LARP

BNL - FNAL - LBNL - SLAC

Nb_3Sn Quadrupoles for the LHC Luminosity Upgrade

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for the LARP collaboration

CERN, January 12, 2010

LARP Program Goals

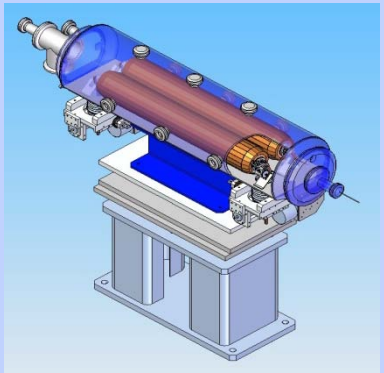
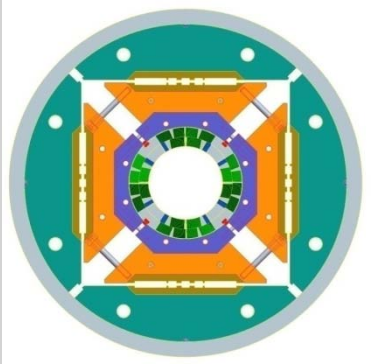
Coordinate US LHC Accelerator Research:

- 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
- Funding level: $12-13M/year (FY06-FY10)

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

Overview of LARP Activities

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

Magnet R&D Collaboration Network

LARP (MagSys)
- Participants: BNL, FNAL, LBNL + CERN
- Goal: fully qualified Nb_3Sn quadrupoles for SLHC

CARE (NED)
- Participants: CCLRC, CEA, CERN, CIEMAT, INFN, UT, WTU
- Goal: basic R&D on conductor, insulation, design, quench protection

EUCARD (HFM)
- Participants: CERN, CEA, CNRS, COLUMBUS, DESY, EHTS, FZK, INFN, PWR, SOTON, STFC, TUT, UNIGE
- Goal: high field Nb_3Sn dipole model & very high field (HTS) insert

Inter-Laboratory collaborations on specific topics:

- CERN, RAL, CEA, LBNL on Short Model Coil development
- KEK, NIMS, FNAL on Nb_3Al model coils
- LBNL, KEK on Nb_3Sn coil, structure and assembly methods
- KEK & CERN on Nb_3Al technology for the LHC upgrades
- CERN & CEA, UT, LBNL/LARP on magnet testing
- LBNL & FNAL, BNL, CERN, UT, TAMU on cable development

Luminosity Upgrade (SLHC)

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 by up to 30%*

Implementation:

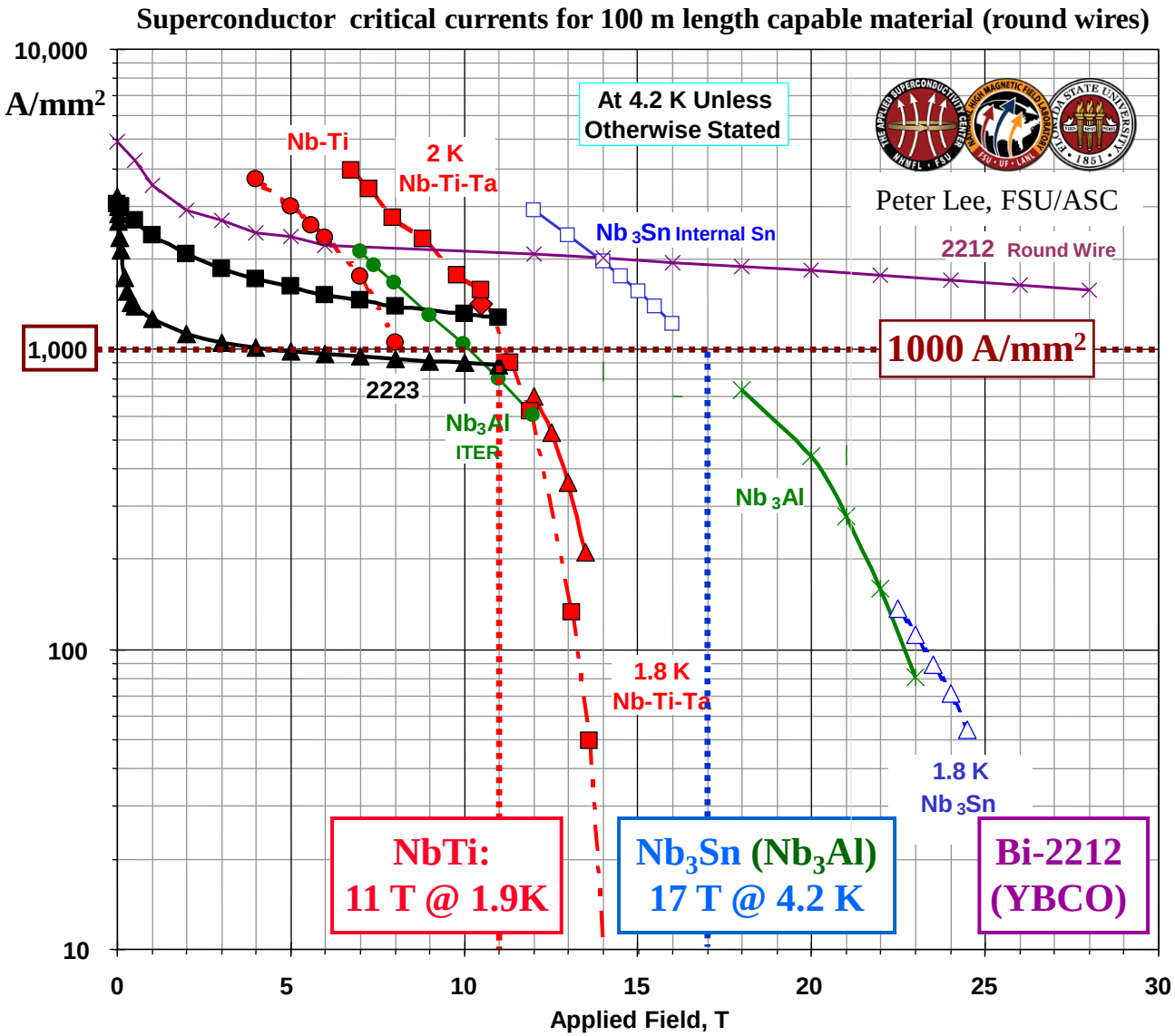
- *Phase 1 (2-3 times increase from nominal* $L=10^{34}\ cm^{-2}sec^{-1}$*)*
- *Phase 2 (up to a factor of 10 increase from nominal)*

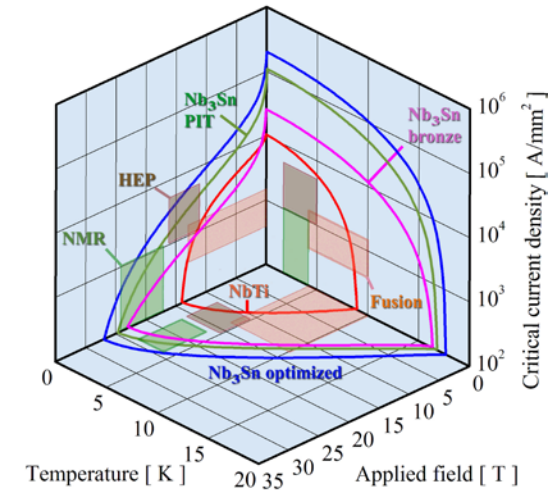
Required accelerator upgrades include new IR magnets:

- *Directly increase luminosity through stronger focusing*
  $\Rightarrow$ *decrease* β^*
- *Provide design options for overall system optimization/integration*
  $\Rightarrow$ *collimation, optics, vacuum, cryogenics*
- *Be compatible with high luminosity operation*
  $\Rightarrow$ *Radiation lifetime, thermal margins*

Major detector upgrades are also required to take full advantage of SLHC

Technology Options

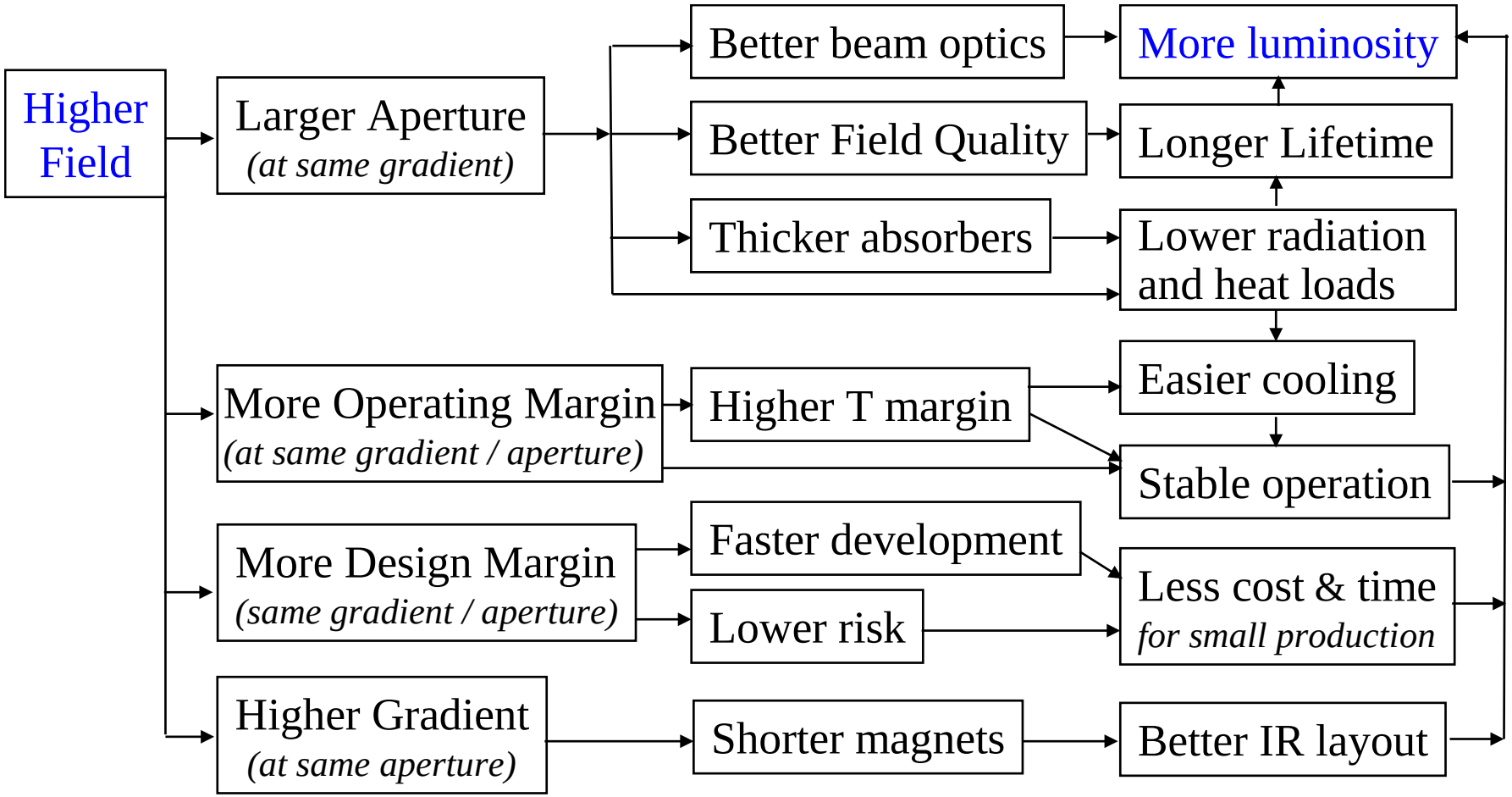




- Nb-Ti: Example of Best Industrial Scale Heat Treated Composites ~1990 (compilation)
- Nb-Ti(Fe): 1.9 K, Full-scale multifilamentary billet for FNAL/LHC (OS-STG) ASC'98
- Nb-44wt.%Ti-15wt.%Ta: at 1.8 K, monofil. high field optimized, unpubl. Lee et al. (UW-ASC) '96
- Nb-37Ti-22Ta: at 2.05 K, 210 fil. strand, 400 h total HT, Chernyi et al. (Kharkov), ASC2000
- Nb_3Sn: Bronze route VAC 62000 filament, non-Cu 0.1μW·m 1.8 K J_c, VAC/NHMFL data courtesy M. Thoener.
- Nb_3Sn: Non-Cu J_c Internal Sn OI-ST RRP #6555-A, 0.8mm, LTSW 2002
- Nb_3Al: Nb stabilized 2-stage JR process (Hitachi,TML-NRIM,IMR-TU), Fukuda et al. ICMC/ICEC '96
- Nb_3Al: JAERI strand for ITER TF coil
- Bi-2212: non-Ag J_c, 427 fil. round wire, Ag/SC=3 (Hasegawa ASC2000+MT17-2001)
- Bi 2223: Rolled 85 Fil. Tape (AmSC) B||, UW'6/96
- Bi 2223: Rolled 85 Fil. Tape (AmSC) B|_, UW'6/96

Quadrupole Upgrade Roadmap

High field technology provides design options to maximize luminosity



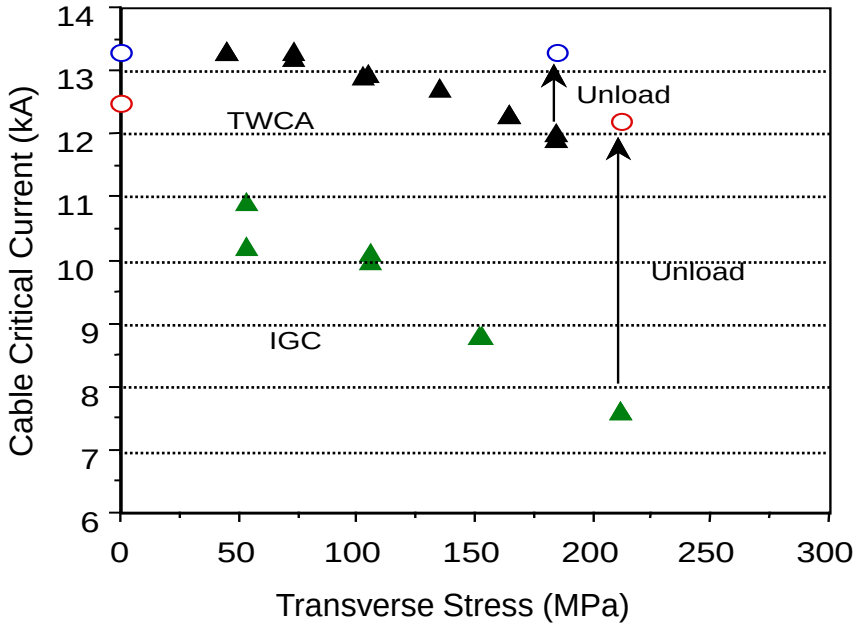
Nb_3Sn Challenges

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

Magnet R&D 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 Quadrupole (SQ)*
   - *Long Racetrack (LR)*

