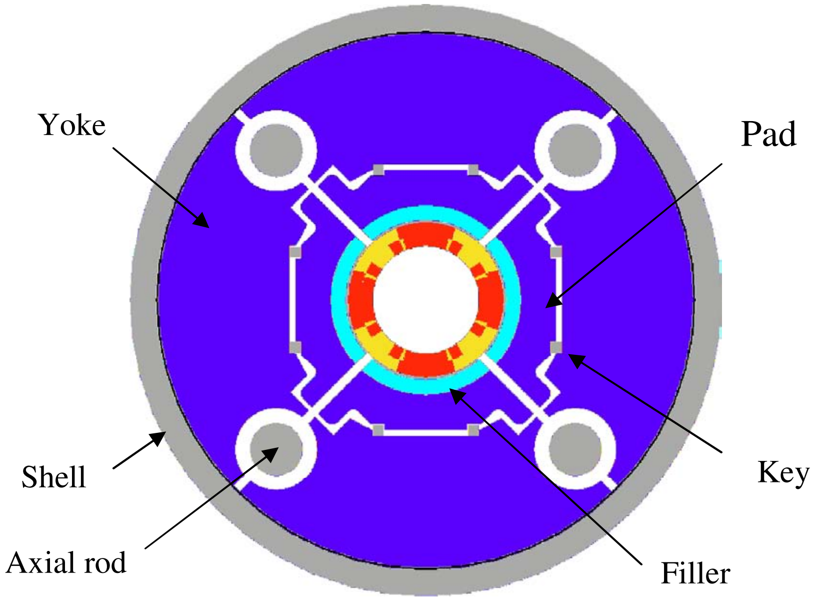
J_c = 3 kA/mm^2
(12 T, 4.2 K)

RRP strand
Final models

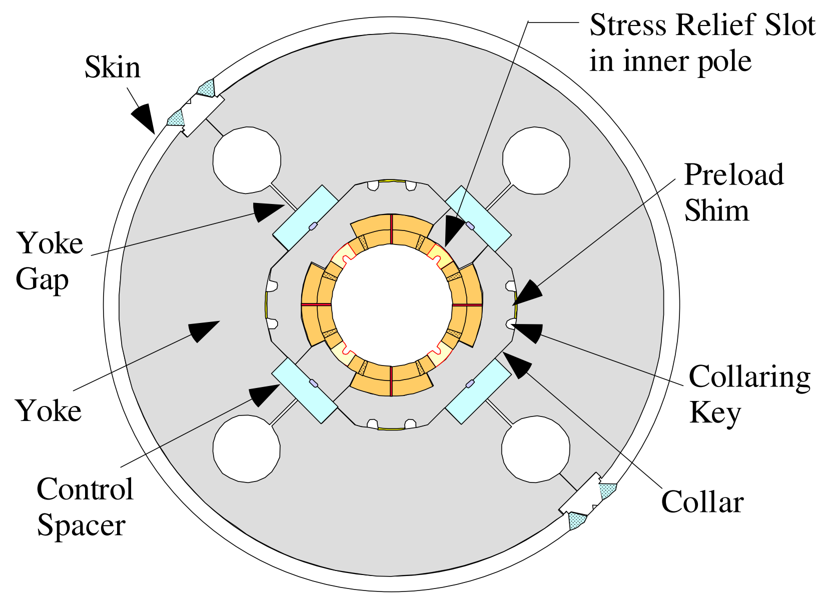
Magnet	T_{op} [K]	G_{ss} [T/m]	$B_{ss}^{(body)}$ [T]	I_{ss} [kA]
TQS	4.2	245	12.6	13.9
	1.9	264	13.5	15.1
TQC	4.2	239	12.4	14.4
	1.9	255	13.2	15.5

- I_c data from extracted strands determine common performance reference for TQS/TQC
- Issue: relatively wide range of extracted strand I_c (TQ01: 1862-1984 A/mm^2 @12T, 4.2K)
- *Reference magnet performance limits* for a given test run are adjusted for measured T_{bath}
- Actual *conductor-limited quench levels* may be lower due to other degradation effects

TQS and TQC Design Concepts



TQS

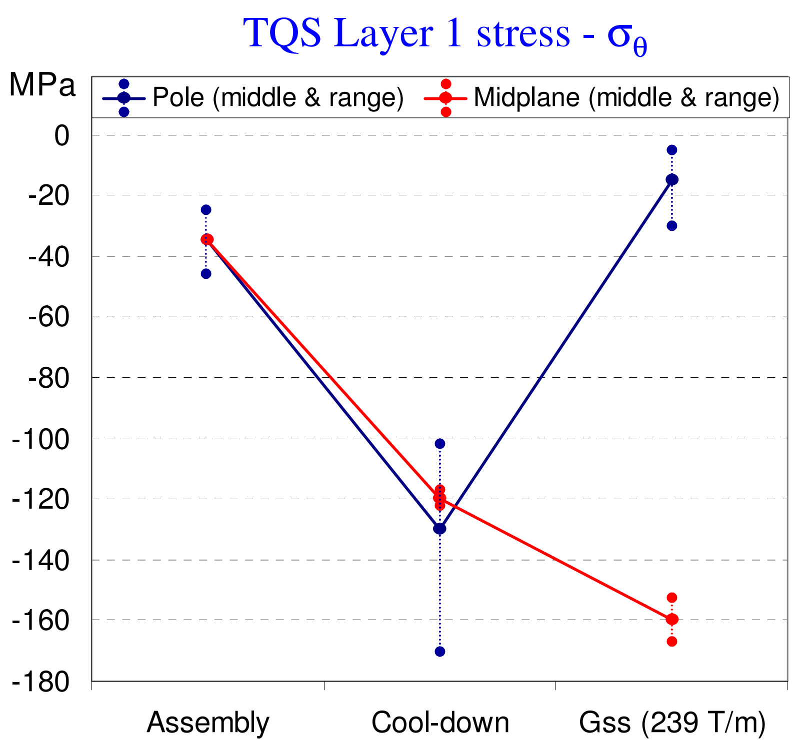


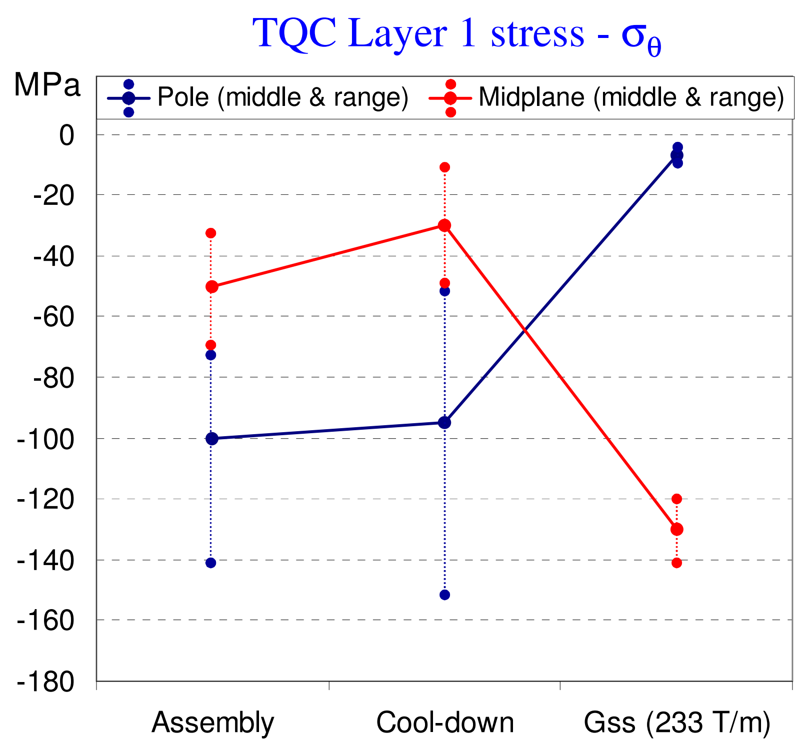
TQC

- Aluminum shell over iron yoke
- Assembly with bladders and keys
- Aluminum rods for axial pre-load

