About the longitudinal pre-load of magnets built at LBNL

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* Many thanks to the BNL, FNAL and LBNL SMP groups

General Statements

The mechanical state of superconducting magnets has the most impact on performance and training.

Understanding the 3D mechanical state of SC magnets is complex and requires a dedicate effort.

Approach

- **<u>The 2D cross-section design assumes axial condition :</u>**
  - ➢ **<u>Plane-Stress</u>**

    the ends are lightly supported when transverse pressure is applied (like when collars are used)

  - ➢ **<u>Plane-Strain</u>**

    the ends are externally supported with end-plates and rods

  - ➢ **3D lamination symmetry**

    the ends are internally supported by a spar like in the CCT

- **The above assumptions are not needed in 3D modeling**

- **Modeling and measuring the reaction process is not a simple task**

3D Mechanical Estimates

Strain “ε” in two principal directions “z,θ” (and no shear) is converted into stress “σ” using the relationships below (*modulus of elasticity* (E), and *Poisson’s ratio* (ν))

$$\sigma_\theta = \frac{E}{(1-\nu^2)}(\varepsilon_\theta + \nu\varepsilon_z) \qquad \sigma_z = \frac{E}{(1-\nu^2)}(\varepsilon_z + \nu\varepsilon_\theta)$$

– HQ bore diameter 60 mm, 4 aluminum rods each r=17mm

<u>Assume:</u>

– Coil is a cylinder

– Modulus E=40 Gpa, Poisson ratio ~1/3, no friction

– **Coil azimuthally stress Sigma_t=-150 Mpa**

– **<u>Constrains:</u>**

Plain-stress radial forces generate -150 Mpa azimuthal stress, **ends slide axially**

Plain-strain radial forces generate -150 Mpa azimuthal stress, **ends fixed axially**

Coil Estimates

Plane-Stress Sigma_z=0 (free-axial, sliding)

Sigma_t = **-150 MPa (solid cylinder)**

- → Epsilon_t = **-3750 Mic-strain**
- → Epsilon_z = **+1250 Mic-strain**
- → Sigma_z= **0 MPa**

- → Magnet length L=1m
- → **Coil change in length** = **+1.25 mm**

Plane-Strain Epsilon_z=0 (fixed-axial)

Sigma_t = **-150 MPa (solid cylinder)**

- → Epsilon_t = **-3333 Mic-strain**
- → Epsilon_z = **0 Mic-strain**
- → Sigma_z = **-50 Mpa coil**

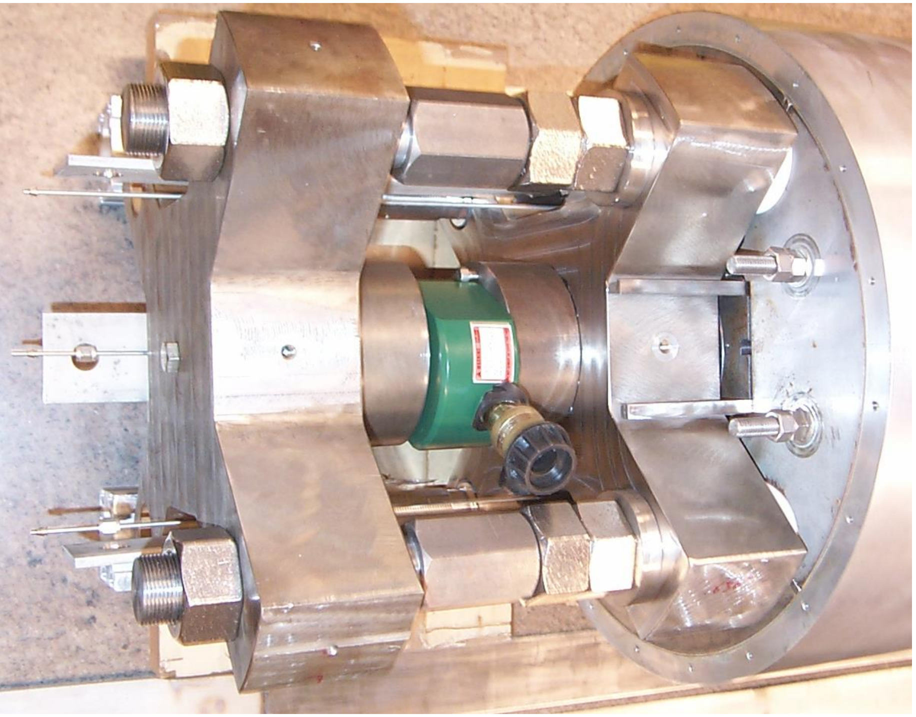
- → Sigma_rods=-F_z/A_rods = +**195** MPa (r-17mm)
- → Aluminum rods E=80 GPa, 1 m long

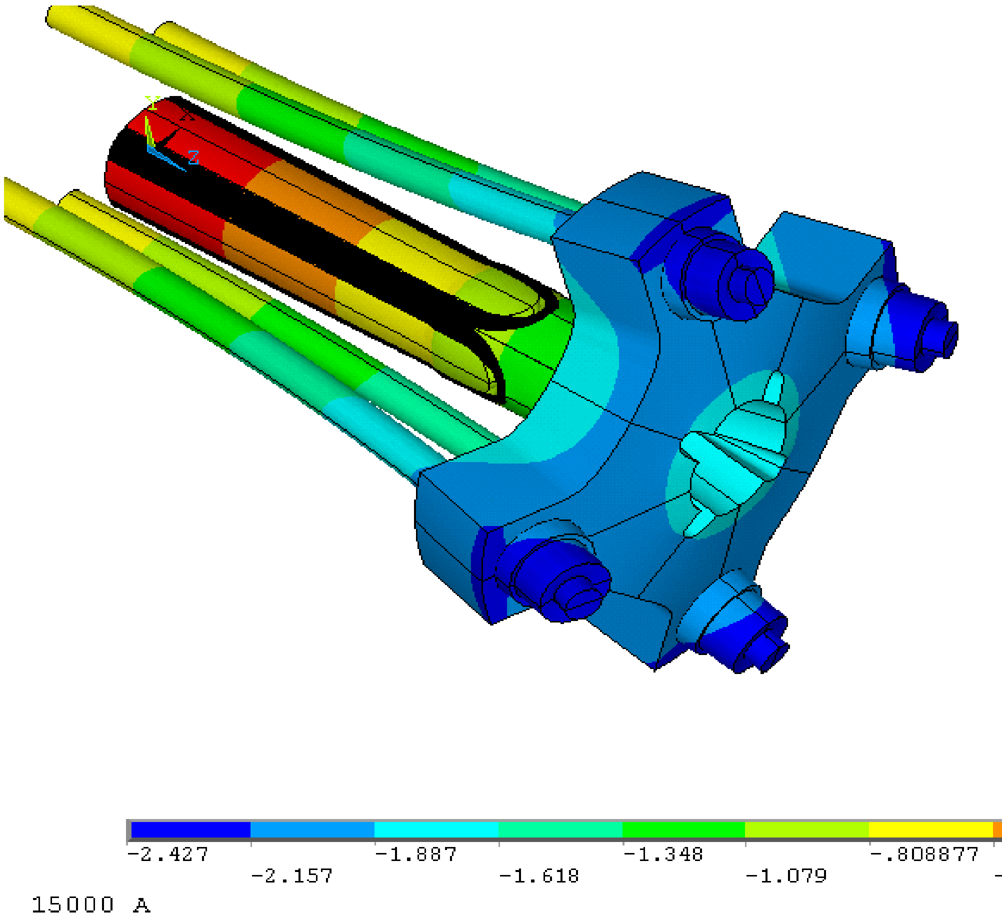
- → Rods_strain_z=195/80 = **+2437 Mic-strain**

- → **1m rods change in length** = +**2.4 mm**

$$\sigma_\theta = \frac{E}{(1-\nu^2)}(\varepsilon_\theta + \nu\varepsilon_z) \qquad \sigma_z = \frac{E}{(1-\nu^2)}(\varepsilon_z + \nu\varepsilon_\theta)$$

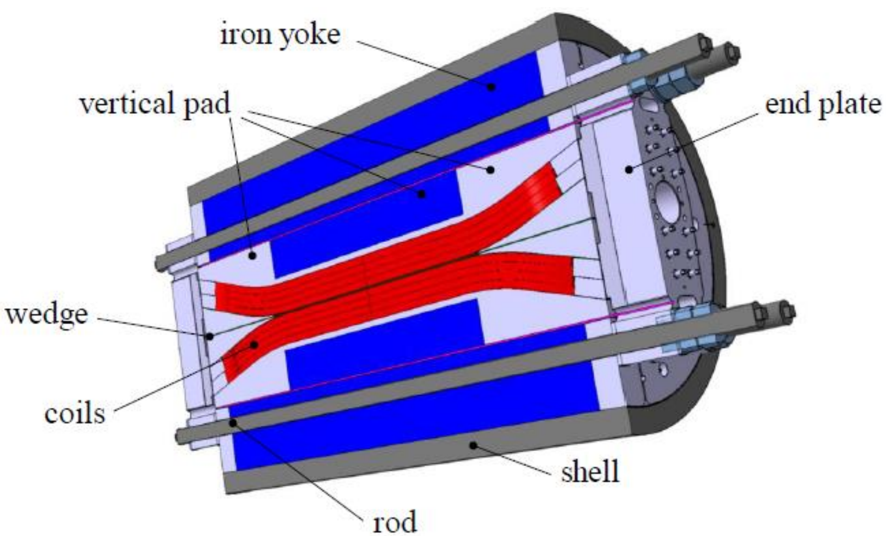
Axial Support Structure





3D mechanical analysis
Support structure design

- Axial support composed by
  - Aluminum rods with a diameter of 60 mm
  - Nitronic 50 end plate 150 mm thick
    - Bullets to deliver pre-load to end-shoes and wedge
- Rods axial force
- FRESCA2 (13 T): **2.8 MN**
  - HD2 (13 T): 0.7 MN
  - LQ (240 T/m): 0.5 MN
  - TQ (>200 T/m): 0.35 MN
  - HQ (170 T/m, 4 rods 34mm): 0.8 MN
  - HQ (219 T/m, 34mm): 1.327 MN

