Shell-based Support Structures for Nb_3Sn Accelerator Quadrupole Magnets

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U.S. LARP

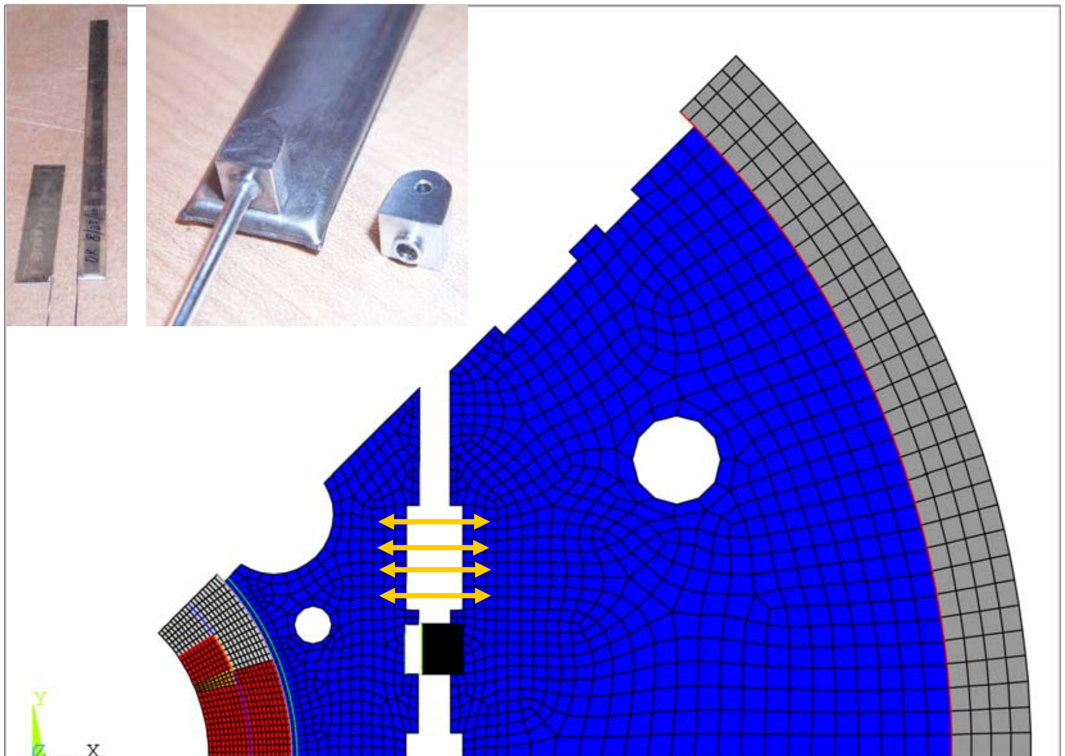
Outline

- Introduction: shell based support structures
- Principles of operation
- Overview of LARP shell-base structures
- Assembly, cool-down effect and excitation
- Axial support
- Length scale-up
  - Shell axial strain
  - Flexural rigidity and LHe containment
- Alignment
- Conclusions

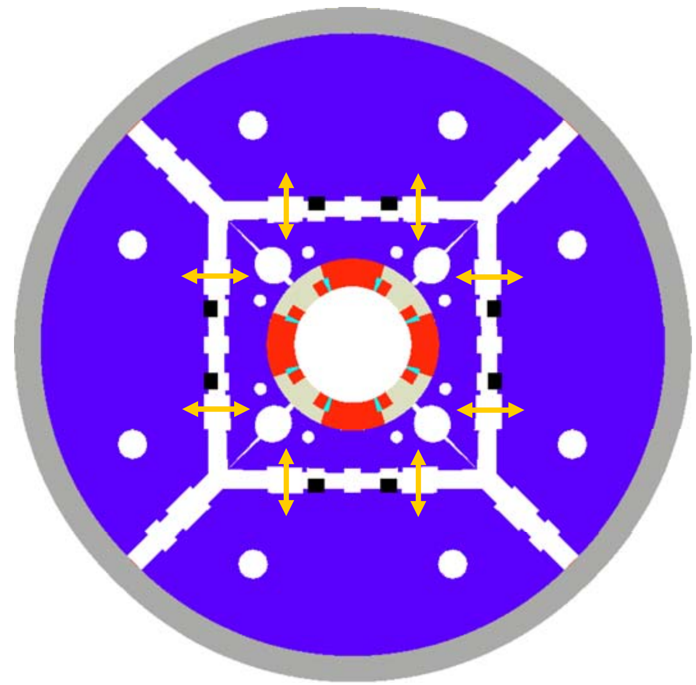
Introduction
Shell based support structure

- Shell-based structures
  - Aluminum segmented shell (solid tube)
  - 4-piece yoke with open gaps during operation
  - Assembly through two sub-assemblies
  - Pre-loading with water pressurized bladders
  - Maximum stress reached after cool-down
  - Axial coil support by end-plate and axial rods
- The concept has been adopted to cope with the requirements of high field (high forces) Nb_3Sn (brittle conductor) magnets
  - Capability of providing large forces
  - Precise control of coil pre-load
- Through LARP Magnet R&D → accelerator quality features

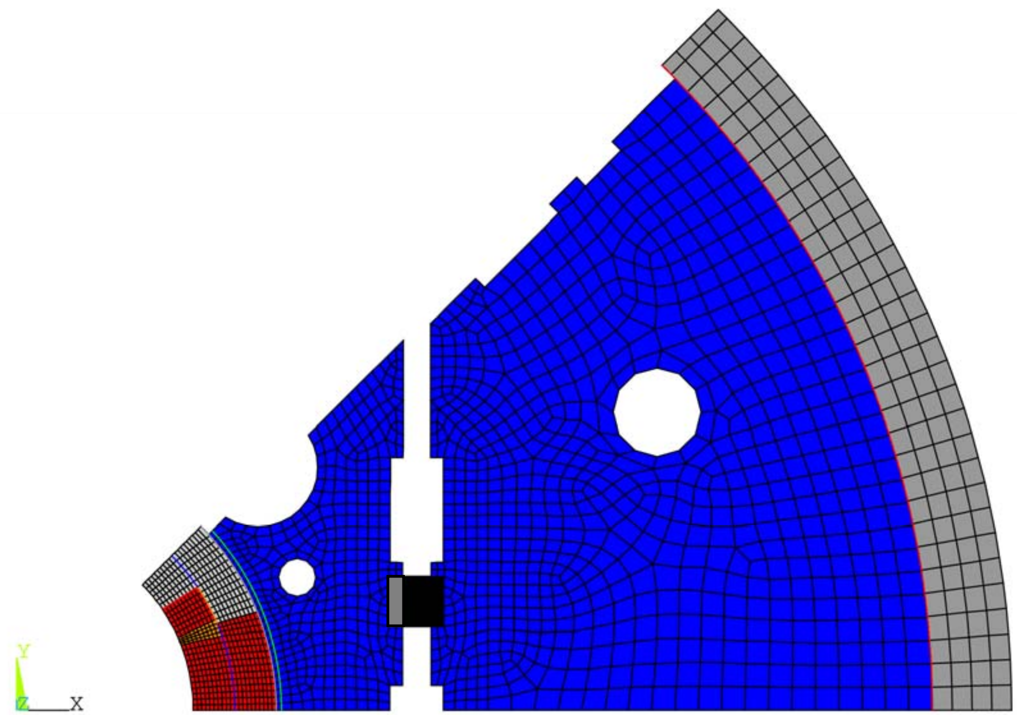
Principles of operation
Bladder pressurization



