Development of Long Nb_3Sn Magnets by the LARP Collaboration

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for the US LHC Accelerator Research Program

2011 Particle Accelerator Conference
New York, March 30, 2011

US LHC Accelerator Research Program

LARP

Goal: **Extend and improve the performance of LHC**

- Progression from the US LHC Accelerator Construction Project
- Collaboration of four national Labs: BNL, FNAL, LBNL, SLAC

Major focus: **Develop Nb_3Sn quadrupoles for HL-LHC**

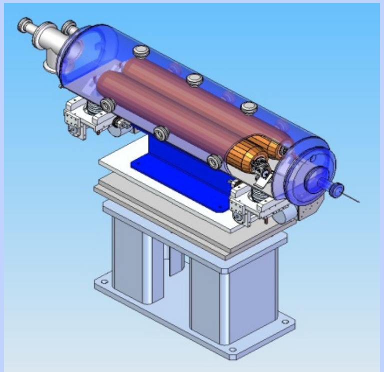
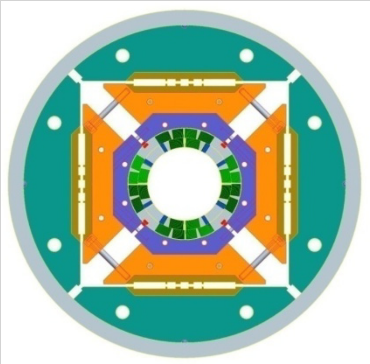
- Potential to operate at higher field and/or larger temperature margin
- Follows Nb_3Sn development and demonstration by CDP & US Labs

Technical challenges: **Nb_3Sn is brittle and strain sensitive**

- Requires high temperature coil reaction after winding
  - ➢ Materials compatibility (coil parts, insulation)
  - ➢ Thermal expansion differentials (more critical for long magnets)
- Large forces are generated in high field magnet coils
  - ➢ Need to prevent degradation under stress

Overview of LARP Activities

LARP

Accelerator Systems	Instrumentation	• Luminosity monitor • Tune tracker, AC dipole • Schottky monitor
	Accelerator Physics	• Electron cloud instability • Beam-beam studies • Crab crossing
	Collimation	• Rotatable collimators
Magnet Systems	Materials	• Strand characterization • Cable development
	Model Quadrupoles	• Technology Quadrupoles • High-field Quadrupoles
	Long Quadrupoles	• Coil fabrication • Structure and assembly • Instrumentation and Test
Program Management	Programmatic Activities	• Toohig Fellowship • Long Term Visitors

LARP Presentations at PAC11

- Design and Test of Long Nb3Sn Magnets within the LARP Collaboration
- Field Quality Measurements of LARP HQ Magnets (TUP174)
- Mechanical Design of an Alternate Structure for LARP Nb_3Sn Magnets for LHC (TUP170)
- Tevatron Accelerator Physics and Operation Highlights
- Beam Losses Due To Abrupt Crab Cavity Failures In HL-LHC
- Studies of RF Noise Induced Bunch Lengthening at the LHC
- Operational Results from the LHC Luminosity Monitors
- LARP LHC 4.8 GHz Schottky System Initial Commissioning with Beam
- Results of Head-on Beam-beam Compensation Studies at the Tevatron
- Advanced Crystal Collimation Studies at the Tevatron (T-980)
- Impact of Arc Phase Advance Tuning on Chromatic Optics in RHIC
- Estimation of Ecloud and TMCI Driven Vertical Instability Dynamics from SPS MD Measurements
- Crab Cavity Simulation in SPS
- Multipacting Analysis for the Half-Wave Spoke Resonator Crab cavity for the LHC Upgrade
- Simulations of the LHC High Luminosity Monitors at Energies from 3.5 TeV to 7.0 TeV
- Simulation of Jitter Effects in Crab Cavity Compensation for LHC Upgrade
- Simulated Performance of an FIR-Based Feedback System to Control the Electron Cloud Single-Bunch Transverse Instabilities in the CERN SPS
- Experimental Study of Magnetically Confined Hollow Electron Beams in the Tevatron as Collimators for Intense High-Energy Hadron Beams
- Direct Numerical Modeling of E-cloud Driven Instability of a Bunch Train in the CERN SPS, and its Mitigation using a Feedback Model

High Luminosity LHC

Physics goals:

- *Improve measurements of new phenomena seen at the LHC*
- *Detect/search low rate phenomena inaccessible at nominal LHC*
- *Increase mass range for limits/discovery*

Timeline and decision points:

- *~2014: complete design study and select technology*
- *~2020: installation (driven by lifetime of existing IR, ~500 fb^{-1})*

Required accelerator upgrades include IR magnets:

- *Support new optics solutions that directly increase luminosity*
- *Provide design options for overall system optimization/integration*
- *Tolerate high peak (10^{35} $cm^{-2}s^{-1}$) & integrated (3000 fb^{-1}) luminosity*

  $\Rightarrow$ *Thermal margins, radiation lifetime*

Magnet Program Components

1. Materials R&D:
   - *Strand specification and procurement*
   - *Cable fabrication, insulation and qualification*
   - *Heat treatment optimization*

   Ongoing

2. Technology development with Racetrack Coils:
   - *Subscale Dipole & Quad (SM & SQ, 30 cm long)*
   - ***Long Racetrack (LR, 4 m long)***

   Completed

3. Cos 2θ Quadrupoles with 90 mm aperture:
   - *Technology Quadrupole (TQ, 1 m long)* — *Completed*
   - ***Long Quadrupole (LQ, 4 m long)*** — *~75%*

4. Cos 2θ Quadrupoles with 120 mm aperture:
   - *High-Field Quadrupole (HQ, 1 m long)* — *~35%*
   - ***Long High-Field Quadrupole (LHQ, 4 m long)*** — *Starting*

Present focus: LQ and HQ

Long Quadrupole LQ *(90 mm aperture, 4 m long):*

- *LQS01: achieved 220 T/m, 10% above initial LQ target*
- *LQS02: assembly is completed with 4 new coils*
- *LQS03: four coils under fabrication with new conductor design*

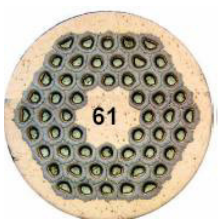
High Field Quadrupole HQ *(120 mm aperture, 1 m long):*

- Achieved >155 T/m gradient in first test, at 4.5K
  - *Already above NbTi intrinsic limit at 1.9K*
- First quench >150 T/m in second test
- Observed coil failures due to insulation & conductor damage
  - *Traced to high compression during coil fabrication*
- New & more challenging design - requires optimization

LARP Conductors

Three strand designs, all from Oxford Superconducting Technology:

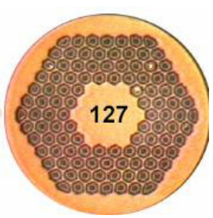
- *MJR 54/61:* *TQS01, TQC01, SQ*
- *RRP 54/61:* *LR, TQ02, LQS01(2), HQ01a/b/c/d*
- *RRP 108/127:* *TQS03, HQ01a/b/c/d, (LQS03)*



RRP 54/61:

☺ Production wire, highest Jc, long piece length, best characterized

☹ Large sub-elements, flux jumps esp. in larger diameter wires



RRP 108/127:

☺ D_{eff} reduced by 30%, very good results in TQS03

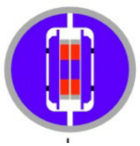
☹ Lower J_c for same RRR, not fully optimized for production