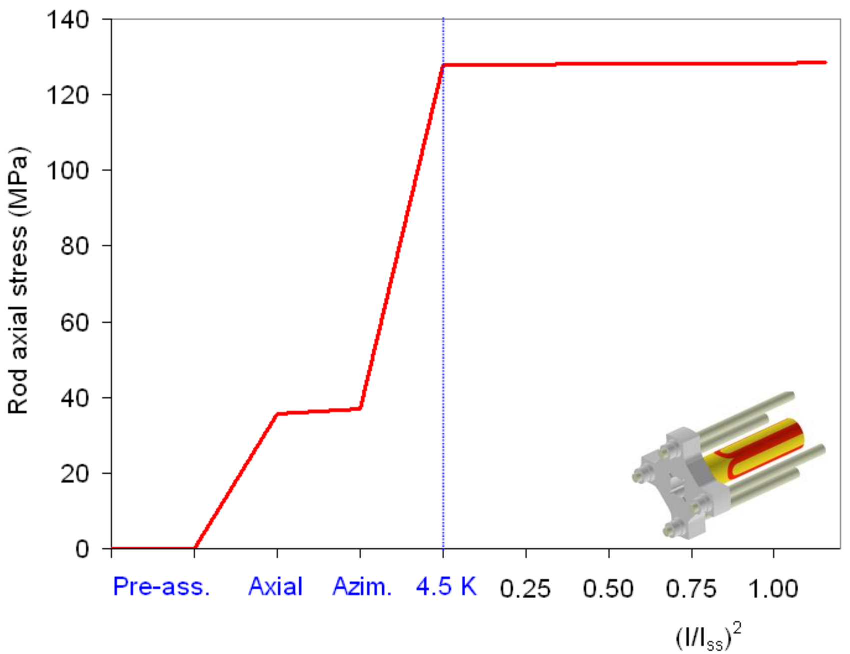


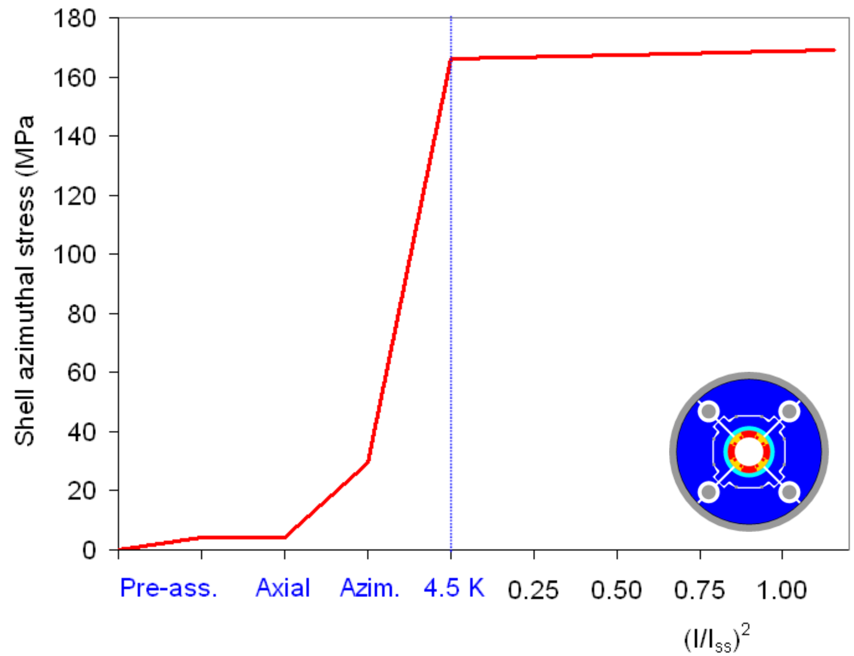
LQ axial support system, composed by four, 25.4 mm diar
stainless steel axial rods with two stainless steel end-plate
50 mm thick. = 500mm^2 per rod

Paolo Ferracin and Attilio Milanese
March 2012

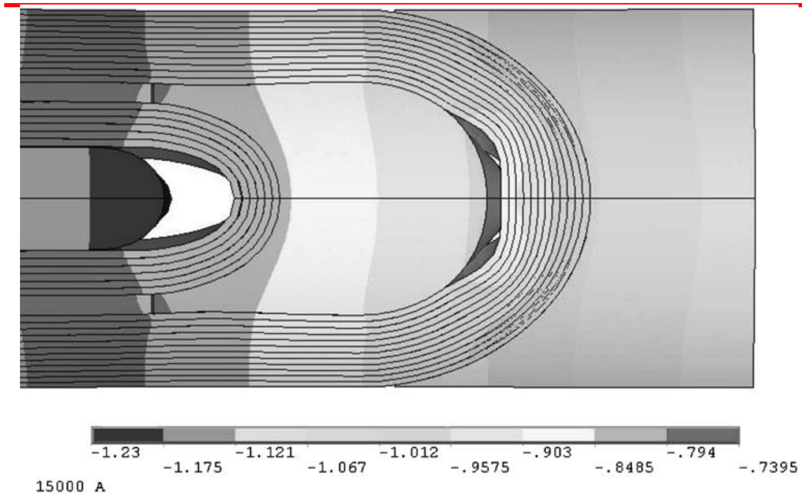
Overview of assembly and pre-load

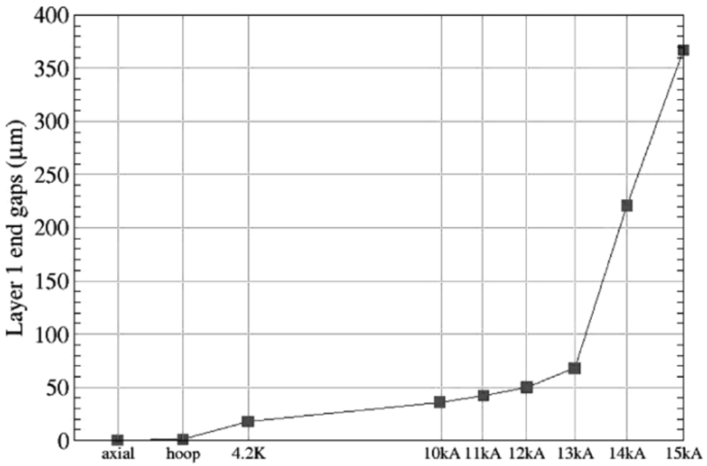
- Aluminum rods
  - 37 MPa at 293 K (230 kN)
  - 128 MPa at 4.3 K (800 kN)
  - Small variation during ramp
- Aluminum shell
  - 30 MPa at 293 K
  - 166 MPa at 4.3 K
  - Small variation during ramp

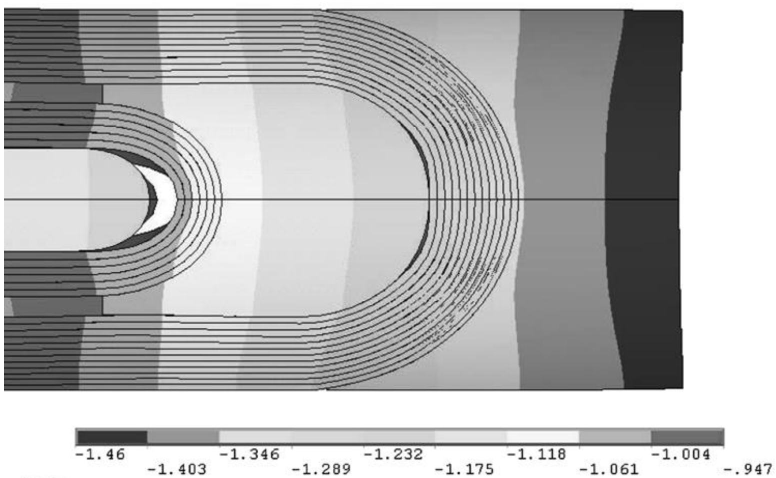


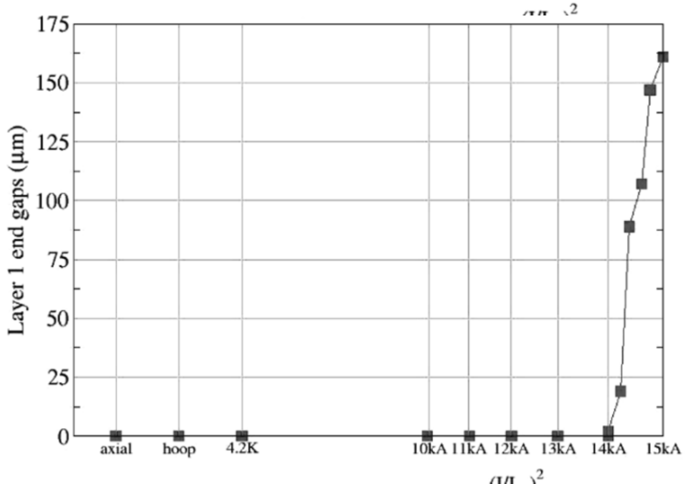


END GAPS





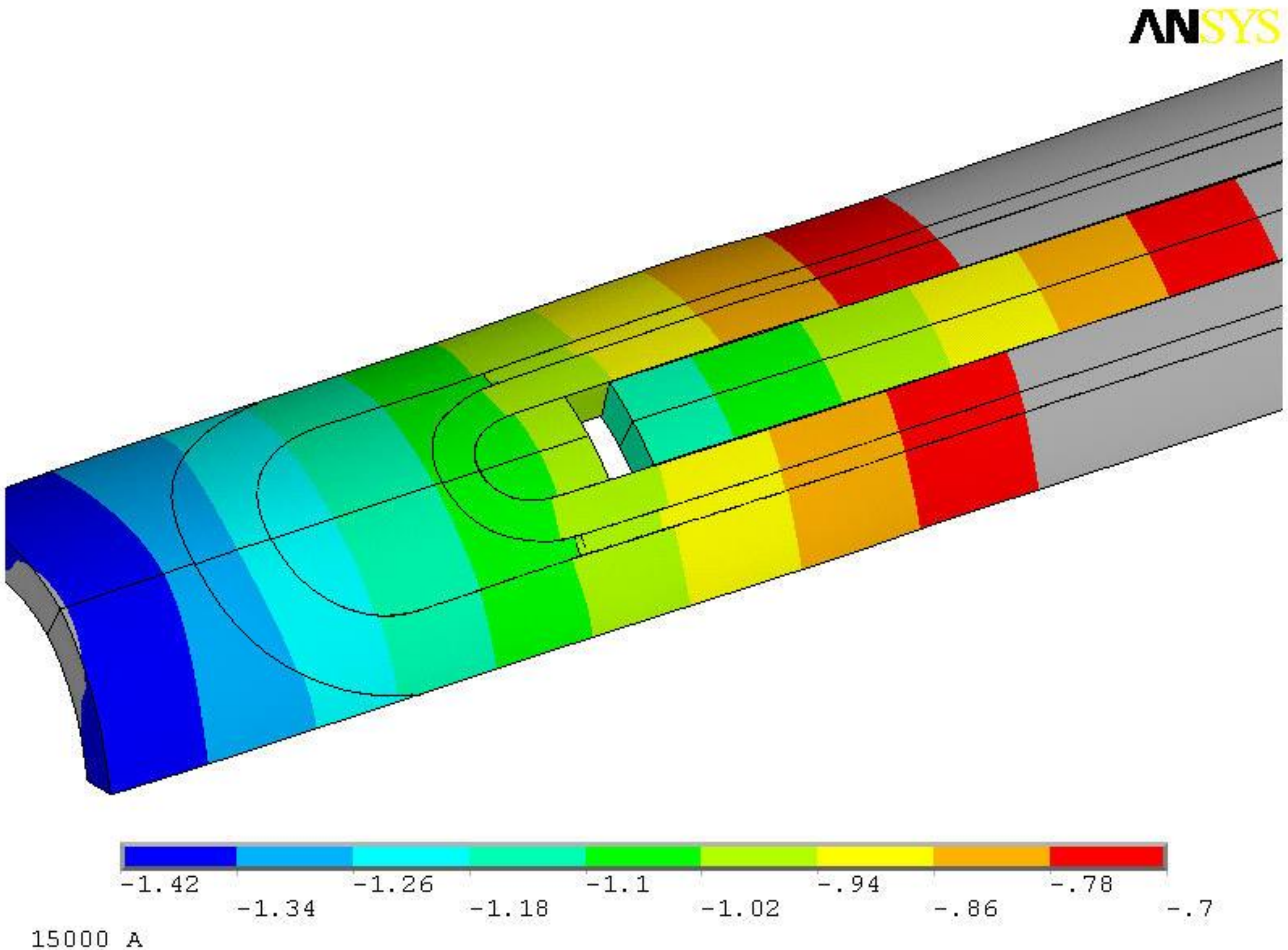




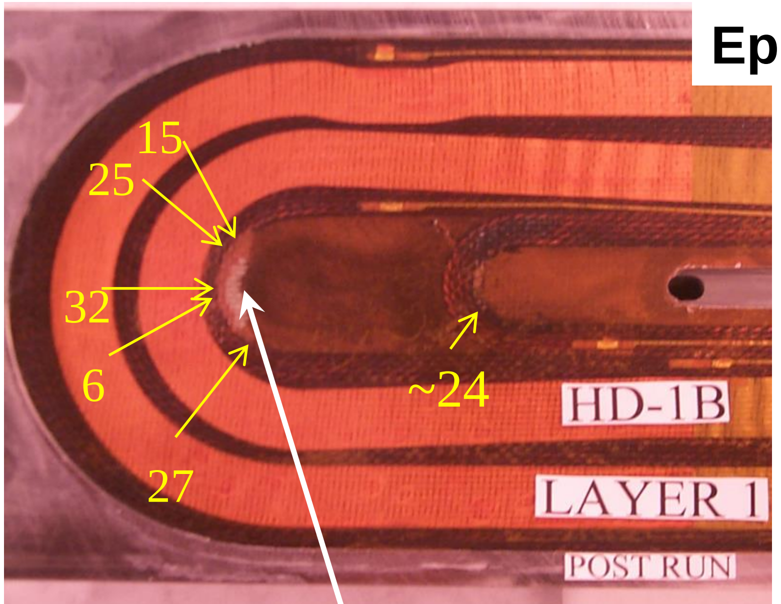
Axial displacements of inner layer's (0.2 friction factor assumed). Limited axial support (top) and full axial support (bottom).