- Stainless steel collars and skin
- Control spacers to limit pre-load
- End support plates, no pre-load

Coil Stress Comparison (2D FEA)

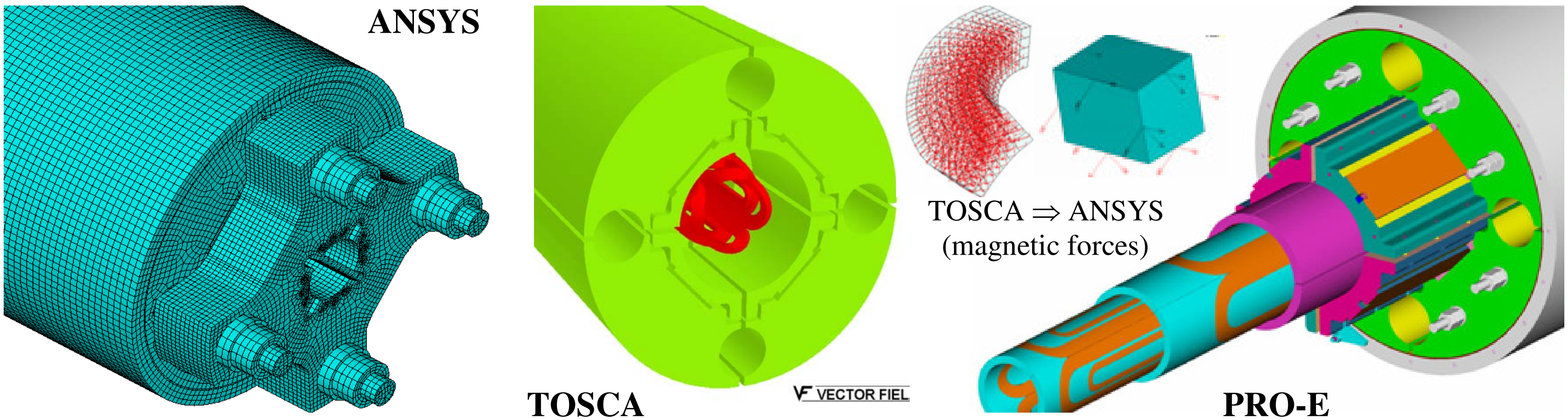




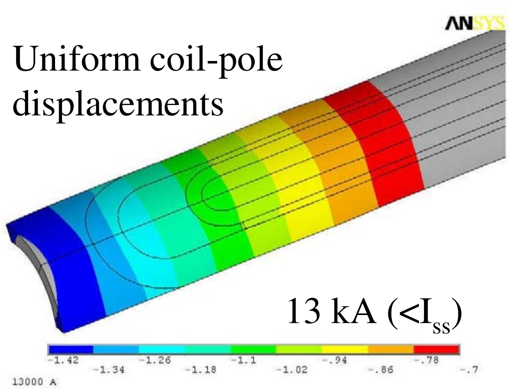
- Main differences: warm pre-load, cool-down effect, stress uniformity (pole to mid-plane)
- Peak stresses are high & no consensus on degradation limits → cable testing required
- Peak stress ~20 MPa difference: stress-relief slot, different G_{ss} & pole stress range at G_{ss}
- Detailed FEA shows that 3D effects have a significant impact on actual coil stresses

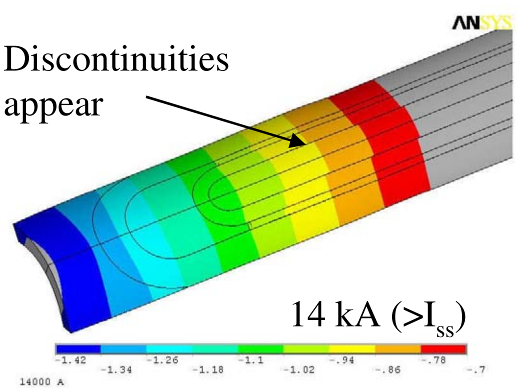
3D FEA (TQS)

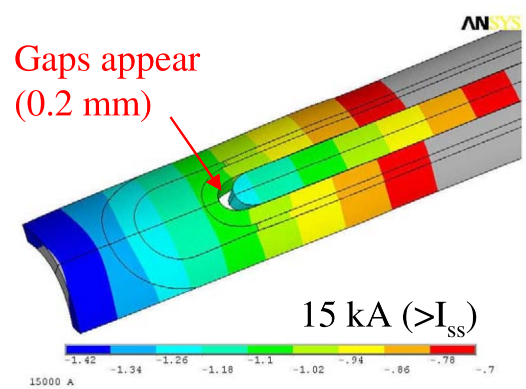
LARP



- Interfaces for integrated use of CAD, mechanical and electro-magnetic packages
- Studies of the effects of friction among interfaces (coil-pole, coil-pads, yoke-shell)
- Design goal: *maintain contact between coil and structure at all steps and locations*