   Completed

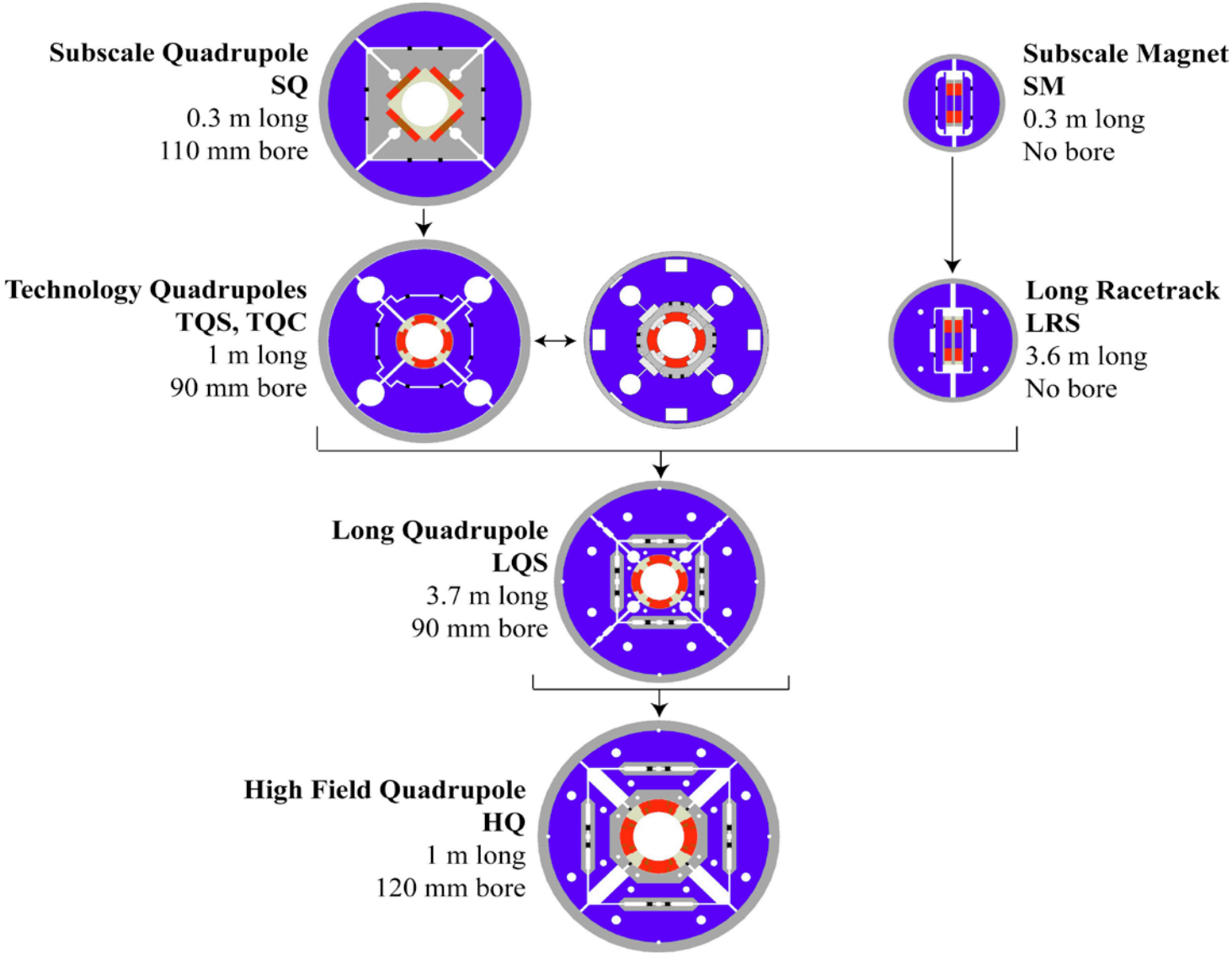
3. Cos 2θ Quadrupoles with 90 mm aperture:
   - *Technology Quadrupole (TQ)*
   - *Long Quadrupole (LQ)*

   ~75%

4. Cos 2θ Quadrupoles with 120 mm aperture:
   - *High-Field Quadrupole (HQ)*

   ~25%

Magnet Development Chart



Sub-scale Quadrupole (SQ)

Design features:

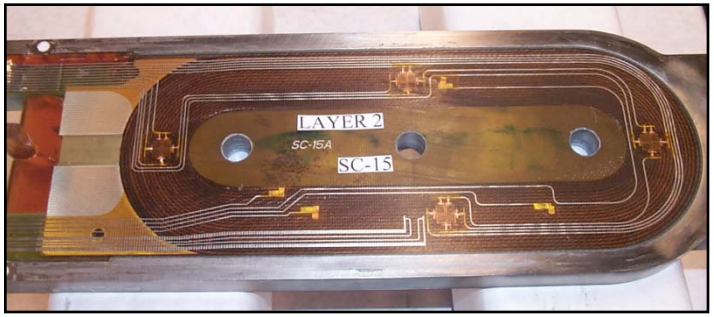
- Based on LBNL "SM" design
- Four racetrack coils, square bore
- Aperture 130 mm, Length 30 cm

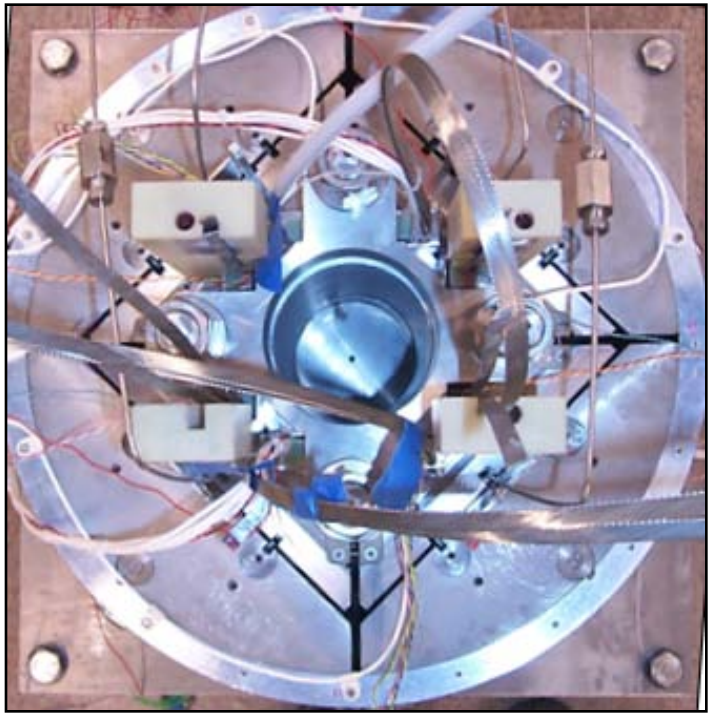
R&D Goals:

- *Conductor performance verification*
- *First shell-based Quadrupole structure*
- *FEA models verification*
- *Quench propagation analysis*

Results (2004-2006):

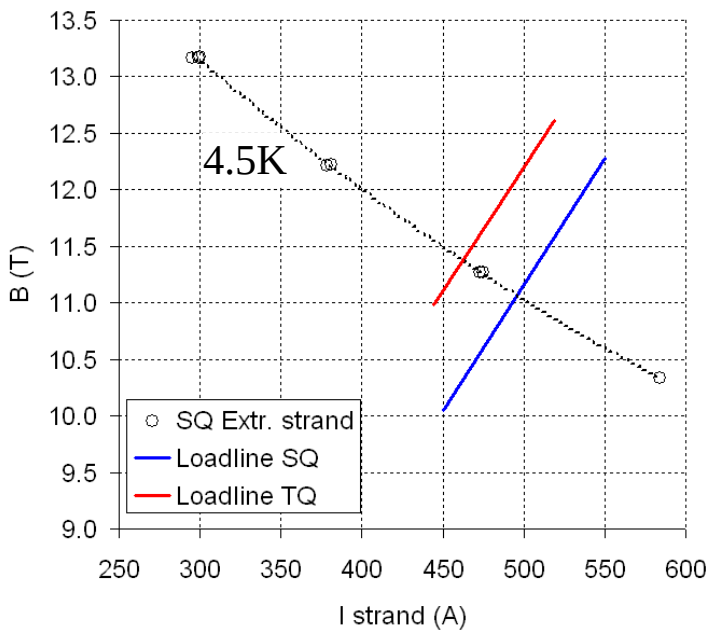
- Two models tested at LBNL & FNAL
- SQ02: **97% of SSL at 4.5K & 1.9K**

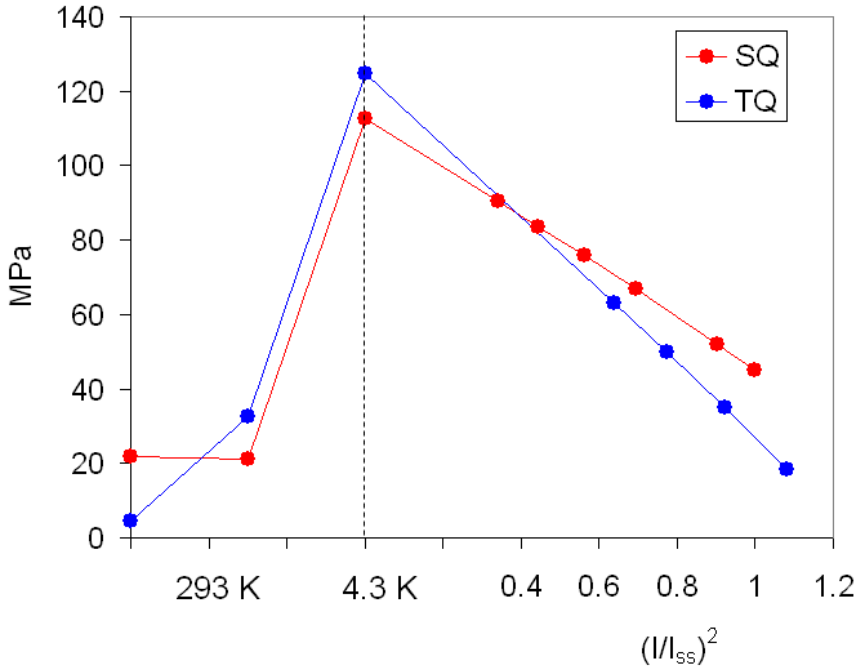




SQ vs. TQ/LQ Parameters

SQ and TQ (LQ) closely match in terms of <u>operating point, forces and stresses</u>

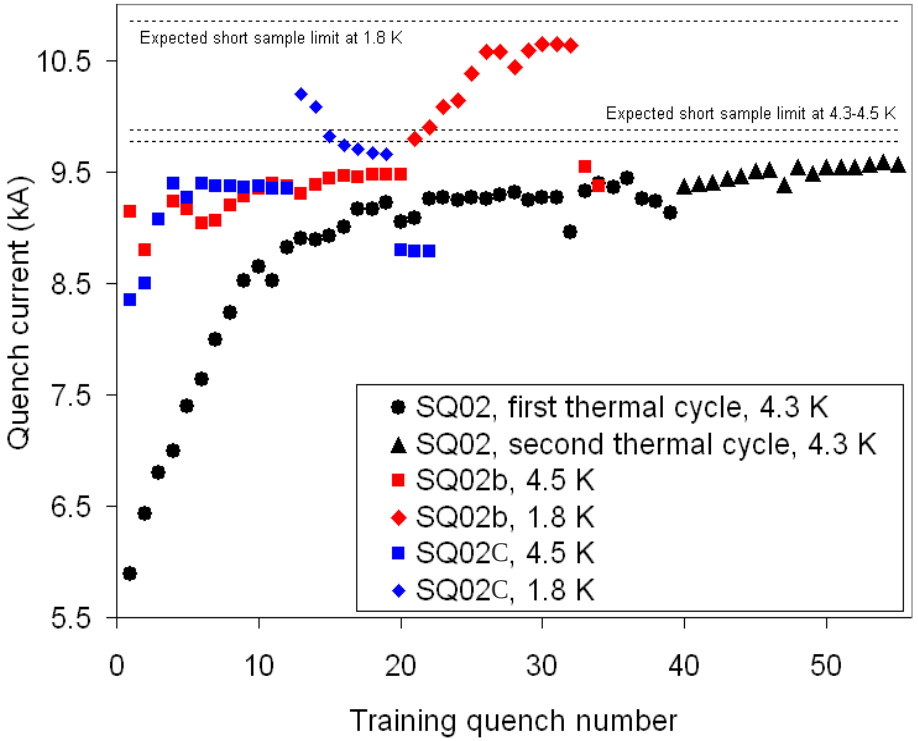


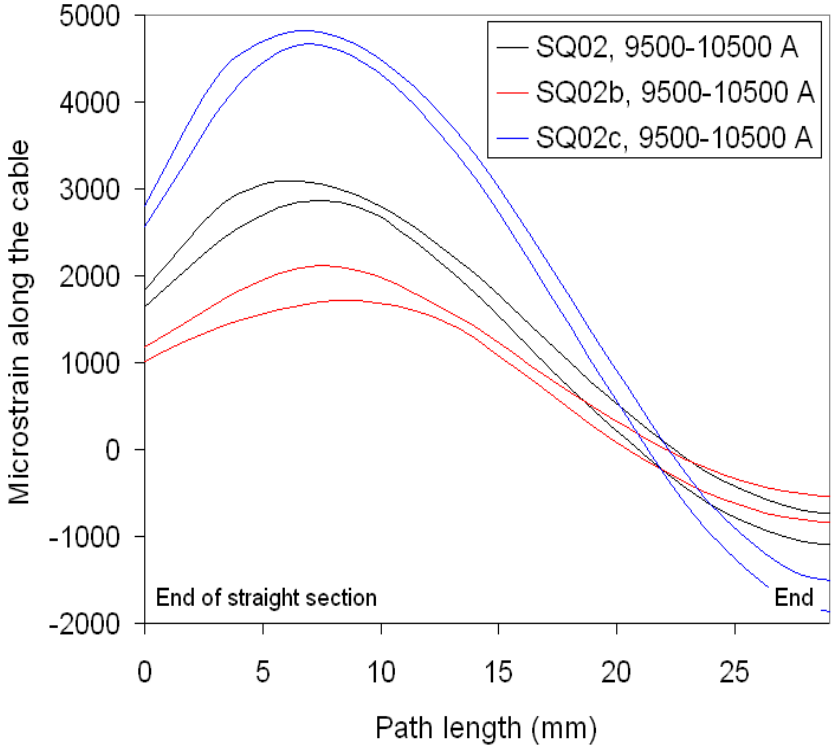


	D_{strand} (mm)	I_{strand} (A)	B_{peak} (T)	$\sigma_{\perp}$ (MPa)	F_z (kN)	S_z (MPa)
SQ	0.7	490	11.1	100-150	340	87
TQ (LQ)	0.7	460	11.3	100-150	350	81