S. Caspi, P. Ferracin., "Towards integrated design and modeling of high field accelerator magnets," IEEE Trans. Appl. Supercond., vol. 16, no. 2, pp. 1298–1303, June 2006.

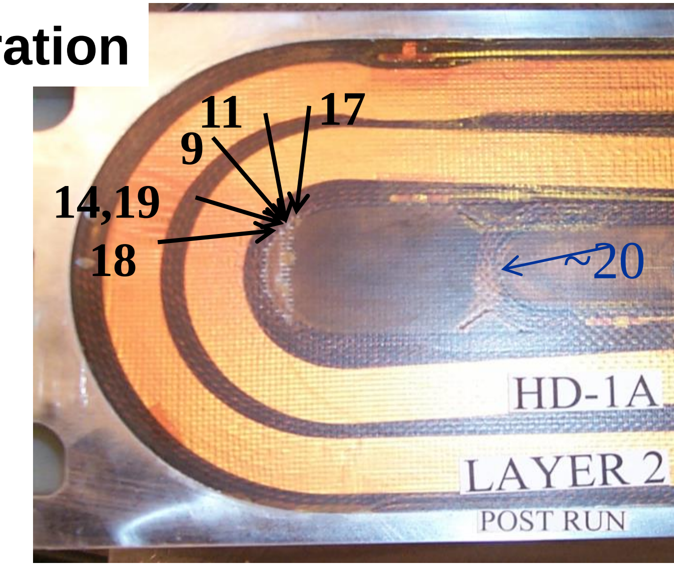
Axial displacement - pole with cut (with friction)

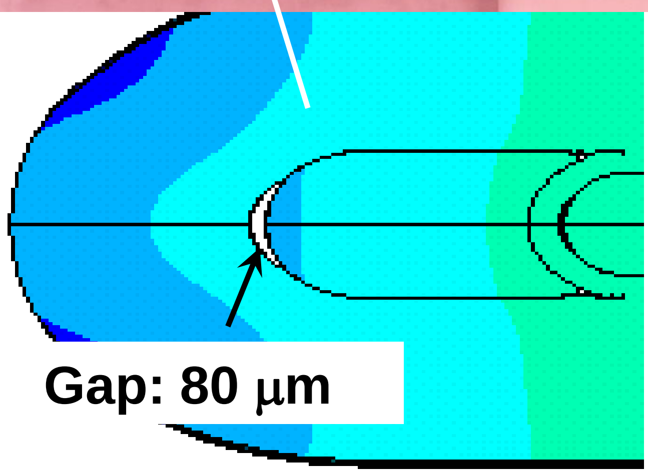


Axial displacements and quench location (HD1, TQ)