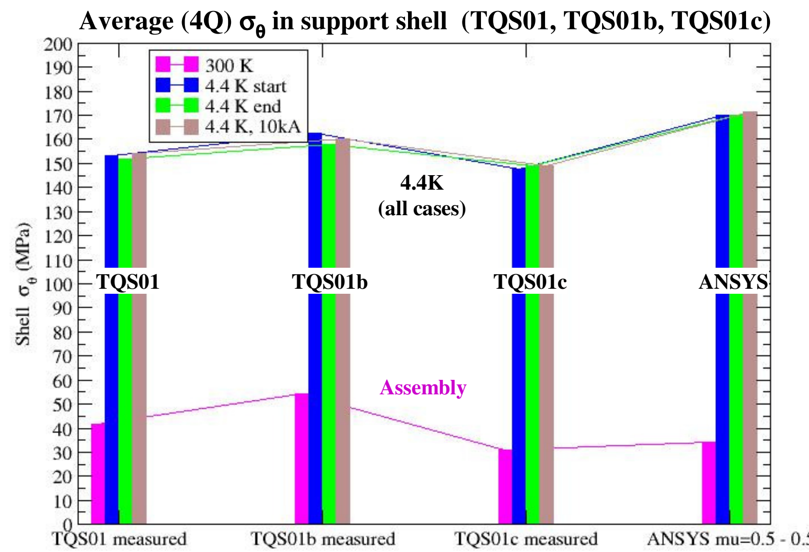
TQ Program Status

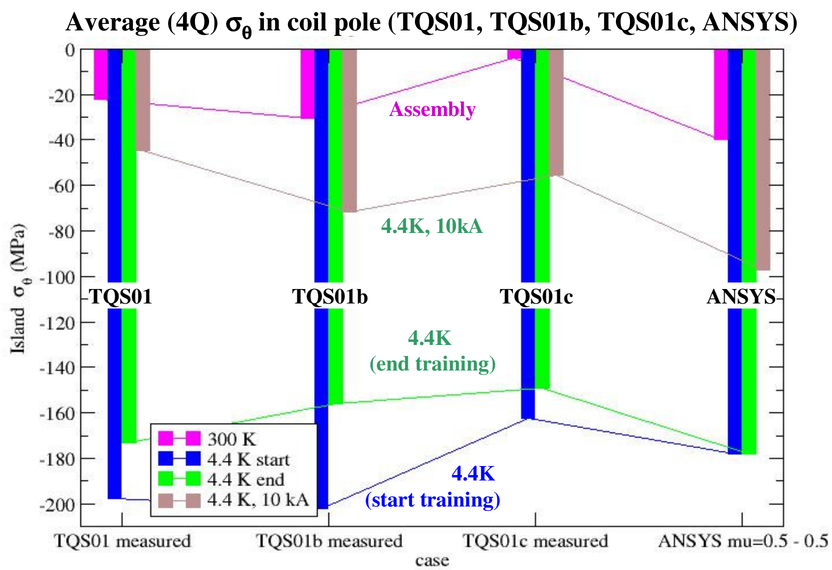
- **Cable and Coil fabrication:**
  - 23 coils completed, 4 more spares in production
  - Long TQ cable lengths (well above LQ unit length) routinely fabricated
- **Model magnet assembly and test:**
  - TQS01 model assembled (all new coils) and tested (4.5K, LBNL)
  - TQS01b assembled (1 new coil, same pre-load) and tested (4.5K, LBNL)
  - TQS01c assembled (1 new coil, lower pre-load) and tested (1.9K, FNAL)
  - TQS02 model assembled (all new coils) and tested (1.9K, FNAL)
  - TQC01 model assembled (all new coils) and tested (1.9K, FNAL)
- **TQ01 Evaluation Review (TQS01, TQS01b, TQC01) in November 2006**
- **In progress:**
  - TQS02 analysis, TQC01b test preparations
  - Fabrication of spare coils for TQC02 and TQS02b

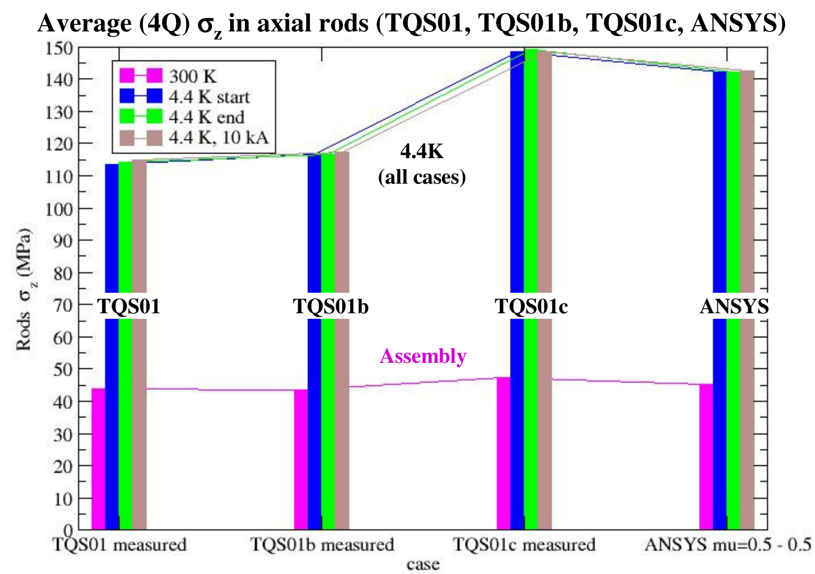
TQS Measured and Calculated Stresses

LARP

- Low coil stress at assembly (5-30 MPa)
- Fine tuning with bladders & key shims
- Large pre-load gain during cool-down
- 3D FEA is critical for cool-down phase
- Interfaces (friction) play significant role
- Transverse and axial effects are coupled
- Measure both transverse & axial strain
- Variations among quadrants need study

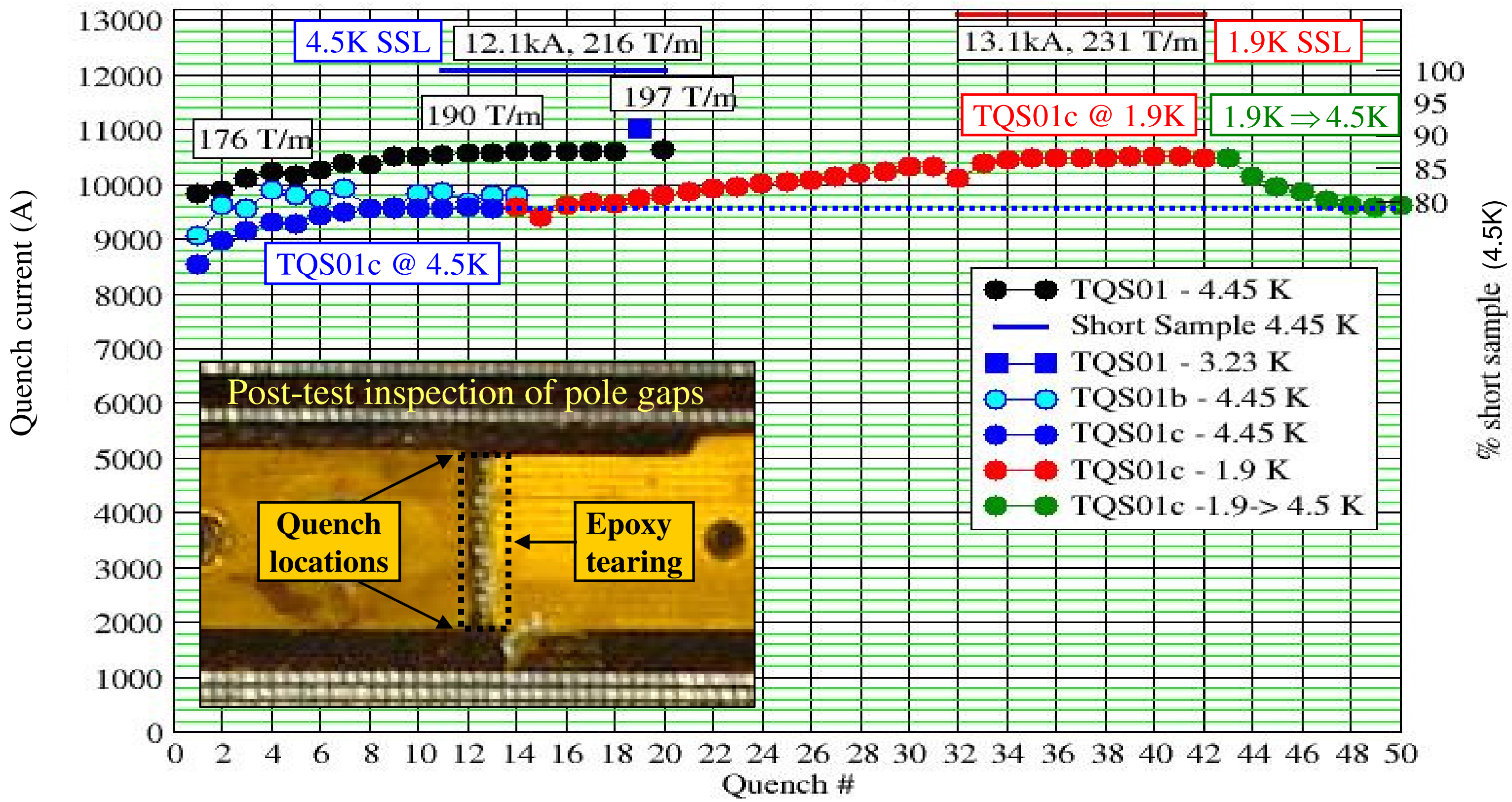






TQS(01,01b,01c) Test Results

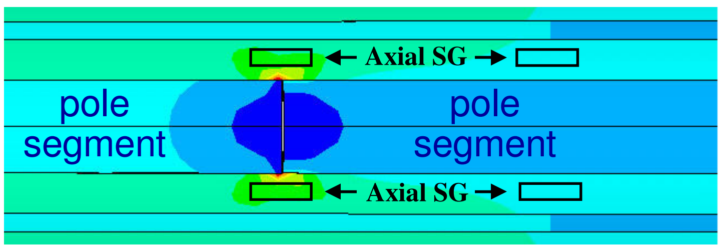
- TQS01 achieved 87% of extracted-strand short sample limit (no stress)
- TQS01b, TQS01c: fully trained to an ~80% conductor-limited plateau
- Plateau quenches occur near gaps between pole parts; no end quenches