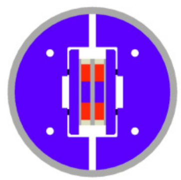
New options from the HEP Conductor Development Program:

- Ti-doped RRP: HQ cable/coil fabricated for evaluation
- RRP 217: promising but still requiring R&D

Length Scale-up Projects in LARP

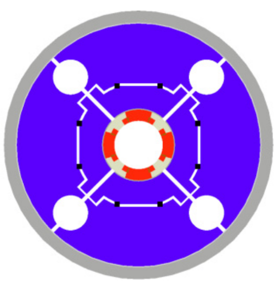
SM ⇒ LR

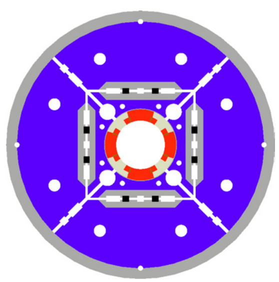




- From 0.3 m to 4 m
- Started in 2005, competed in 2008
- Racetrack coils, shell based structure

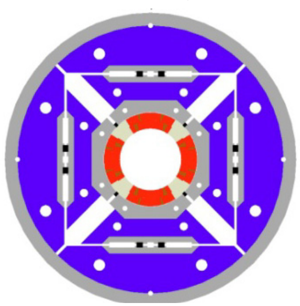
TQS ⇒ LQS





- From 1 m to 4 m
- Started in 2007, exp. completion 2012
- 90 mm aperture cos2θ coils
- Structure alignment

HQ ⇒ LHQ



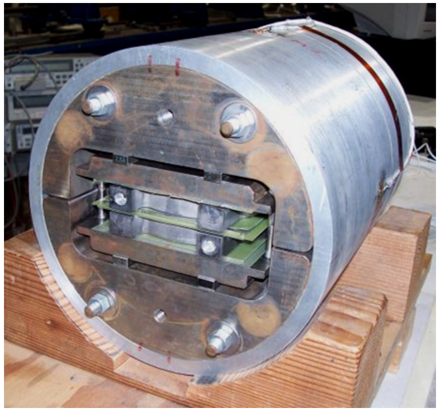
- From 1 m to 4 m
- Starting in 2011, exp. completion 2016
- 120 mm aperture cos2θ coils
- Full coil and structure alignment

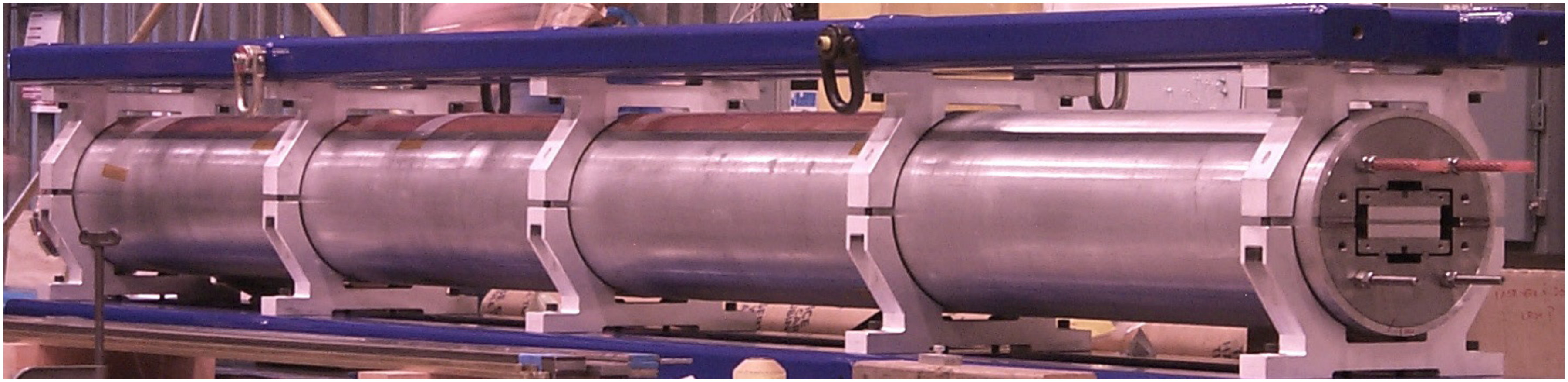
Long Racetrack (LR)

- Scale up LBNL SM coil and structure: 30 cm to 4 m
- Coil R&D: Cable, handling, reaction, impregnation
- Structure R&D: friction effects, magnet assembly

- *BNL: coil fabrication, magnet assembly and test*
- *LBNL: magnet design, structure fabrication/assembly*

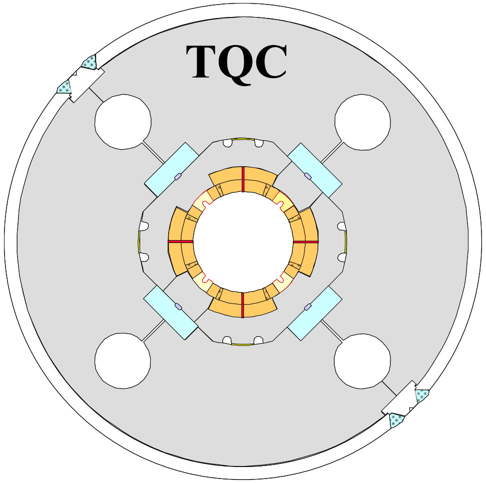
- Fast training: LRS01 first quench at 84% of SSL
- LRS02 achieved 11.5 T, **96% of short sample limit**

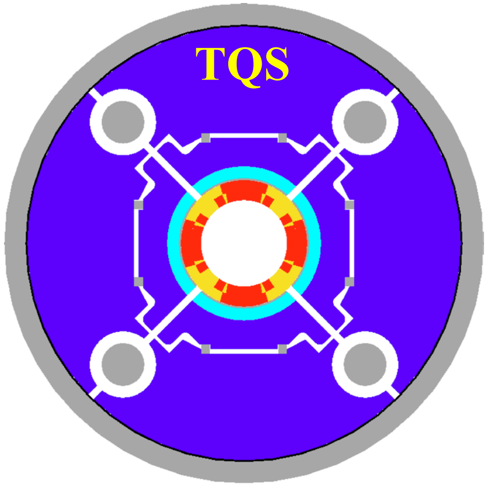




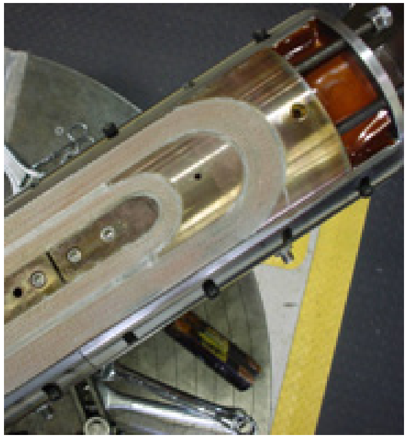
Technology Quadrupole (TQ)

- Double-layer, shell-type coil
- 90 mm aperture, 1 m length
- Two support structures:
  - *TQS (shell based)*
  - *TQC (collar based)*
- <u>Target gradient</u> **200 T/m**