SQ Findings

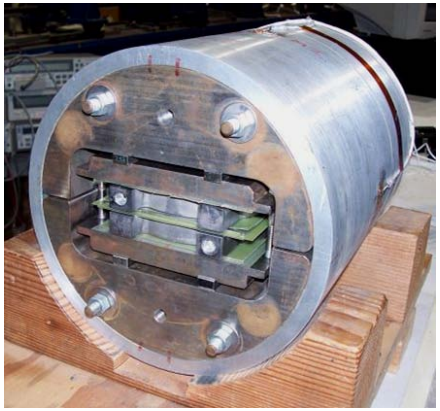
- Achieved 97% of short sample at both 4.5 K and 1.9K (SQ02b test)
  - *Validated conductor used in the TQ01 Models (MJR 54/61)*
  - *Minimal/no degradation due to transverse or axial stress*
- Showed critical role of axial coil support at high field (SQ02c test)





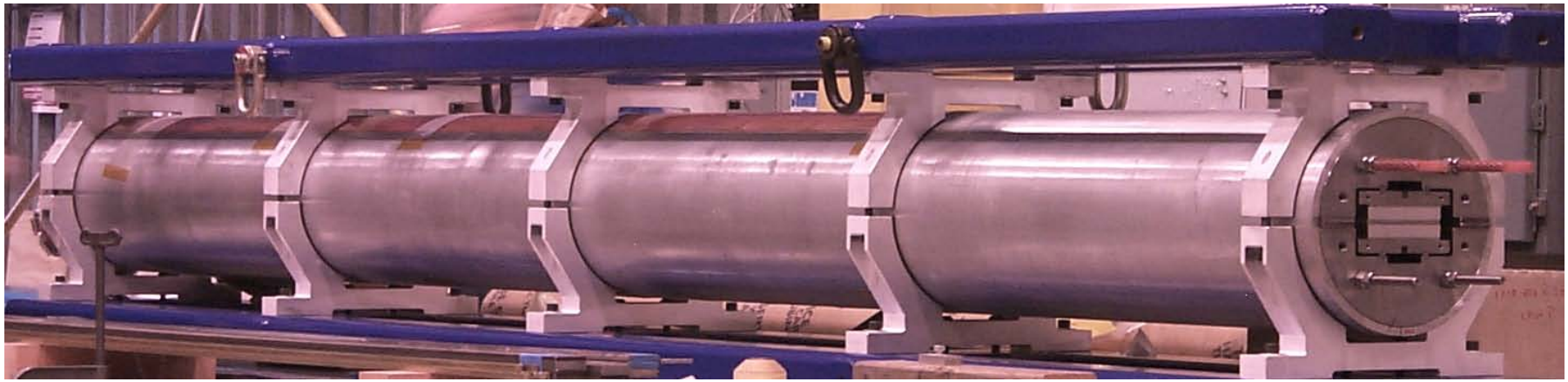
Long Racetrack (LR)

- 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



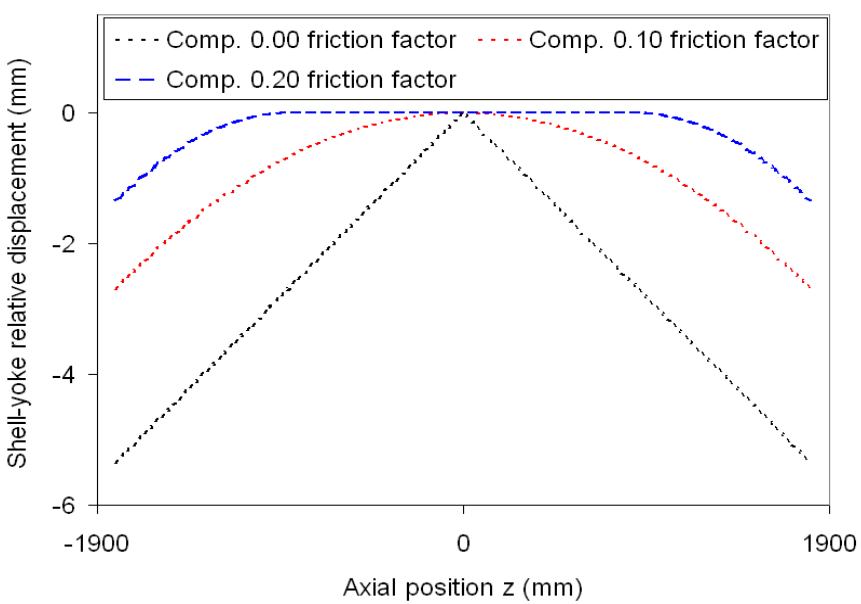
- *BNL: coil fabrication, magnet assembly and test*
- *LBNL: magnet design, structure fabrication/assembly*

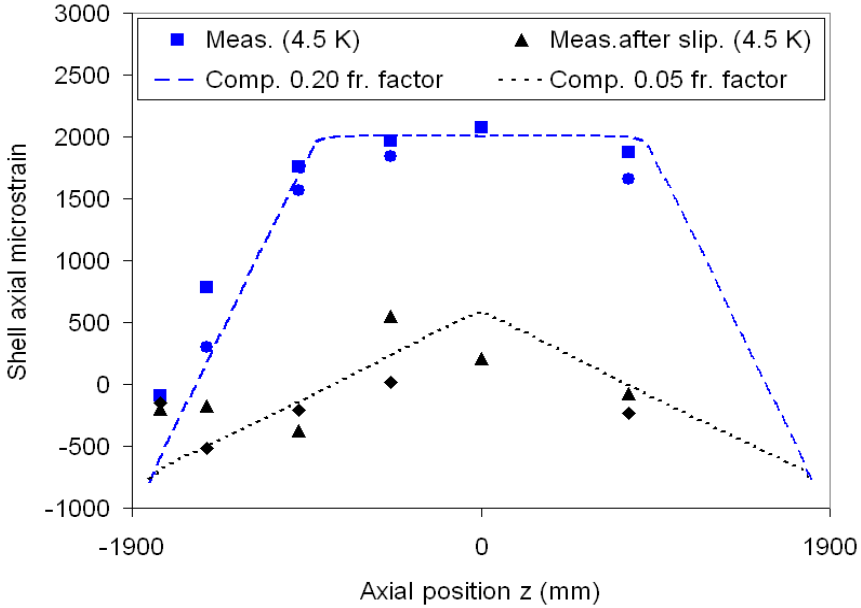
- Fast training and 96% of short sample limit
- No fundamental issues with coil/structure scale-up



Longitudinal Strain in LRS01 Shell

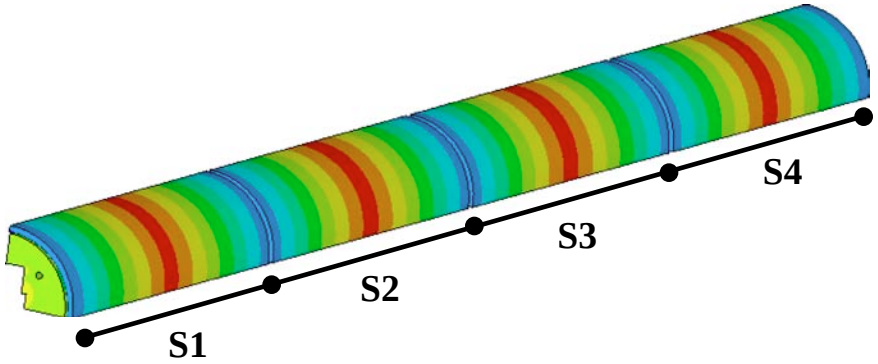
- FEA models predicted strong dependence of axial strain on shell-yoke friction
- Six strain gauge stations were included to measure axial strain dependence
- Measurements during initial cool-down and excitation show μ=0.2
- Slippage occurred during the test, after which measurements show μ=0.05

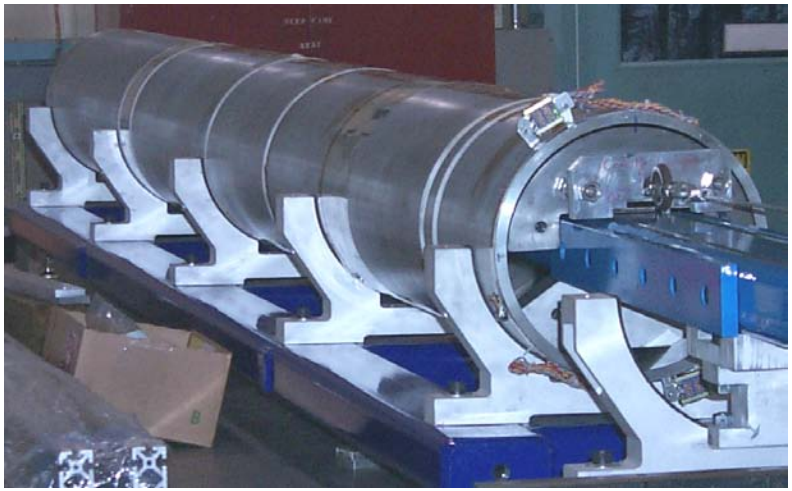




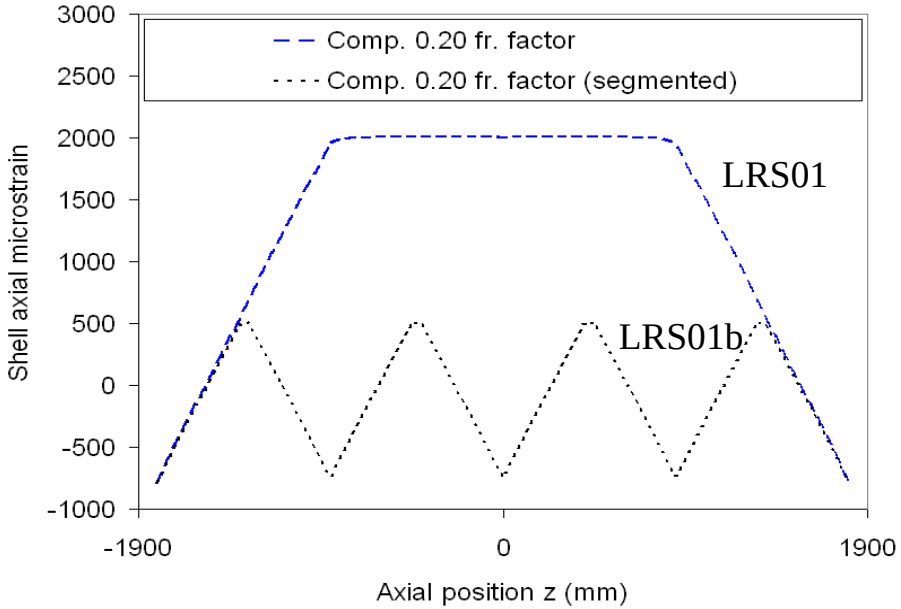
Segmented Shell in LRS02

- Shell was divided in 4 segments
- No axial strain accumulation
- Required for very long shells
- Factor of 2 improved homogeneity
- Increased field and no slippage
- 96% SSL with minimal training



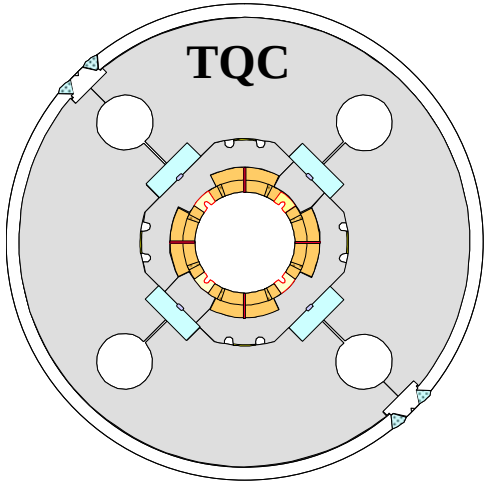


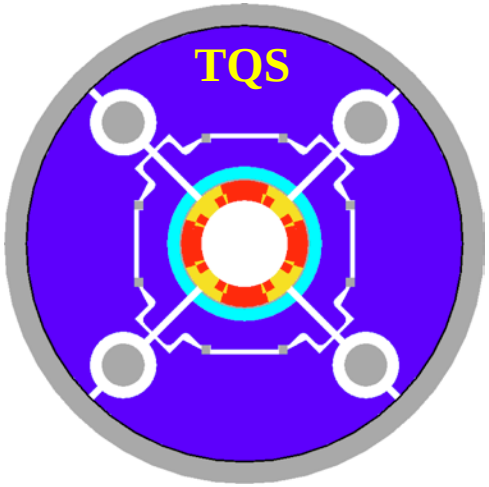
Structure re-assembly with segmented shell



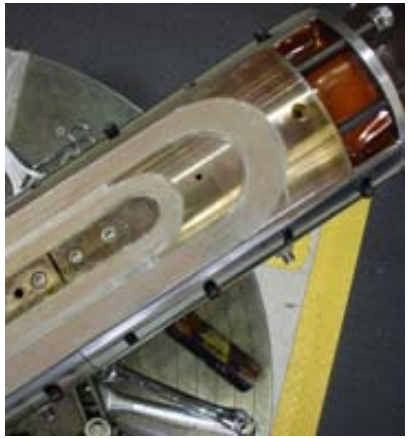
Technology Quadrupole (TQ)

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





Winding & curing (FNAL - all coils)



Reaction & potting (LBNL - all coils)

Strand, Cable and Coil Design

Conductor design:

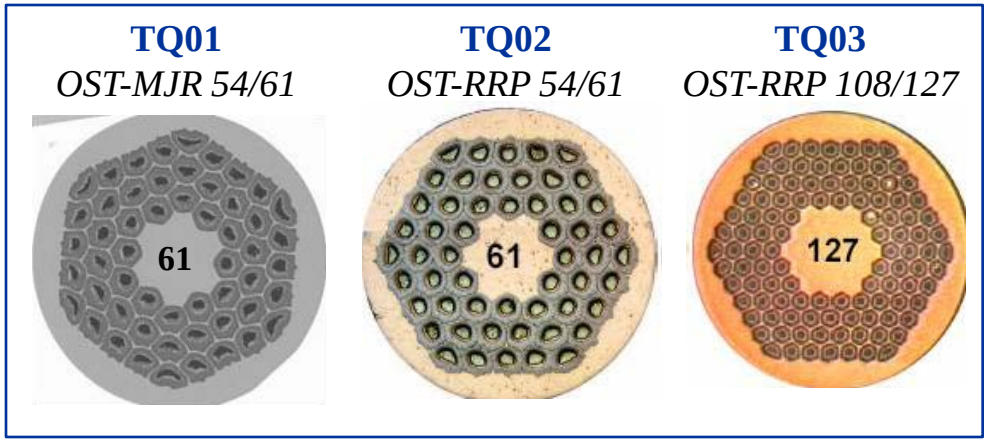
- TQ01: OST MJR 54/61
- TQ02: OST RRP 54/61
- TQ03: OST RRP 108/127

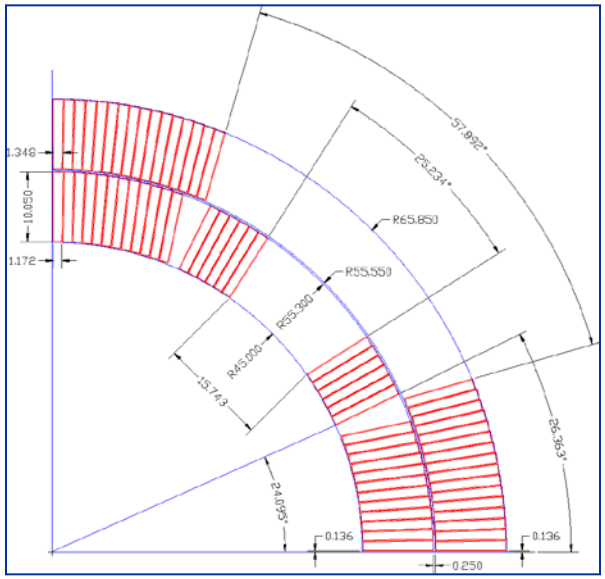
Cable:

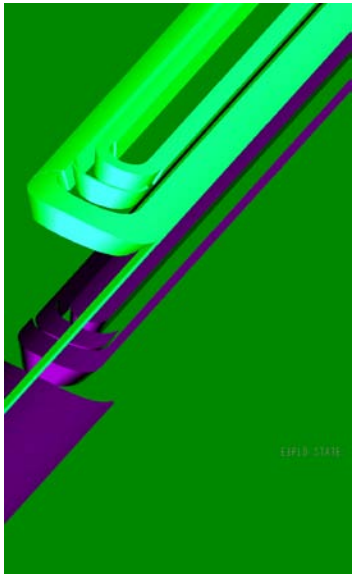
- 27 strands, 0.7 mm diameter
- Width: 10.05 mm
- Mid-thickness: 1.26 mm
- Keystone angle: 1.0 deg
- Insulation: S-2 glass sleeve

Coil:

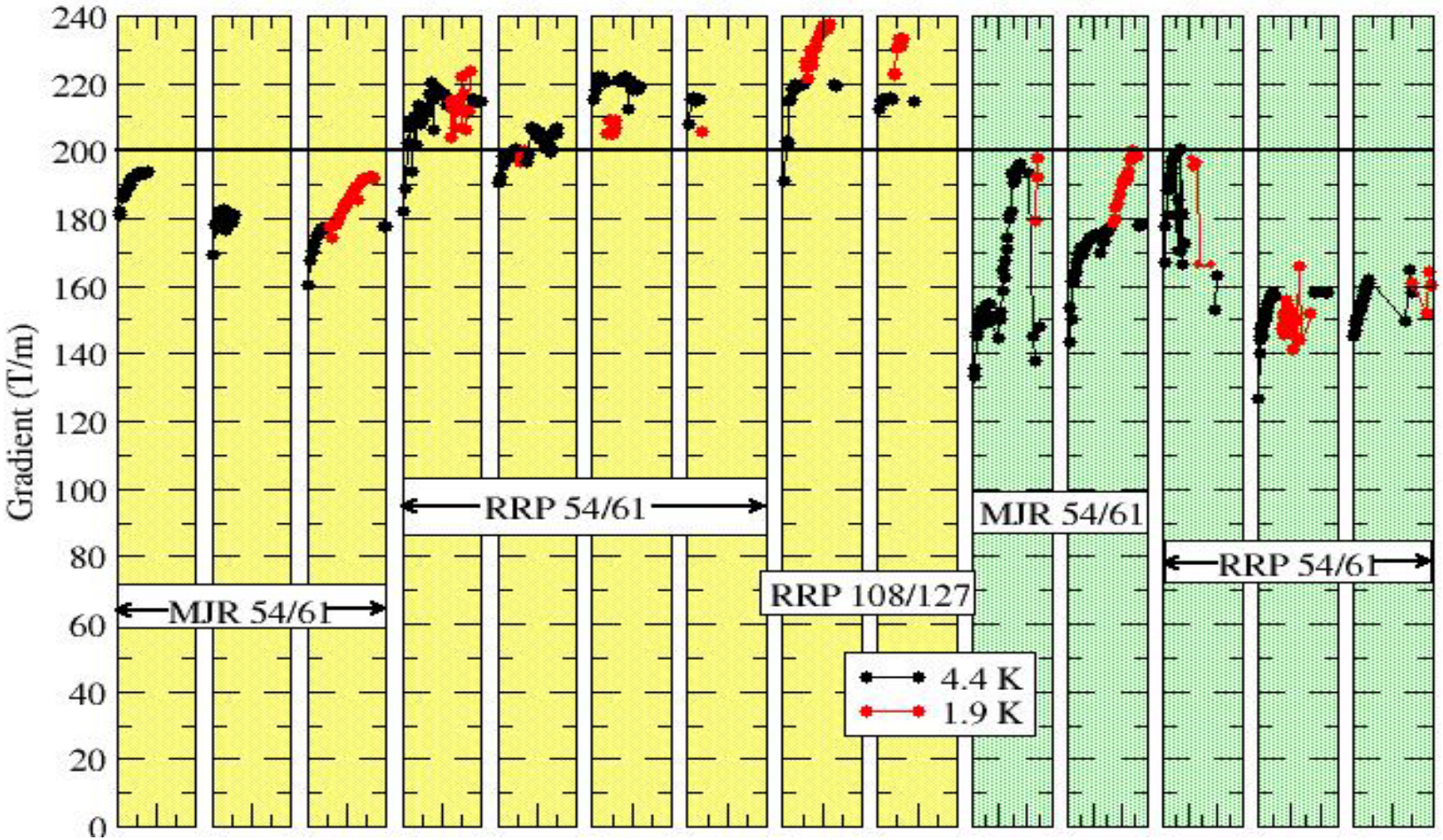
- double-layer, shell-type
- one wedge/octant (inner layer)





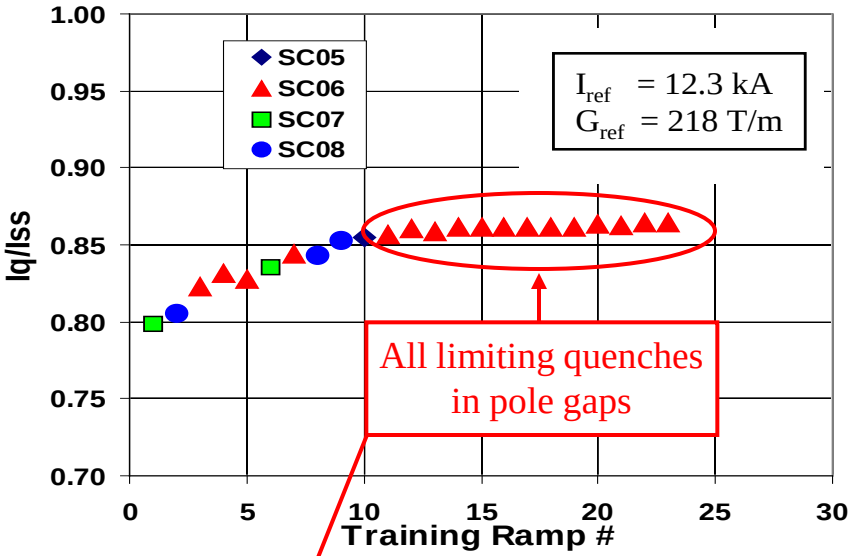


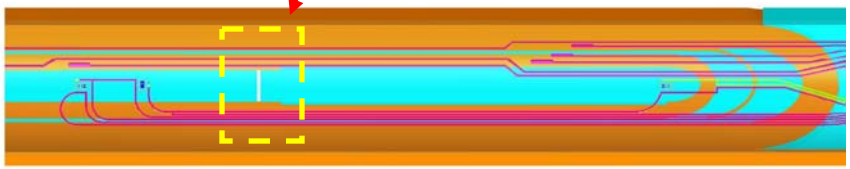
TQ Tests: Quench Training at 20 A/s

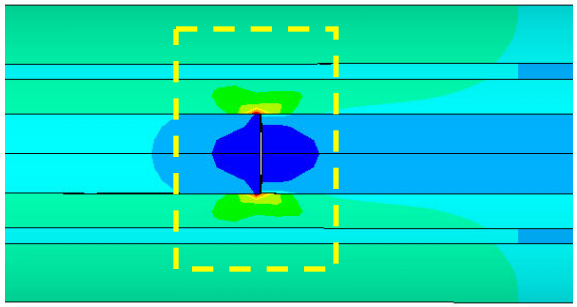


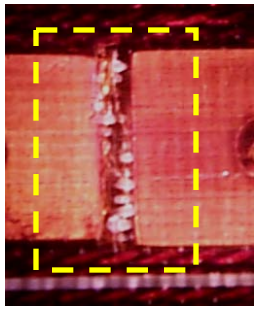
Model:	S01a	S01b	S01c	S02a	S02b	S02c	S02d	S03a	S03b	C01a	C01b	C02E	C02a	C02b
Tested by:	LBNL	LBNL	LBNL	FNAL	CERN	CERN	CERN	CERN	CERN	FNAL	FNAL	FNAL	FNAL	FNAL