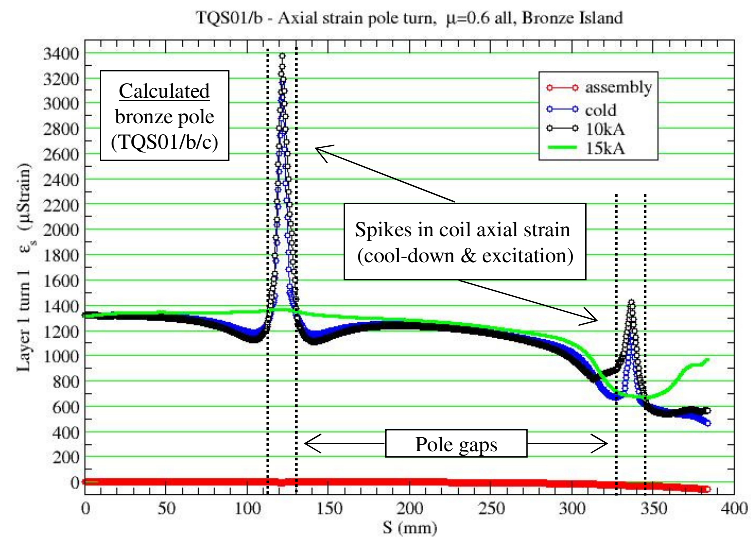


Coil Stress near Pole Gaps in TQS

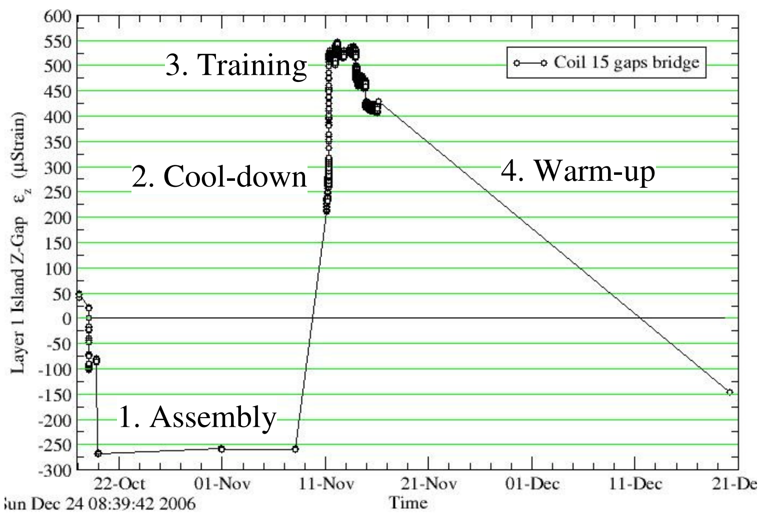
LARP

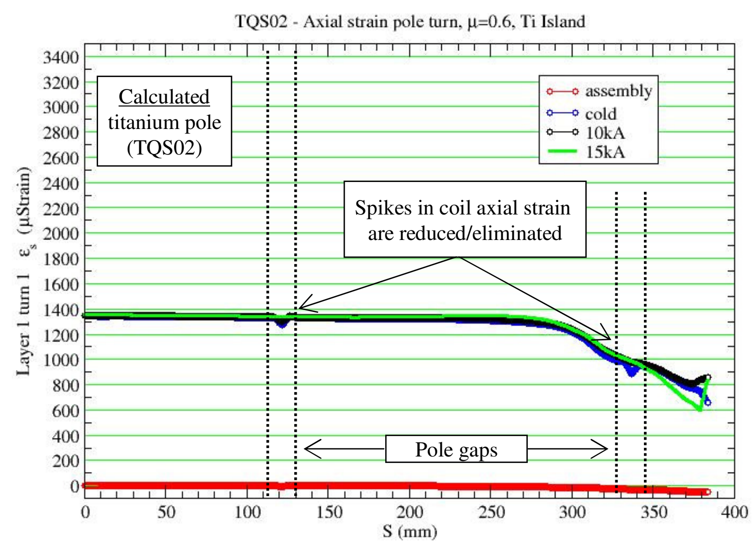
- 3D ANSYS calculations and TQS01b measurements indicate high longitudinal tension in coil across gaps, possibly leading to conductor degradation
- This effect depends on the interfaces between coil, pole (bronze or titanium) and *outer support elements*





Differential measurements of coil axial strain in TQS01b





TQS02 Fabrication and Test

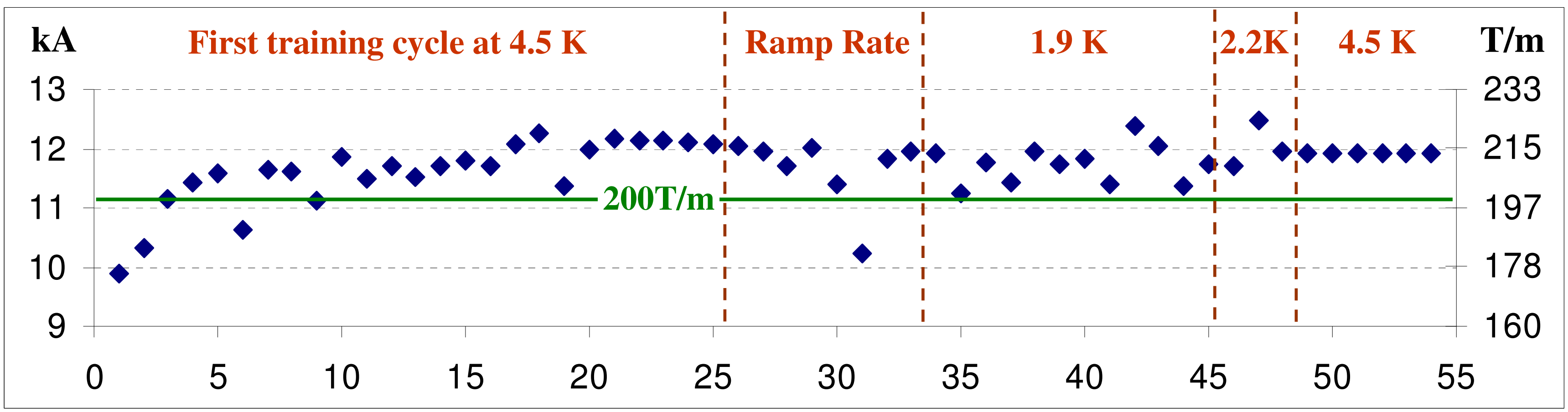
New design features:

- First TQ test using the LARP baseline conductor (OST RRP 54/61)
- Ti poles: eliminate longitudinal stress near gaps, reduce required axial preload, improve end parts fit after reaction, reduce/eliminate gaps between pole pieces

Test results:

- Performs well above 200 T/m (4.5K & 1.9K) using RRP 54/61 conductor
- Confirms the analysis of the cause of the TQS01 limitation and its cure