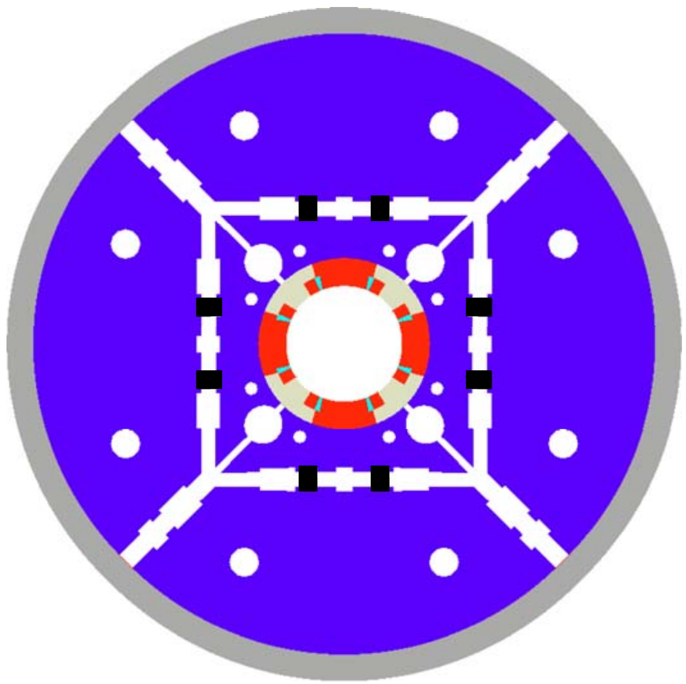
Deform. shape with displ. scaling = 20



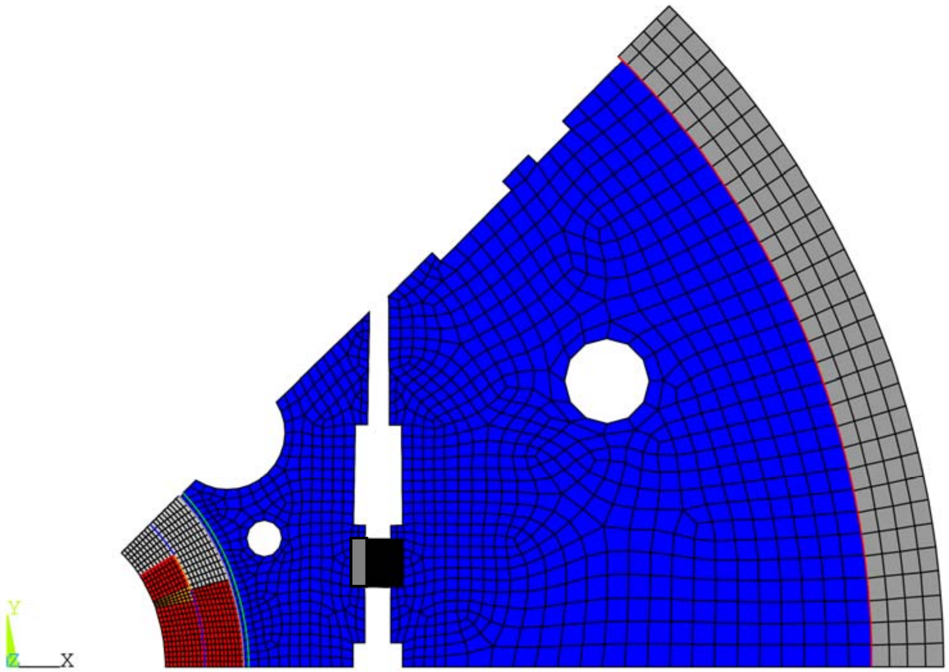
Principles of operation
Key insertion and bladder deflation



Deform. shape with
displ. scaling = 20



Principles of operation
Cool-down



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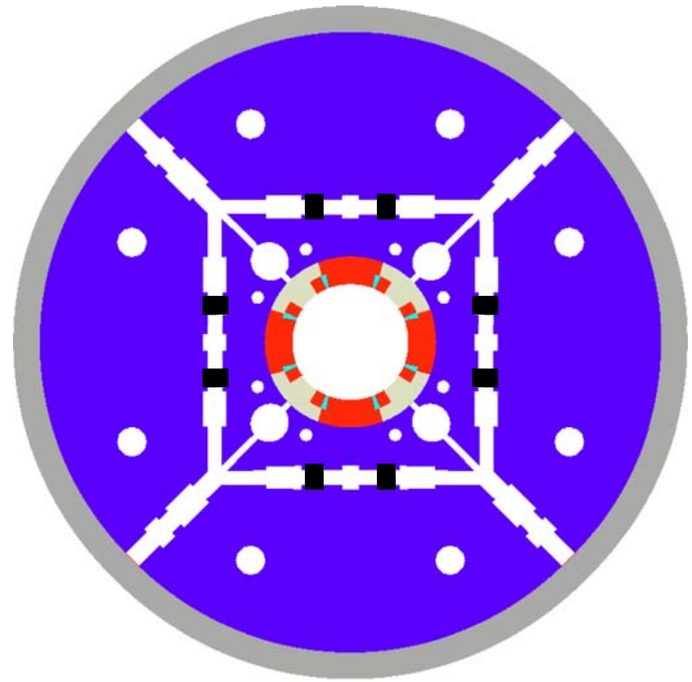
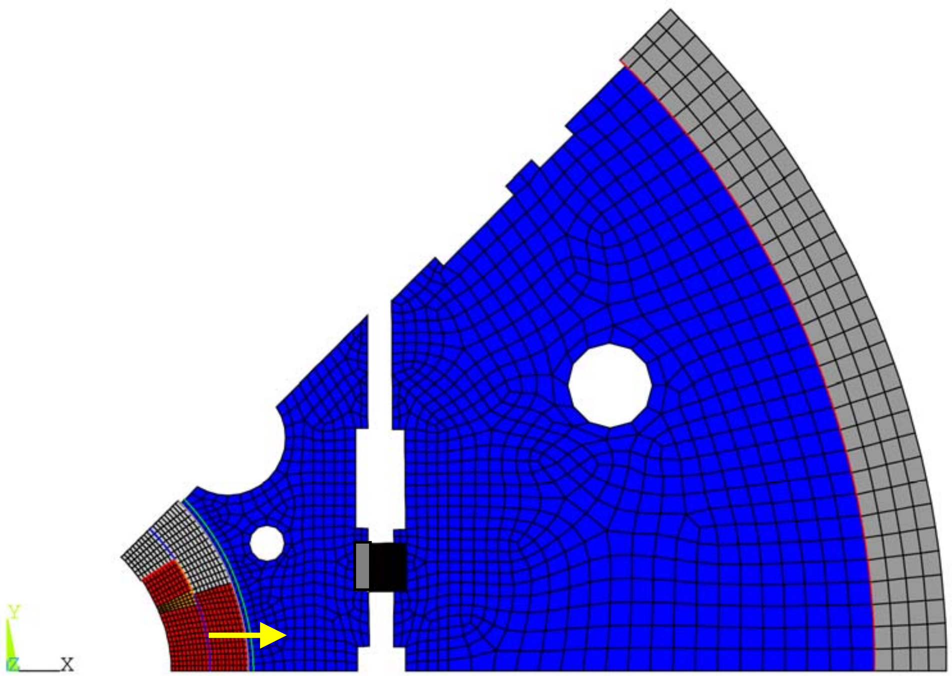
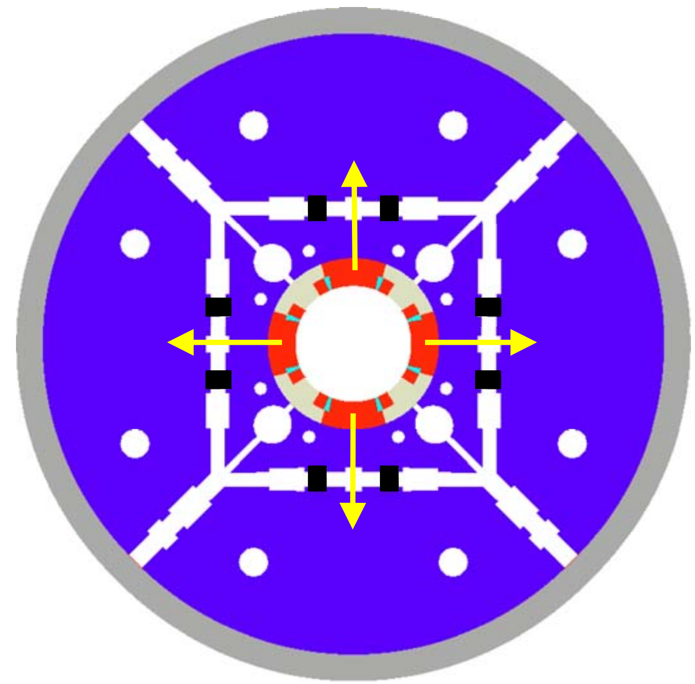