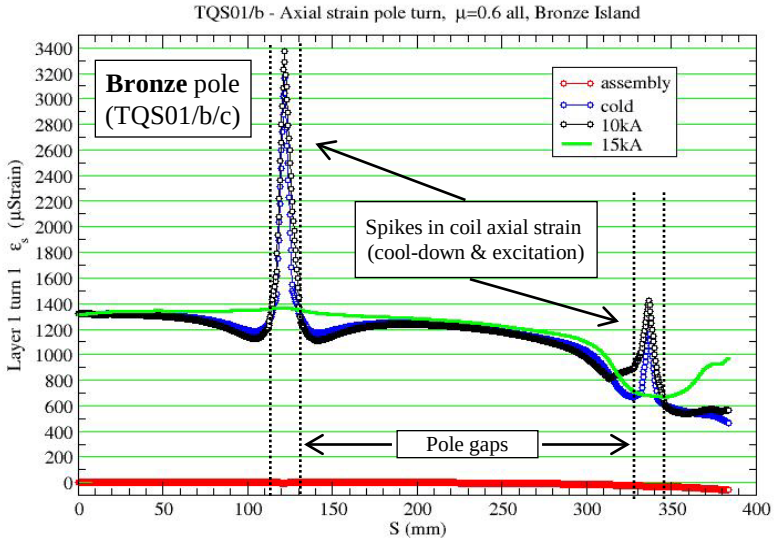
TQ Studies: Axial Tension at Pole Gaps

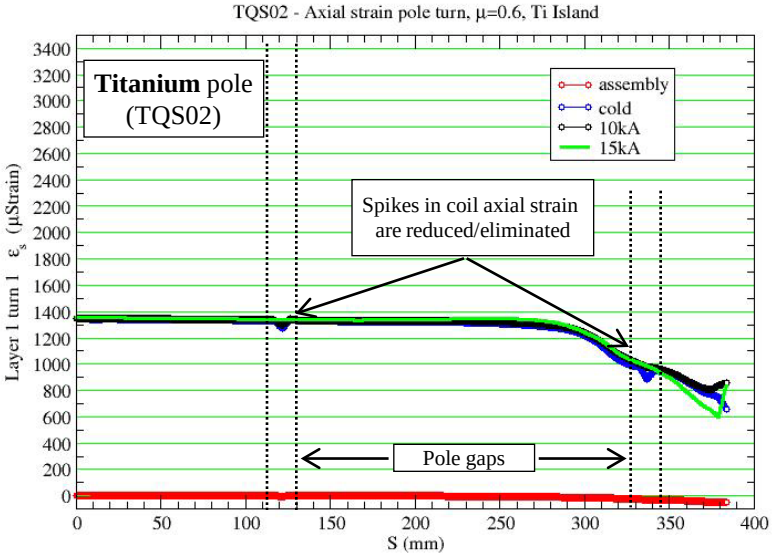




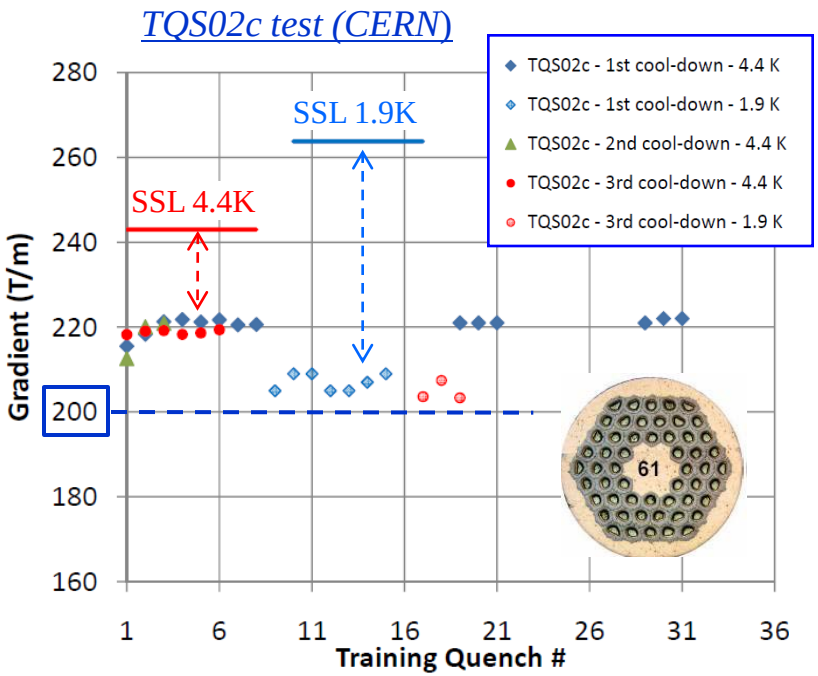


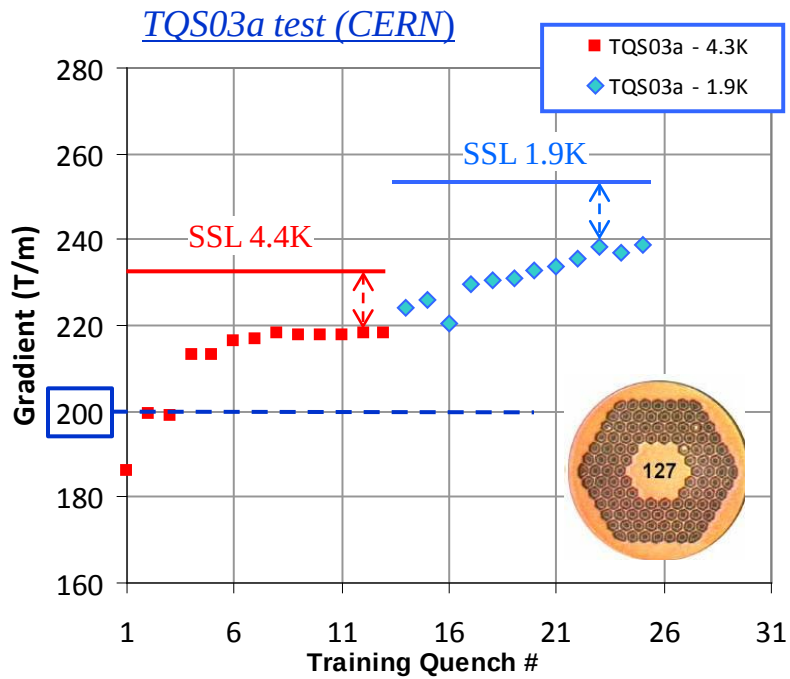






TQ Studies: Conductor Stability



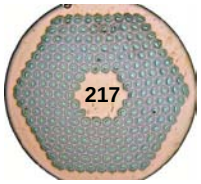


TQS02c limit at 1.9K: conductor instability, enhanced by local degradation:

- *Limiting quenches in the same coil & location (c23 ramp) at 4.5K and 1.9K*
- *1.9K stability limit in magnet is lower than expected from strand data*

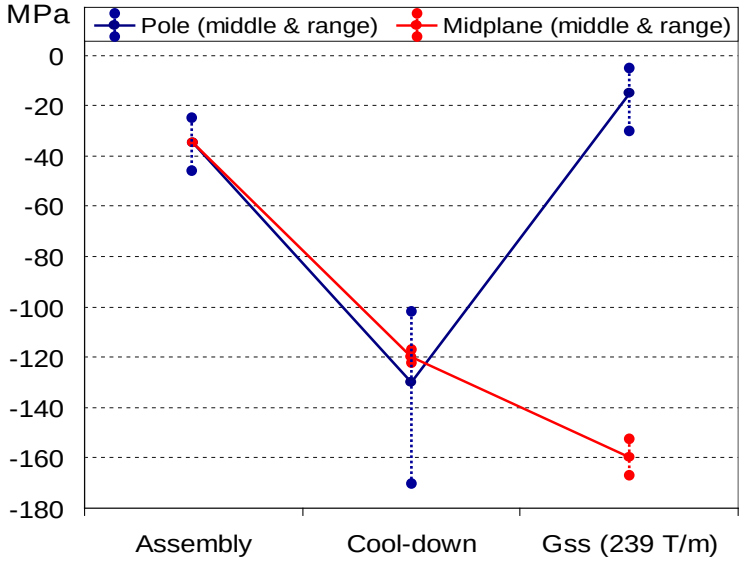
TQS03a with RRP 108/127 shows expected increase at 1.9K

- *Qualifies RRP 108/127 as new baseline conductor for LARP*
- *CDP is funding R&D on RRP conductor with 217 sub-elements*

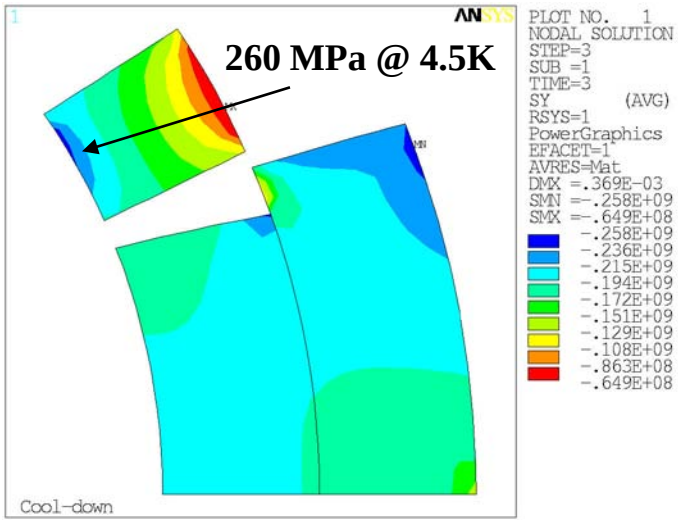


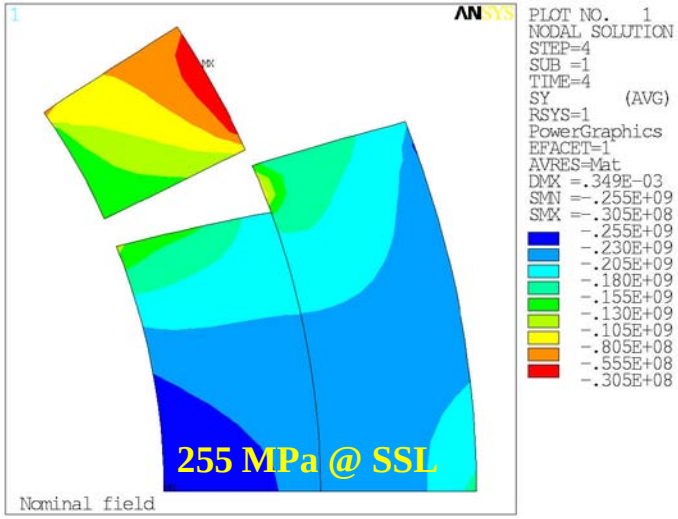
TQ Studies: Stress Limits

Coil layer 1 stress evolution - σ_θ



Calculated peak stresses in TQS03c





<u>Systematic investigation in TQS03</u>:

- 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 →

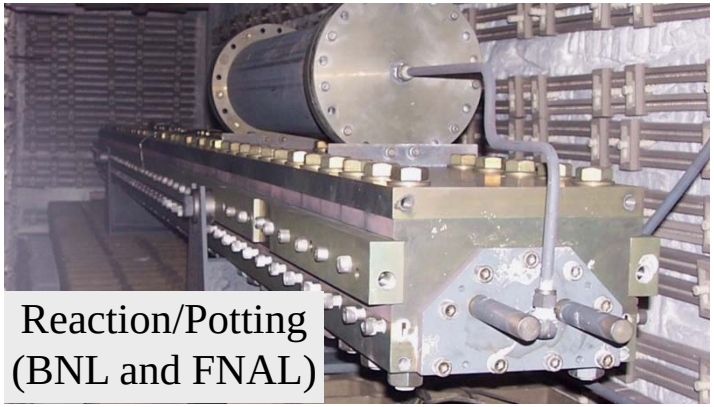
Considerably widens design window

Long Quadrupole (LQ)

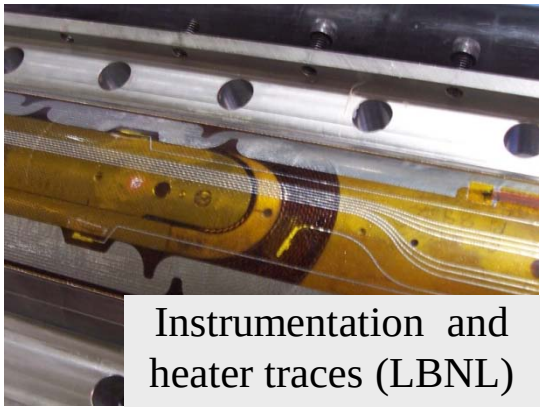
Winding/curing (FNAL)

Scale up of TQ design from 1 m to 3.6 m length

- *Cable fabrication (w/RRP 54/61 wire): LBNL*
- *Coil parts, winding and curing: FNAL*
- *Coil reaction and potting: BNL & FNAL*
- *Instrumentation traces, strain gauges: LBNL*
- *Structure fabrication/assembly: LBNL*
- *Magnet test: FNAL*

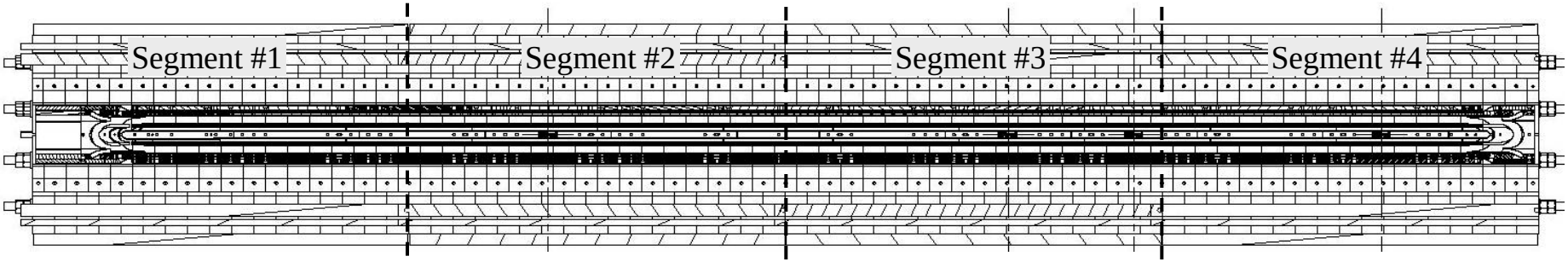


Reaction/Potting (BNL and FNAL)



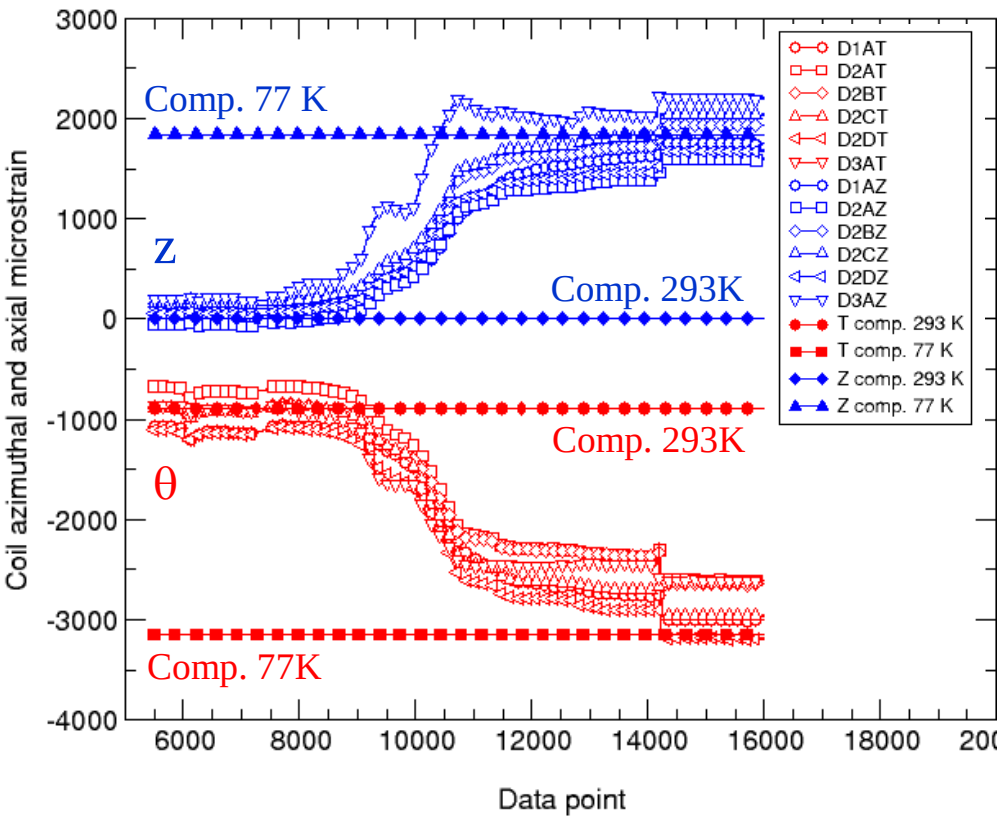
Instrumentation and heater traces (LBNL)

