New Magnets for the IR

How far are we from the HL-LHC Target?

GianLuca Sabbi

for the US LHC Accelerator Research Program

LHC Performance Workshop – Chamonix 2012

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Presentation Outline

Topics/guidelines:

1. Summary of LARP magnet program components and achievements
2. Focus on remaining challenges, both technical and ***programmatic***
   - Selecting a conductor design and developing it for production
   - Managing stress/strain in the final design and during production
   - Incorporating design elements for accelerator integration
   - Project organization and timelines for prototyping/production

   ➢ *…and wait, how far from what?* ***Converging on targets*** for HL-LHC
3. Build on collaboration meeting discussion, minimize repetitions
   - LARP program goals and organization
   - Details of conductor development, magnet designs, test results

https://indico.cern.ch/conferenceDisplay.py?confId=150474

US LHC Accelerator Research Program

LARP

- Started by DOE in 2003, expected to be completed around 2014
- Progression from the US LHC Accelerator Research Project
- Collaboration of four national Labs: BNL, FNAL, LBNL, SLAC

General goals:

- Extend and improve the performance of LHC
  - *Maximize scientific output in support of the experiments*
- Maintain and develop US Labs capabilities
  - *Prepare for a leadership role in future projects*
- Research and training for US accelerator physicists and engineers
- Advance international collaboration on large accelerator projects

Major focus: development of Nb_3Sn IR Quadrupoles for HL-LHC

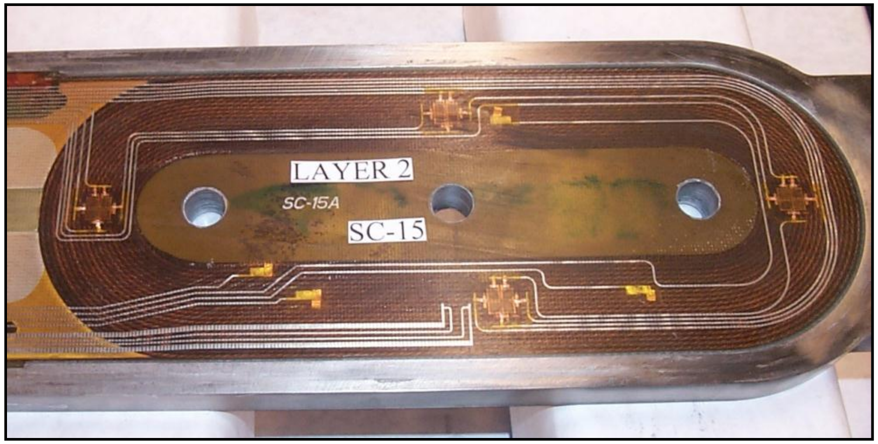
Nb_3Sn Technology Challenges

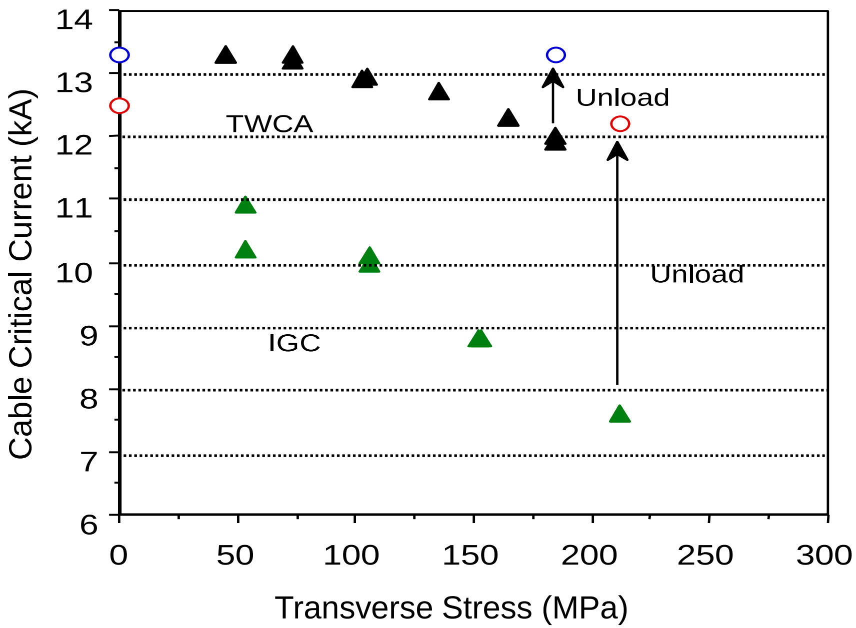
Brittleness:

- React coils after winding
- Epoxy impregnation

Strain sensitivity:

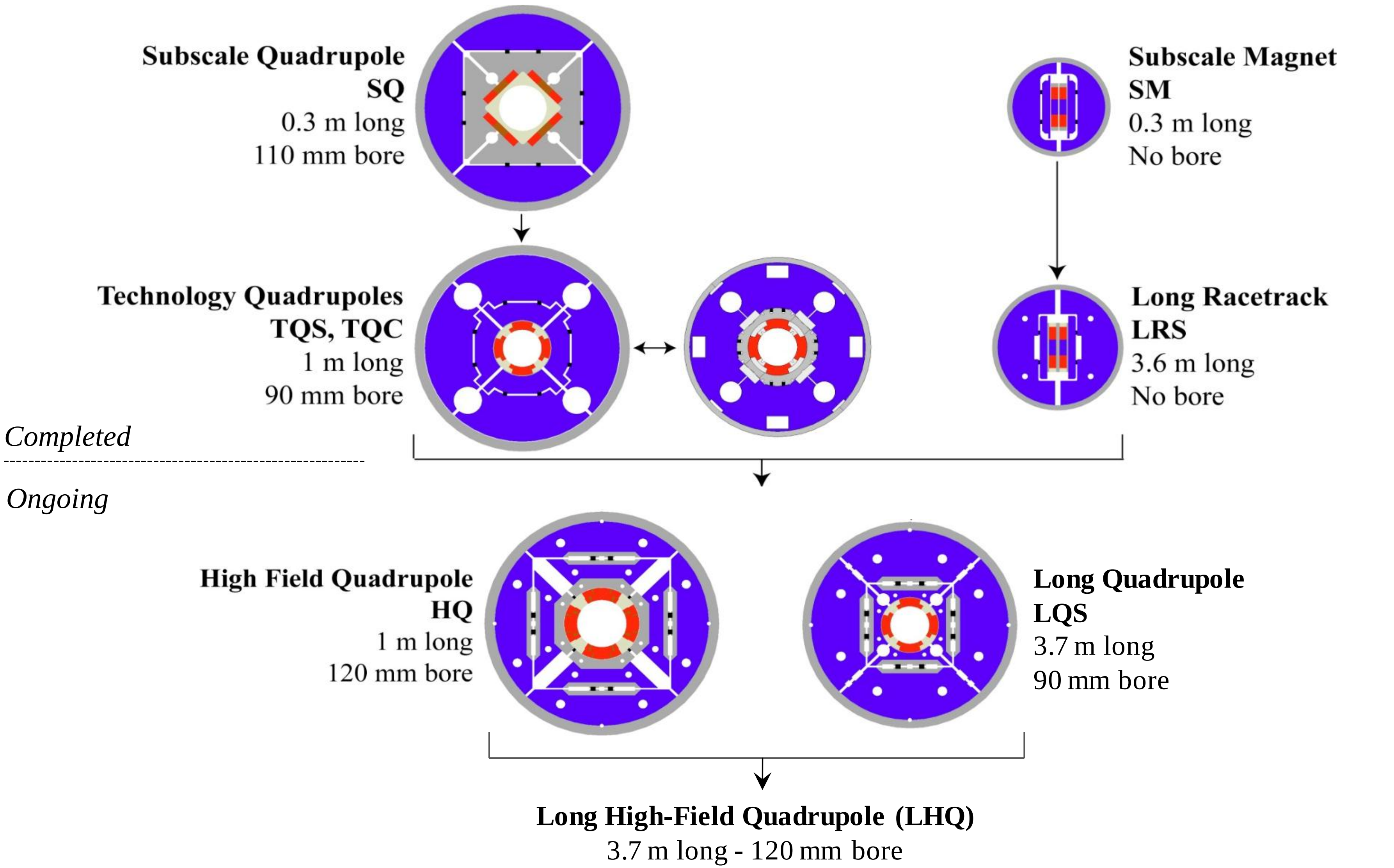
- Mechanical design and analysis to prevent degradation under high stress