Principles of operation
Excitation

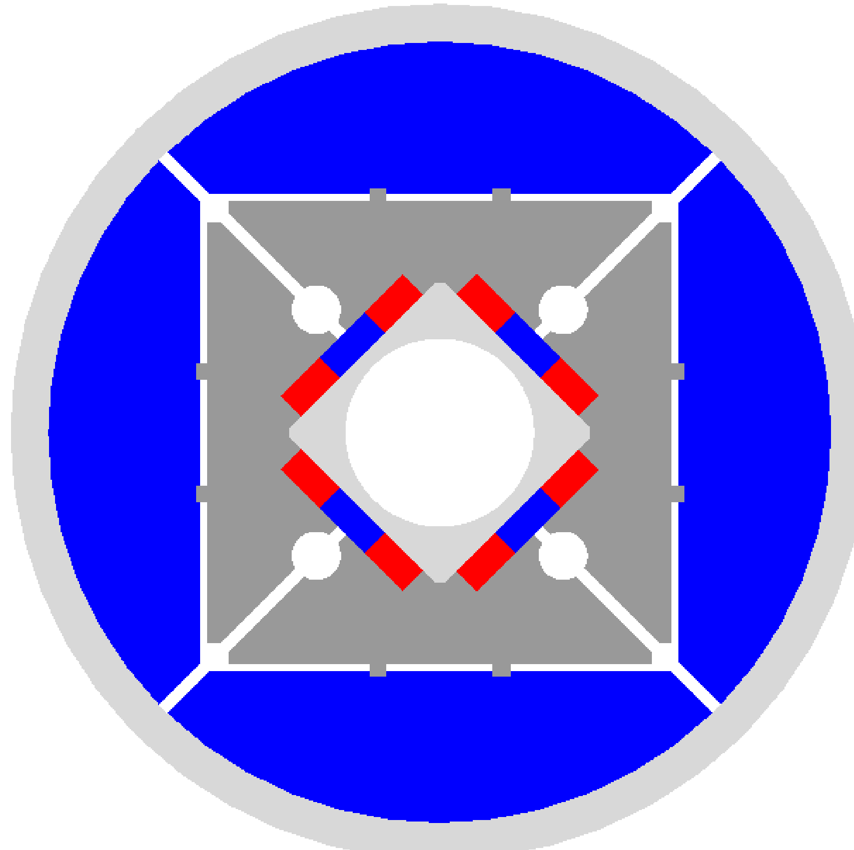




Deform. shape with displ. scaling = 20

Overview of LARP shell-base structures
Subscale quadrupole (SQ)

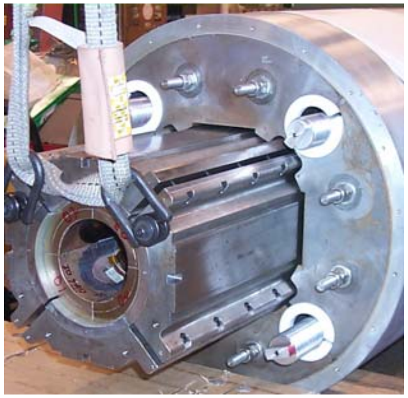
- 2005: first racetrack quad. in a shell-based structure
- 0.3 m long
- Bore-coil aperture: 110-130 mm
- I_{max} (SQ02b, 1.9 K) = 98% I_{ss}
- B_{peax_max}: 11.8 T
- G_{max}: 89 T/m
- Structure components aligned

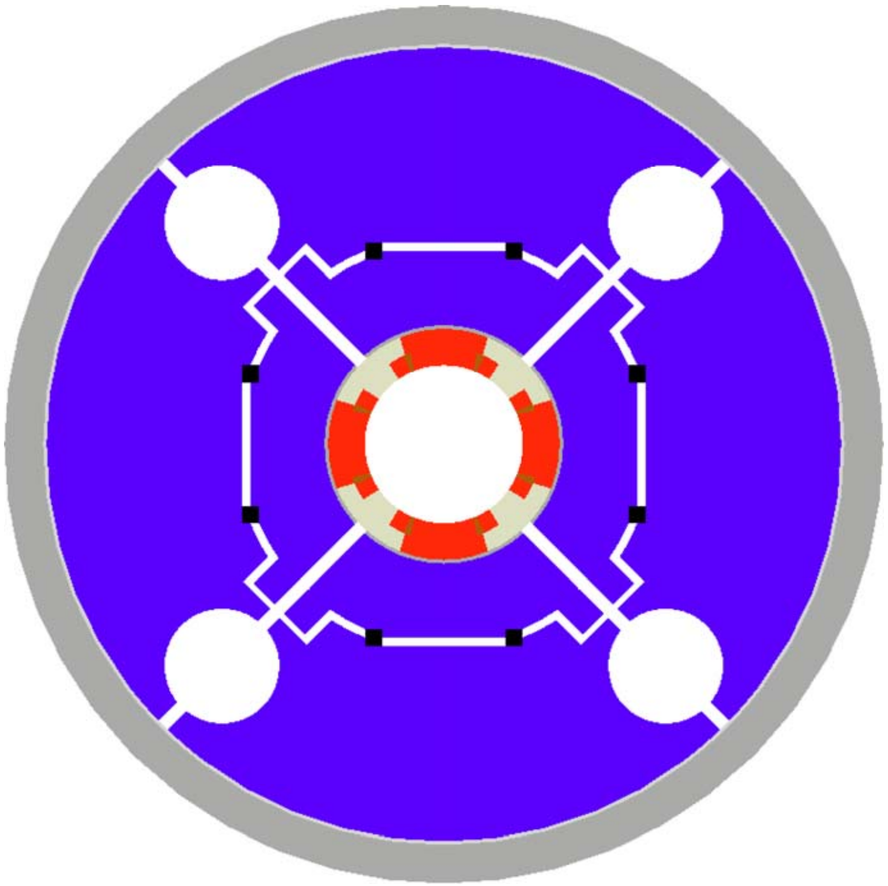


Coils: LBNL
Structure: LBNL
Test: LBNL, FNAL

Overview of LARP shell-base structures Technology quadrupole (TQS)

- 2006: First cos-theta quad. in a shell-based structure
- 1 m long
- Bore-coil aperture: 90 mm
- I_{max} (TQS02a, 4.5 K) = 90% I_{ss}
- B_{peax_max}: 11.2 T
- G_{max}: 220 T/m
- No alignment

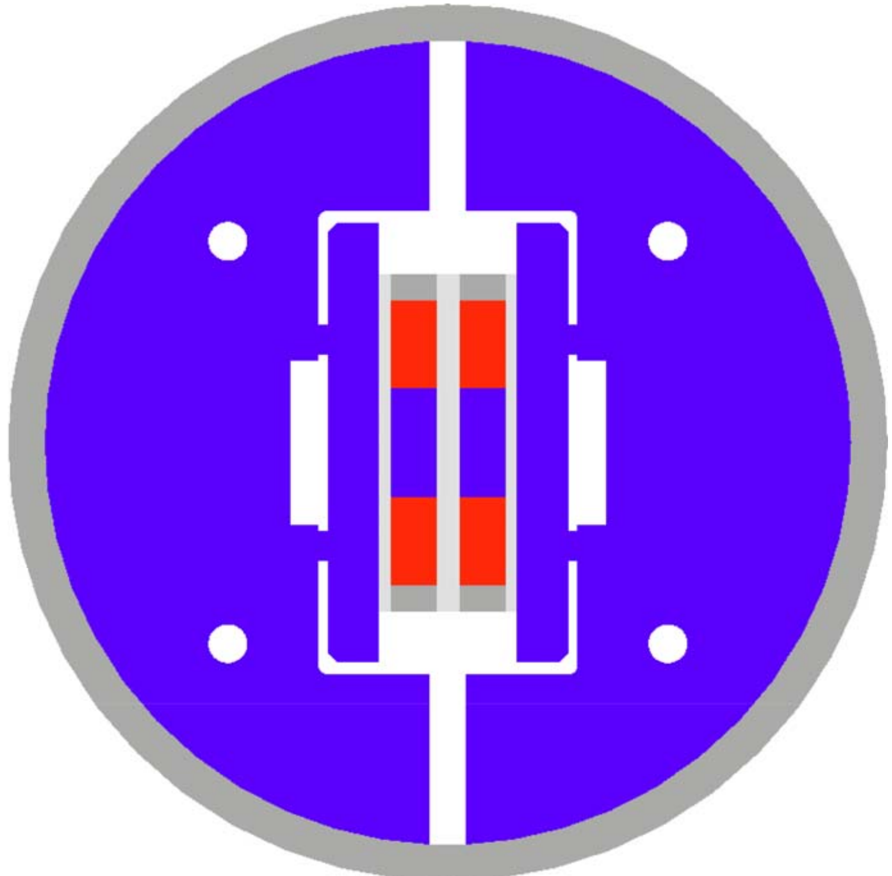




Coils: FNAL, LBNL
Structure: LBNL
Test: LBNL, FNAL

Overview of LARP shell-base structures
Long Racetrack (LRS)