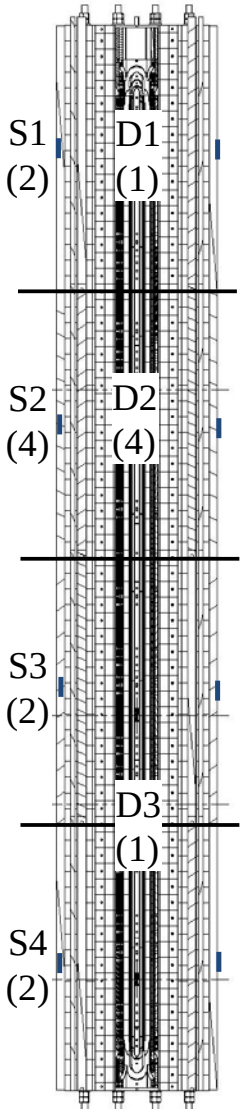
LQS Structure and Assembly



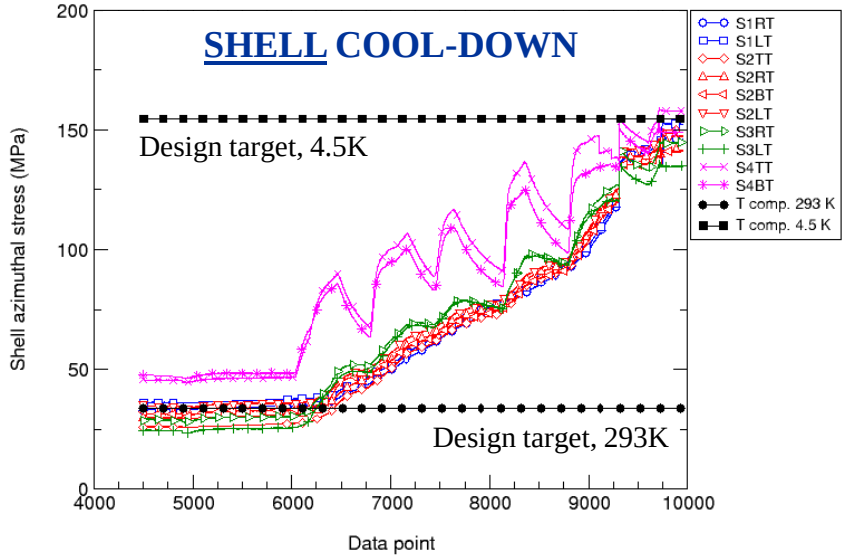
LQSD Mechanical Model

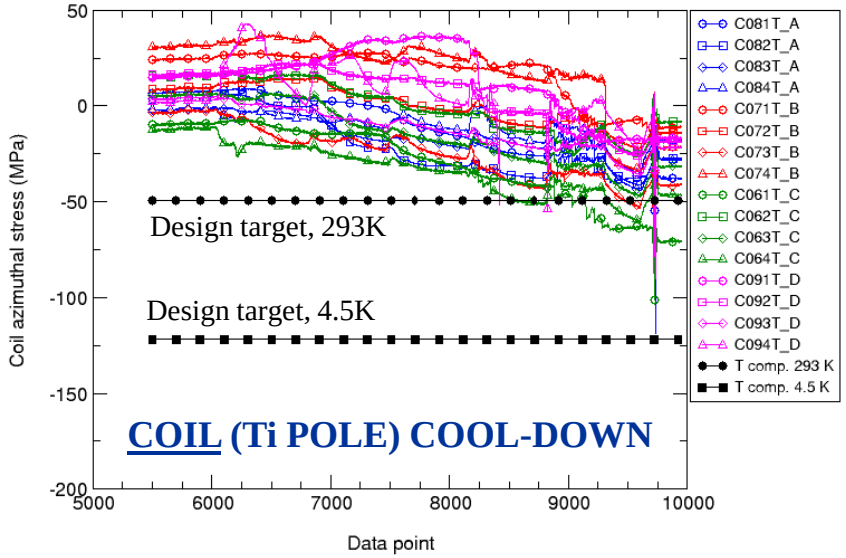
- LQ Shell structure assembly w/ Dummy coils
- Verify design calculations, qualify structure
- *Practice transport, test setup, cool-down*

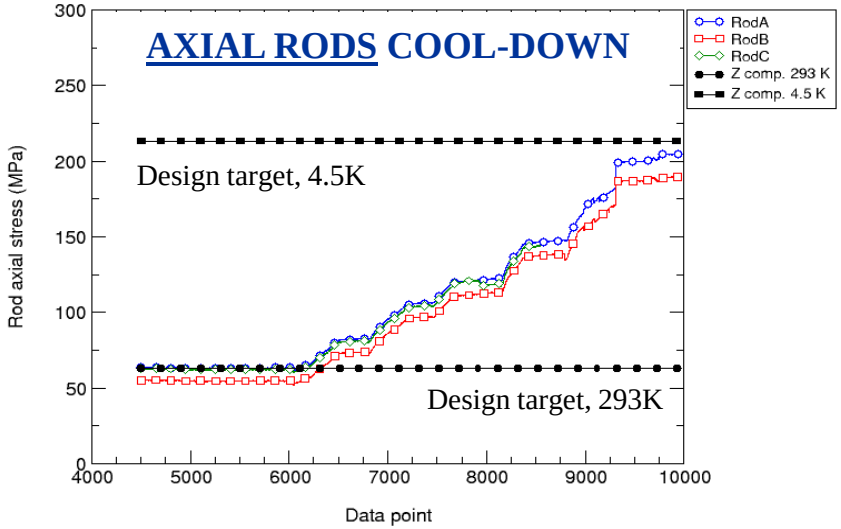


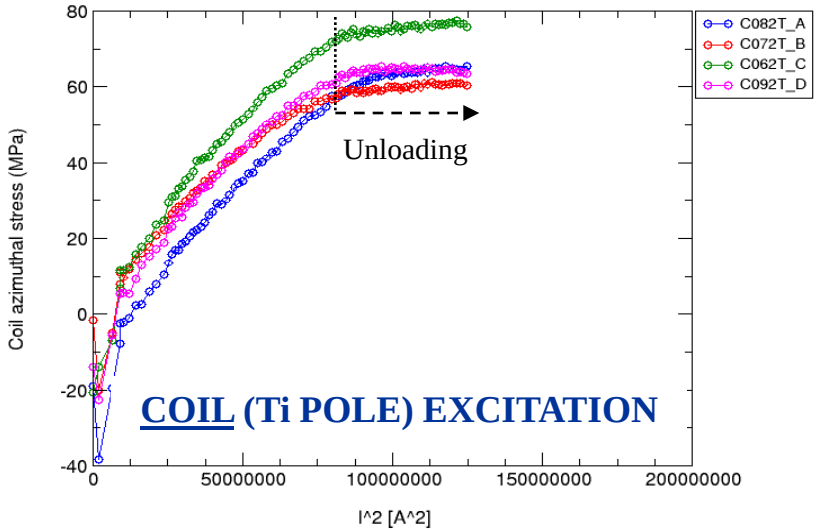


LQS01 Test: Strain Gauge Measurements



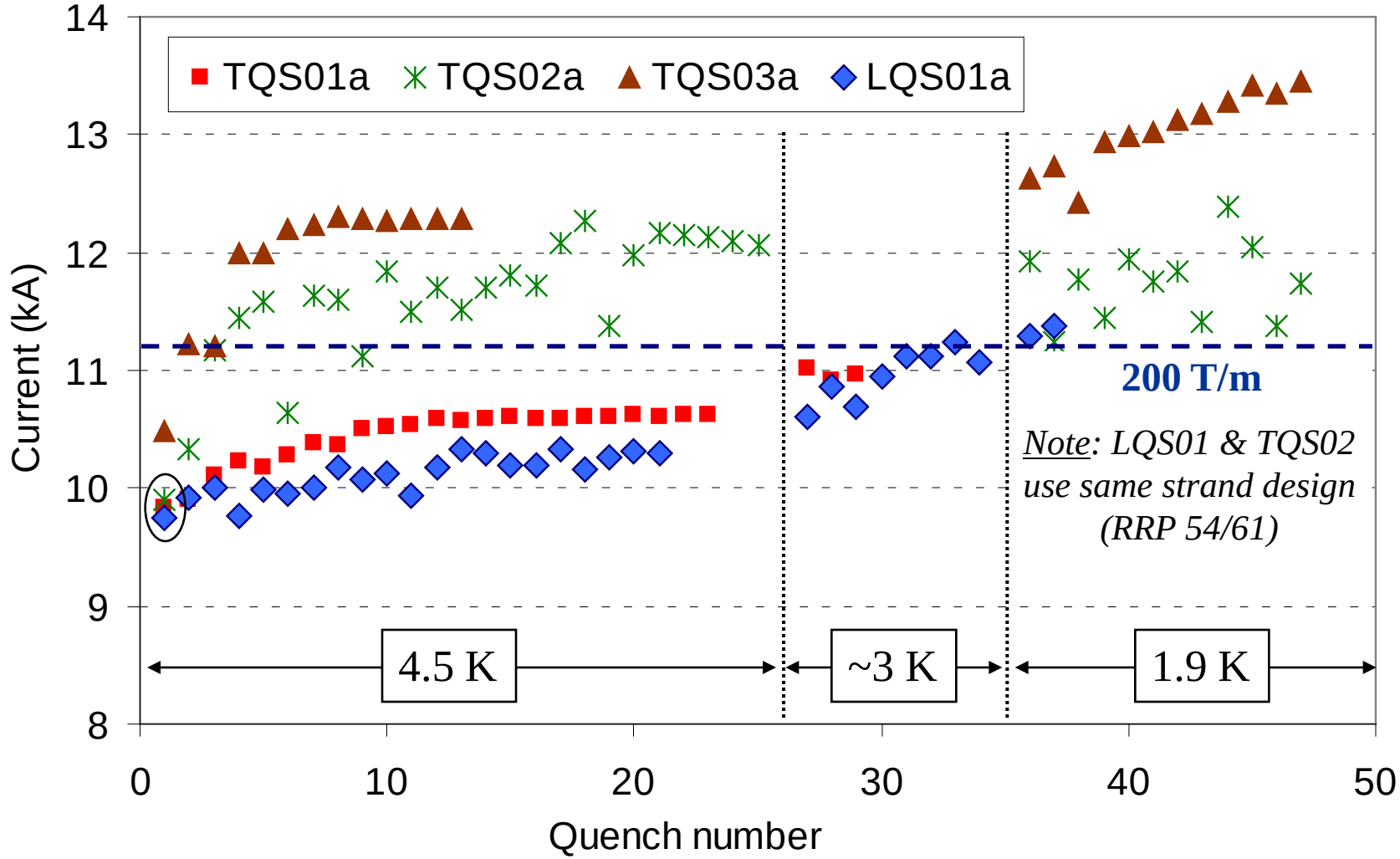






LQS01 & TQS Quench Performance

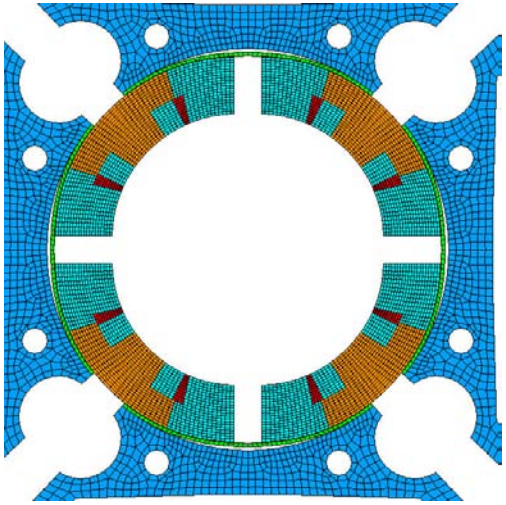
Comparison of first training sequences at each temperature with all new coils



LQ Summary and Next Steps

Achieved 200 T/m target at first attempt, no major issues discovered

Further optimization work is needed:



2010: using current coil series (RRP 54/61)

- Improve coil pre-load distribution
- SG data consistent with coil-pad mismatch
- Conductor performance at 1.9K
- Quench protection studies

2011 (2012): With a new series of coils (RRP 108/127)

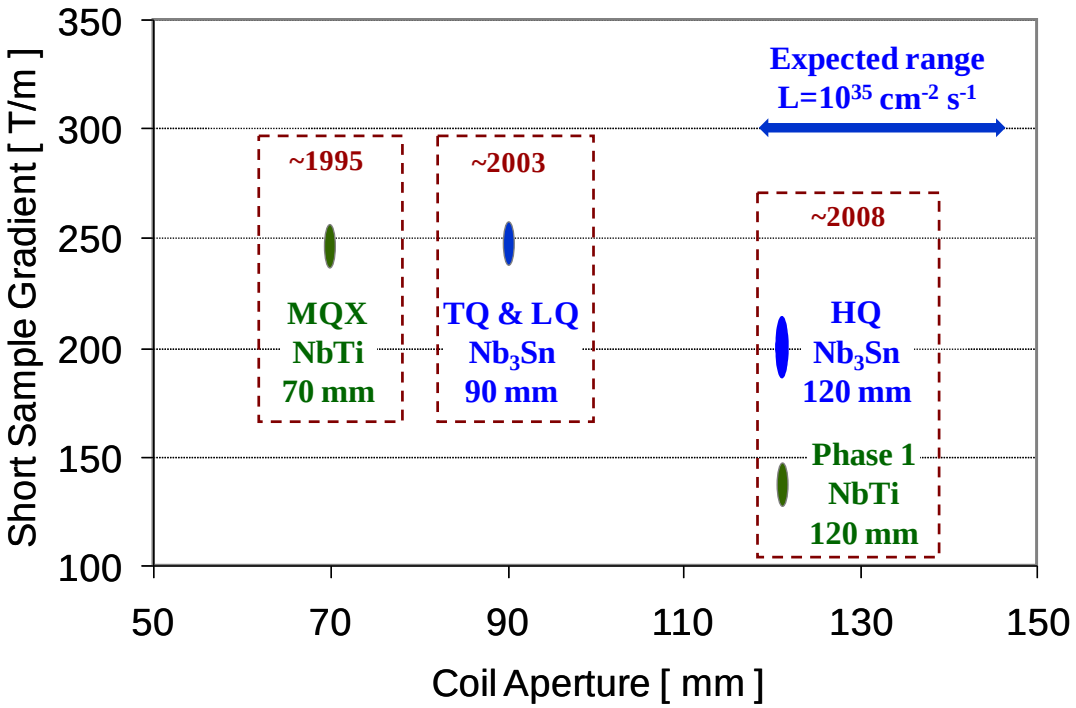
- Fully reproduce best TQ performance
- Faster training, increased stability and stress tolerance

120 mm Quadrupoles

- IR Studies show *large aperture quads required* for $L=10^{35}$ cm^{-2} sec^{-1}
- Phase 1 ($L=2\ 10^{34}$ $cm^{-2}sec^{-1}$) will use NbTi Quads with *120 mm aperture*
- The *same aperture* was chosen for the next series of Nb_3Sn models (HQ)

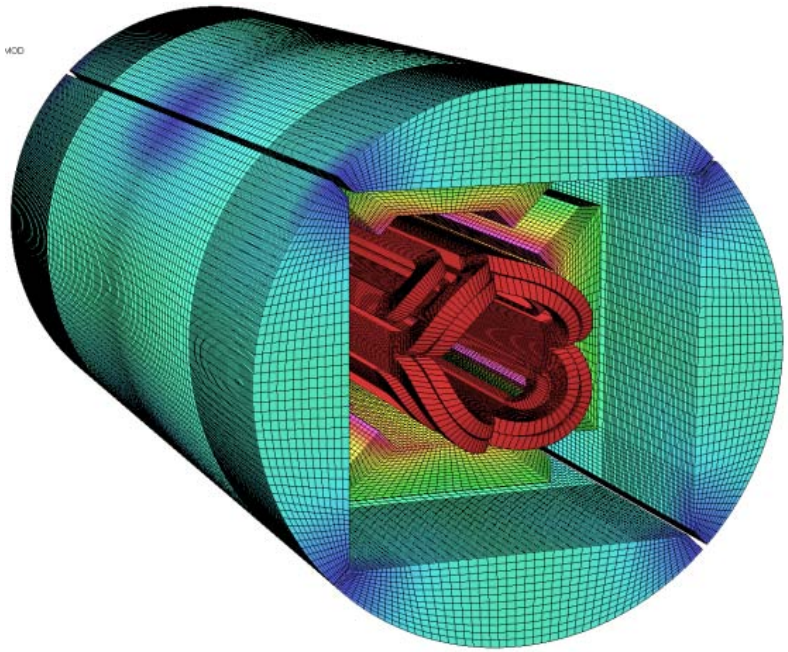
Aiming at:

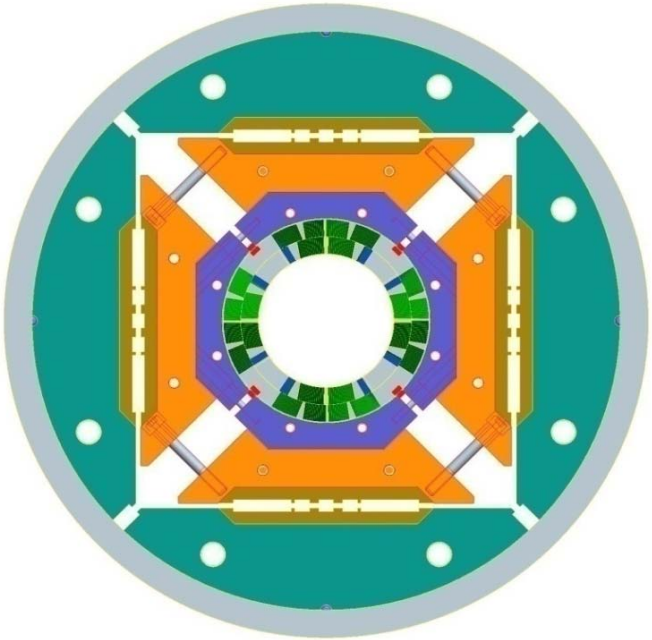
- Nb_3Sn qualification based on Phase 1 upgrade specifications
- Providing performance reference for Phase 2 upgrade design



HQ Design Features and Parameters

- Coil peak field of 15.1 T at 219 T/m (1.9K un-degraded SSL: 19.5 kA)
- 193 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



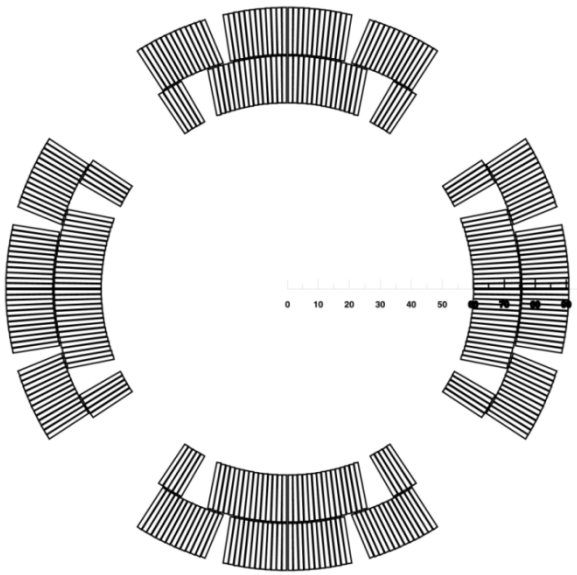


Coil and Cable Design

Coil parameters:
- 120 mm aperture, 2 layer
- One wedge in each layer
- 46 turns/quadrant

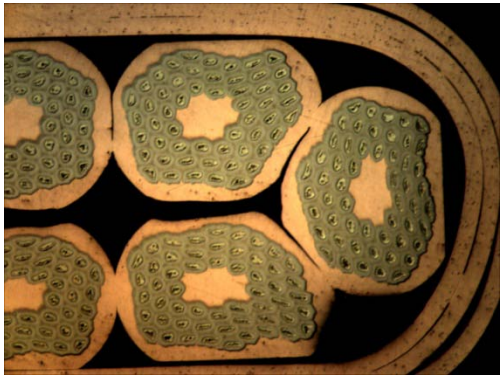
Cable parameters:
- 35 strands, 0.8 mm diam.
- Width: 15.15 mm
- Mid-thickness: 1.44 mm
- Keystone angle: 0.75^0

Cable insulation:
- Glass sleeve, 0.1 mm thick

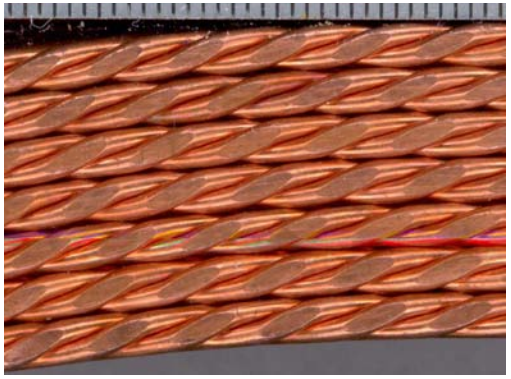


Test windings

Sub-element deformation

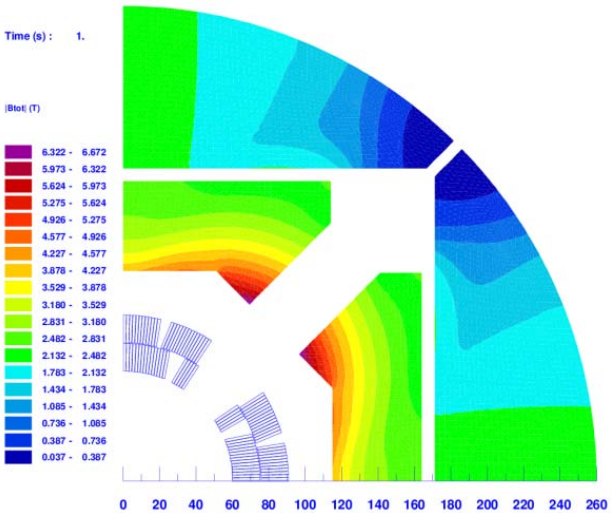


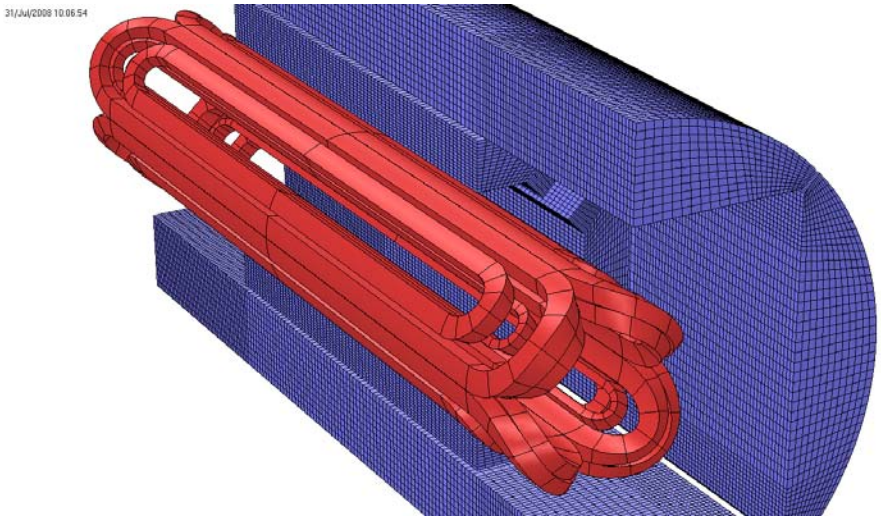
Edge facets

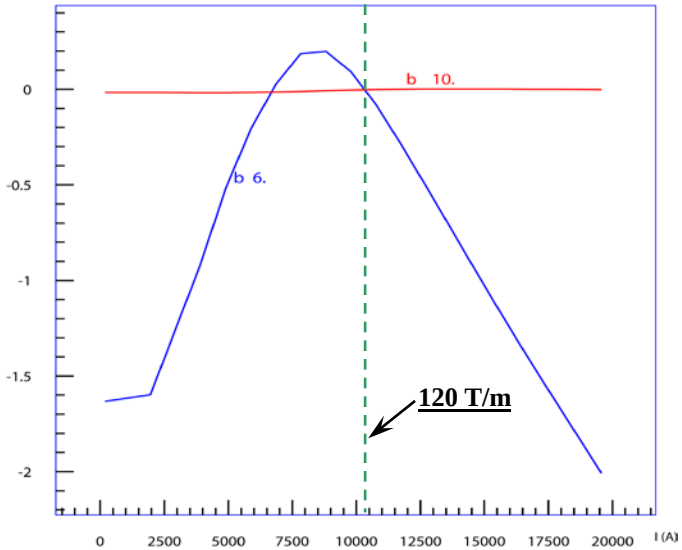


Magnetic Design and Field Quality

- Reference radius 40 mm (2/3 aperture)
- Small geometric harmonics (2 wedges)
- Saturation b_6 1 unit from 0 to 20 kA
- Optimized for 120 T/m gradient
- End design optimized for minimum field
- No additional spacers in the ends



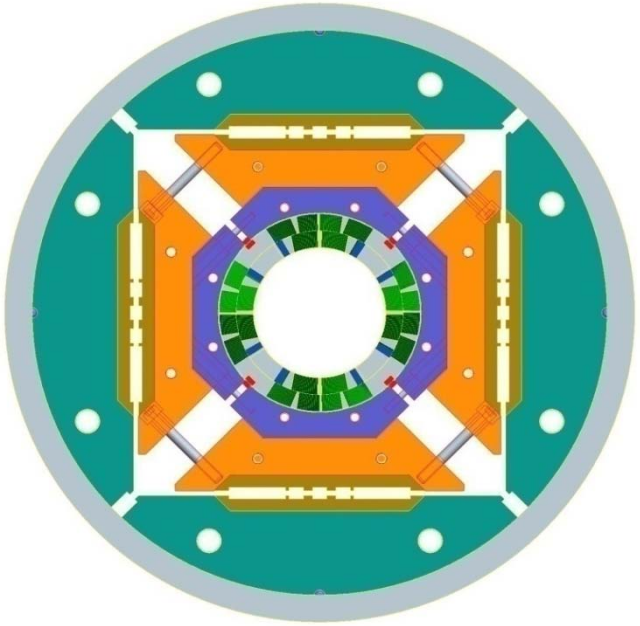


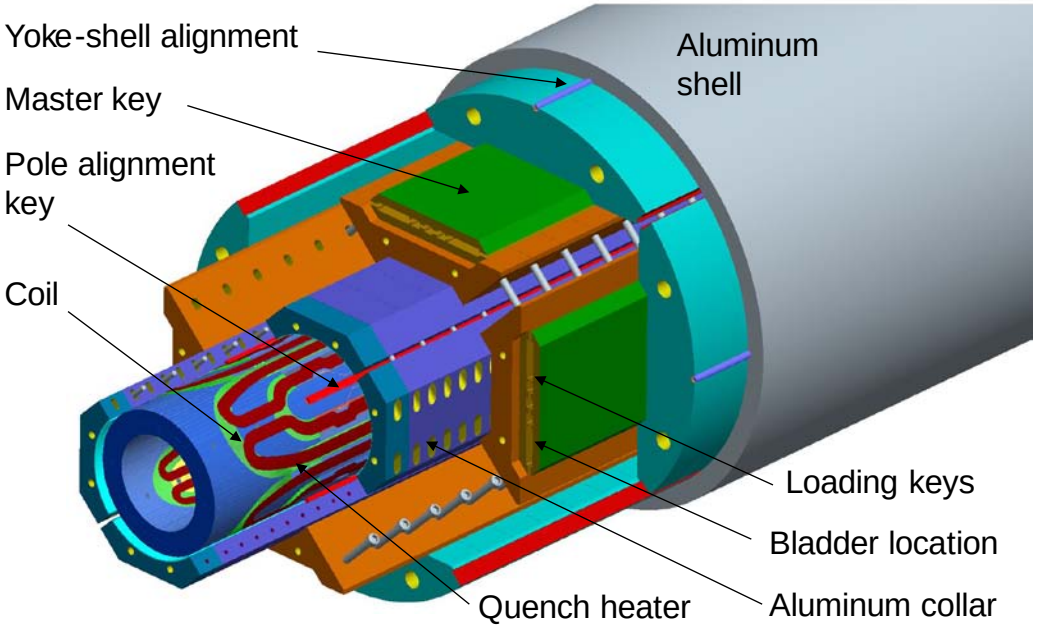


Mechanical Design

Main structural components:

- Aluminum shell: 25 mm thick, OD = 570 mm (same as LHC dipole)
- 4-split iron yoke
- Iron pads provide space for axial rods and cooling channels
- Iron masters house 50 mm wide bladders, loading and alignment keys
- Aluminum collars align poles while transferring pre-load to the coils





Mechanical Analysis

Pre-loading for 219 T/m

Pole contact pressure:

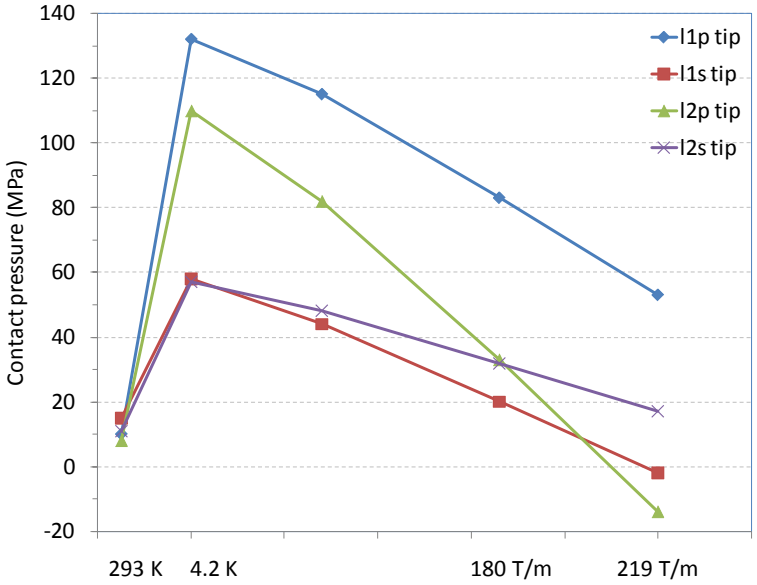
- 140 MPa compression at 0 T/m
- 20 MPa max. tension at 219 T/m