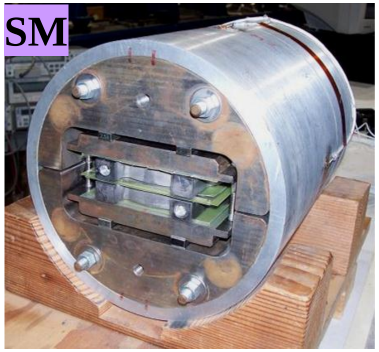


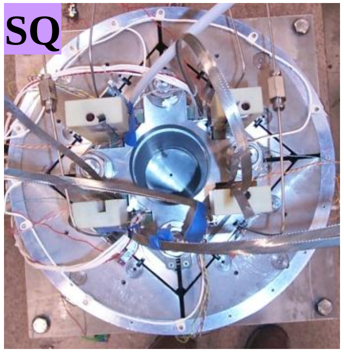
Material	NbTi	Nb_3Sn
Dipole Limit	~ 10 T	~ 17 T
Reaction	Ductile	~ 675^0C
Insulation	Polymide	S/E Glass
Coil parts	G-10	Stainless
Axial Strain	N/A	~ 0.3 %
Transverse stress	N/A	~ 200 MPa

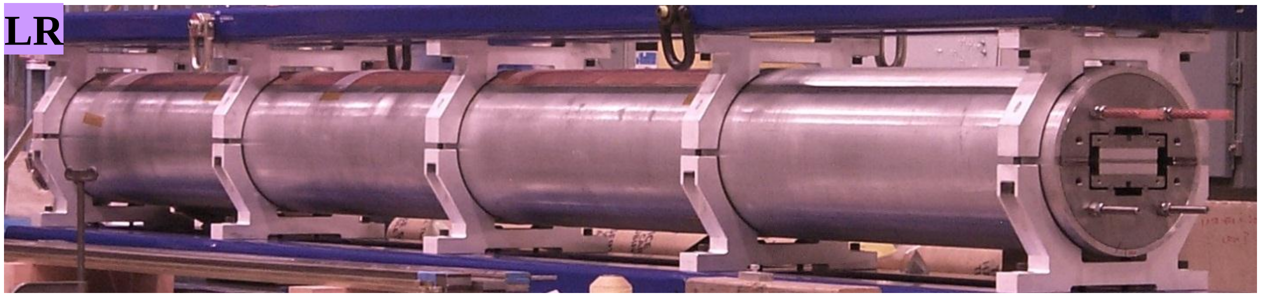
LARP Magnet Development Chart

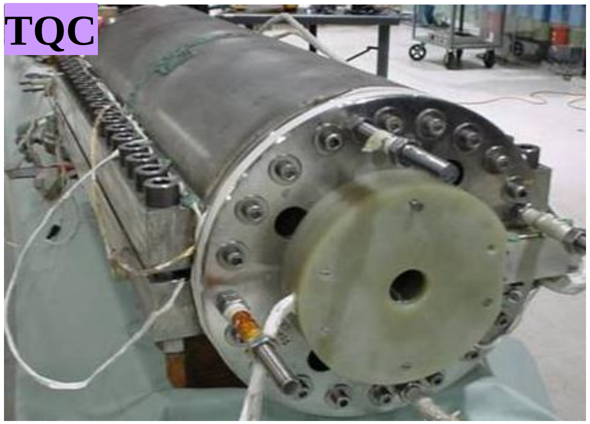


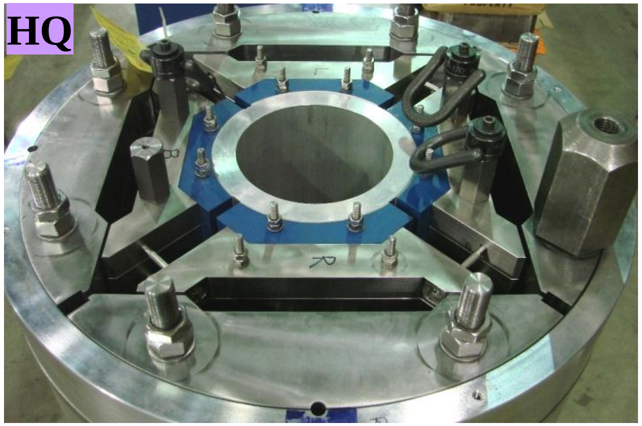
LARP Magnets











Program Achievements - Timeline (1/2)

LARP

Mar. 2006 — SQ02 reaches 97% of SSL at both 4.5K and 1.9K
- *Demonstrates MJR 54/61conductor performance for TQ*

Jun. 2007 — TQS02a surpasses 220 T/m at both 4.5K and 1.9K (*)
- *Achieved 200 T/m goal with RRP 54/61 conductor*

Jan. 2008 — LRS02 reaches 96% of SSL at 4.5K with RRP 54/61
- *Coil & shell structure scale-up from 0.3 m to 4 m*

July 2009 — TQS03a achieves 240 T/m (1.9K) with RRP 108/127 (*)
- *Increased stability with smaller filament size*

Dec. 2009 — TQS03b operates at 200 MPa (average) coil stress (*)
- *Widens Nb_3Sn design space (as required…)*

(*) Tests performed at CERN

Program Achievements - Timeline (2/2)

Dec. 2009 LQS01a reaches 200 T/m at both 4.5K and 1.9K
- *LARP meets its "defining" milestone*

Feb. 2010 TQS03d shows no degradation after 1000 cycles (*)
- *Comparable to operational lifetime in HL-LHC*

July 2010 LQS01b achieves 220 T/m with RRP 54/61
- *Same TQS02 level at 4.5K, but no degradation at 1.9K*