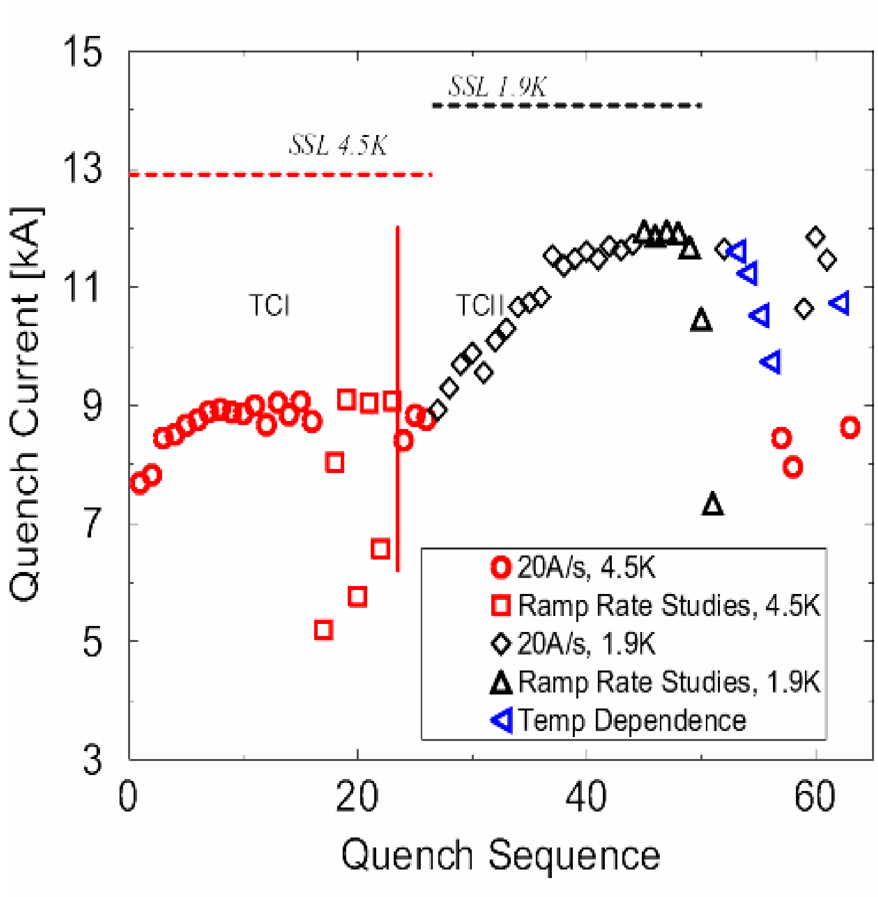
TQS02a Quench History



TQC01 Test Results

- At 1.9K, TQC01 achieved 85% of extracted-strand short sample limit (no stress)
- Highest gradient achieved was 200 T/m
- Limited to 70% of short sample at 4.2K (by different mechanism before/after 1.9K cycle)
- Most quenches before #42 occurred in the pole turn of the inner layer (all coils)
- Straight section quenches occurred in areas where the outer pole pieces were not glued
- Quenches after #42 occurred in the outer layers of coil 9 and 13:
    - *Coil 13: mid-plane turn, lead side*
    - *Coil 9: multi-turn (up to mid-plane)*
- Evidence of conductor degradation in mid-plane area
- Reliable results from bullet and skin gauges
- Mixed results from gauges on control spacers and on coils

TQC01 Quench Training & Studies



Analysis of TQC01 Test Results (1/2)

LARP

Slow training/plateau observed up to quench #42 can be attributed to:

1. Low azimuthal pre-load in the straight section with respect to design targets
   - *Overestimation of assembly pre-load (high coil modulus applied to gauge readings)*
   - *Longitudinal stress-relief cut was filled with epoxy, while the design assumed G10*
   - *Implementation steps tended toward the low end of the acceptable preload window (due to fears of over-compression causing cable degradation)*
   - *During cool-down there was some additional decrease of the pre-load*

TQC01 stress analysis	Baseline			As-built		
	300K	1.9K	14kA	300K	1.9K	12kA
Pressure at inner pole (MPa)	-100	-95	± 9	-47	-53	15
Max azimuthal stress (MPa)	162	144	146	83	67	93

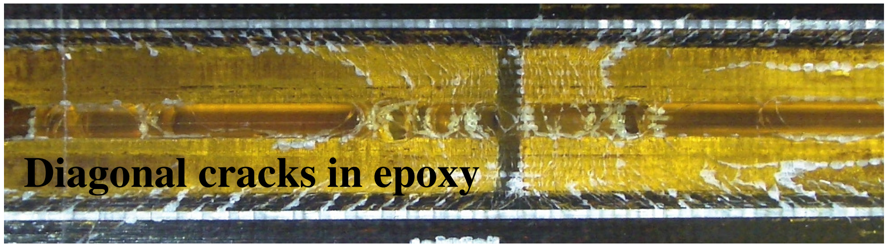
2. Outer pole pieces in most of the straight section not bonded to the coil
   - *Due to initial plan to remove outer pole and replace with "tabbed" collar*
   - *Results in motion of the pole block & increase of bending due to low pre-load*

3. Low collar-to-yoke preload ratio causing further bending in the collared area

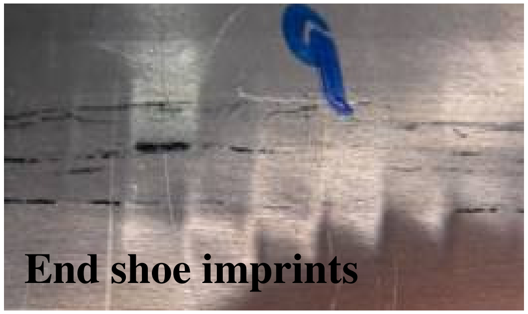
Analysis of TQC01 Test Results (2/2)

Mid-plane degradation observed after quench #42 can be attributed to:

1. Axial coil motion during excitation (in turn due to low azimuthal pre-load)



2. Bending due to the application of local pressure at the mid-planes
   - *Rigid metal parts dominate the cross-section near the coil ends*
   - *Ends used stainless steel yoke packs resulting in higher stresses after cool-down*
   - *Combined effects may have resulted in excessive coil pressure at mid-plane*

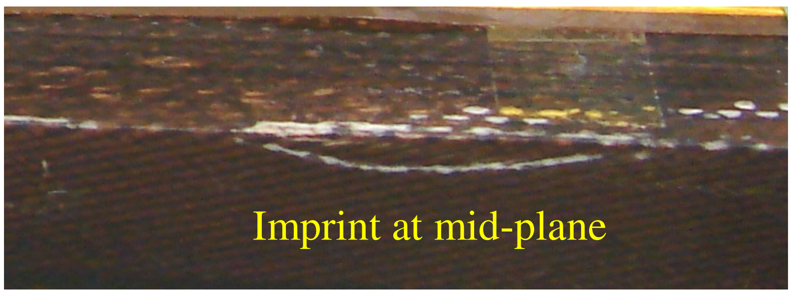


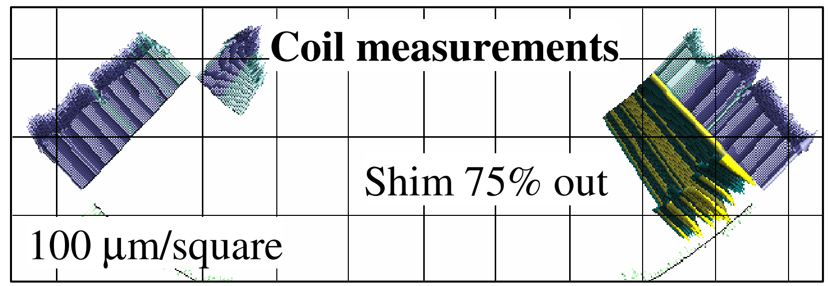
New Mechanical Features in TQC02

- Warm azimuthal preload is increased to **150 MPa**, based on non-linear coil MOE
- Collared preload is increased to a peak stress of **120 MPa**
- Added strain gauges on the bronze poles; will be monitored during assembly
- Preload at the collared coil level is measured based on collar deflection measurements and bronze pole gauges readings, in conjunction with FEA
- Preload in the final assembly is based on readings from the skin gauges, control spacer gauges and bronze pole gauges, in conjunction with FEA
- Azimuthal gauges are placed on the coil at both the pole and mid-plane and read during all phases of assembly and testing, but are not used as the "primary" method of determining preload.
- Contact area of yoke upon collars is increased with respect to TQC01, allowing radial support over a greater azimuthal area. This should also result in a rounder final coil shape.
- The pole slot is filled with G-10 (nominal design material) instead of epoxy
- Yoke laminations will be made of iron over the entire magnet length