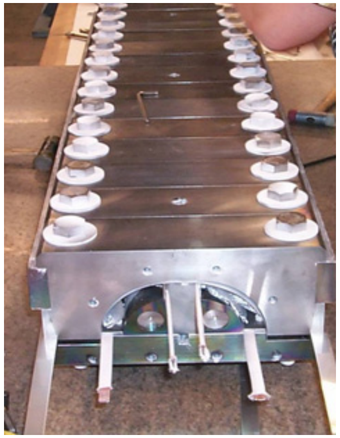




<u>Winding & curing (FNAL - all coils)</u>

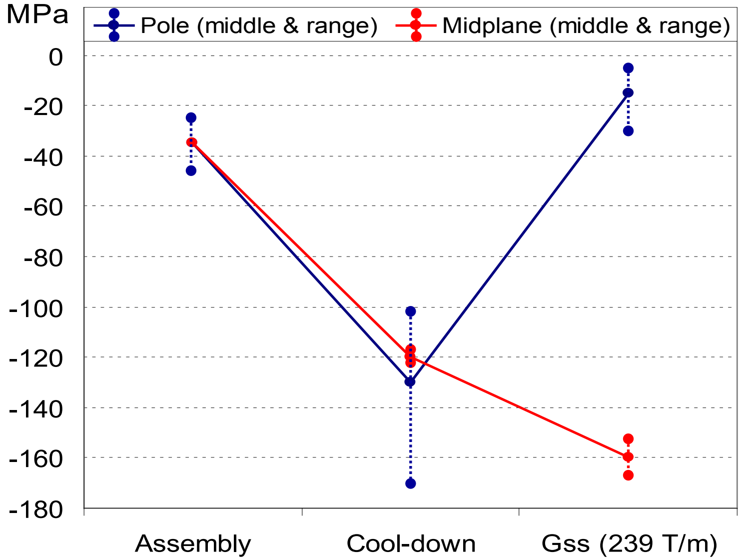


<u>Reaction & potting (LBNL - all coils)</u>

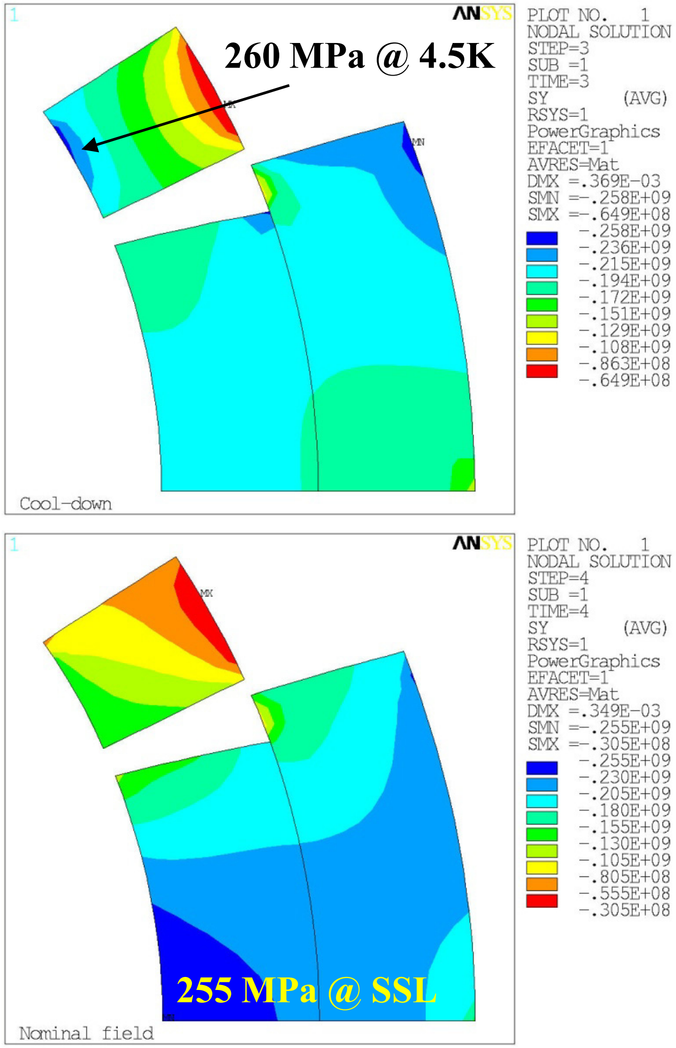


TQ Studies: Stress Limits

Coil layer 1 stress evolution - σ_θ



Calculated peak stresses in TQS03c



Systematic investigation in TQS03:

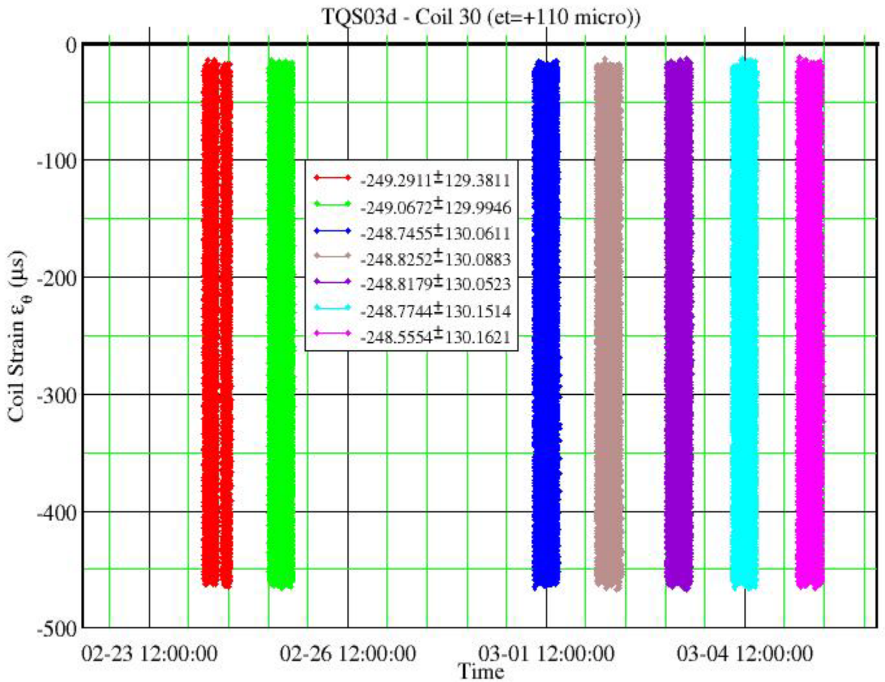
- TQS03a: 120 MPa at pole, 93% SSL
- TQS03b: 160 MPa at pole, 91% SSL
- TQS03c: 200 MPa at pole, 88% SSL