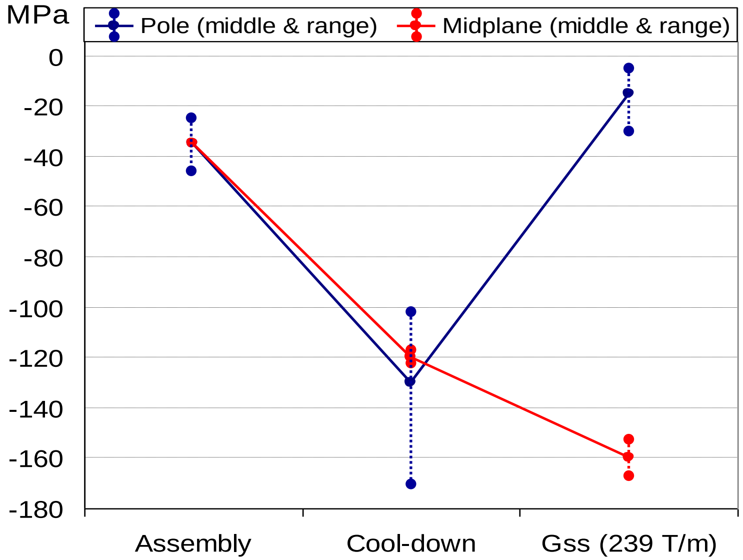
Apr. 2011 HQ01d achieves 170 T/m in 120 mm aperture at 4.5 K
- *At HL-LHC operational level with good field quality*

Oct. 2011 HQM02 achieves ~90% of SSL at both 4.6 K and 2.2 K
- *Reduced compaction results in best HQ coil to date*

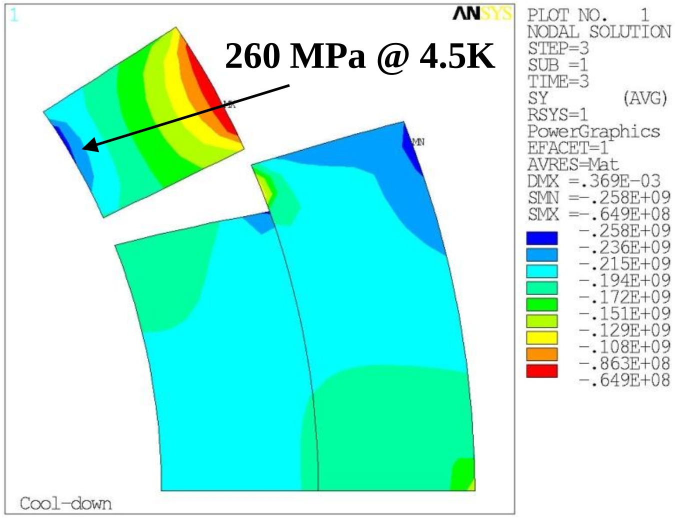
(*) Test performed at CERN

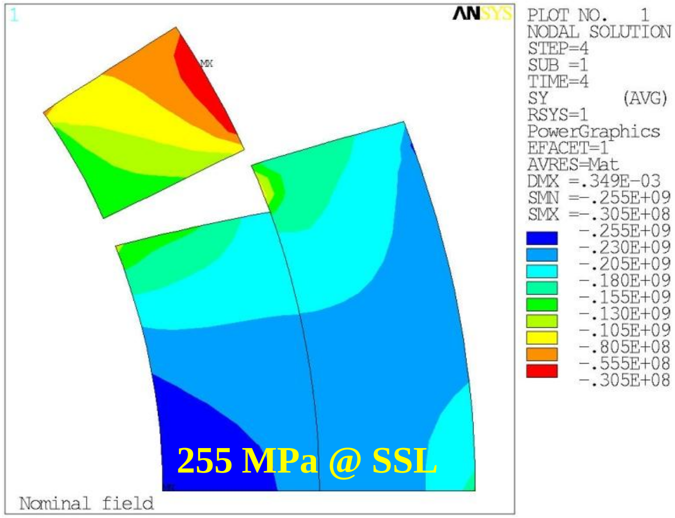
TQ Studies: Stress Limits

Coil layer 1 stress evolution - σ_θ



Calculated peak stresses in TQS03c





Systematic investigation in TQS03:

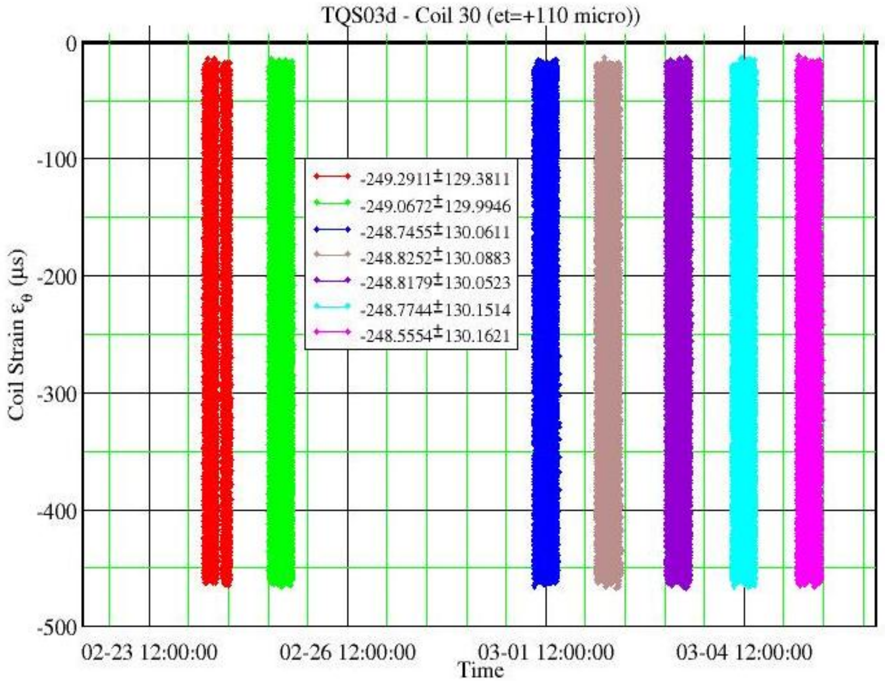
- TQS03a: 120 MPa at pole, 93% SSL
- TQS03b: 160 MPa at pole, 91% SSL
- TQS03c: 200 MPa at pole, 88% SSL