TQC Status and Plans

- TQC02 has been collared: results from strain gauges as well as collar deflection measurements were consistent with analysis
- However, after collaring one mid-plane shim was found to have been out of place, causing probable permanent damage to 2 coils





- Two additional coils are being fabricated to replace the damaged ones
- A new TQC test (TQC01b) was introduced using coils from TQC01 &TQS01

  Primary goal: verify shim system and analysis with respect to preload for TQC during assembly, cool-down and excitation
- TQC01b has been fabricated and test preparations are underway
- The completion and test of TQC02 will follow shortly after TQC01b

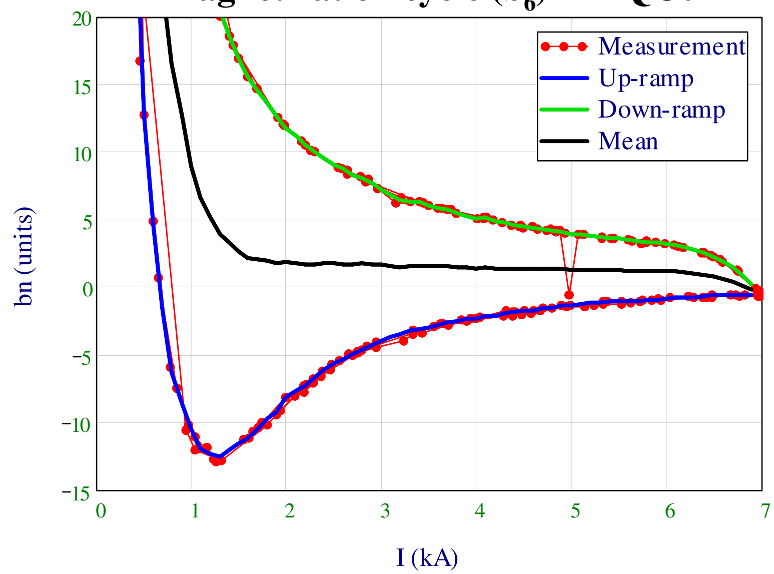
TQ Magnetic Measurements

- Field quality measurements of TQC01 and TQS01 show encouraging results
- Normal dodecapole is large but "as built" calculated values are close to measured
- Design/fabrication/assembly need improvements to reduce non-allowed harmonics
- Alignment features and single-coil reaction/potting will be implemented in LQ
- Need AP guidance on requirements for magnetization and eddy current harmonics
- Conductor and cable choices are limited: discuss/understand options and priorities

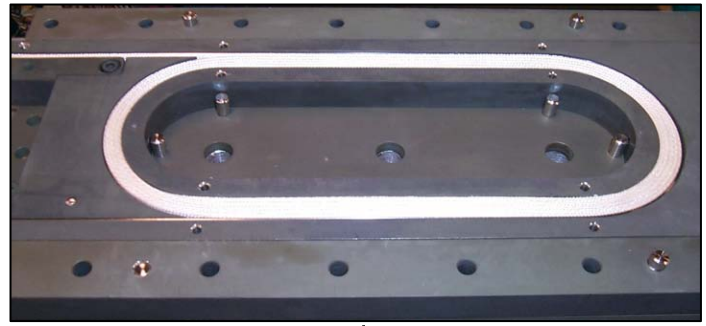
Harmonics at 45 T/m (average up-down ramp)

R = 22mm	Normal (b_n)		Skew (a_n)	
n	TQC	TQS	TQC	TQS
3	2.01	-1.46	-1.72	4.41
4	-1.90	-0.52	0.62	-1.99
5	0.58	3.06	-1.33	0.71
6	1.71	5.40	-0.10	-0.37
7	0.07	0.07	0.10	-0.11
8	0.01	-0.11	-0.03	-0.18
9	0.04	0.02	0.08	-0.02
10	-0.06	0.02	0.00	0.00

Magnetization cycle (b_6) in TQC01

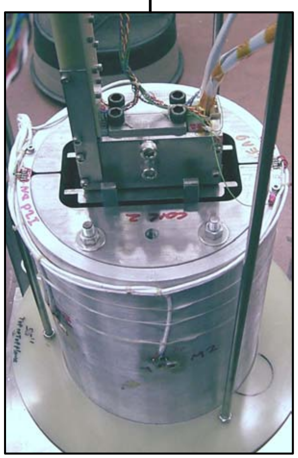


Sub-scale Coils and Structures

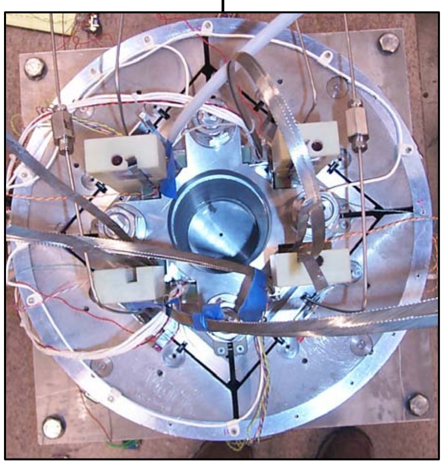


Nb3Sn

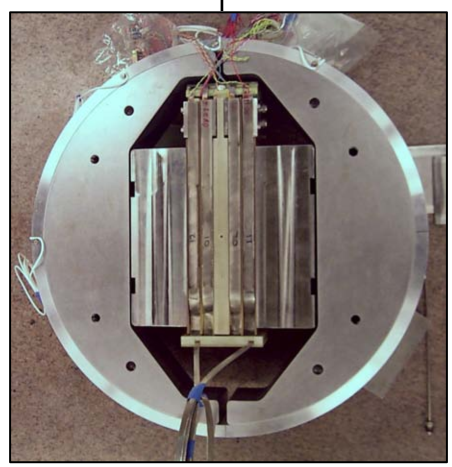
Bi-2212



SM
Low field
Low stress



SQ
High stored energy
High Axial forces



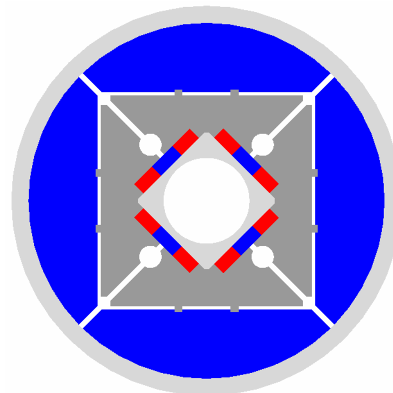
NMR
4-coil layout
High field

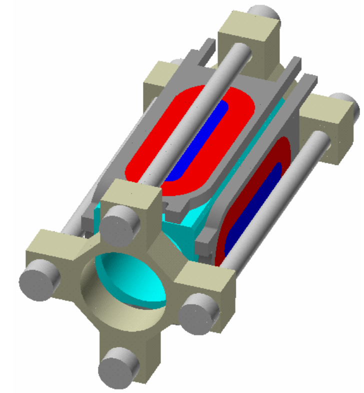
SD
High field
High stress

Sub-scale Quadrupole Series (SQ)

Design:

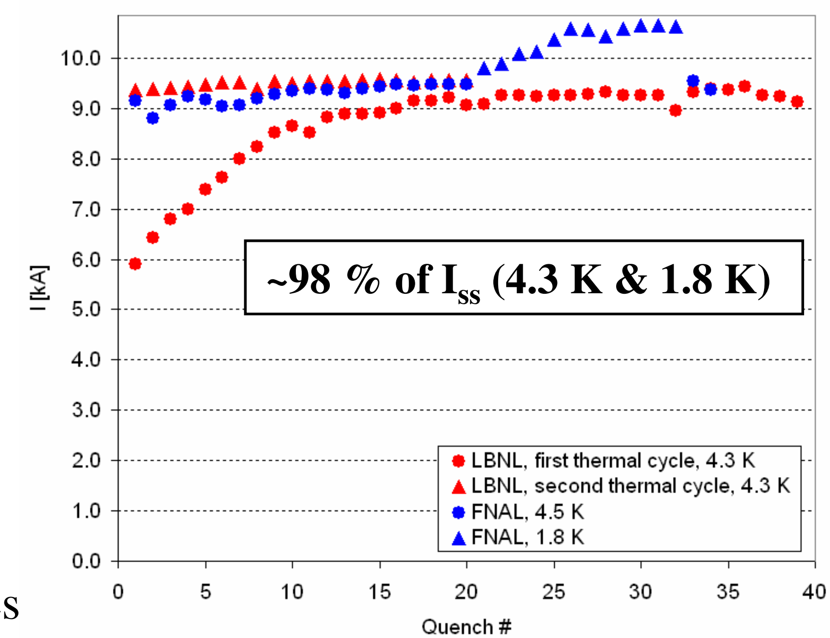
- 4 racetrack coils in square configuration
- Coil aperture 130 mm (clear bore 110 mm)
- Similar load line as TQ (11.3 T @460 A)
- Similar coil stress as TQ (100-130 MPa)
- Similar axial force as TQ (350 kN @ Iss)





Results:

- 2 magnets, 2 tests each (LBNL/FNAL)
- Cable and MJR conductor evaluation
- Verification of heat treatment for TQ
- Verification of conductor stability
- Evaluation of stress degradation
- Analysis of quench initiation and training
- Study of the effect of axial load
- Improved assembly procedure

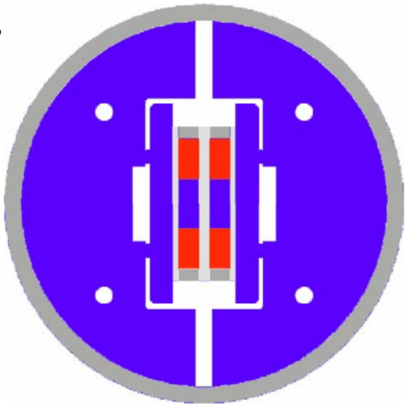


Next step (SQ03):

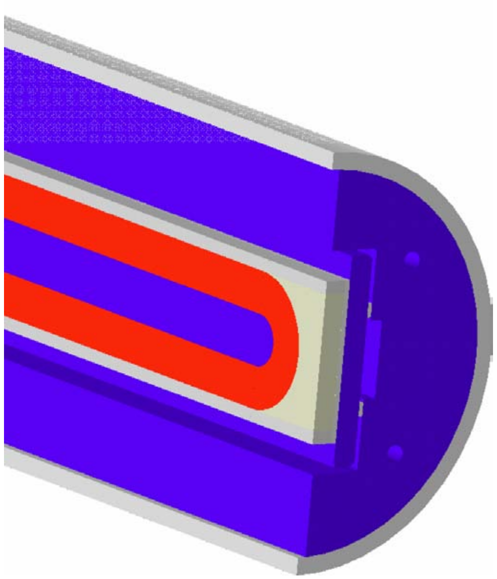
- RRP conductor evaluation, continued studies

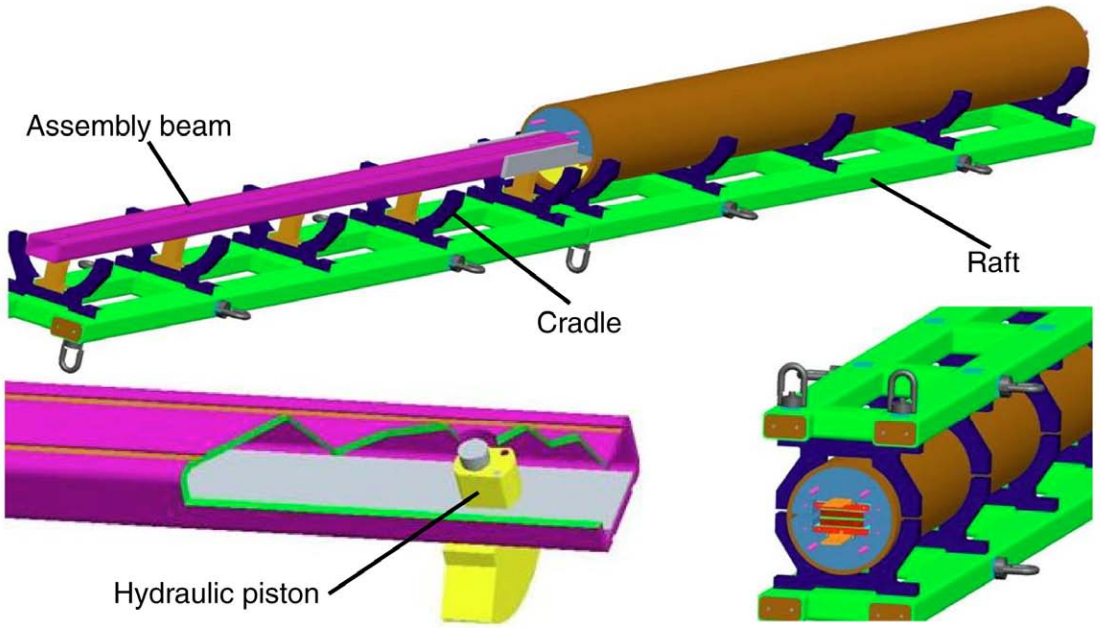
Long Racetrack Magnet Design

First step for scale-up, based on LBNL SC/SM coil & structure



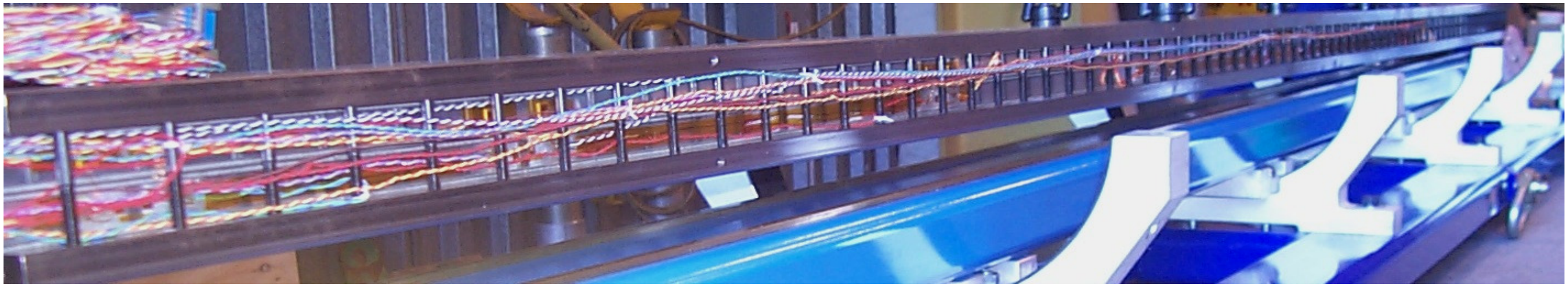
- simple coil design → focus on length dependent issues
- well understood SC (SM) baseline: 20+ coils tested
- common coil dipole – lower forces, energy, pre-stress
- coil disassembly/reassembly in different configurations
- **demonstration of bladder & key technology scale-up**