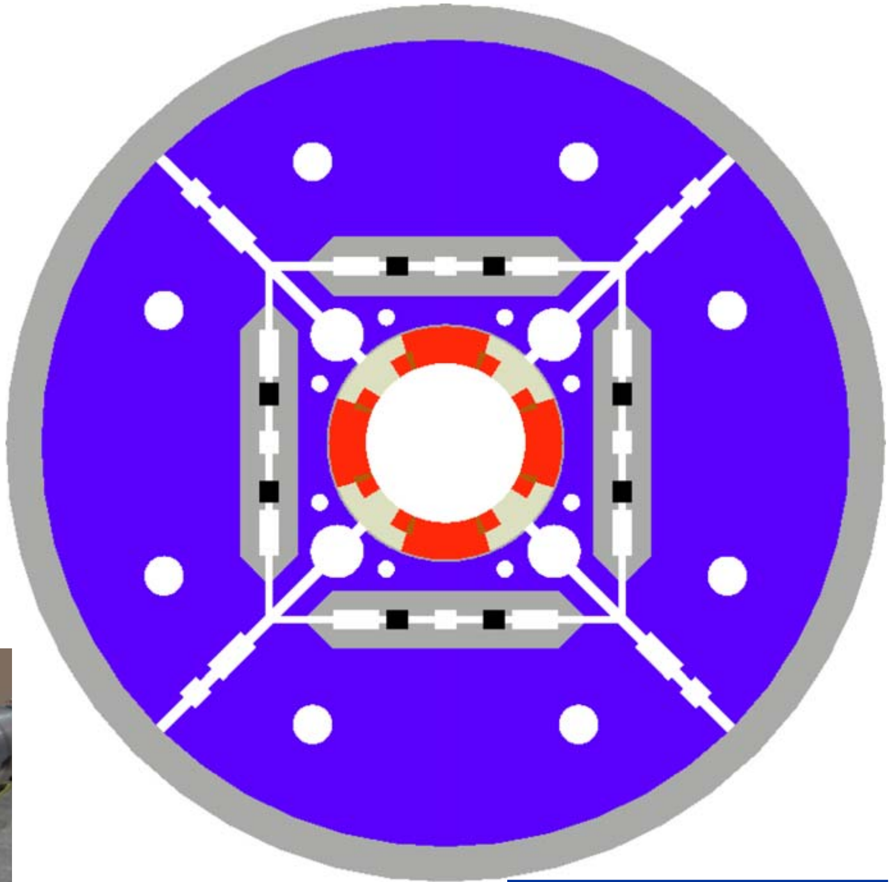
- 2007: first long racetrack dipole in a shell-based structure
- Common-coil configuration
- 3.6 m long
- I_{max} (LRS02, 4.5 K) = 96% I_{ss}
- B_{peax_max}: 11.5 T
- No alignment

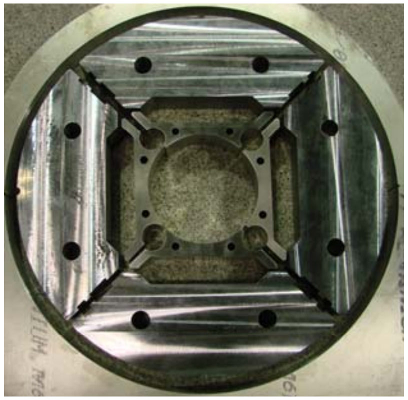


Coils: BNL
Structure: LBNL
Test: BNL

Overview of LARP shell-base structures Long Quadrupole (LQS)

- 2008 (under construction): first long cos-theta quad. in a shell-based structure
- 3.6 m long
- I_{ss} (4.5 K) = 13.8 kA
- B_{peax_ss}: 12.3 T
- G_{ss}: 240 T/m
- Structure components aligned

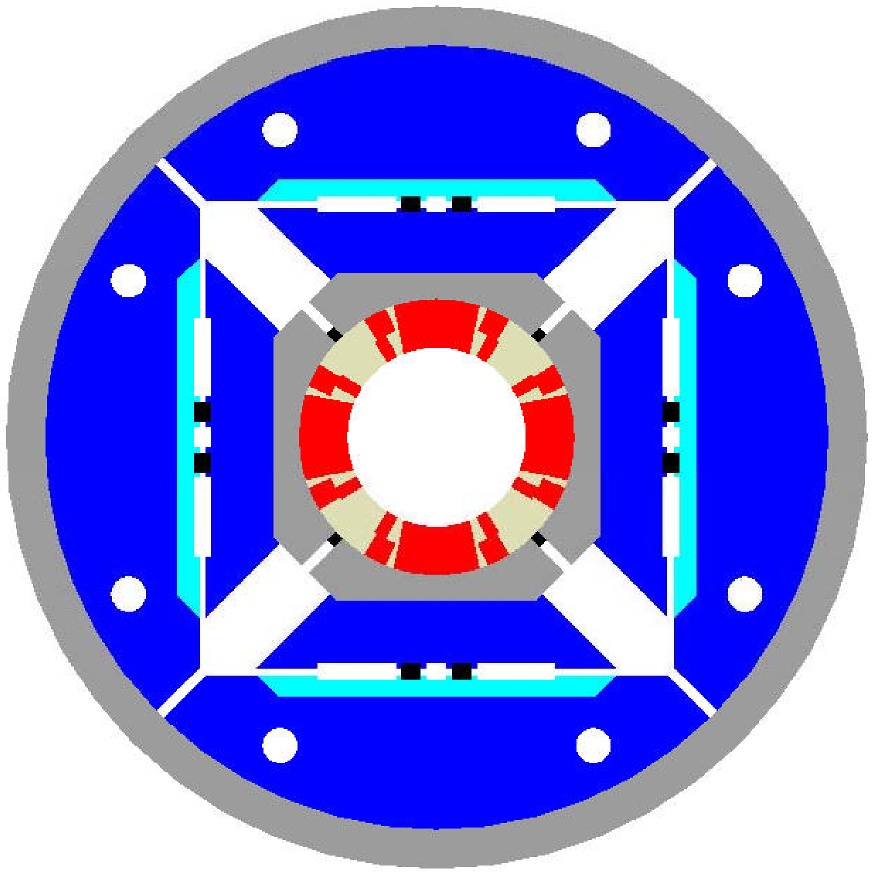




Coils: FNAL, BNL
Structure: LBNL
Test: FNAL

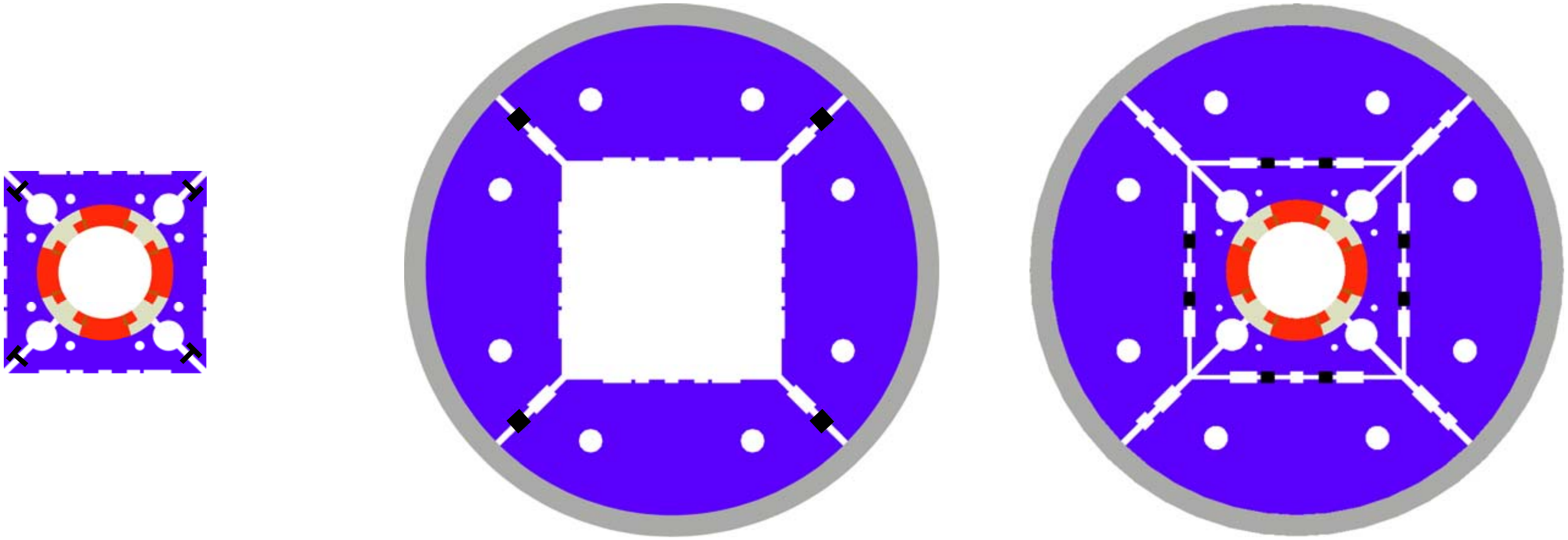
Overview of LARP shell-base structures High Field Quadrupole (HQ)