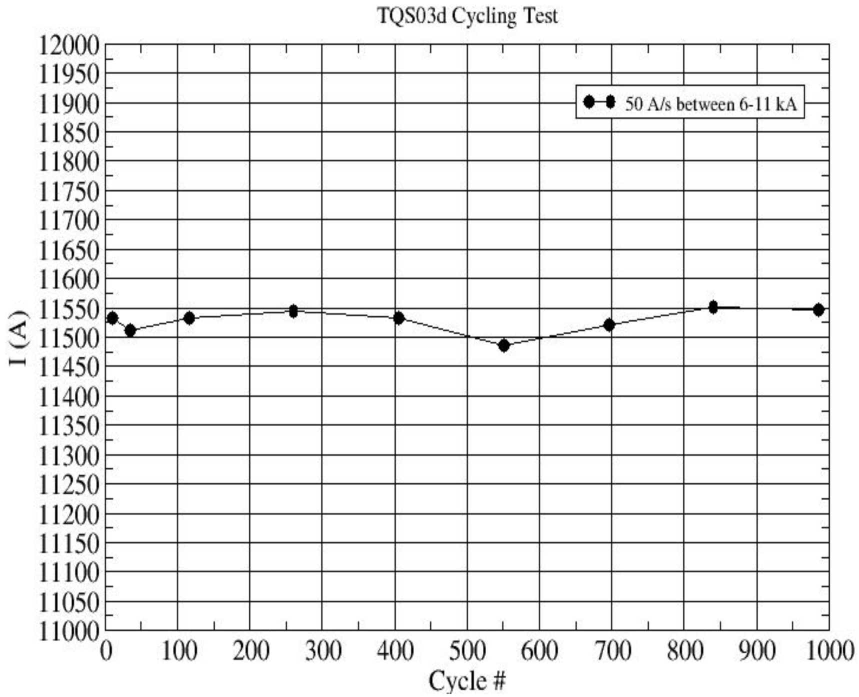
Peak stresses are considerably higher →

Considerably widens design window

TQS03d Cycling Test

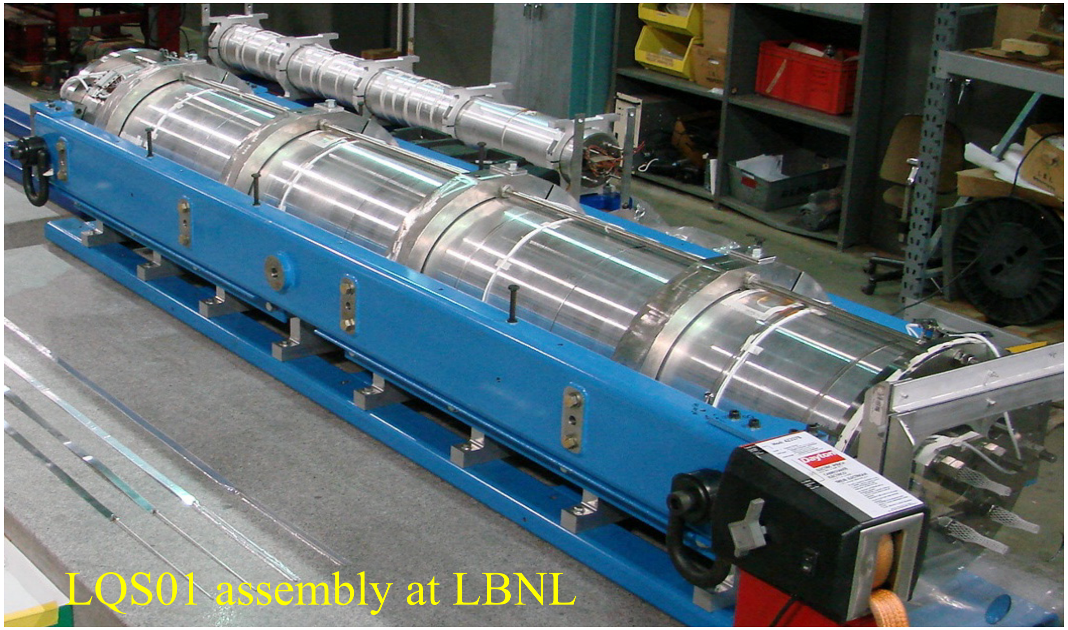
- Reduced coil stress to TQS03b levels (160 MPa average)
  - *Pre-loading operation and test performed at CERN*
- Did not recover TQS03b quench current (permanent degradation)
- Performed 1000 cycles with control quenches every ~150 cycles
- No change in mechanical parameters or quench levels

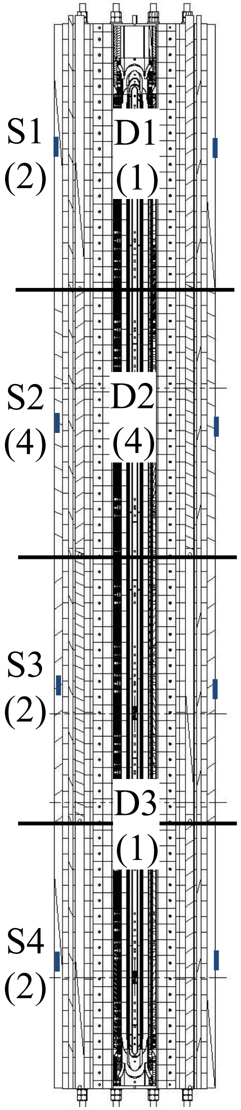




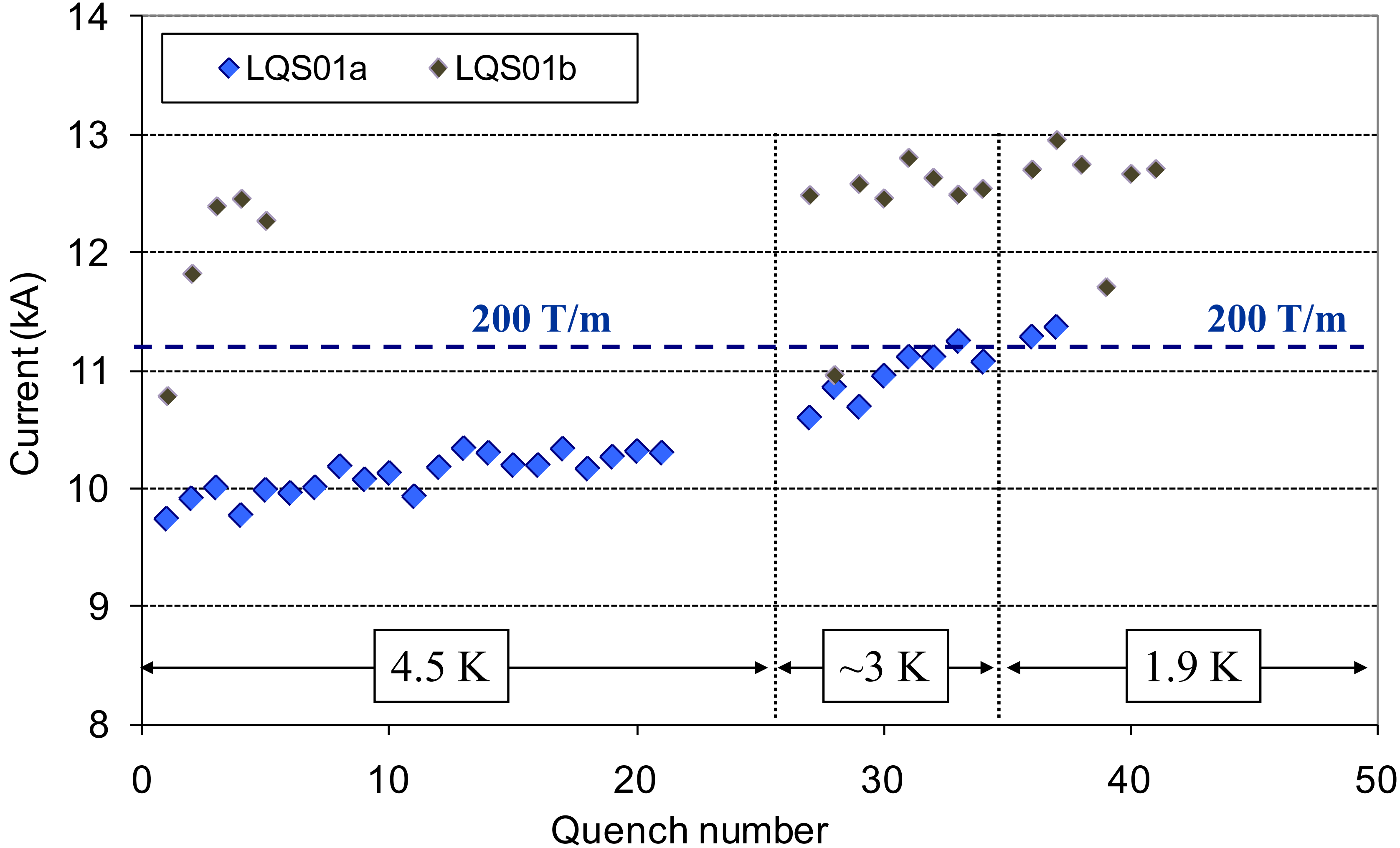
Long Quadrupole (LQ)