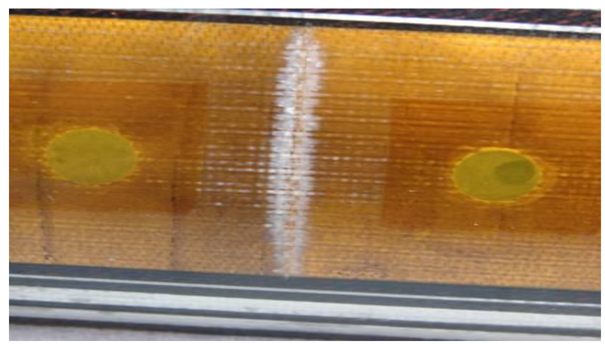


Epoxy discoloration

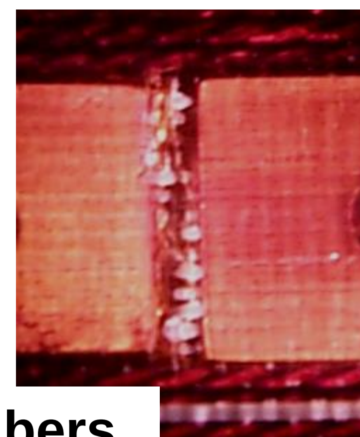




Gap: 80 μm

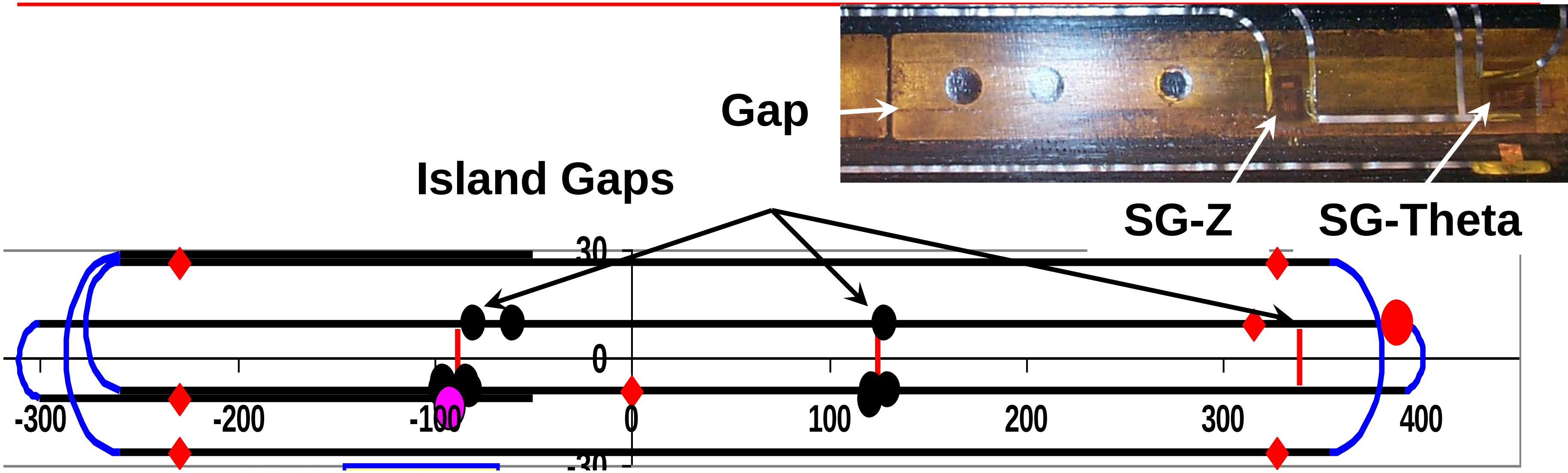


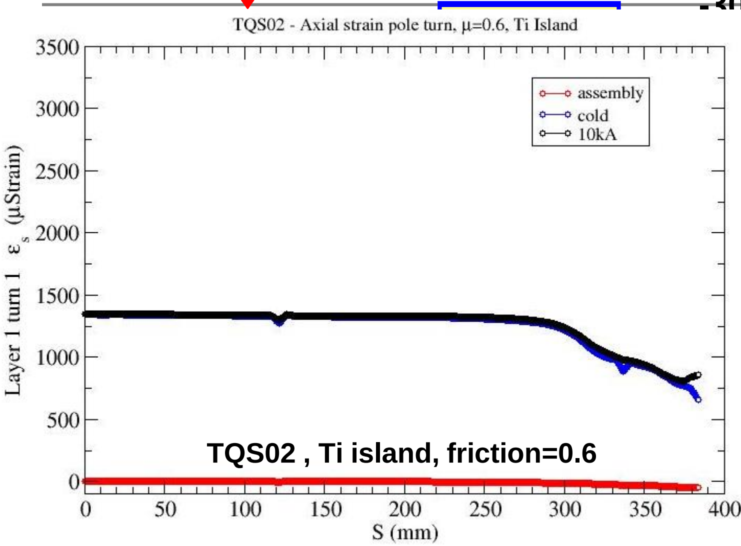
Coil 7

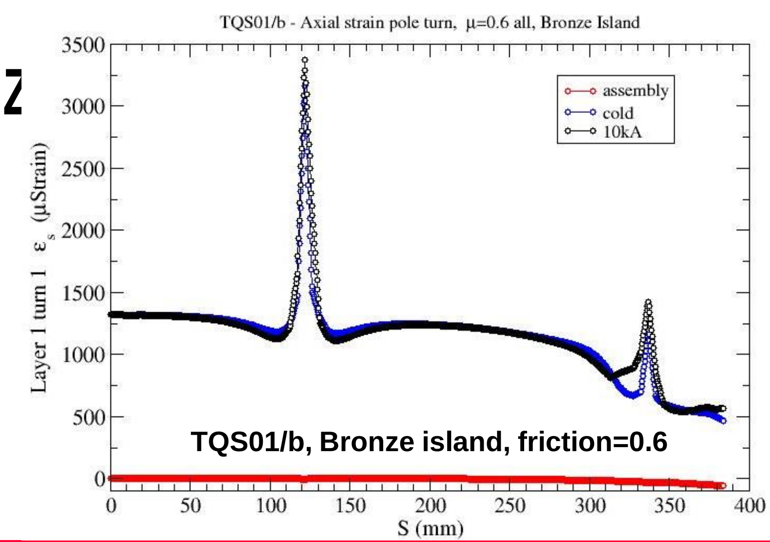


Broken fibers

Conductor axial Strain - Bronze versus Ti



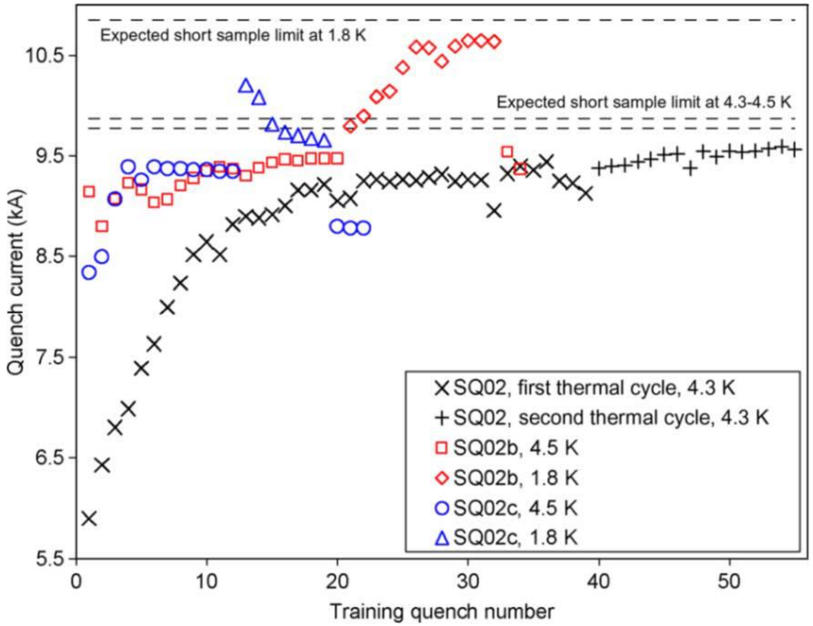


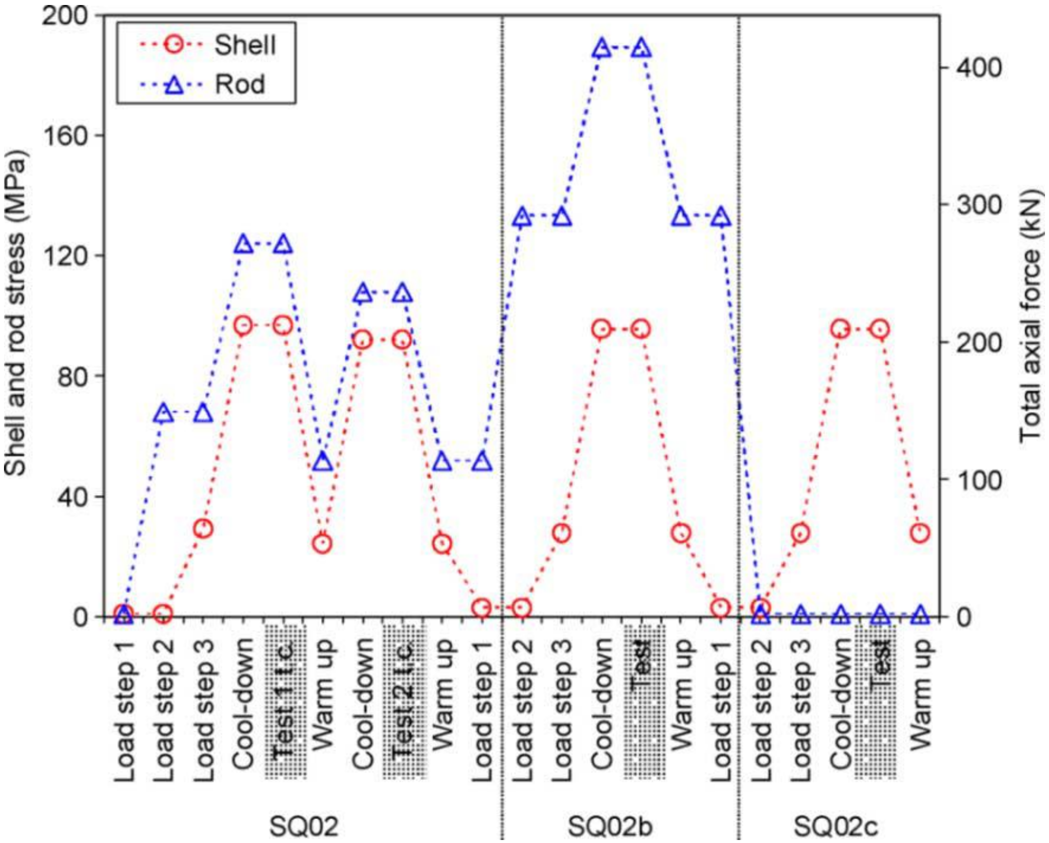


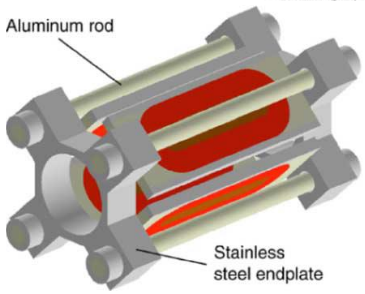
Axial tension in bronze-islands is a source of localized strain in the coil near gaps.

SQ02 axial support system

Fz @ Iss = 0.37 MN/end



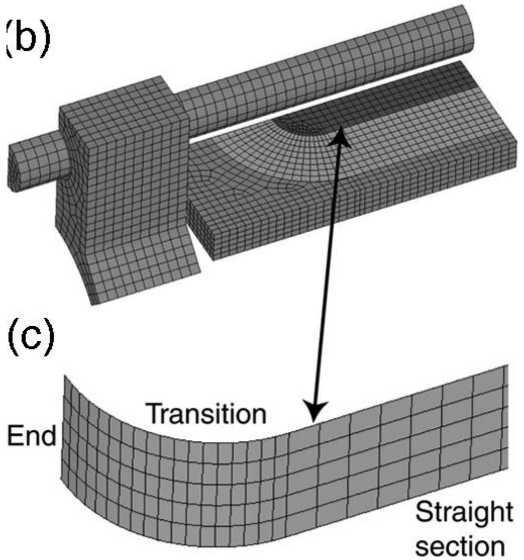




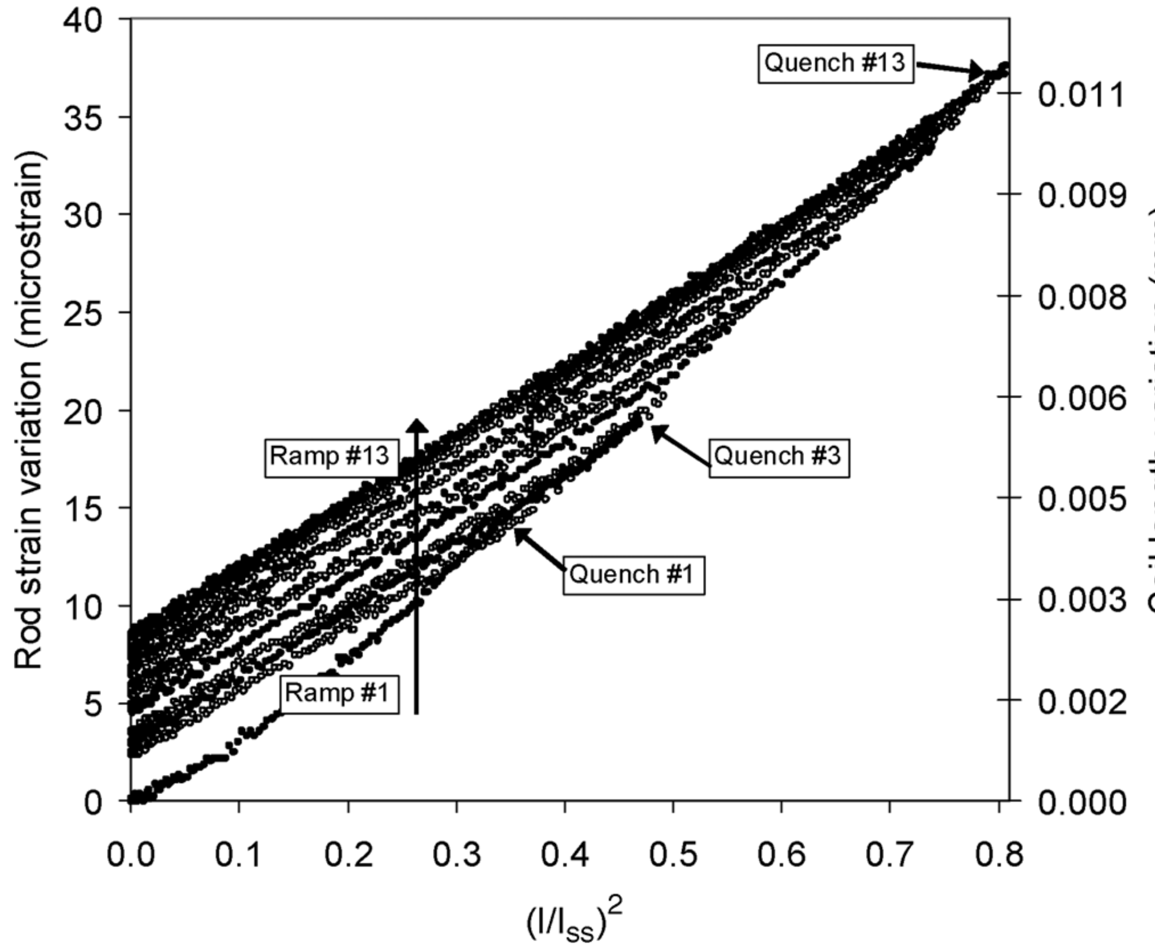
P. Ferracin et al "*Effect of Axial Loading on Quench Performance in Nb3Sn Magnets*"
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 18, NO. 2, JUNE 2008

SQ02 - Ratcheting Model

frictional stress and sliding between coil and island result in an energy dissipation that quench the magnet



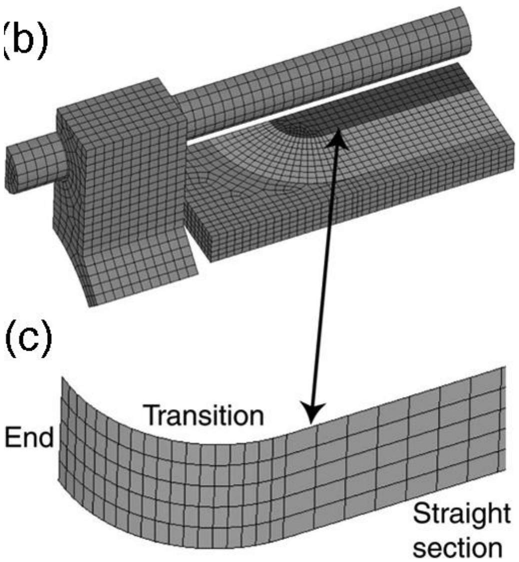
SQ02 geometry with contact region between coil and island



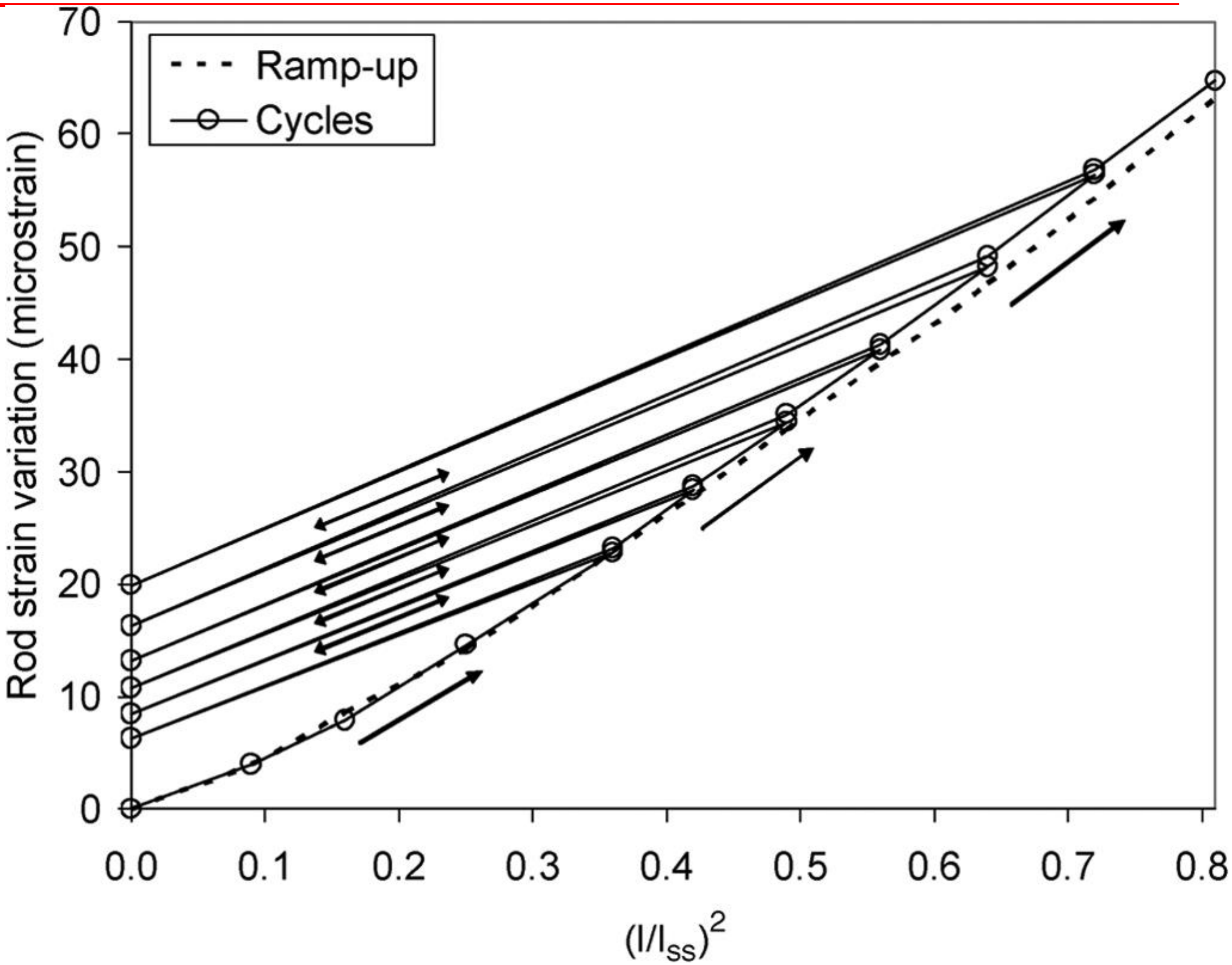
Measured rod strain as a function of the Lorentz force.