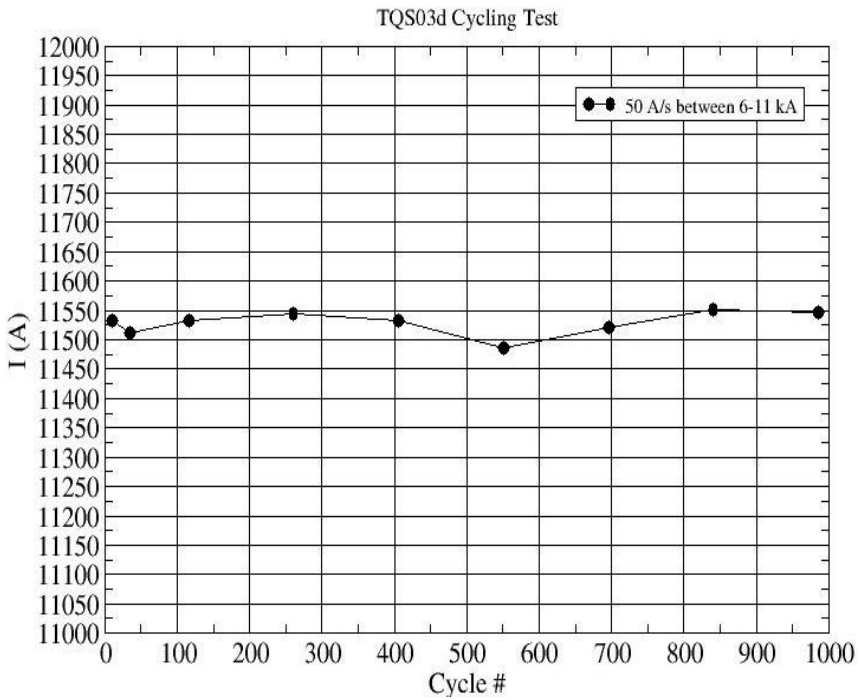
Peak stresses are considerably higher →

Considerably widens design window

TQS03d Cycling Test

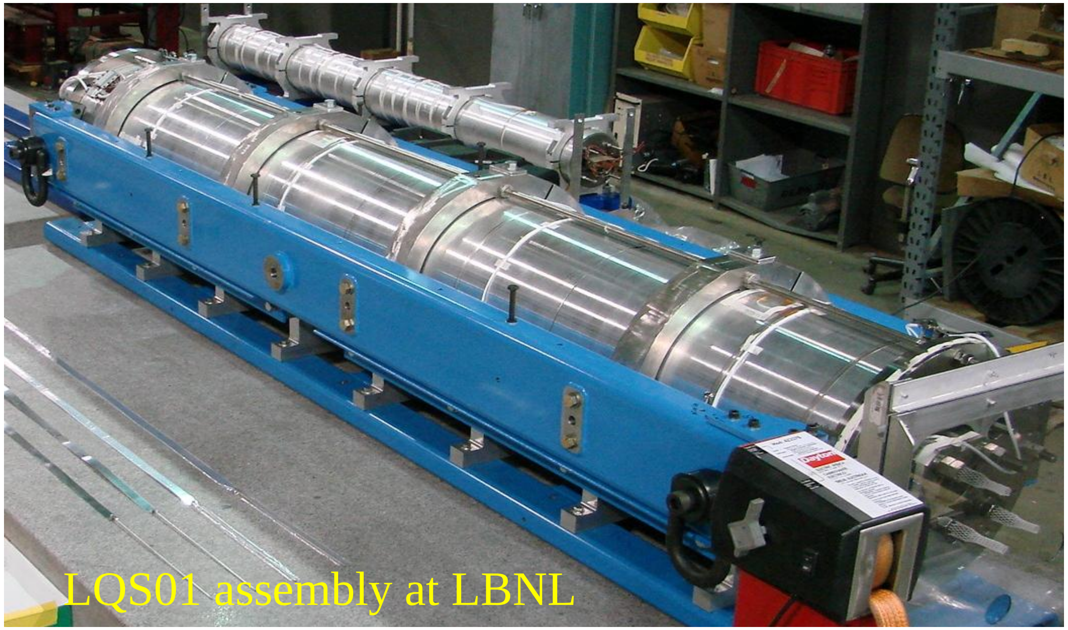
- Reduced coil stress to TQS03b levels (160 MPa average)
  - *Pre-loading operation and test performed at CERN*
- Did not recover TQS03b quench current (permanent degradation)
- Performed 1000 cycles with control quenches every ~150 cycles
- No change in mechanical parameters or quench levels





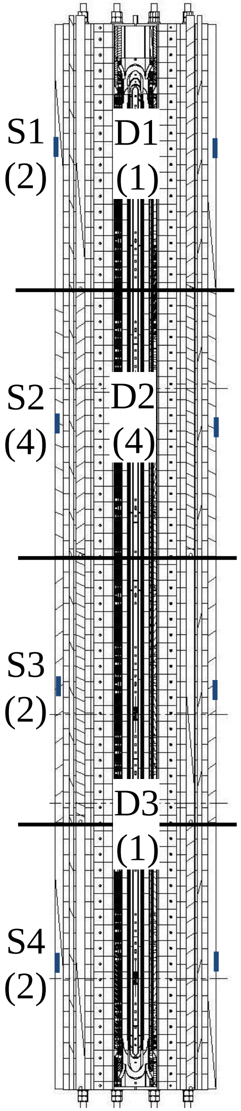
Long Quadrupole (LQ)