- TQ length scale-up from 1 m to 4 m
- Coil Fabrication: FNAL+BNL+LBNL
- Mechanical structure and assembly: LBNL
- Test: FNAL
- Target gradient **200 T/m**





LQS01 & LQS01b Quench Performance



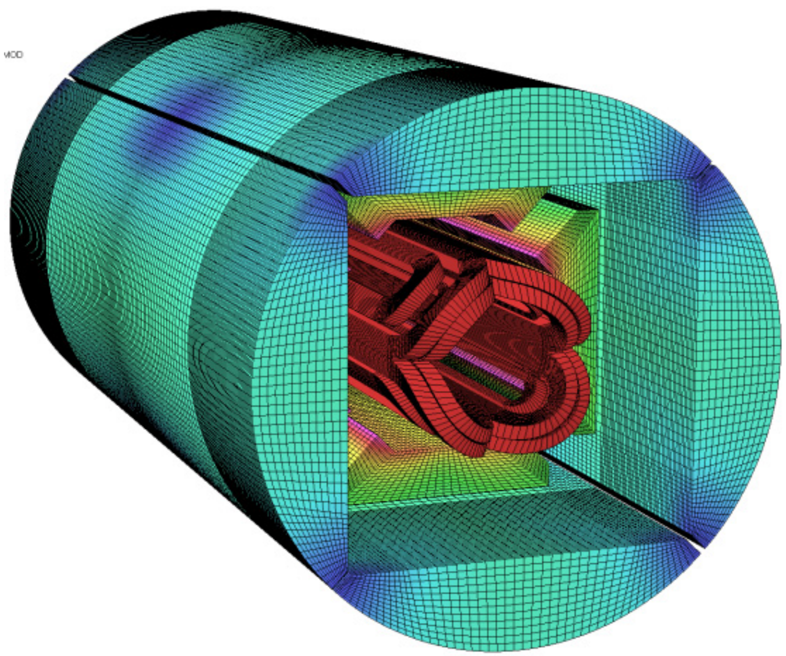
Next Steps in the LQ Program

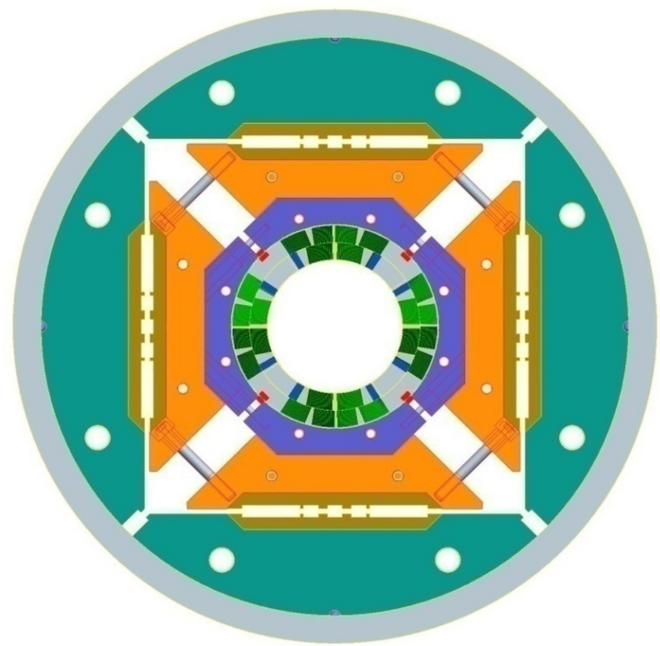
LQ surpassed its initial target by 10%. Current R&D goals are:

- Fully reproduce the performance of the TQ short models
  - *Higher gradient (240 T/m in TQS03)*
  - *Fast training (plateau in 5-10 quenches, no retraining)*
- Systematic analysis of coil length effects
  - *Detailed modeling of the reaction process*
  - *Understand/optimize coil strain state after reaction*
- Design and process optimization for construction
  - *Coil size control/reproducibility*
  - *Protection heater design, esp. for inner layer*
  - *One-side loading with 4 m keys/bladders*
  - *Cable insulation techniques for production*

High-Field Quadrupole (HQ)

- 120 mm aperture, coil peak field of 15.1 T at 219 T/m (1.9K SSL)
- 190 MPa coil stress at SSL *(150 MPa if preloaded for 180 T/m)*
- Stress minimization is primary goal at all design steps (from x-section)
- Coil and yoke designed for small geometric and saturation harmonics
- Full alignment during coil fabrication, magnet assembly and powering





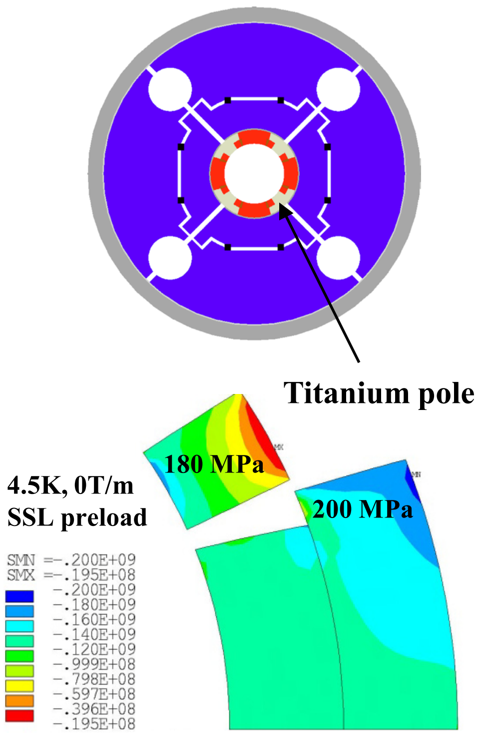
HQ: a fully integrated program

• Cable design and fabrication	LBNL
• Magnetic design & analysis	FNAL, LBNL
• Mechanical design & analysis	LBNL
• Coil parts design and procurement	FNAL
• Instrumentation & quench protection	LBNL
• Winding and curing tooling design	LBNL, FNAL
• Reaction and potting tooling design	BNL
• Coil winding and curing	LBNL
• Coil reaction and potting	BNL, LBNL
• Coil handling and shipping tooling	BNL
• Structures (baseline, revised, mirror)	LBNL, BNL, FNAL
• Assembly (baseline, revised, mirror)	LBNL, BNL, FNAL
• Magnet test	LBNL, CERN, FNAL
• Accelerator Integration	BNL, LBNL, FNAL

Handling High Stress in Magnet Coils

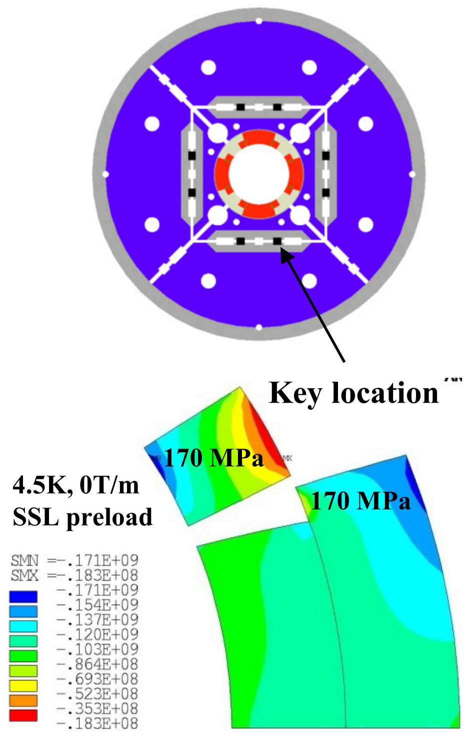
1. Understand limits

TQ (90 mm, ~12 T)