- 2008-2010 (under development)
- High coil field and forces
  - From 11-12 T to 15 T
- Include accelerator quality features required for the LHC luminosity upgrade
  - Large aperture
  - Alignment and field quality
  - Cooling channels and LHe containment
- First 1 m long model test planned for September 2009



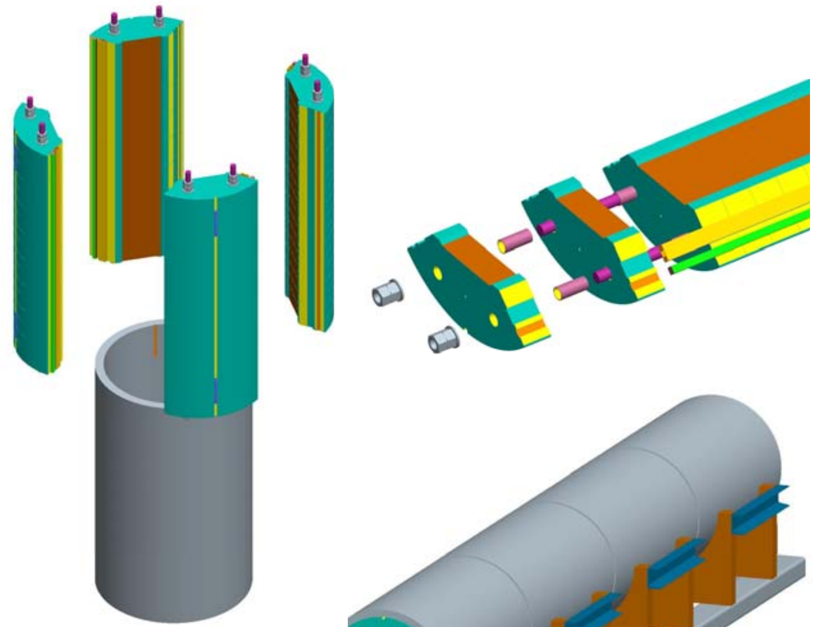
Assembly (I)

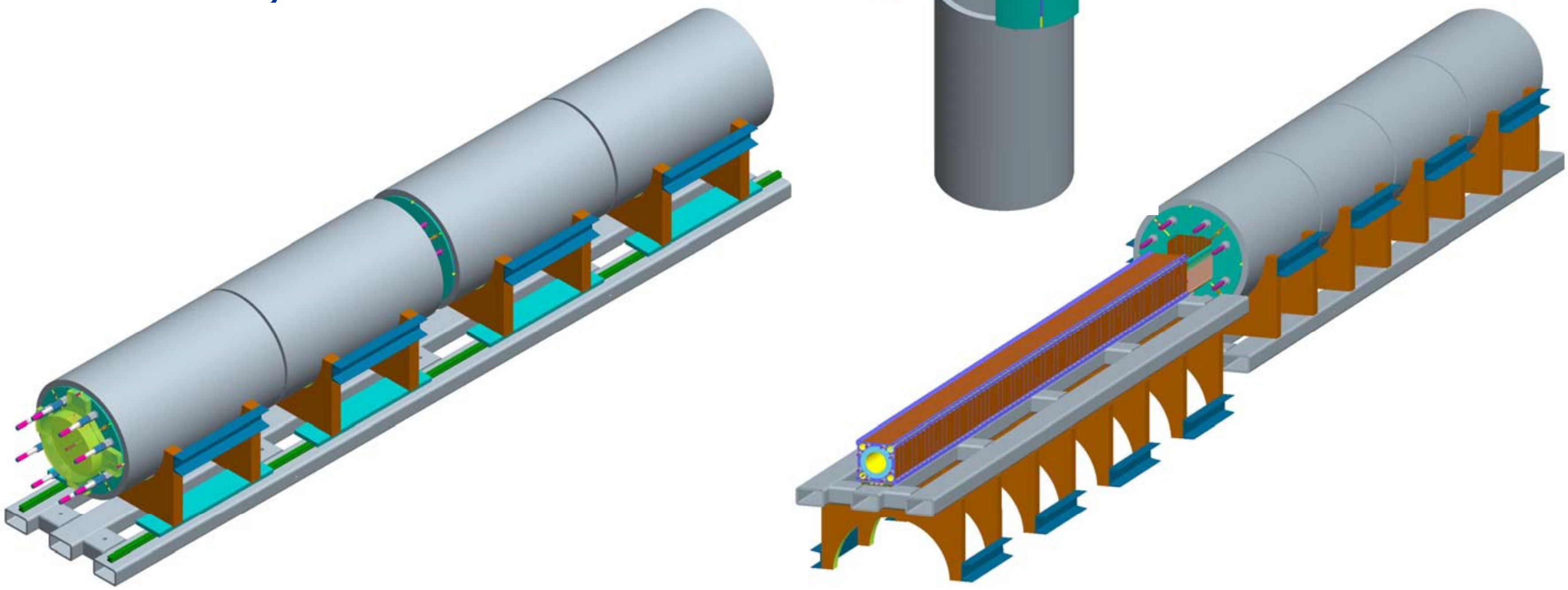
- Coil-pad sub-assembly
  - Pads bolted around the coil
  - Bolts “disappear” under compression
- Yoke-shell sub-assembly
  - Gap keys keep yoke stacks apart and pre-tension the shell



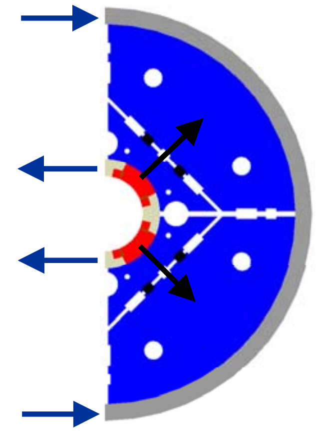
Assembly (II)

- Assembly of 4 single shell-yoke sub-assemblies
- Connection of shell-yoke sub-assemblies with tie rods
- Insertion of coil-pad sub-assembly