- 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**

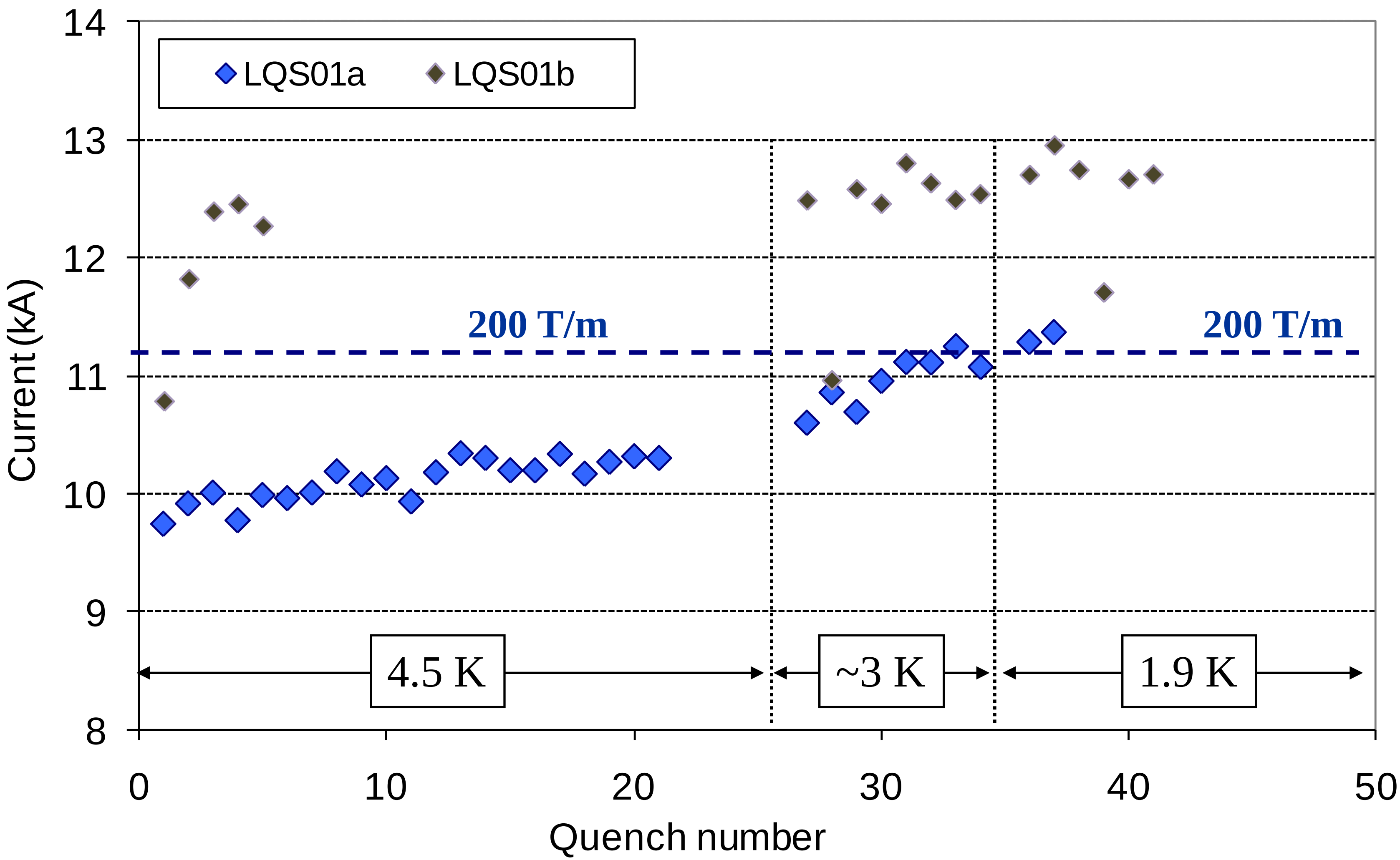


LQS01 assembly at LBNL

LQSD test at FNAL



LQS01 & LQS01b Quench Performance



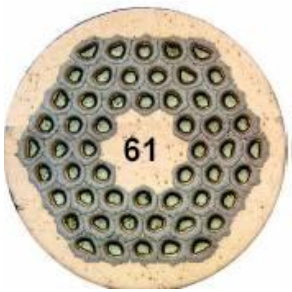
Conductor – Technical Issues

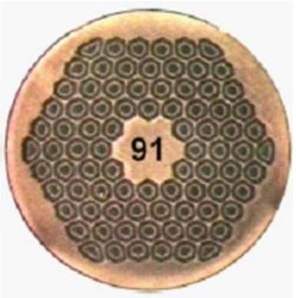
Two leading processes:

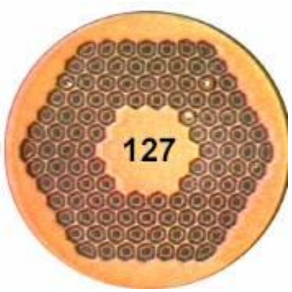
➢ *Internal tin (US-OST-RRP) and powder in tube (EU-Bruker-PIT)*

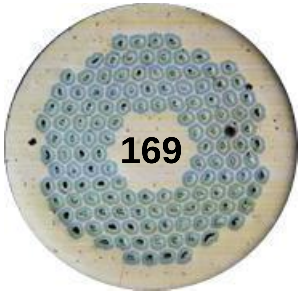
A quasi-continuous range of "stacks" using fewer or more sub-elements

➢ *Mainly exercised for RRP, for programmatic and historical reasons*









Low range: ☺ Better developed (high/controlled Jc/RRR; long pieces
☹ Larger filament size (magnetization effects, flux-jumps)

High range: ☺ Smaller magnetization effects and in principle more stable
(only if tolerance to cabling and reaction can be preserved)
☹ Less developed: control of properties, piece length

Conductor – Programmatic Issues

LARP

- Multiple applications with different requirements, priorities, time scales
  - *IR Quads, 11 T dipoles, cable testing and HE-LHC dipoles*

- Developing a single conductor suitable for all applications is difficult
- Pursuing parallel routes & incremental improvements is inefficient

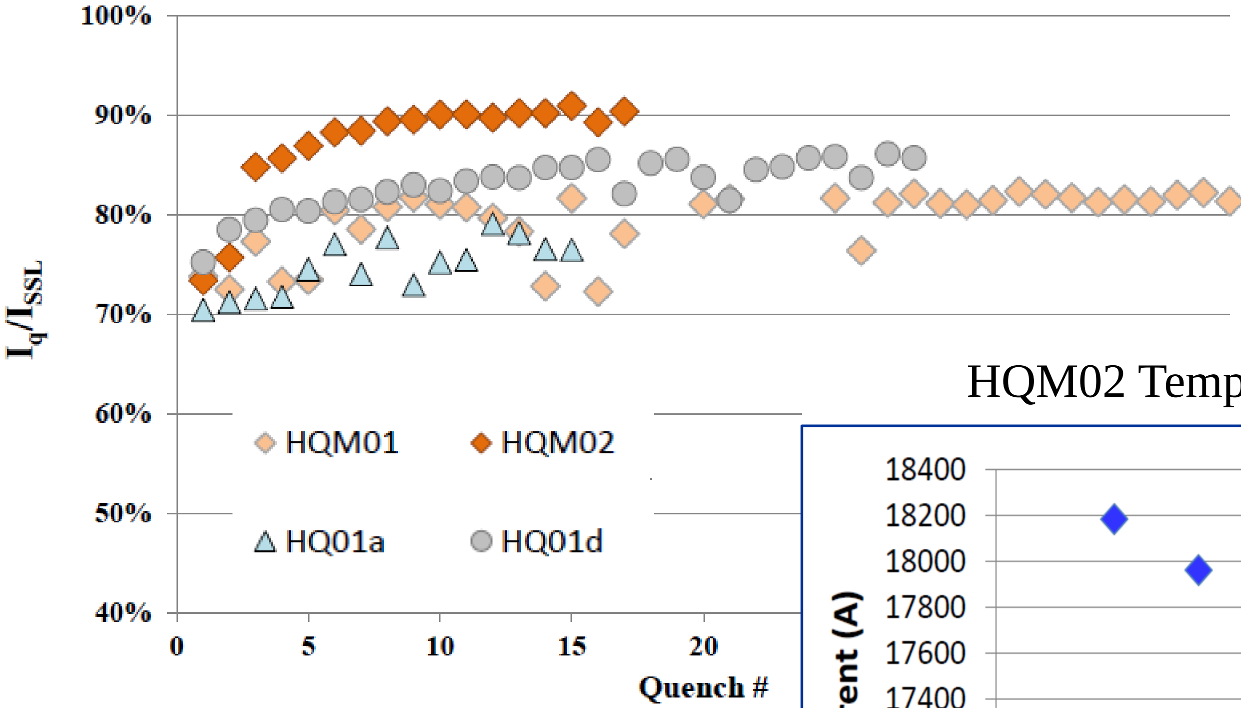
- Need to ***define a clear strategy for the HL-LHC IR Quads***. Examples:
  I. Focus on "middle range" 108/127 (moderate improvement from 54/61, close to production readiness)
  II. Select/push a more ambitious target (RRP 217 and/or PIT 192) and analyze/qualify a fall back option using RRP 54/61