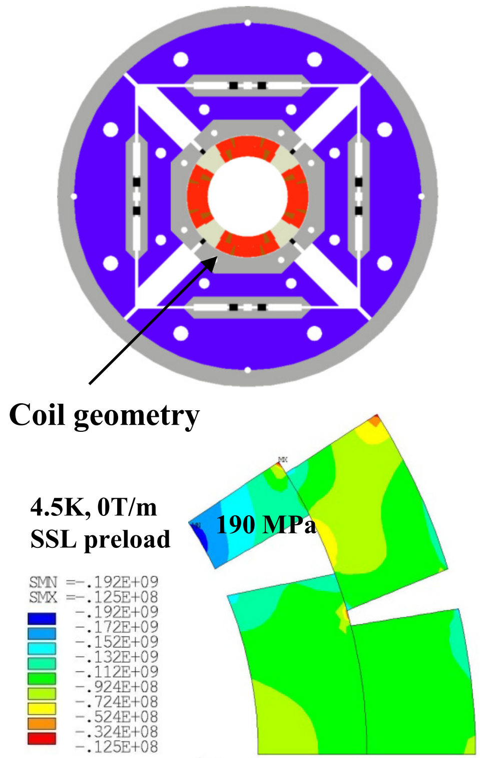


2. Optimize structure and coil for minimum stress

LQ (90 mm, ~12 T)

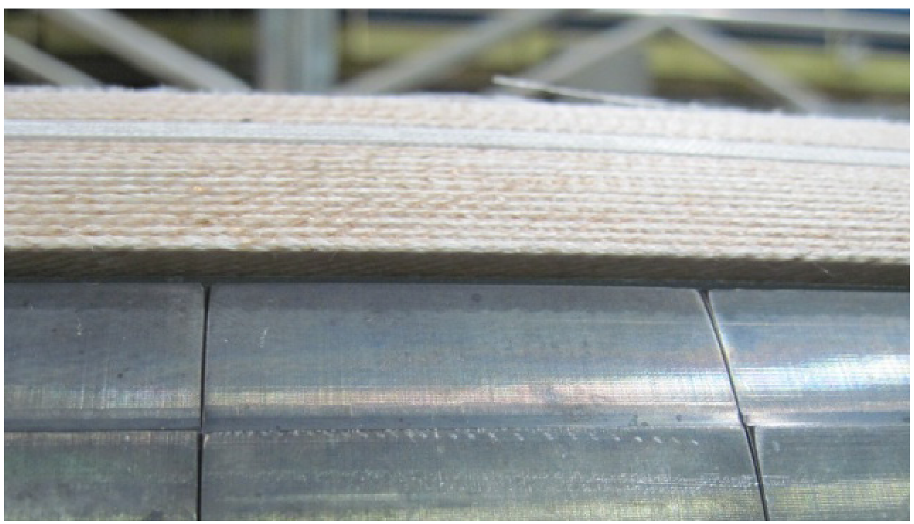


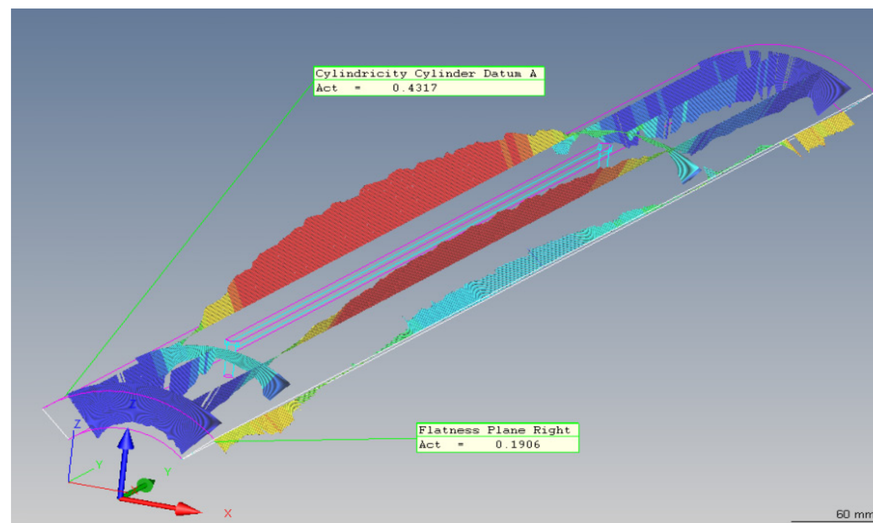
HQ (120 mm, ~15 T)



HQ Coil Design and Fabrication

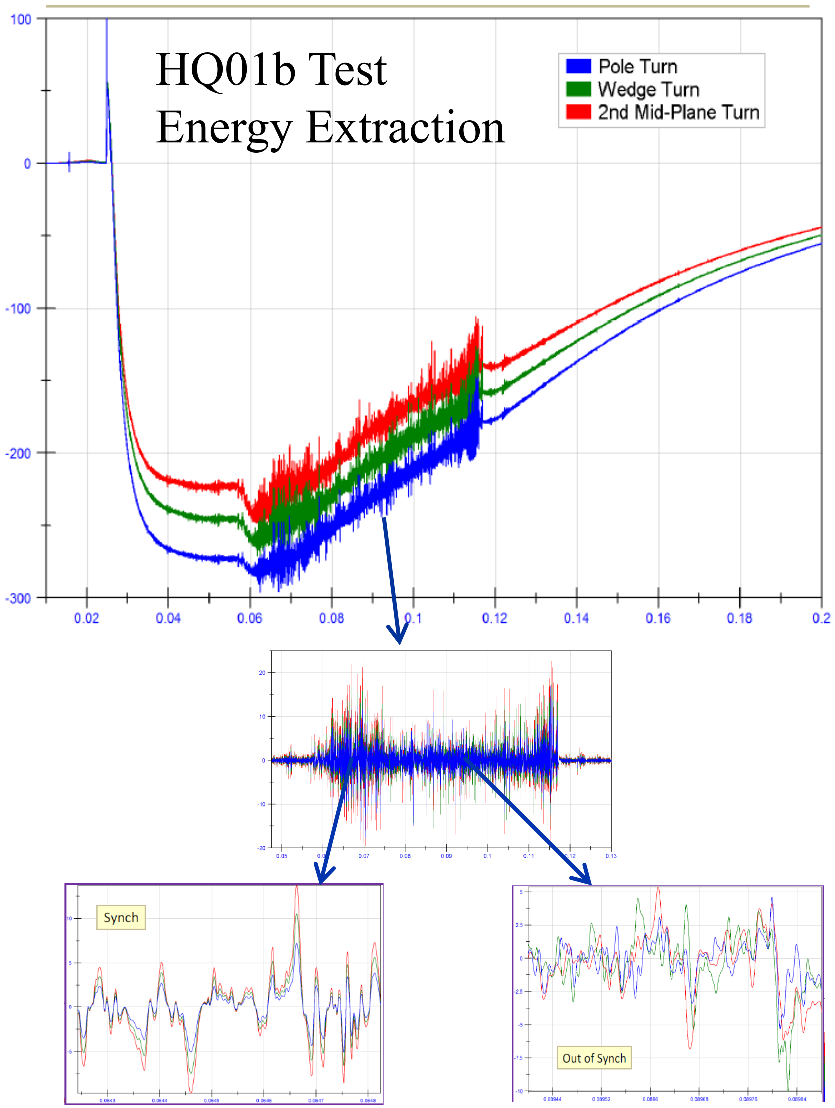
- HQ design assumed less space for inter-turn insulation than TQ/LQ
- Based on measurements, but limits expansion during reaction
- As a result, coils are over sized and over compressed