P. Ferracin, S. Caspi, and A. F. Lietzke *"Towards Computing Ratcheting and Training in Superconducting Magnets"*
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 17, NO. 2, JUNE 2007

Ratcheting Model

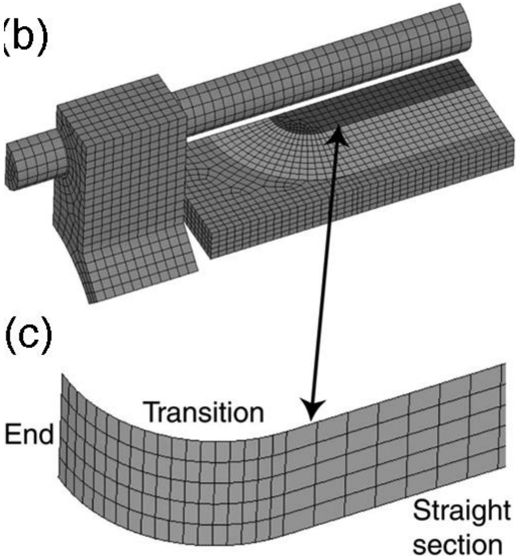


SQ02 geometry with contact region between coil and island

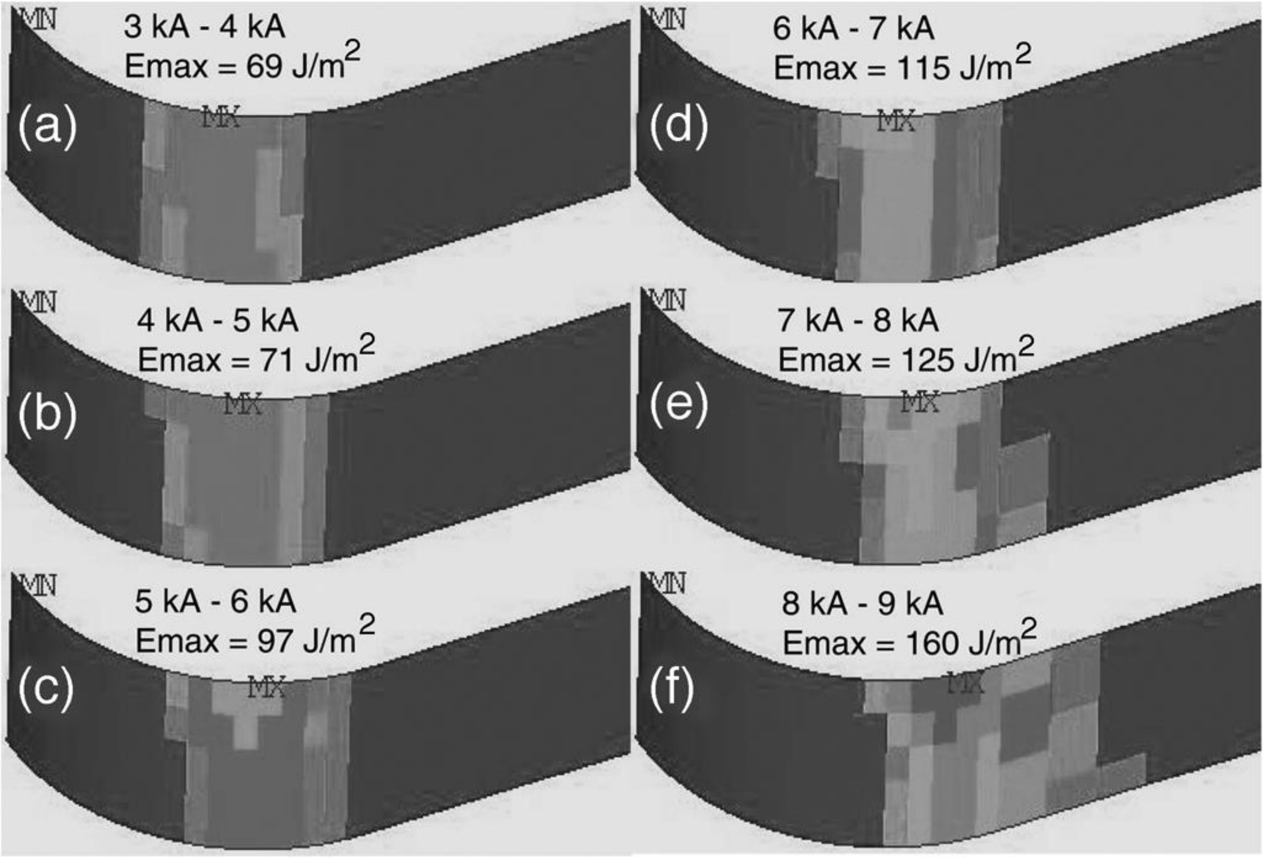


Computed variation of rod strain as a function of the Lorentz force.

Ratcheting Model



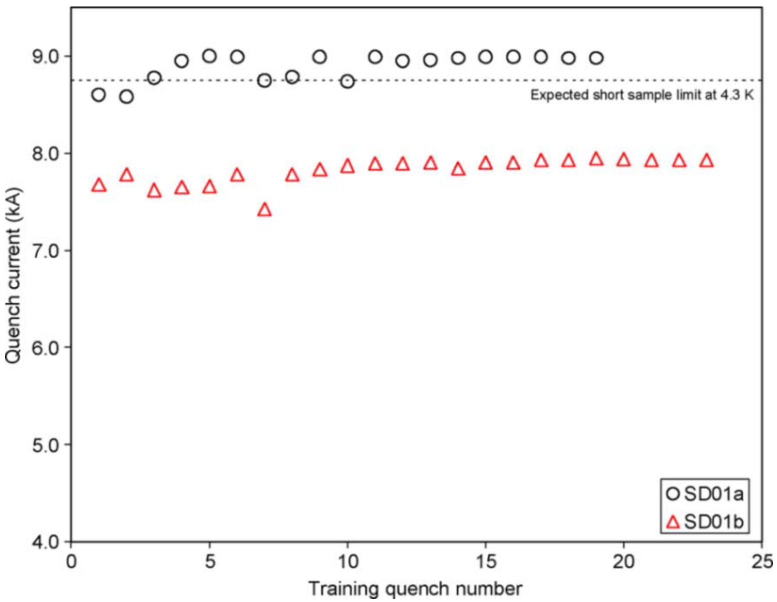
SQ02 geometry with contact region between coil and island

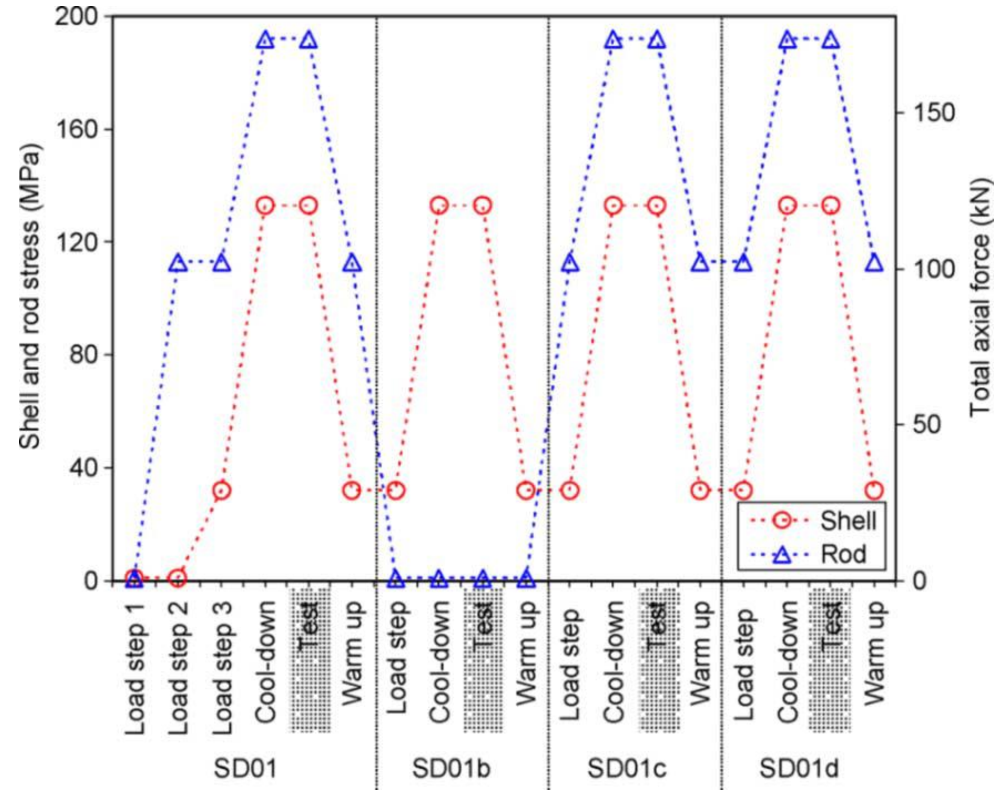


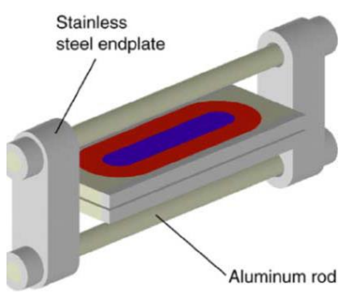
Frictional energy (J/m2) dissipated during excitation from 3 kA to 9 kA in steps of 1 kA. Emax is the peak frictional energy dissipated in one step.