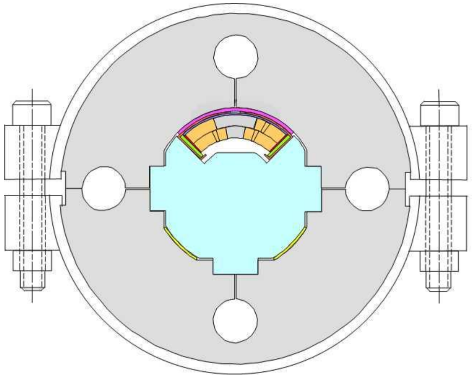
- Perform ***cost/benefits analysis for accelerator, materials, magnet***
- Move from R&D approach to ***project-type organization***
- Engage the DOE-HEP materials R&D community, which appears to be primarily focused on very long term developments (HTS)

RRP 54/61 Performance in HQ Mirror #2

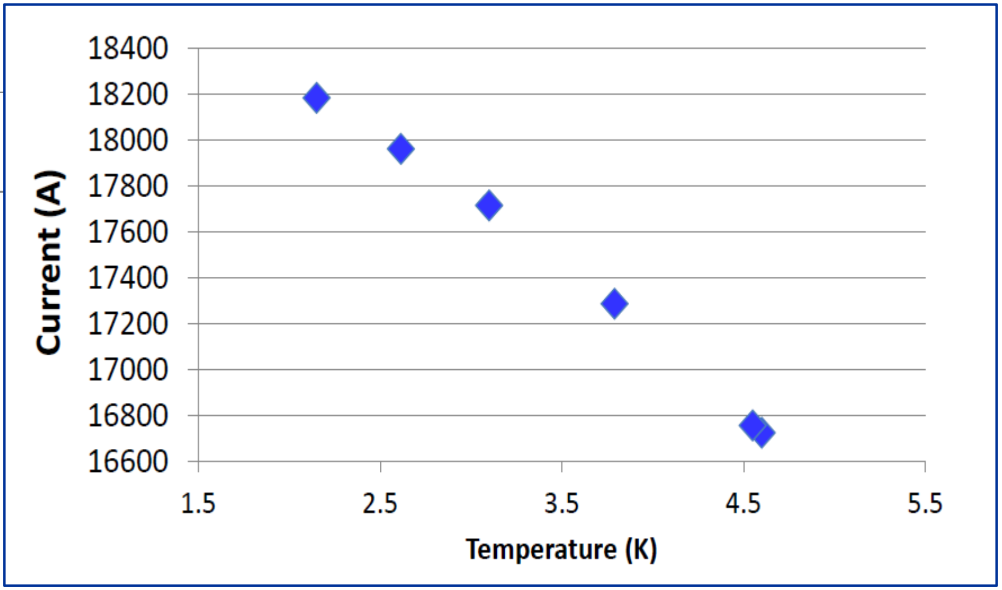
LARP

Training at 4.5K: HQM02 vs. HQM01, HQ01a, HQ01d





HQM02 Temperature Dependence



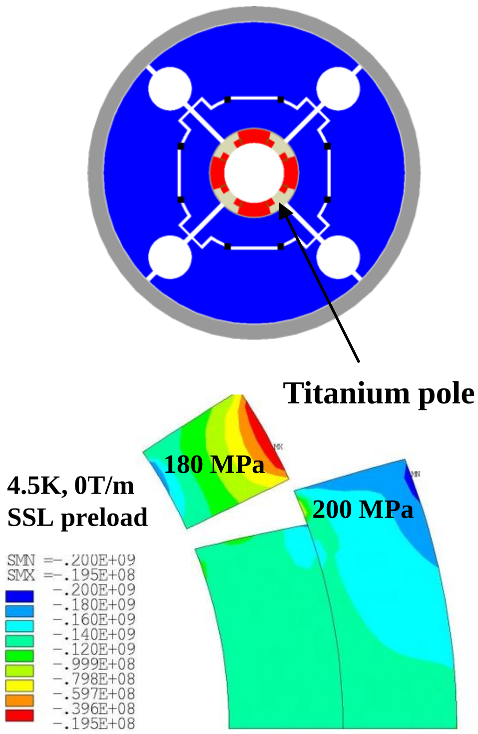
The best performing HQ coil to date was built with RRP 54/61 a production-ready conductor

Handling High Stress in Magnet Coils

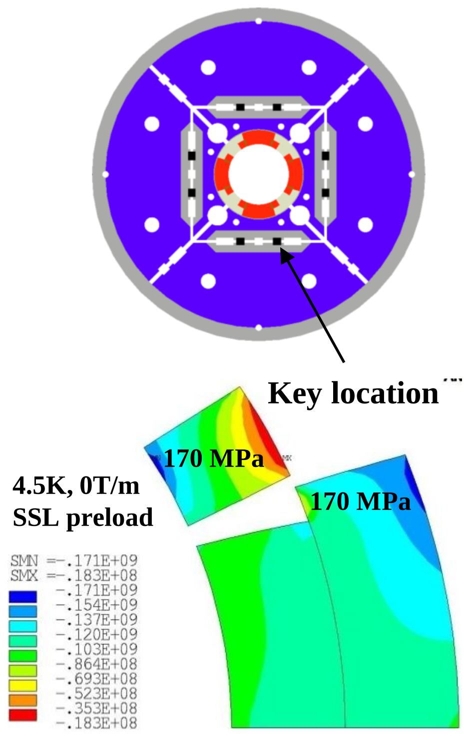
1. Understand limits

2. Optimize structure and coil for minimum stress

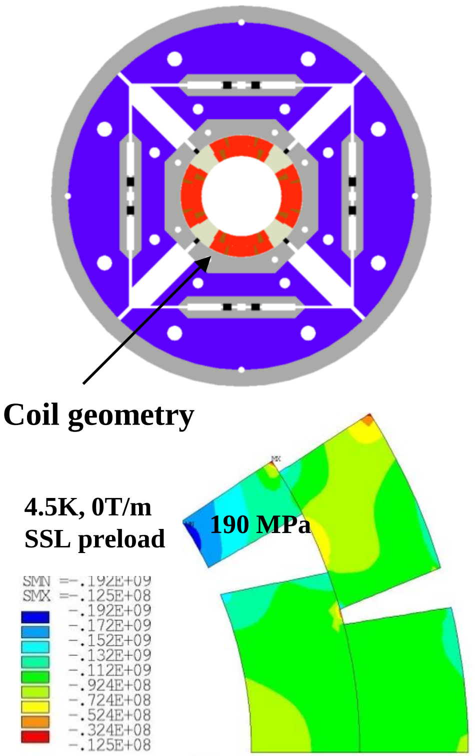
TQ (90 mm, ~12 T)



LQ (90 mm, ~12 T)



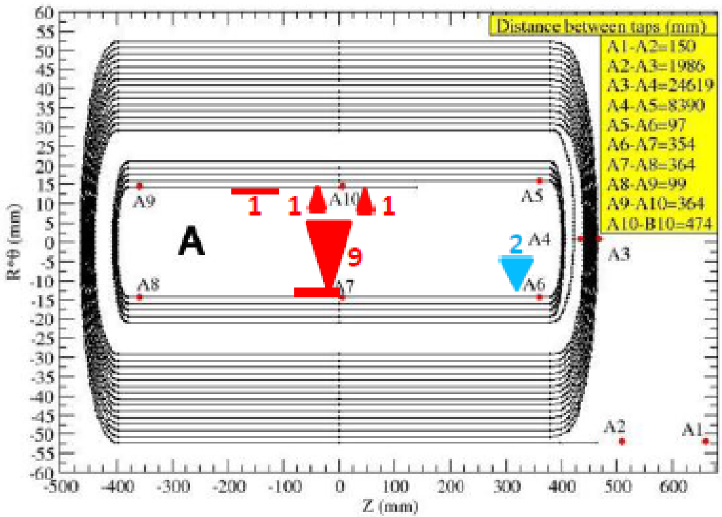
HQ (120 mm, ~15 T)