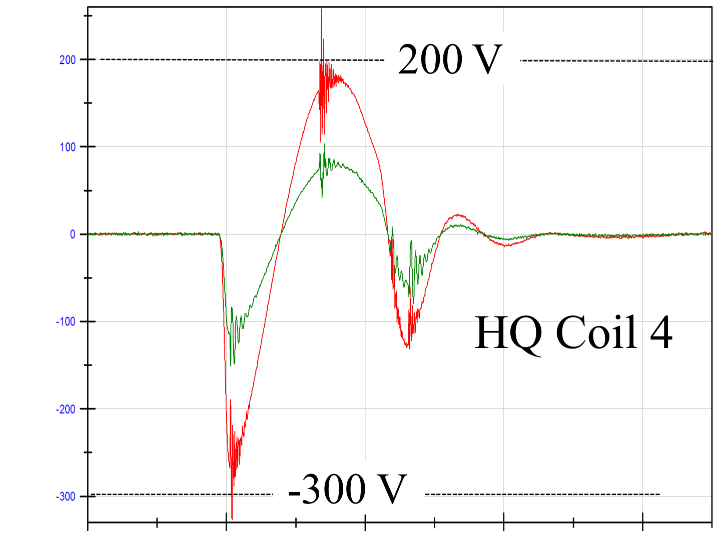


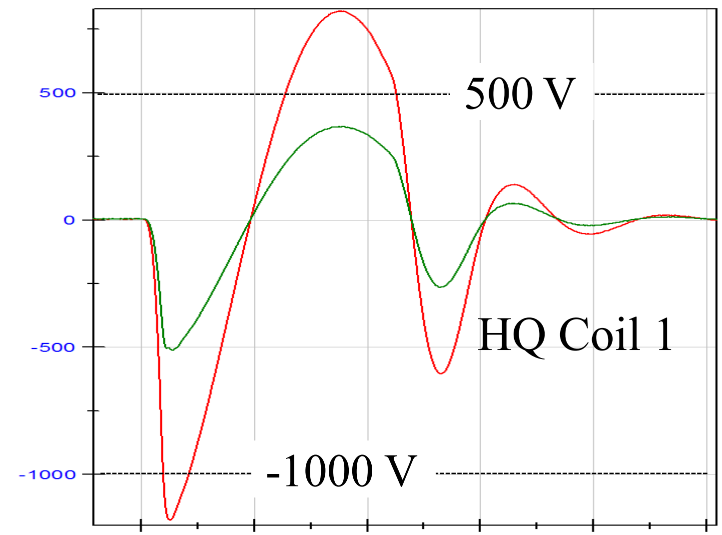


LARP

Magnet and Coil Electrical QA

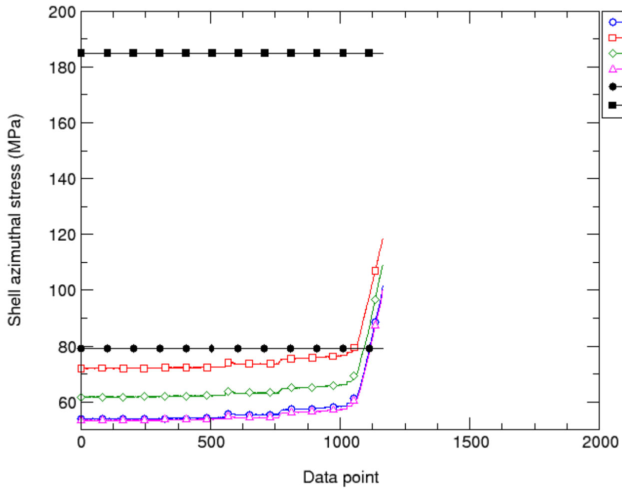


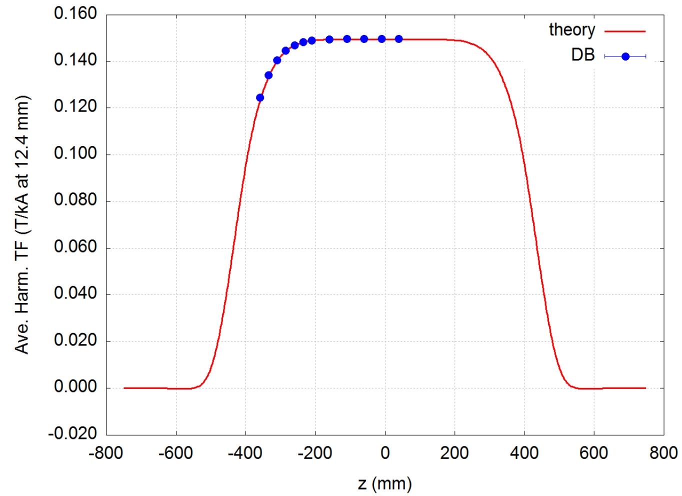




Next Steps in the HQ Program

- HQ01d cool-down is underway
  - *Replaced HQ01c limiting coil, one more coil available*