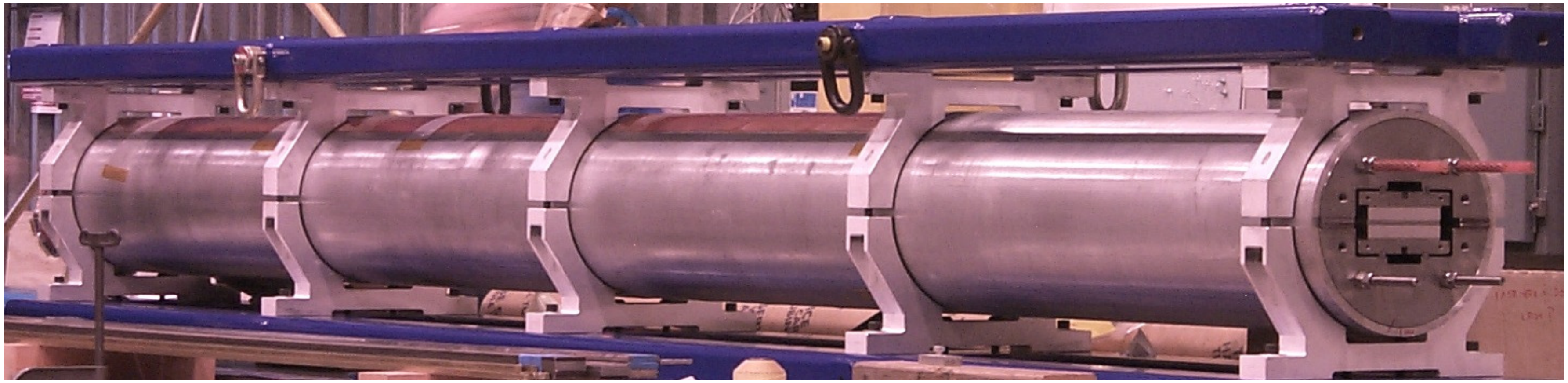


Long Racetrack Magnet Development

Instrumented dummy coil (6 strain gauge stations along magnet length)



Assembled shell-yoke structure with dummy coil



- LBNL: structure design, procurement & qualification; magnet design & analysis
- BNL : fabrication of short and long coils, magnet assembly, cool-down and test

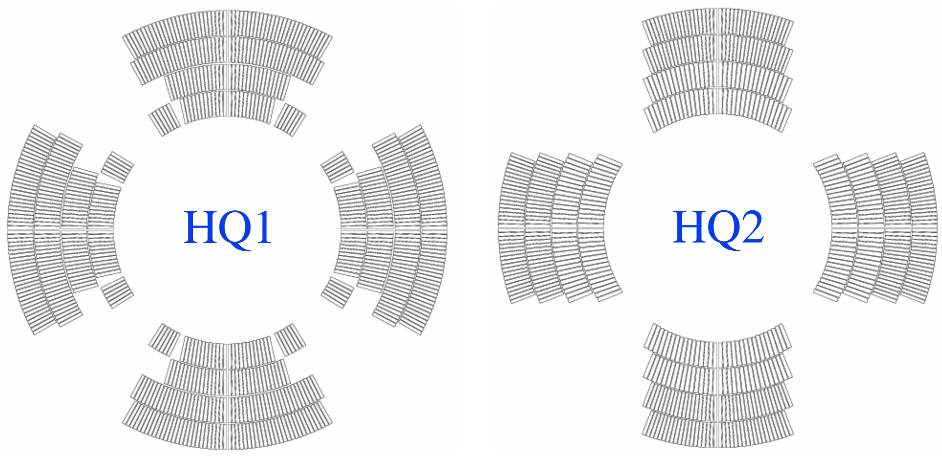
LARP

Long Quadrupole (LQ)

<u>Technical approach and open issues</u>:

- Baseline strand selected and qualified; developing improved options and qualification plans for possible use in later phases
- Present cable and insulation are working well; further developments desired to facilitate magnet production, improve radiation hardness
- Key elements of coil technology scale-up: (1) reaction/potting tooling & fabrication/handling processes; (2) pole/end parts design/materials
- LQ coil fabrication processes will be derived from TQ, LR, and core programs experience
- Alignment becomes more critical and is also needed for field quality: new features implemented in coil fabrication and magnet assembly
- Support structure performance is a key element for success: selection through LQ Design Study

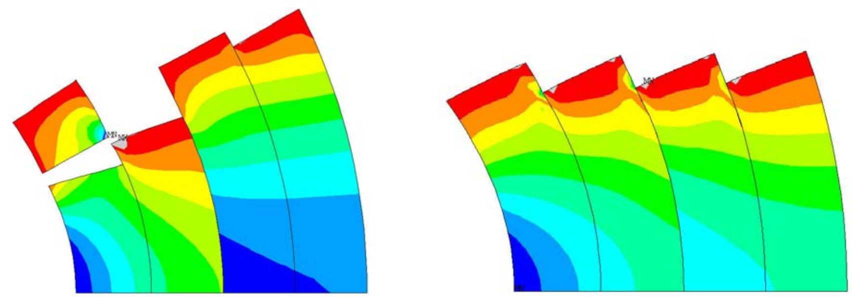
High Gradient Quadrupoles (HQ)



Goals:

- Expand toward higher field/stress
- Feedback to IR optimization

The reference cross-sections were selected taking into account stress considerations:



PERFORMANCE PARAMETERS

Parameter	Symbol	Unit	HQ1	HQ2
Short sample gradient*	G_{ss}	T/m	308	317
Short sample current*	I_{ss}	kA	10.7	12.6
Coil peak field	B_{pk} (I_{ss})	T	15.6	15.8
Copper current density	J_{cu} (I_{ss})	kA/mm^2	2.2/2.2	2.1/2.6
Inductance	L (I_{ss})	mH/m	24.5	18.0
Stored energy	U (I_{ss})	MJ/m	1.3	1.4
Lorentz force/octant (r)	F_r (I_{ss})	MN/m	1.7	1.7
Lorentz force/octant (θ)	F_θ (I_{ss})	MN/m	-6.0	-6.1
Average coil stress (θ)	σ_θ (I_{ss})	MPa	150	152
Dodecapole (22.5 mm)	b_6		-0.2	0.0
10-pole (22.5 mm)	b_{10}		-0.05	-0.92

(*) Assuming J_c(12 T, 4.2 K) = 3.0 kA/mm^2; operating temperature T_{op}=1.9K

LORENTZ STRESS AT 300 TESLA/METER (MPA)

Coil	ANSYS (Fig 3)		Mid-plane stress: Σ F_θ/(layer width)			
Design	L1&2	L3&4	L1	L2	L3	L4
HQ1	176	167	139	98	179	150
HQ2	178	131	148	143	159	114

Acknowledgement

J. Alvarez, M. Anerella, G. Ambrosio, N. Andreev, B, Bingham, P. Bish, B. Bordini, R. Bossert, S. Caspi, D. Cheng, D. Dietderich, H. Felice, P. Ferracin, S. Feher, A. Ghosh, A. Godeke, S. Gourlay, A. Hafalia, R. Hannaford, H. Higley, D. Horler, V. Kashikhin, J. Kerby, M. Lamm, A. Lietzke, J. Lizarazo, N. Liggins, A. McInturff, L. Mokhov, N. Mokhov, I. Novitski, R. Scanlan, J. Schmalzle, J. Swanson, R. Stanek, M. Tartaglia, P. Wanderer, B. Wands, M. Whitson, A. Zlobin, J. Zweibohmer

LARP

Summary

Phase I (TQ and racetrack coil development)

- TQ01 prototypes fabricated and tested: achieved 200 T/m gradient
- TQ02 models test RRP conductor and optimized designs
- TQS02 performed well above 200 T/m at both 4.5 K and 1.9 K
- TQC02 was delayed due to coils damage during magnet assembly
- TQC02 and TQS02b will be tested in the coming months
- SQ models have provided and will provide key information
- Long shell-based structure fabricated and qualified for use in LR
- LR01 magnet assembly completed; test is starting

Phase II (LQ and HQ models):

- LQ coil design based on TQ; tooling/procedures under development
- LQ structure design and selection process is underway
- Good progress on HQ design, implementation depends on priorities