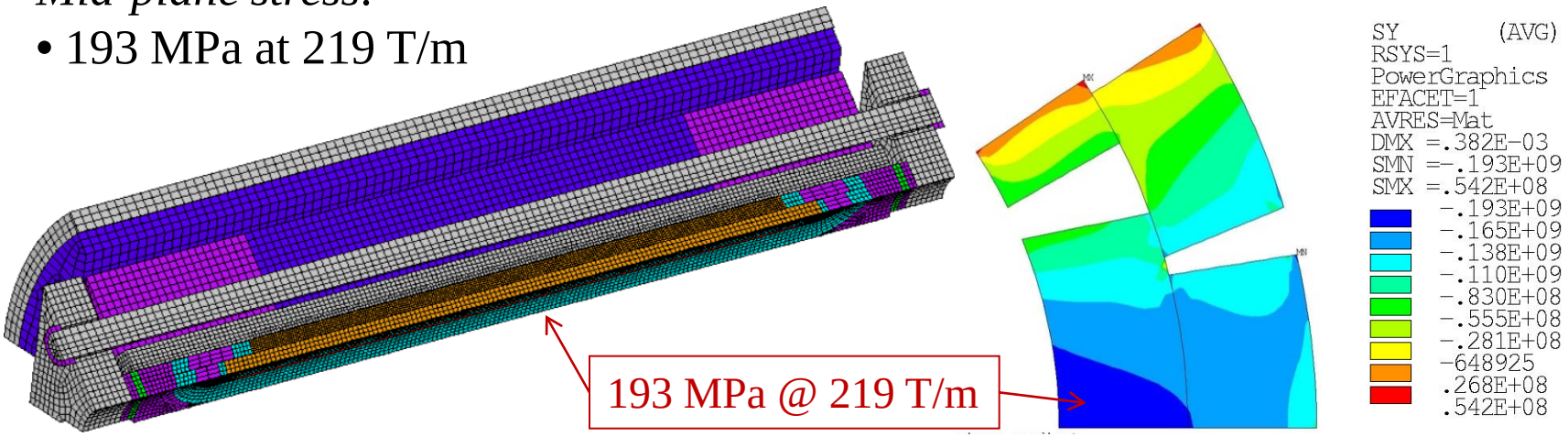
Axial forces:

- E.m. force: 1372 kN
- 620 kN applied at 4.2 K

Mid-plane stress:

- 193 MPa at 219 T/m





HQ Task Distribution by Laboratory

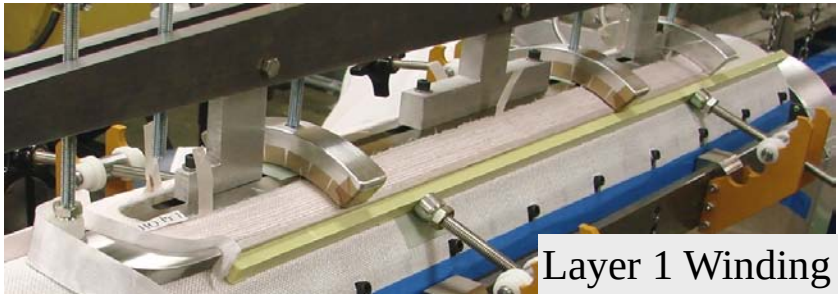
• Cable design and fabrication	LBNL
• Magnetic design	FNAL, LBNL
• Baseline mechanical design	LBNL
• Coil parts design and procurement	FNAL
• Instrumentation & quench protection	LBNL
• Winding and curing tooling design	LBNL, FNAL
• Reaction and potting tooling design	BNL
• Coil winding and curing	LBNL
• Coil reaction and potting	BNL, LBNL
• Coil handling and shipping tooling	BNL
• Structure fabrication and test	LBNL
• Magnet assembly	LBNL
• Magnet test	FNAL
• Structure Optimization	BNL, LBNL, FNAL

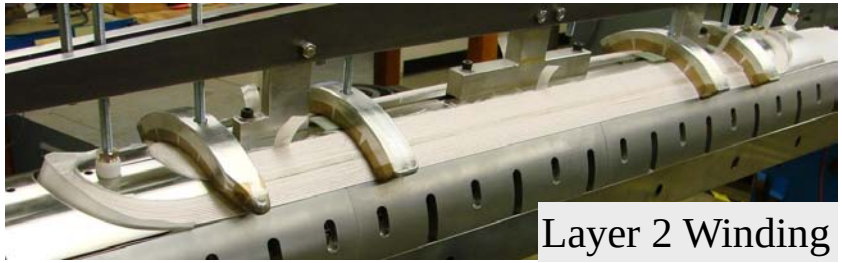
HQ Timeline

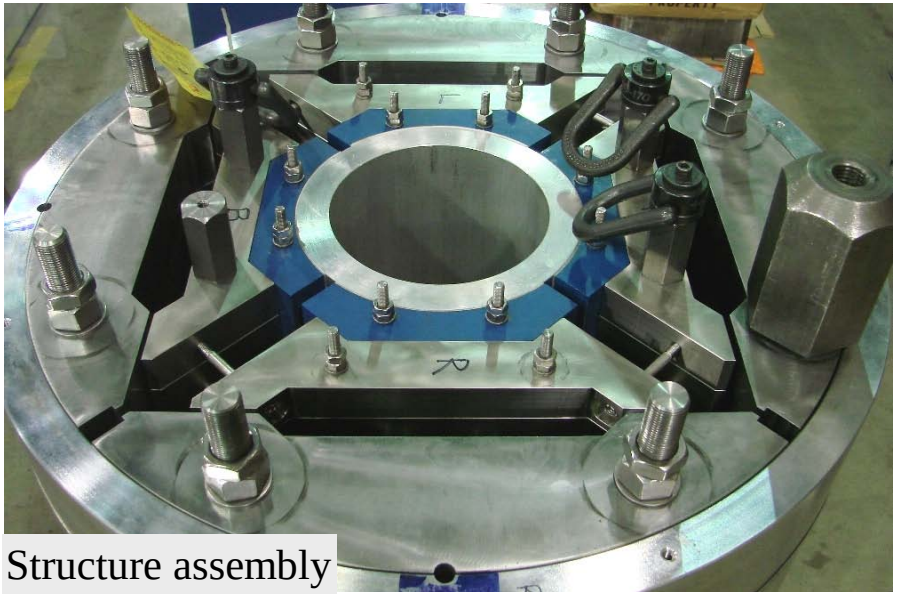
2008	June	Presented conceptual designs for 114 and 134 mm bore
	July	Selection of 120 mm quadrupole aperture for Phase 1
	Aug.	Practice cables fabricated, test windings completed
	Sept.	Cable and coil cross-section geometry finalized
	Oct.	3D magnetic and coil design completed
	Dec.	All coil fabrication tooling in procurement
2009	Jan.	Mechanical analysis completed
	Mar.	All coil and structure components in procurement
	Apr.	Cables for ~10 coils fabricated (54/61 and 108/127)
	June	Practice coil 1 winding/curing completed
	Aug.	All structure components received
	Sept.	Coil 1 completed and coil 2 wound
	Dec.	Coil 2 completed, coil 3-4 reacted, coil 5 wound
2010	Jan.	Structure pre-assembly completed

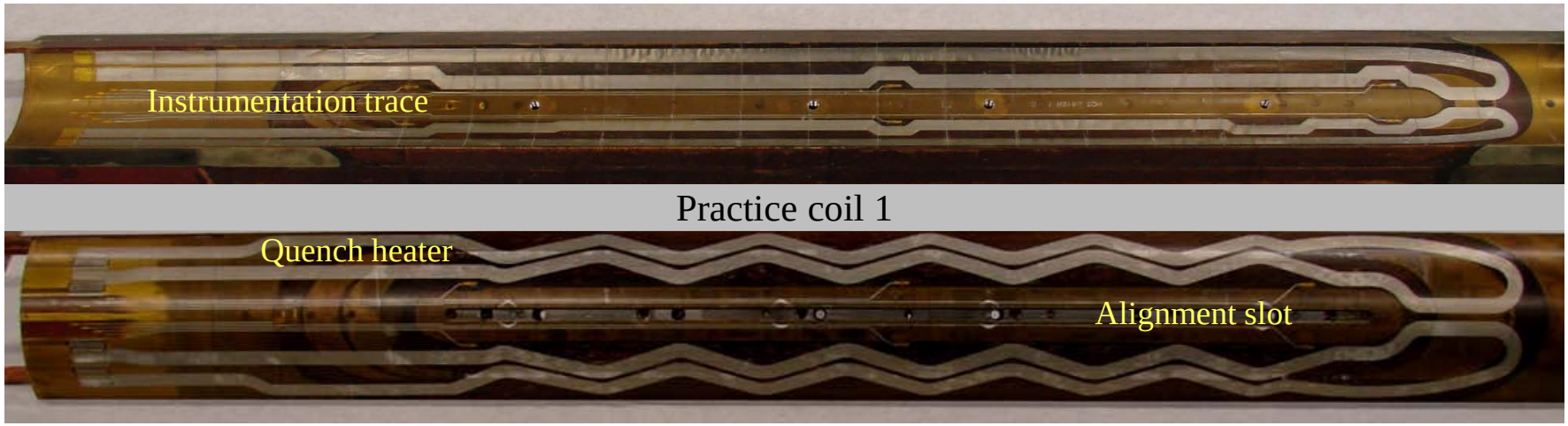
Design and fabrication timeline is comparable to NbTi technology

Coil and Structure Fabrication


Layer 1 Winding


Layer 2 Winding

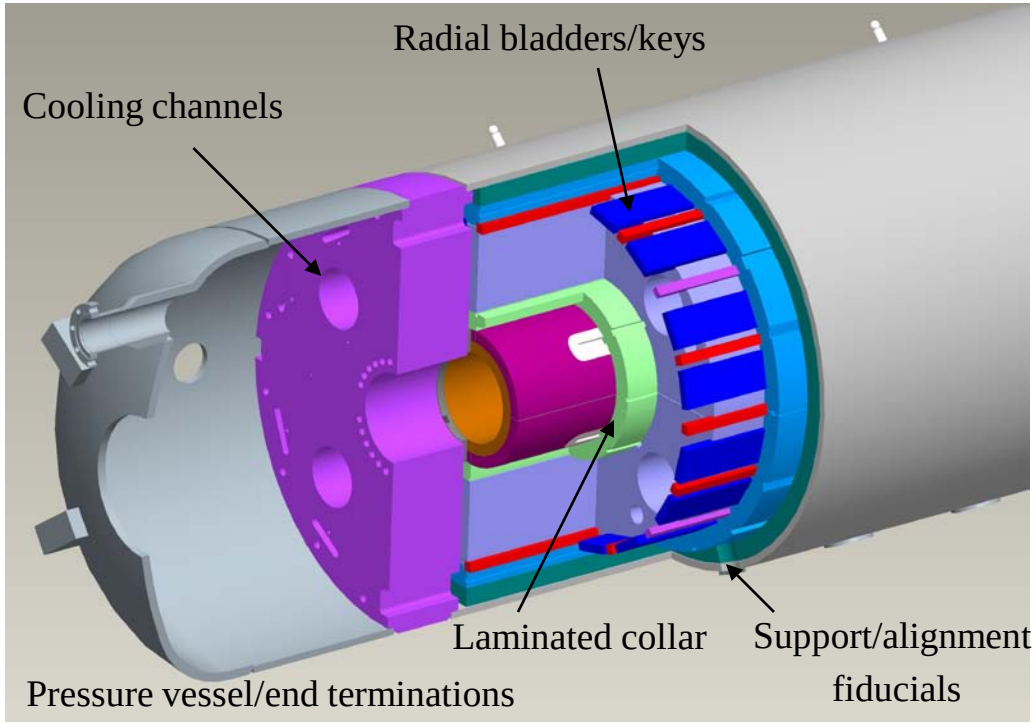

Structure assembly

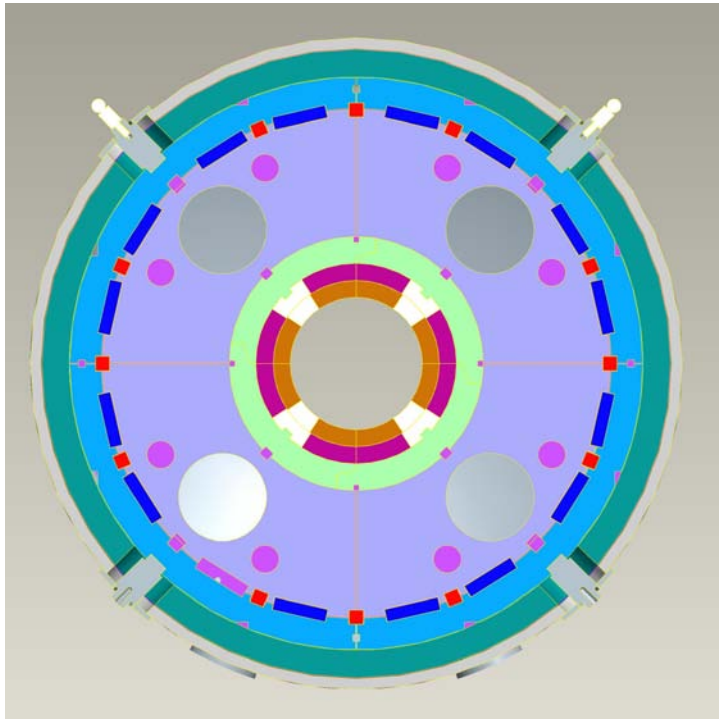


Practice coil 1

Accelerator Integration

- Pre-load optimization for high gradient with minimal training
- Alignment, quench protection, radiation hardness, cooling system
- Field quality: length extension to 2m; cored cable eddy current effects
- Structure and assembly features for magnet production and installation





Future Plans

2010-2012: complete technology demonstration - LARP original goal

- LQ to address all length-related issues:
- HQ to address field/energy limits and accelerator quality
  - *Use Phase 1 specifications as reference*
- No HQ extension to 4 m in this phase

2013-2015: fabricate full scale prototypes for Phase 2 upgrade

Preparations (2010-2012):

- Converge on main specifications by the end of 2012
- Optimize HQ strand/cable for use in prototype
- Upgrade infrastructure as needed

Could be managed by LARP or APUL

Summary

- Strong, efficient collaboration among magnet programs
- Demonstrated all fundamental aspects of Nb_3Sn technology:
  - *Conductor & structure performance, length scale-up*
- Steady progress in understanding and addressing R&D issues
- Complete engineering toolbox and fabrication capabilities
- On track to qualify a 120 mm Quadrupole for the LHC IR

Acknowledgement