SD01 axial support system

Fz @ Iss = 0.17 MN/end



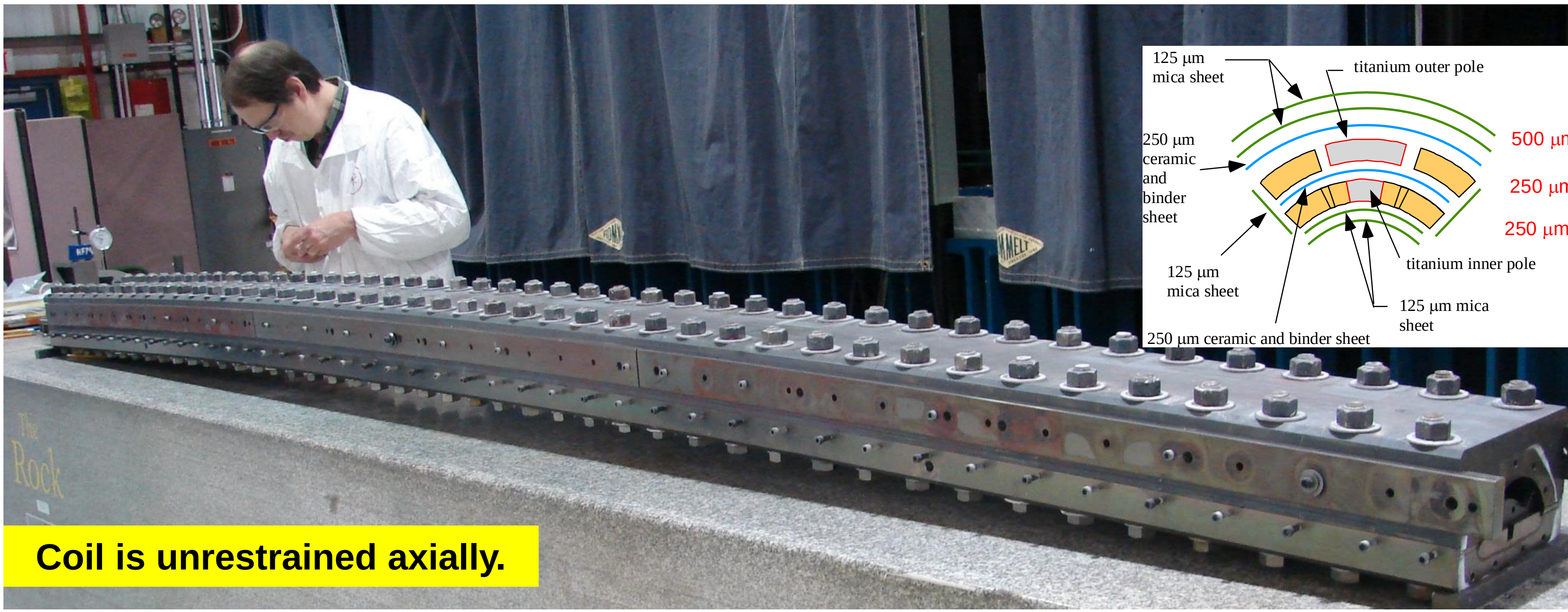




SQ02 ansdSD01 show a clear degradation in training performance with no axial support

LQ – 3.7 m long quad for LARP

A 3.4 mm bowed reaction fixture (using ONE top plate) after heat treatment



Coil is unrestrained axially.

“Development and coil fabrication for the LARP 3.7-m Long Nb3Sn Quadrupole” 19 August 2008

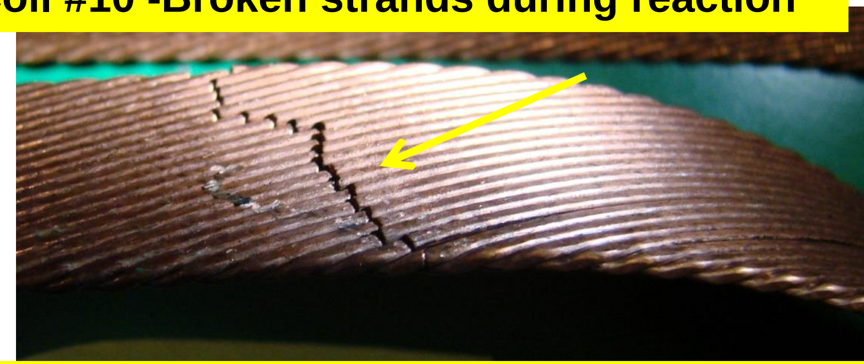
HQ coils after reaction

HQ13

Coil springing out of reaction tooling even with one turn less

What is the impact of winding tension ?

Coil #10 -Broken strands during reaction



No evidence of Sn leak suggests breakage occurred after reaction was completed

CCT3

Cable springing out of mandrel channel
Reaction - Bronze Thermal expansion dominates cable length (~1%)

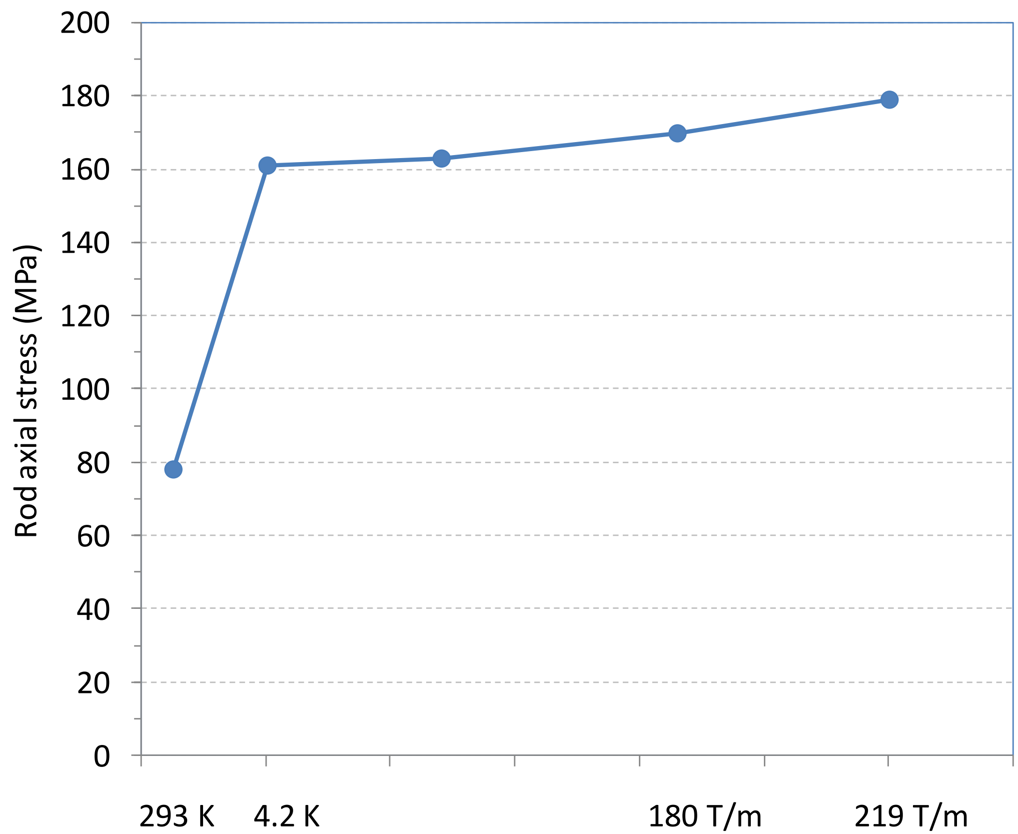
CCT4

Cable remains below surface
with gradual increase in channel size (1.65 mm)

The CCT cable is wound without tension

HQ - 3D mechanical analysis
Aluminum rod tension and coil-pole

- Pre-loading for 219 T/m
  - E.m. force: 1.37 MN
- Pre-loading for 170 T/m
  - E.m. force: 0.82 MN
  - 620 kN applied at 4.2 K



•120 mm bore
1.9 K - 219 T/m, 14.9 T

Mechanical analysis
Axial stress in the pole

Measured

Measured Strain and Stress at 4.5K (300K)

Location Type	Symbol Unit	TQS01a	TQS01b	TQS01c	TQS02a
Rod Strain	ε_z $\mu\varepsilon$	+1435 (+555)	+1475 (+550)	+1400 (+600)	+1118 (+150)
Rod Stress	σ_z MPa	+113 (+44)	+117 (+44)	+110 +47	+88 (+12)

- **TQS01a - Bronze islands**
- **TQS02a - Titanium islands**

Calculated

TQS01 Stress-Strain Calculations

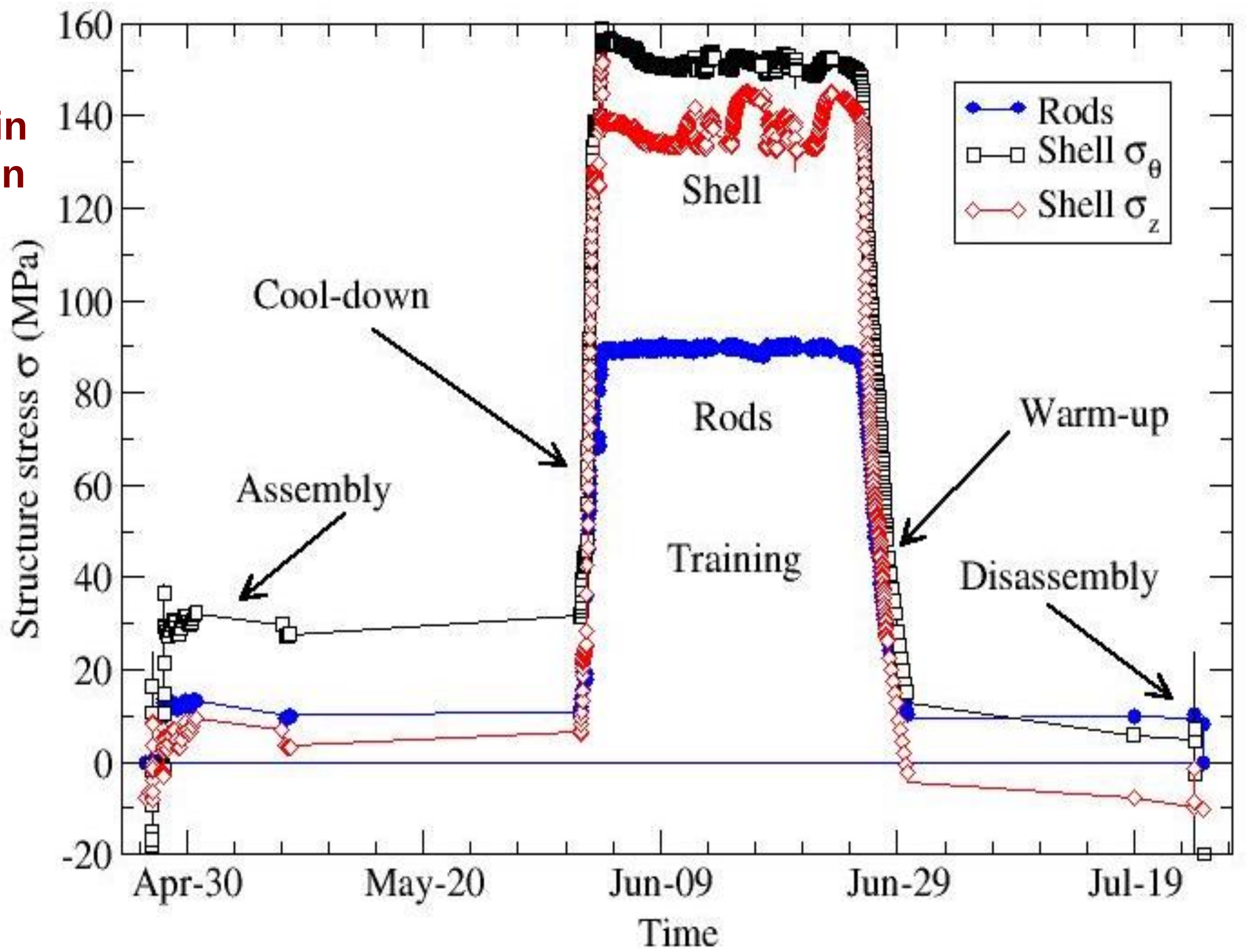
ANSYS	Stress (MPa)		Strain ($\mu\varepsilon$)	
	300 K	4.4 K	300 K	4.4 K
Rods axial Z	+37	+128	+527	+1618
Island axial Z	-43	+25	-250	+765
Turn 1 (layer 1) z	-20	+12	-250	+1000