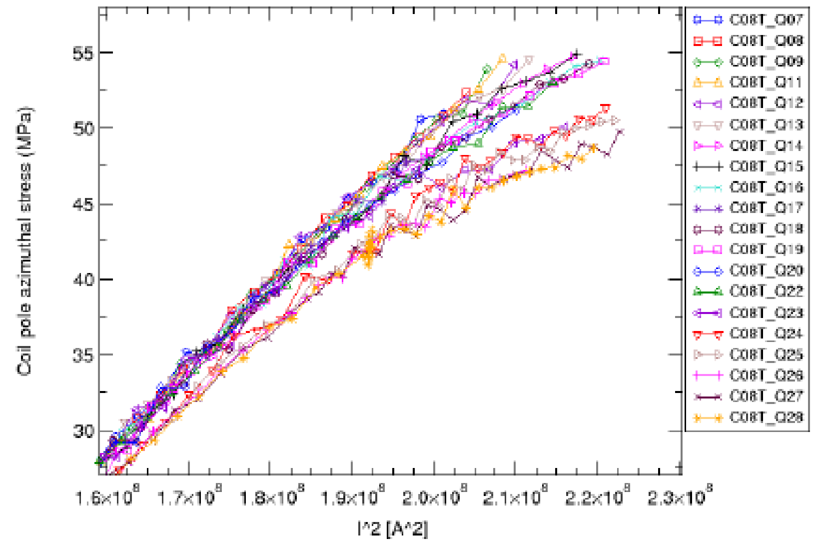
Mechanical Design Space in HQ models

LARP

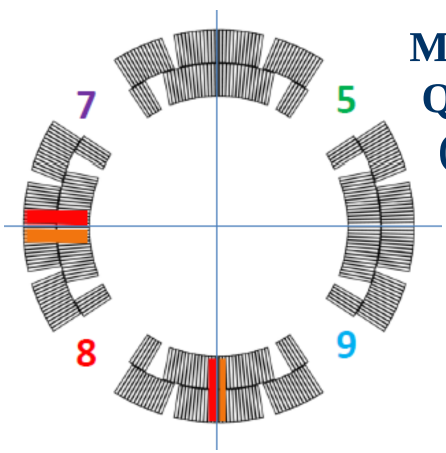
Pole quenches (HQ01d)



Pole stress during ramp to quench (HQ01d)



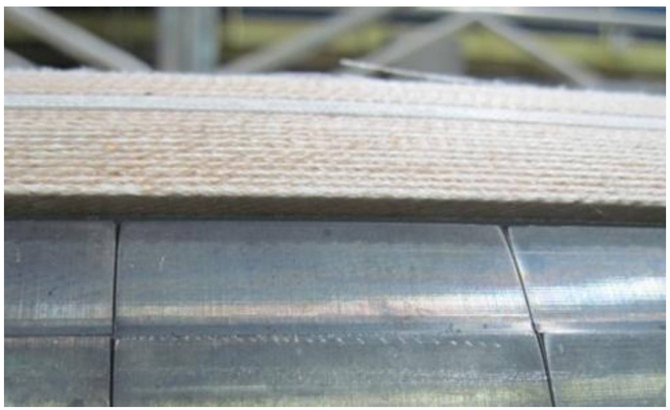
- Pole quenches and strain gauge data indicate insufficient pre-load
- Mid-plane quenches indicate excessive pre-load
- Narrow design and assembly window: ok for an R&D model designed to explore stress limits, may require optimization for production, <u>in particular if the aperture is further increased</u>

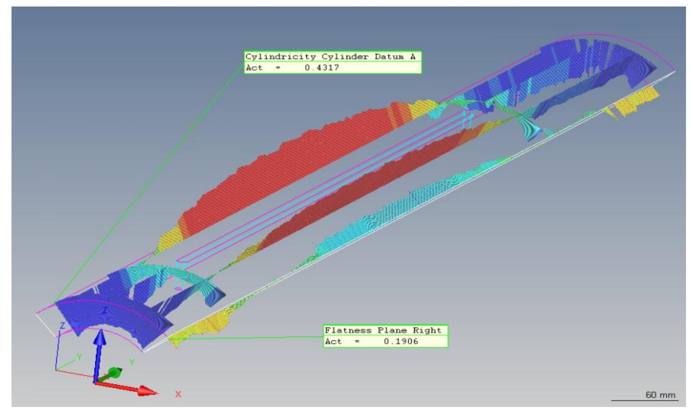


Mid-plane Quenches (HQ01d)

HQ Coil Design – Lessons Learned

- HQ design assumed less space for inter-turn insulation than TQ/LQ
- Based on measurements, but limits expansion during reaction
- As a result, coils were over sized and over compressed
- Also, insufficient pole gaps led to excessive longitudinal strain