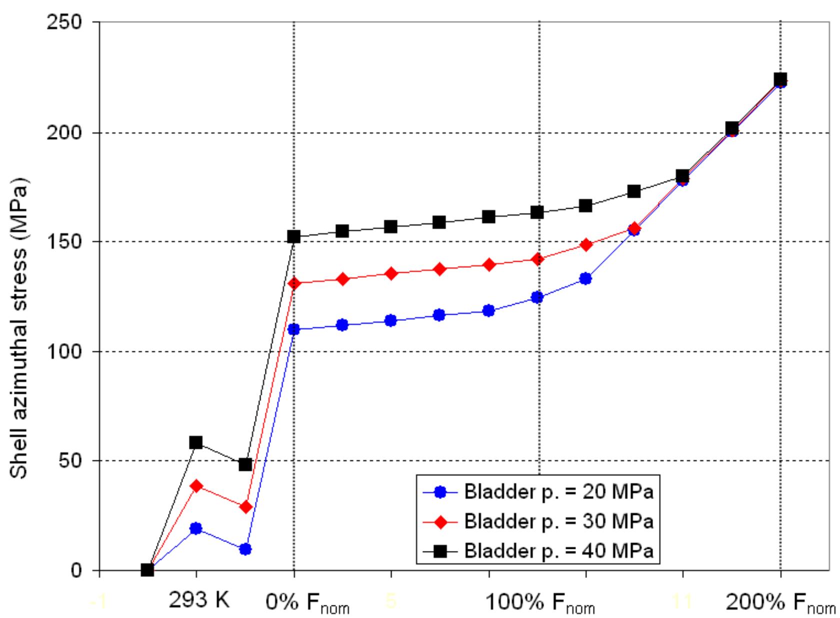


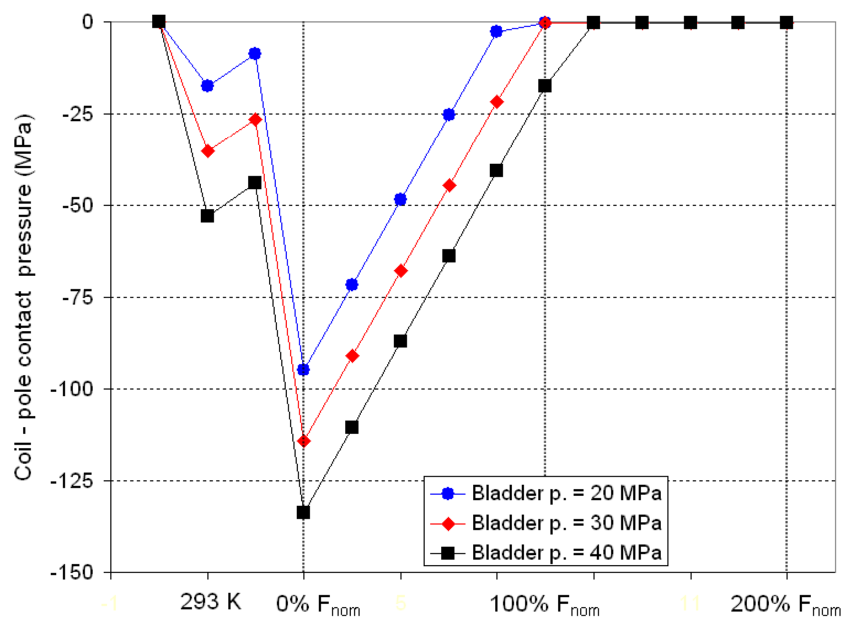


Cool-down effect and excitation



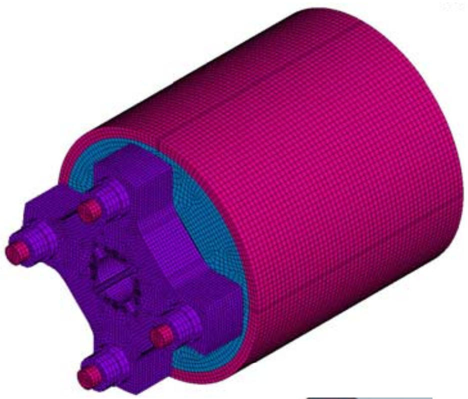
- All the force transferred to the coil (yoke gaps open)
- Increase of shell stress $\Delta\sigma_{shell} \propto \alpha_{shell} - \alpha_{yoke}$ (offset)
- With coil under compression, during excitations to F_{nom}
  - 10 MPa increase of shell tension
- With coil – pole separation: increase of shell tension

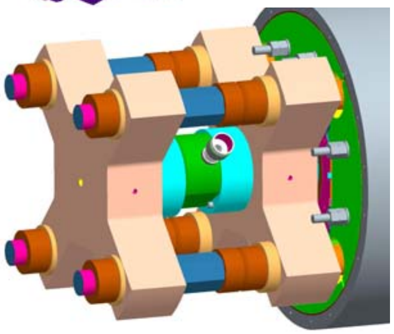


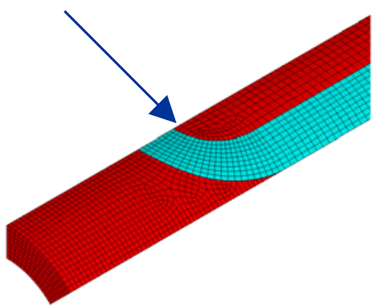


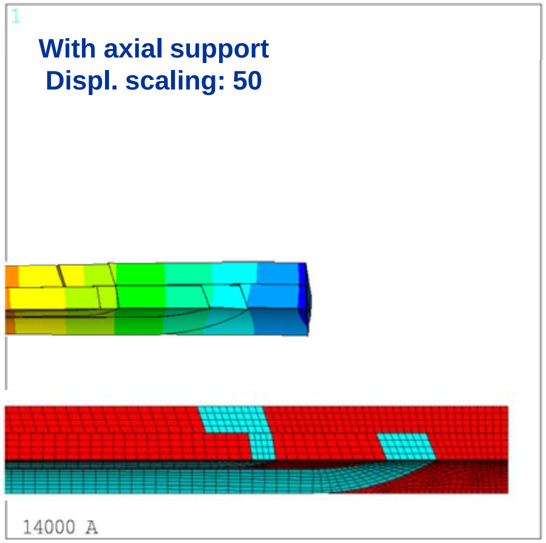
Axial support

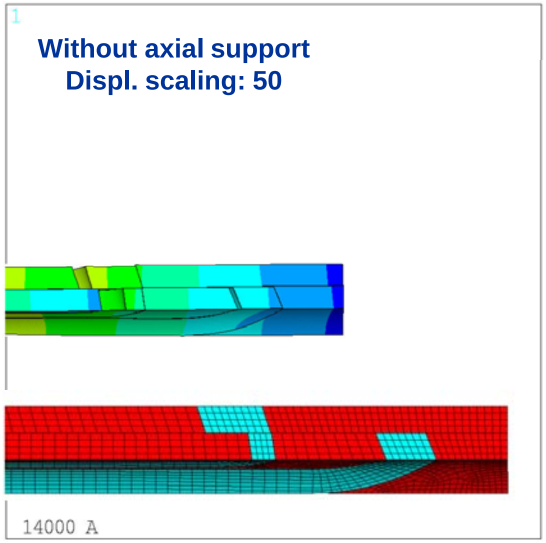
- Same approach as in the straight section
  - Pre-load aimed at minimizing coil – pole separation in the end (based on computations)
- Four aluminum (or stainless steel) axial rods connected to an end plate
  - Increase of rod tension during cool-down
- Pre-load obtained with piston and additional plate







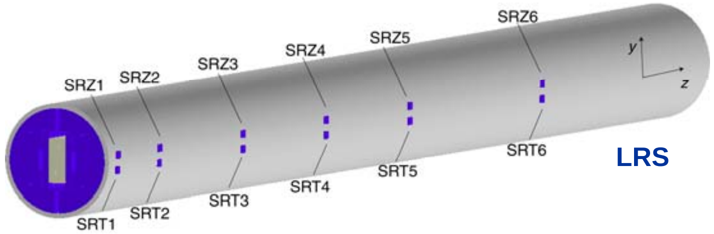




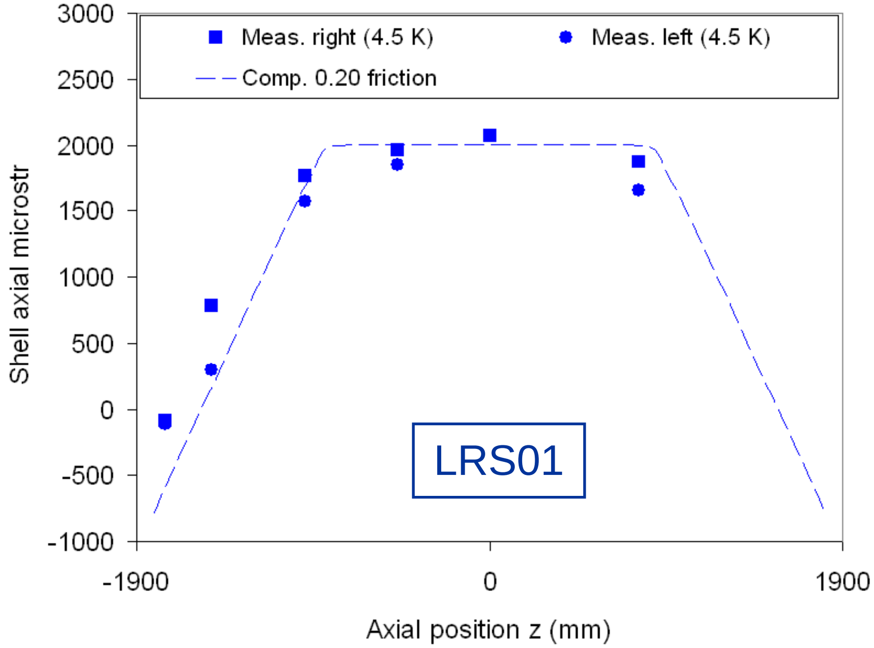
Length scale-up
Shell axial tension in LRS01 and LRS02