TQS02 Stress-Strain Calculations

ANSYS	Stress (MPa)		Strain ($\mu\varepsilon$)	
	300 K	4.4 K	300 K	4.4 K
Rods axial Z	+15	+110	+208	+1398
Island axial Z	-17	-77	-18	-290
Turn 1 (layer 1) z	-10	+12	-19	+1312

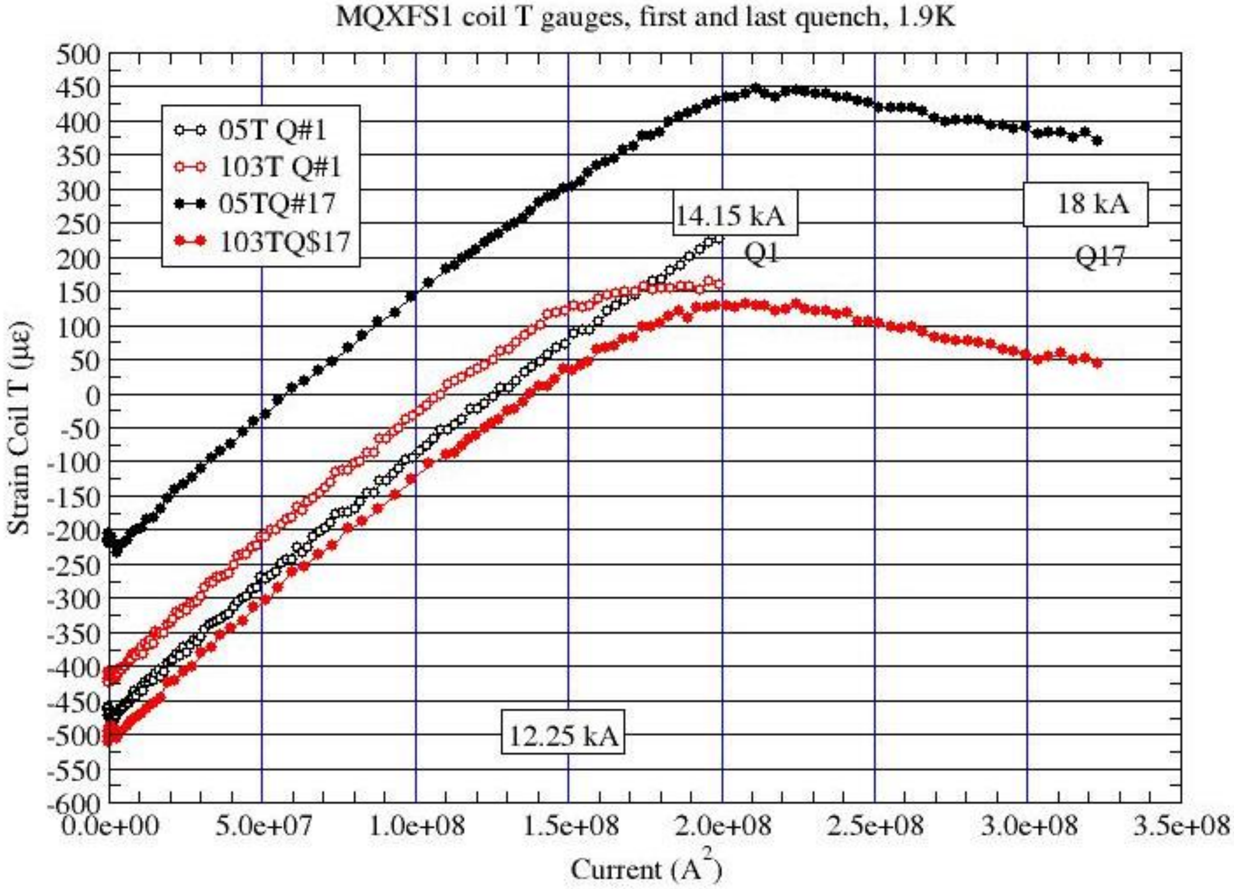
Mechanical analysis TQS02

Shell and rods maintain stress during operation



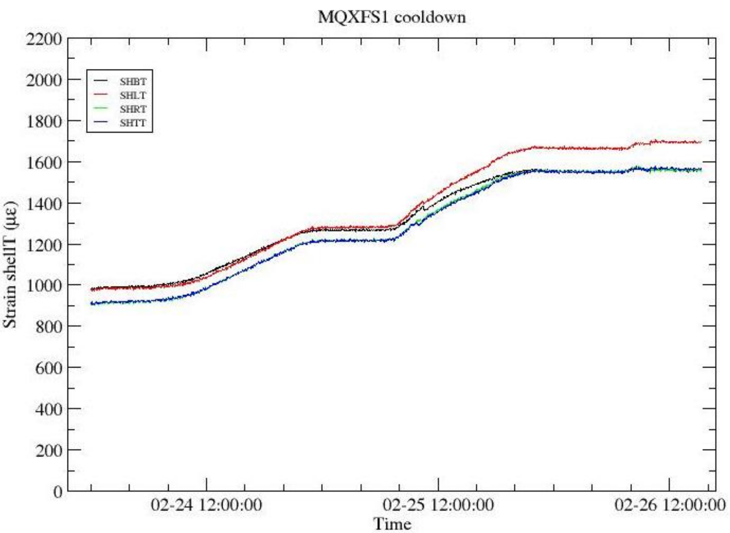
<u>**Coils Island**</u> azimuthal gauges (150mm MQXF)

- **Strain should behave linear with I^2**
- **Coils tare away from poles when pre-stress is insuffecient**

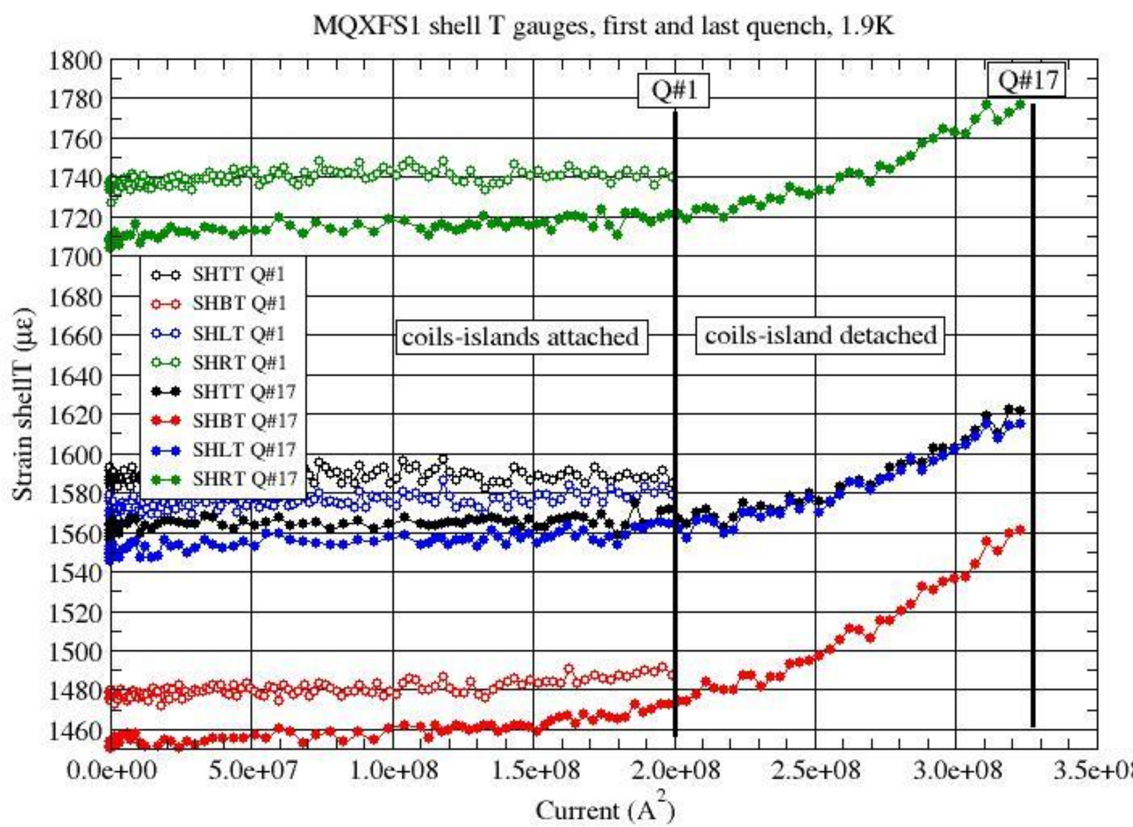


Shell azimuthal gauges (150mm MQXF)

- Strain should behave linear with I^2
- Shell azimuthal strain should not change as long as coils-islands are bonded
- Shell strain increases once detachment takes place



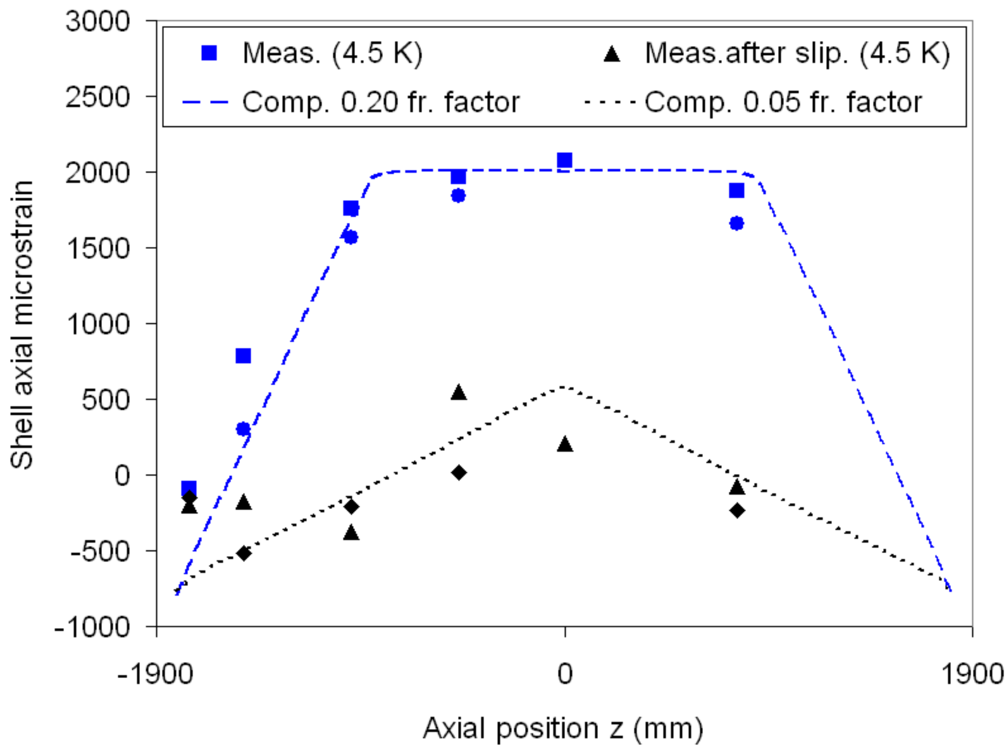
Cool-down



LRS01 Axial strain – long magnets

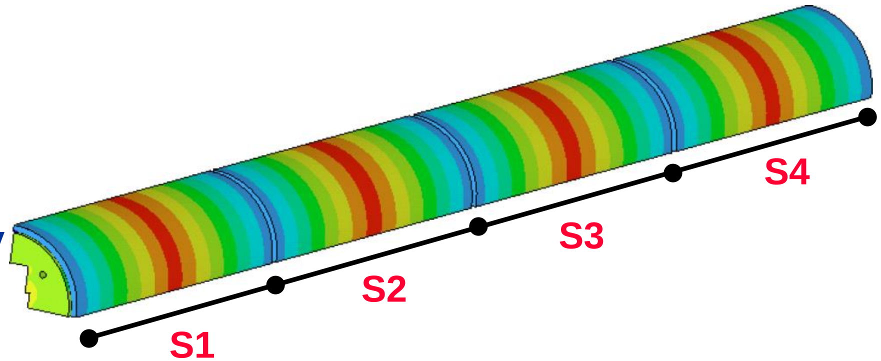
- Shell shrinks more than yoke
- **Friction limits the shell contractions**