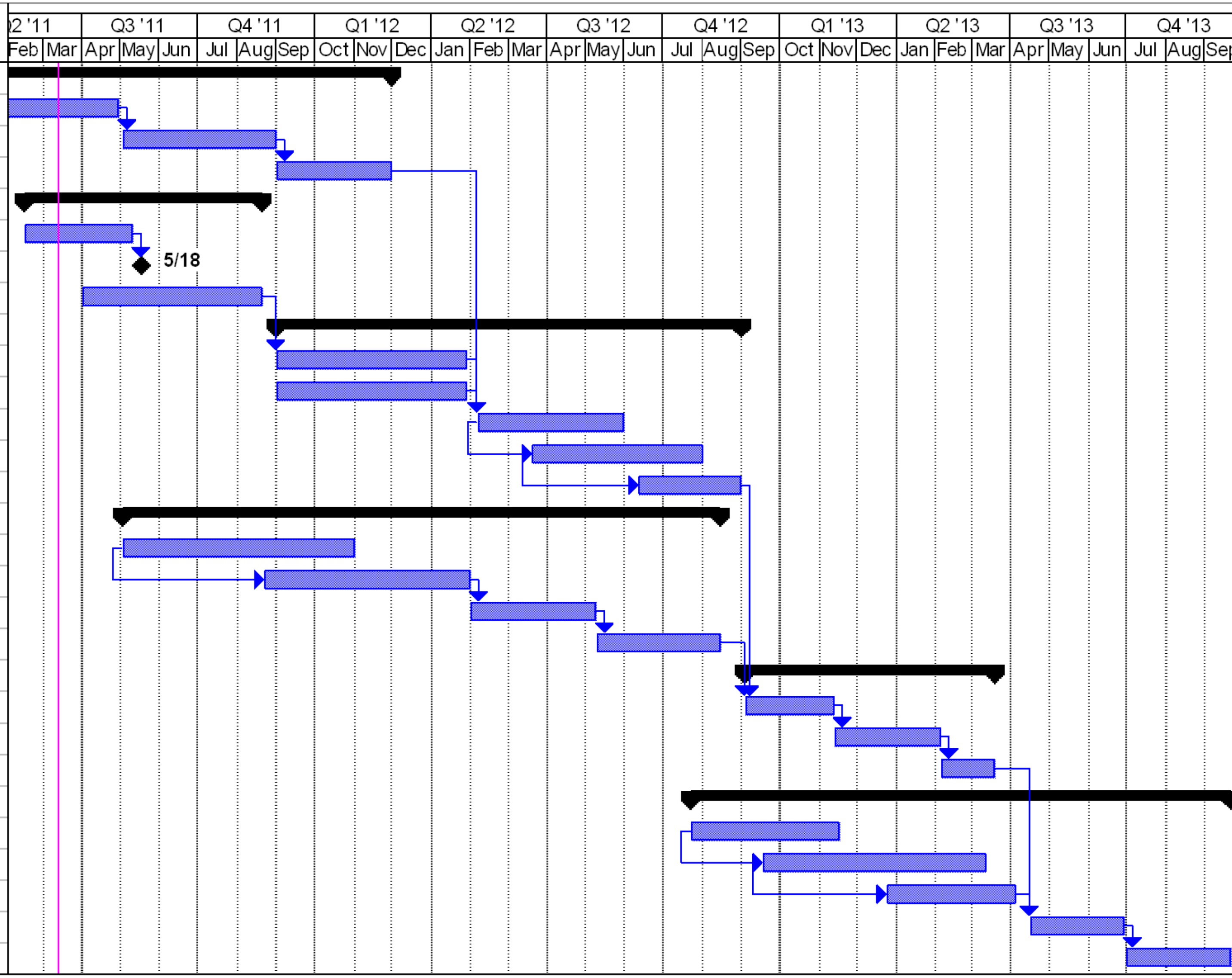




- Two special coils were fabricated with lower compression
  - *#12: increased cavity size; #13: one less turn*
  - *Will be tested in mirror configuration*
- Substantial cable R&D is underway for the next series of coils
  - *Adjust cable size to preserve x-section, parts, tooling*

Long HQ Development Plan for 2011-2013

ID	Task Name
1	**Cable and insulation**
2	Development/evaluation
3	Fabrication
4	Qualification
5	**Design**
6	Coil cross-section
7	Review
8	Parts & tooling
9	**Practice & mirror coils**
10	Tooling procurement
11	Parts
12	Wind/cure
13	React/pot
14	Instrument
15	**Mechanical structure**
16	Design
17	Procurement
18	Pre-Assembly
19	Mechanical model
20	**Single coil (mirror) test**
21	Assembly
22	Test preps & Test
23	Disassembly
24	**LHQ01 Quadrupole**
25	Coil Wind/cure
26	Coil react/pot
27	Coil instrument
28	Assembly
29	Test

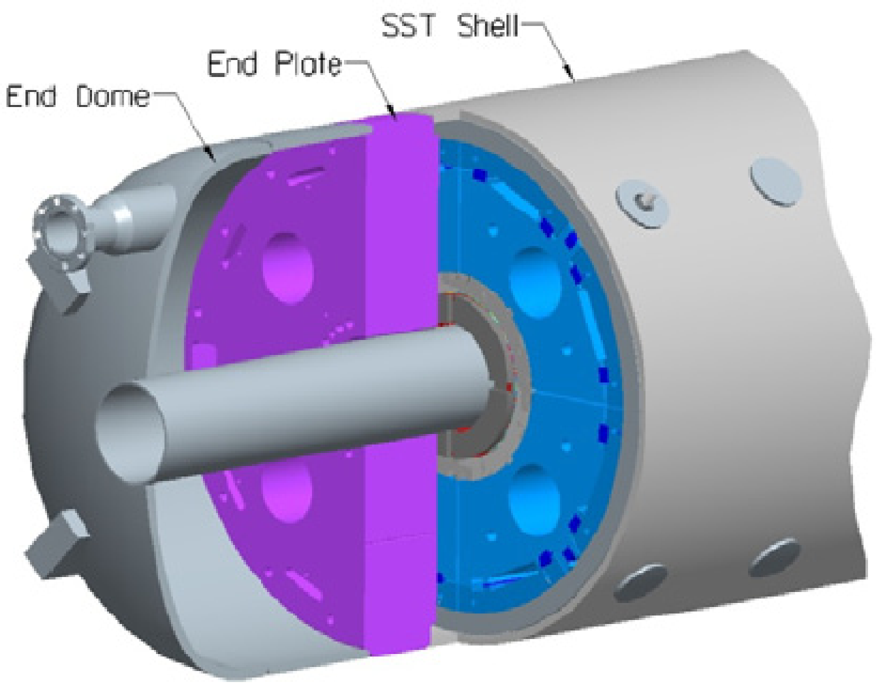


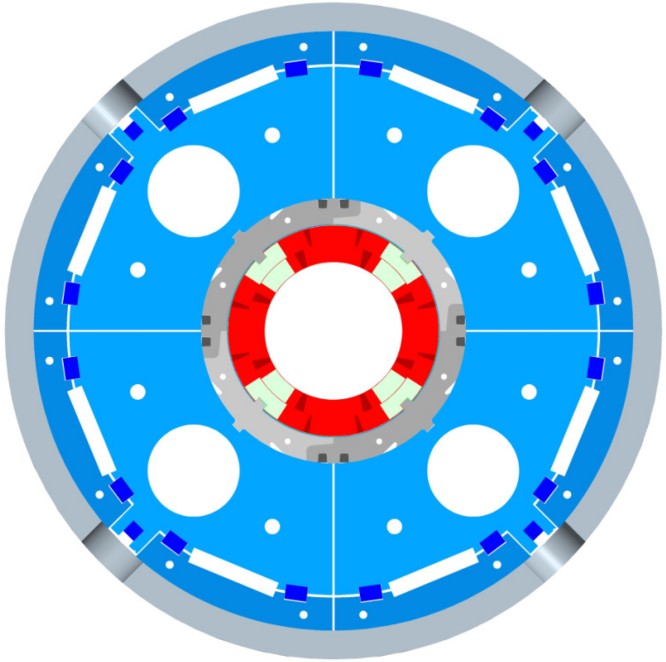
Accelerator Quality in LARP Models

Design Features	LR	SQ	TQS/LQS	TQC/LQC	HQ	LHQ
Geometric field quality					√	√
Structure alignment		√	√	√	√	√
Coil alignment		√			√	√
Saturation effects				√	√	√
Persistent/eddy currents						√
End field margin			√		√	√
Cooling channels				√	√	√
Helium containment				√		√
Radiation hardness						√

Accelerator Integration

- Pre-load optimization for high gradient with minimal training
- Alignment, quench protection, radiation hardness, cooling system
- Field quality: cross-section iteration; cored cable for eddy current control
- Structure and assembly features for magnet production and installation





Summary

- A large knowledge base is available after 5 years of fully integrated effort involving three US Labs and CERN
- Demonstrated all fundamental aspects of Nb_3Sn technology:

  - *Steady progress in understanding and addressing R&D issues*
- R&D effort should now focus on increased reliability, accelerator integration and production-oriented processes
- HL-LHC is a key step for all future high-field applications
- Next few years will be critical and much work is still left to do

  - Integrate effort with CERN, EuCARD, KEK, US core programs

Acknowledgement

U.S. DEPARTMENT OF ENERGY | Office of Science
BROOKHAVEN NATIONAL LABORATORY
BERKELEY LAB
CERN