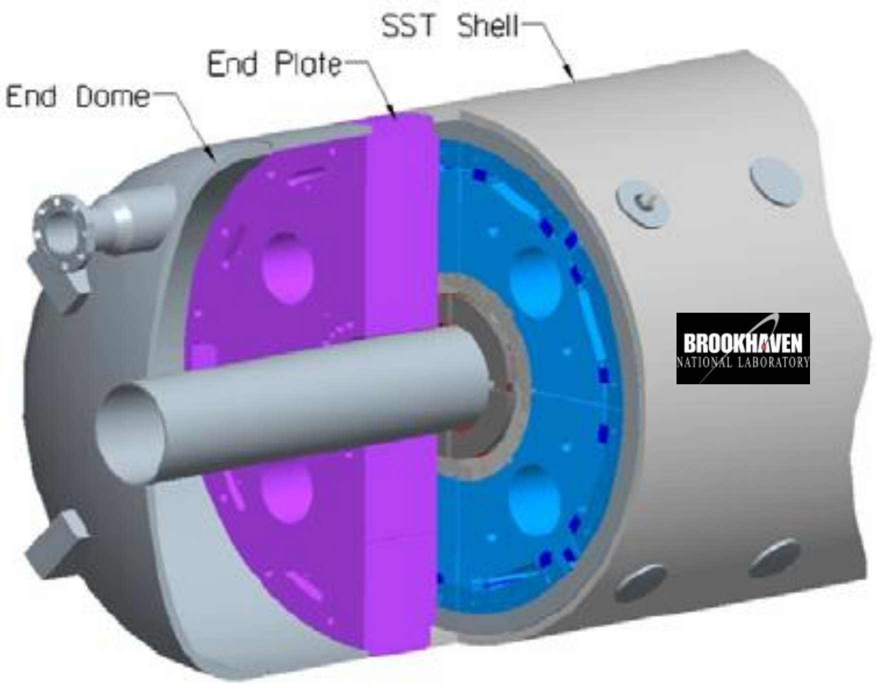


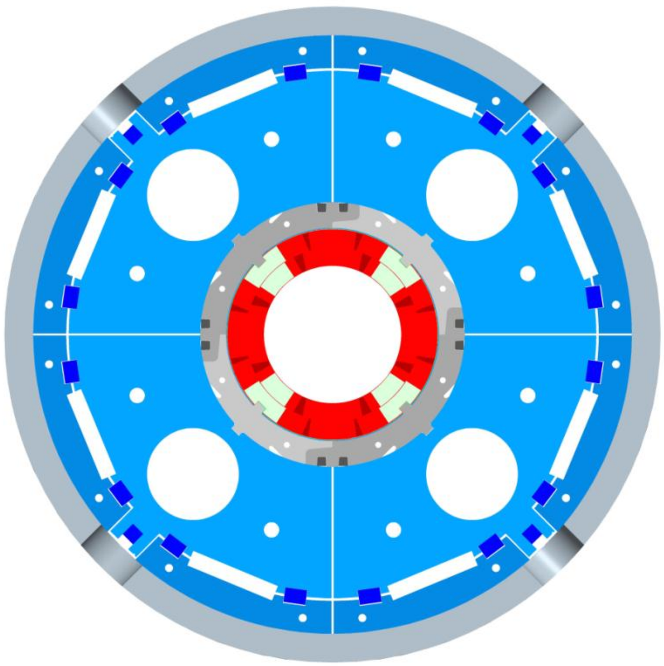
☺ Analyzed, understood and fixed in second generation coils

☹ We do not yet control this technology sufficiently well to scale to a larger aperture or full length coils without experimental verification

Accelerator Integration Issues

- 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





Accelerator Quality in LARP Models

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

Coil Aperture and Length

Two design choices will have significant implications on the project:

- ***Quadrupole aperture*** (120 mm vs. 140-150 mm)
- ***Production coil length***: full (8-10 m) or half (4-5 m)

If the final design uses 120 mm aperture *and* half length coils:

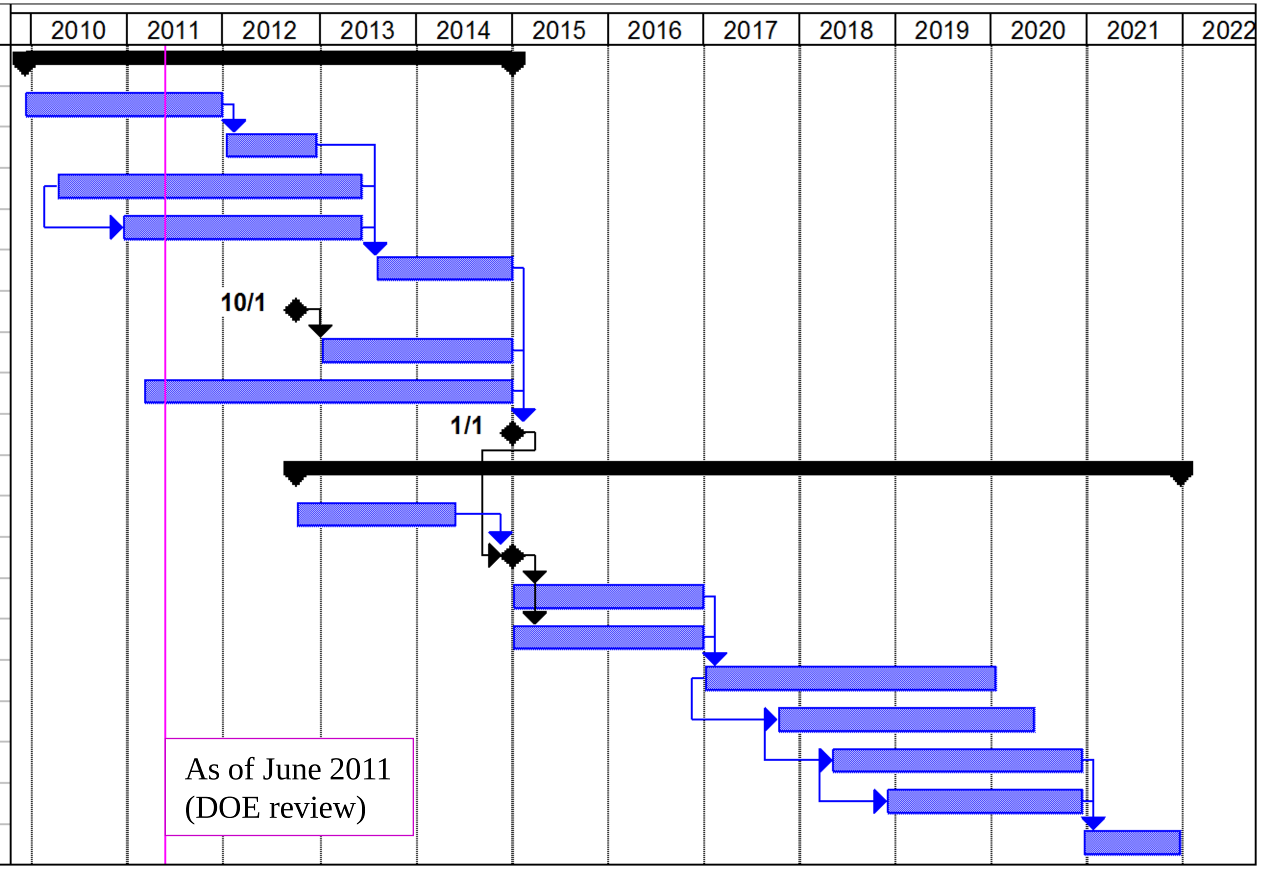
- LHQ can be considered as a pre-prototype
- The coil fabrication infrastructure is (mostly) available
- Simple transition from technology demonstration to production

Otherwise, experimental verification of the final design will be required:

- Larger aperture will require short model development
- Full length coils will require infrastructure and a prototype
- Change of aperture and full length coils will require both (in series)

R&D and Construction Schedule

ID	Task Name
1	**R&D & Design (US+CERN)**
2	LQS01/2 tests (RRP 54/61)
3	LQS03 tests (RRP 108/127)
4	HQ/HQM tests
5	LHQ design and fabrication
6	LHQ tests
7	IR Quad Aperture selection
8	IR Quad short model
9	HL-LHC Design Study
10	IR specification finalized
11	**IR Construction Project (US+CERN)**
12	Prototype infrastructure & tooling
13	Construction project start
14	IR Quad Prototype
15	Production infrastructure & tooling
16	Coil and structure fabrication
17	Magnet assembly
18	Cryostat assembly & test
19	String Tests
20	Installation



Significant contributions from CERN will be required to implement this plan, in particular if the larger aperture and/or the full length coil option is selected

Summary

- A large knowledge base is available after 7 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*
- The remaining challenges have an increasingly programmatic flavor: design integration, production organization and processes
- HL-LHC IR Quads are a key step for 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