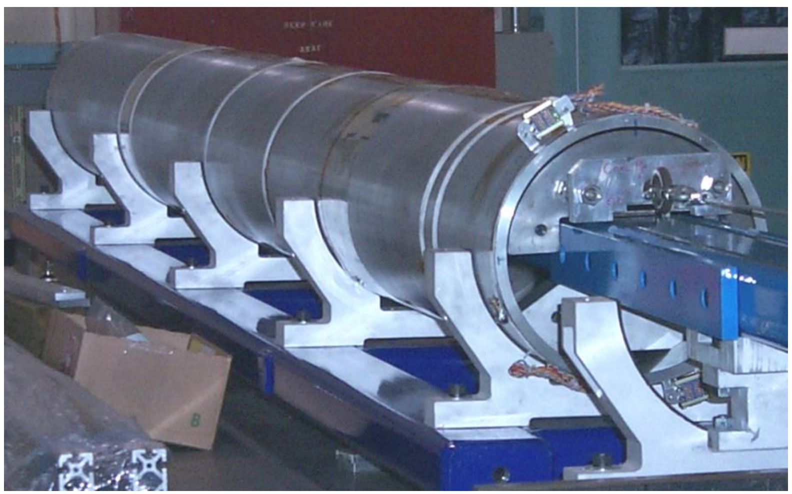
- Strain at 4.5 K consistent with 0.2 friction model results
- During excitation e.m. forces induced slippage



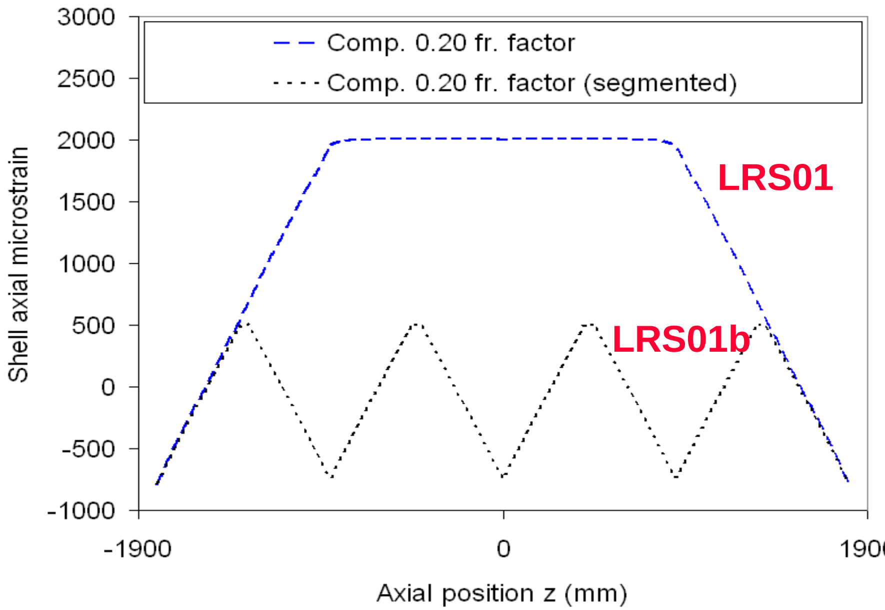
Segmented Shell in LRS02

- 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



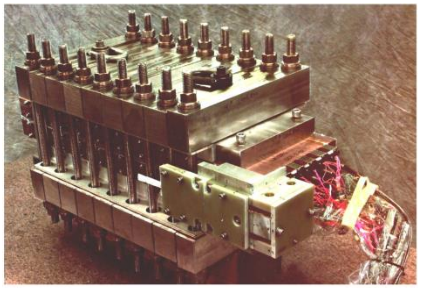


Structure re-assembly with segmented shell



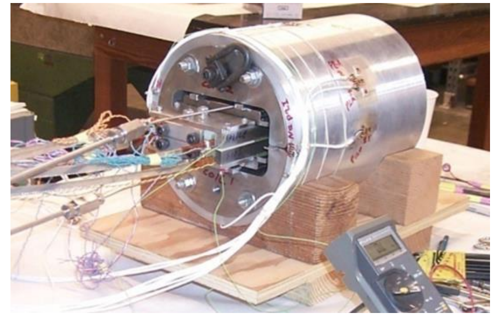
THANK YOU

The road to shell structures at LBNL



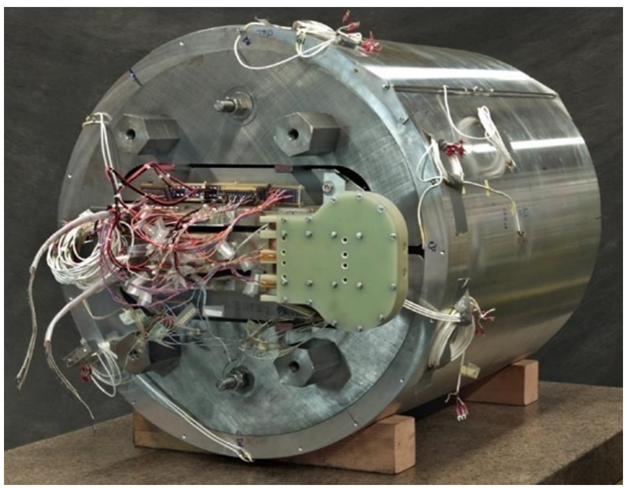
RD2 - 6 Tesla

RT1 - 12 Tesla

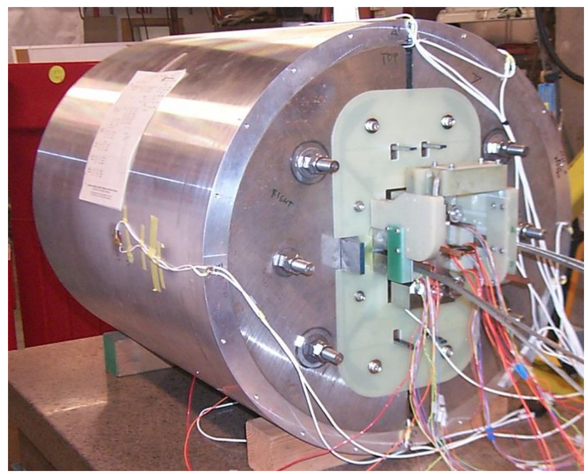


SM-01 - 12 Tesla

•SQ01 short quad



RD3-b - 14.5 Tesla



HD1 - 16 Tesla

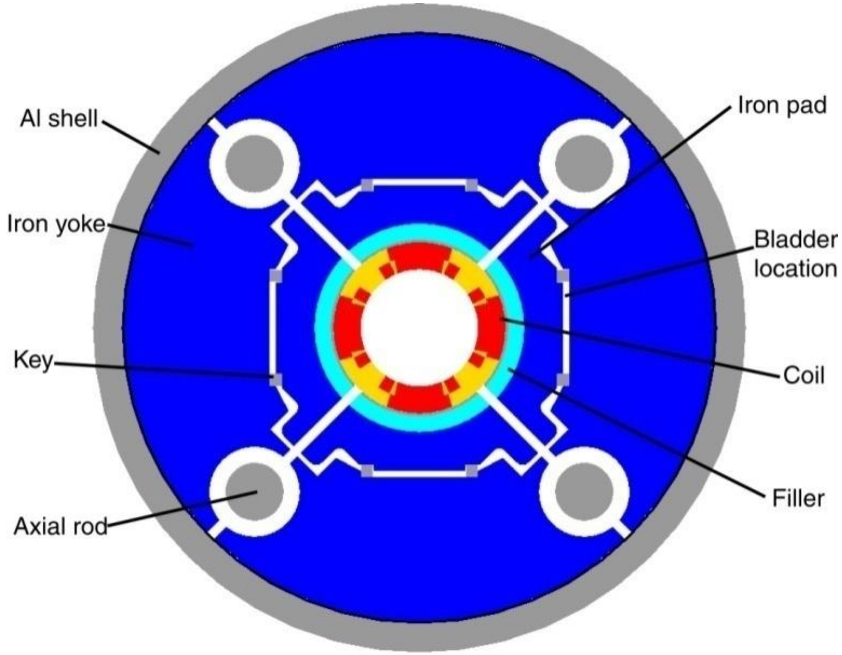
•TQS, quad

LR01 3.6 m long cc, 11.5 T, (2007)

Technology Quadrupole Shell - TQS

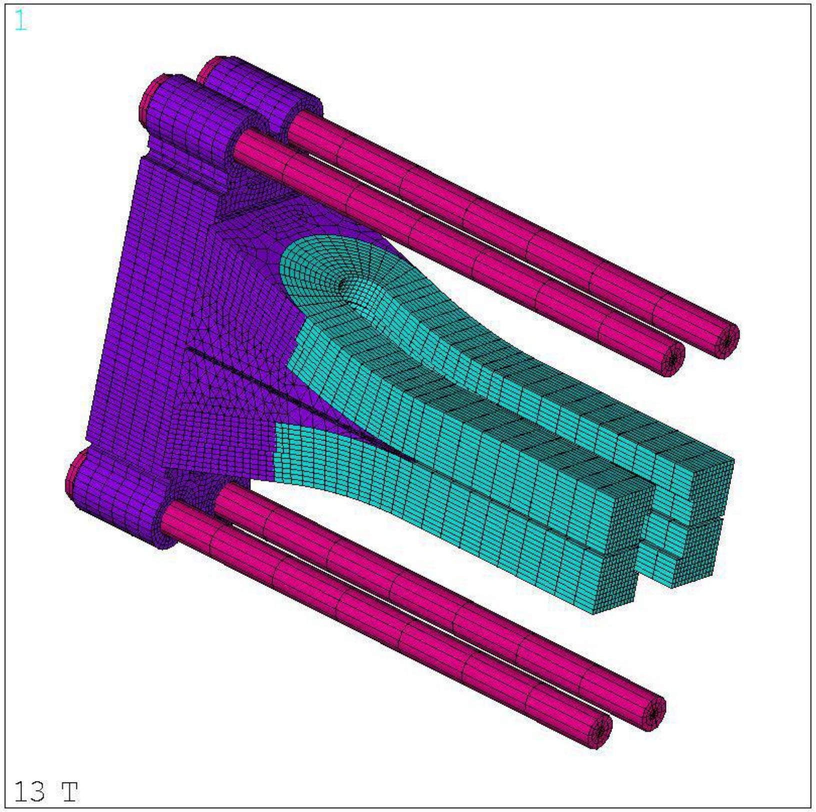
- Aluminum shell over iron yoke
- Assembly with bladders and keys

1. Low pre-stress during assembly
2. High pre-stress with cool-down
3. Reusable structural components



3D mechanical analysis
Axial pre-load

- E.m. axial force
  - 2.8 MN
- Room temperature pre-load
  - Rod stress: 150 MPa
  - 1.7 MN
  - Provided by 150-200 t piston
- 4.2 K pre-load
  - Rod stress: 260 MPa
  - 2.8 MN
  - Provided to end-shoes and wedge (glued)



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March 2012