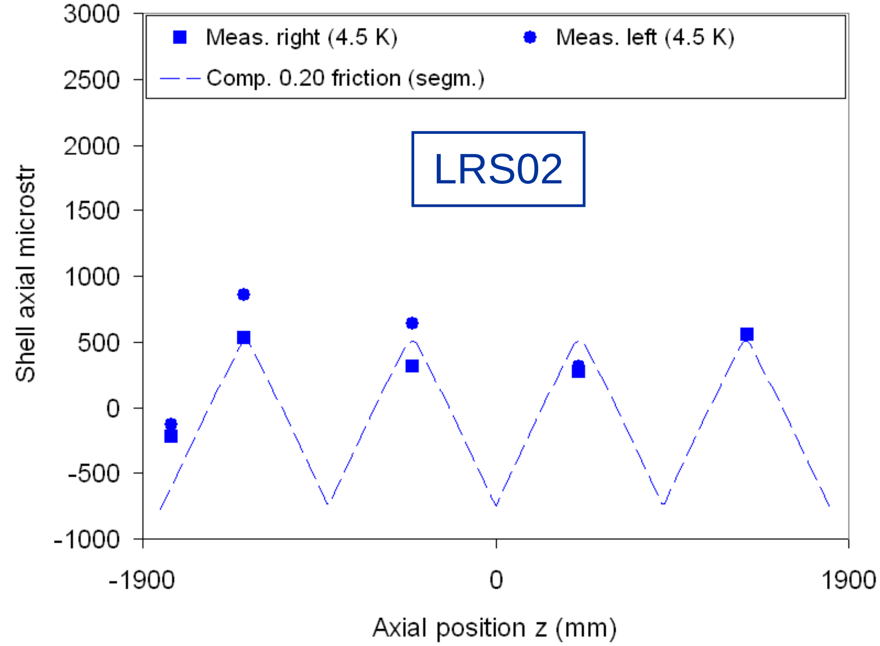
- LRS01
  - High meas. axial strain meas.
  - Effect on azimuthal stress

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



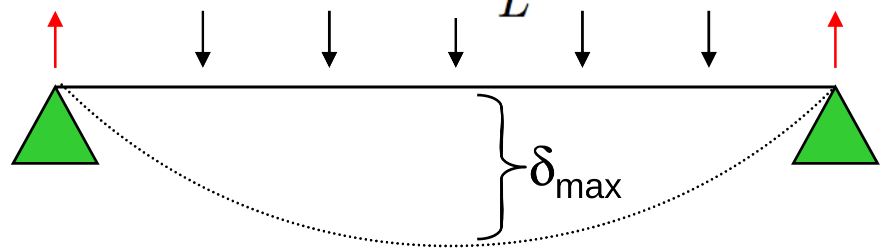
- LRS02 (with segmented shell)
  - Reduced axial strain





Length scale-up
Flexural rigidity and LHe containment

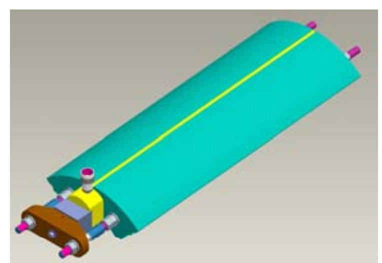
$$F_d = \frac{\rho V g}{L}$$

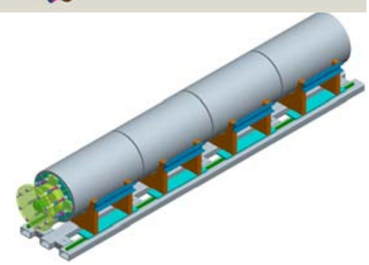


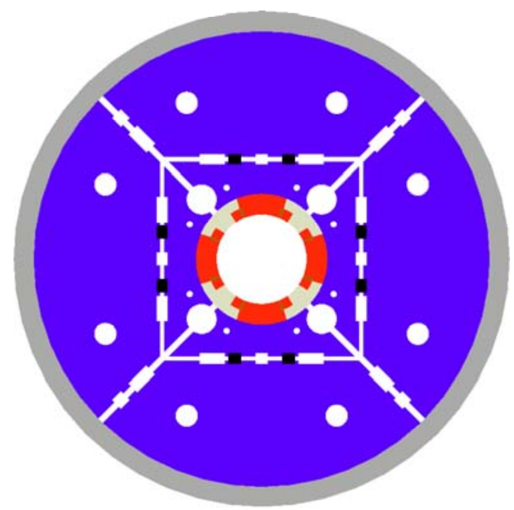
- Assumption: yoke laminations behave like a solid block
  - Tie rods compress yoke
  - No tensile stresses over the range of deformations
- Max. deflection δ_{max} = 0.251 mm
- Required 19.1 mm rod tension
  - 400 MPa at 293 K
- External 5 mm thick ss shell
  - Additional rigity
  - LHe containment

$$\delta_{\max} = \frac{5 F_d L^4}{384 E I_{xx}}$$

$$\sigma_{\max} = \frac{F_d L^2 r_{eff}}{8 I_{xx}}$$

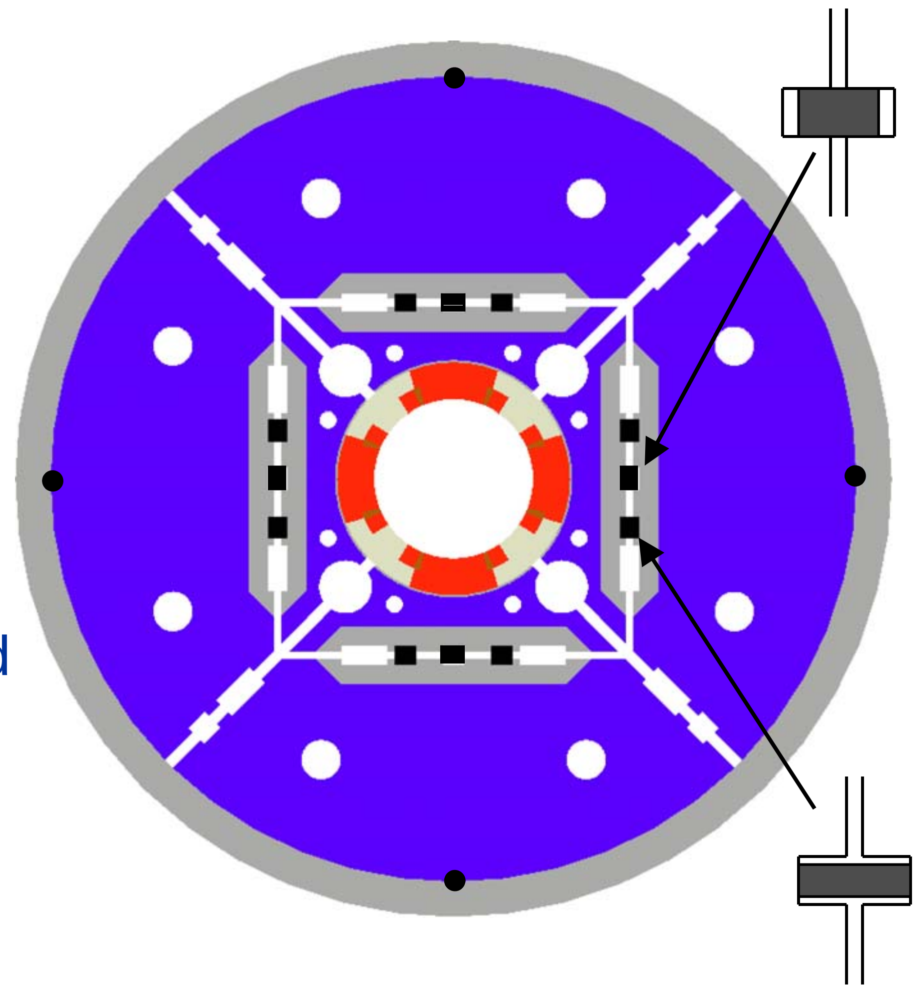






Alignment of support structure (LQS)

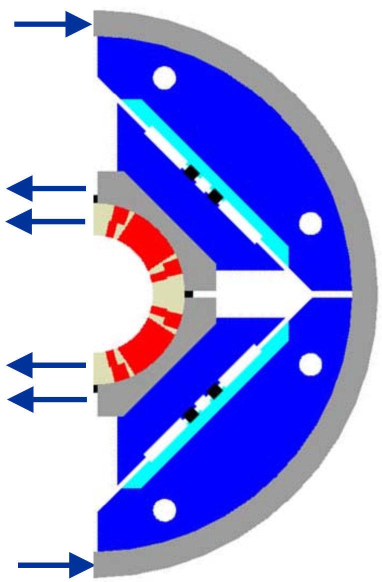
- Pins to align shell and yoke
- Masters
  - Interference key for horizontal alignment
  - Mid-plane key for vertical alignment
- During bladder operation masters expand and align (through tilted sides) pads and yokes
- No alignment coil - pad

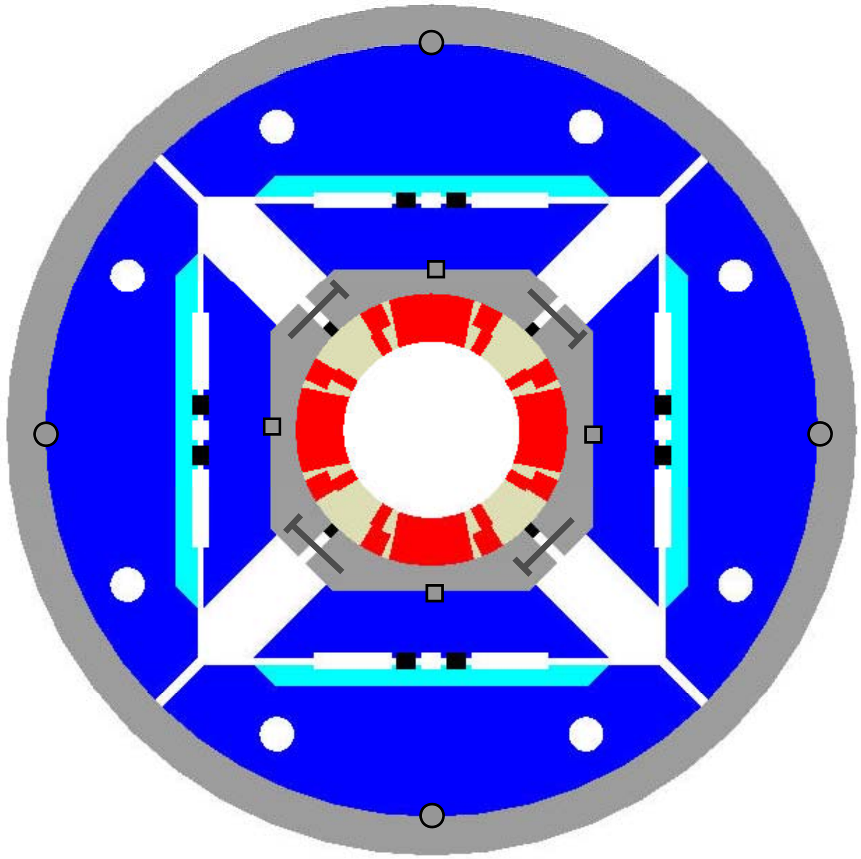


Coil alignment (HQ)

(see H. Felice's talk)

- Aluminum bolted collars on pole keys
- Keys compressed by the collars during all phases
- Part of the shell force intercepted by the collar/ring





Conclusions

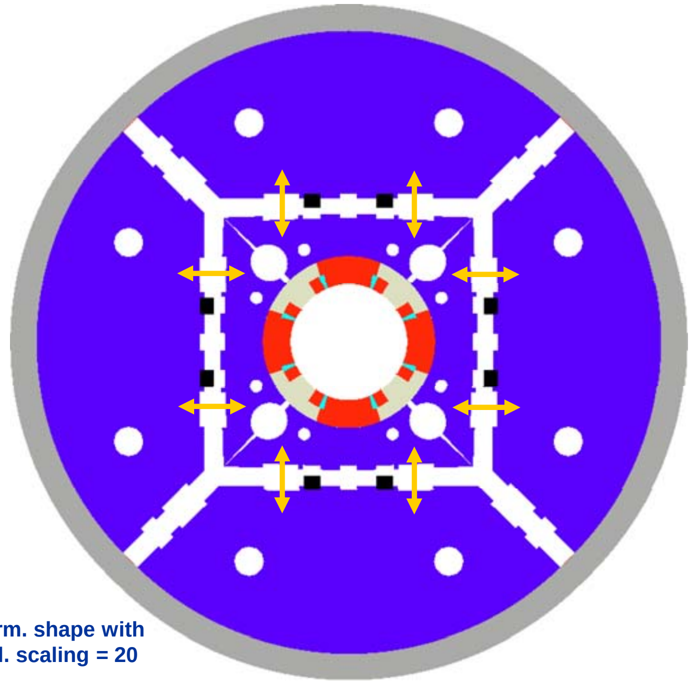
- Shell-based structures have been proven to provide
  - Accurate control and safe assembly pre-load level
    - Reduce risks of degrading brittle Nb_3Sn superconductor
  - Large pre-load force
    - Capability of supporting coils in very high field

- Accelerator quality features are being introduced in the structure design through the LARP Program
  - Assembly and load of cos-theta coils: TQ
  - Alignment of the support structure: SQ, LQS
  - Assembly, load, rigidity of long magnets: LRS, LQS
  - High field and coil alignment : HQ

Appendix

Room temperature pre-load
Bladders pressurization

- Insertion and inflation of bladders
  - Yoke pushed towards shell
  - Pad pushed towards coil
- Pad – yoke gap (interference) open mostly on the yoke side



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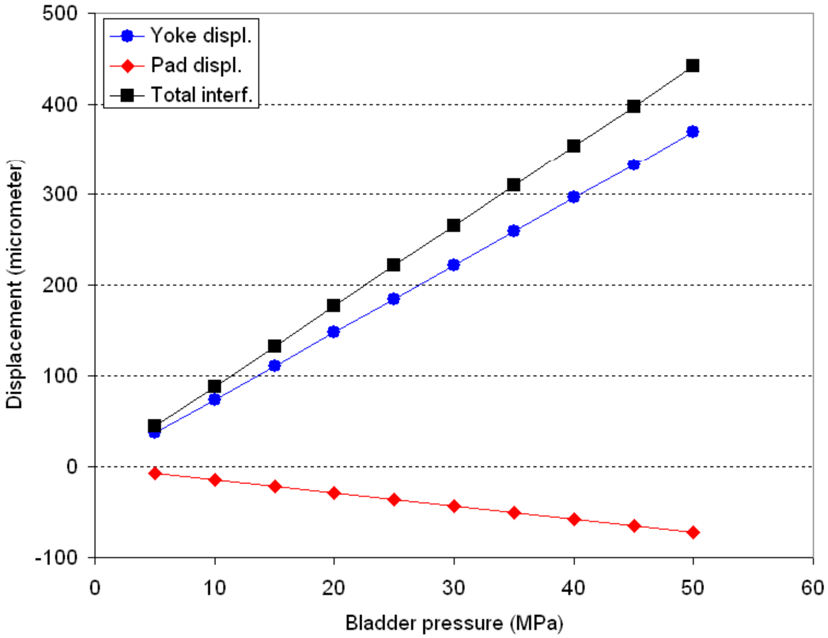
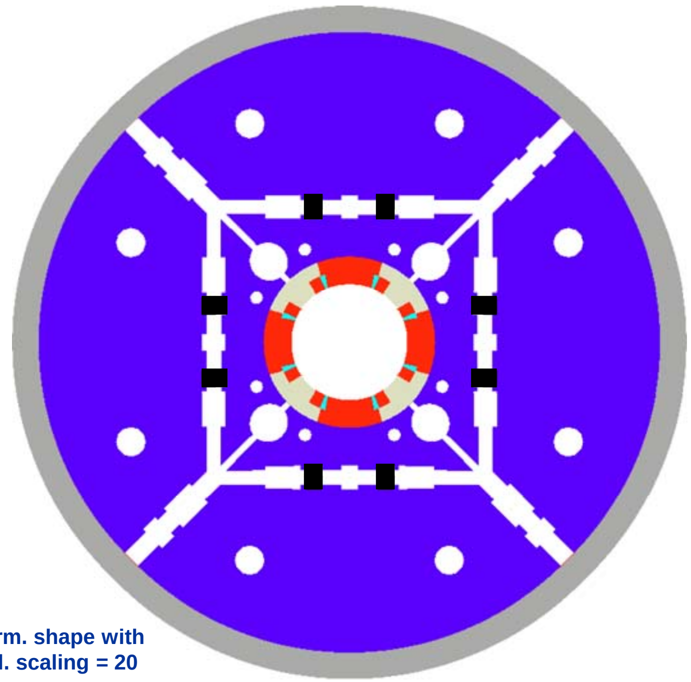


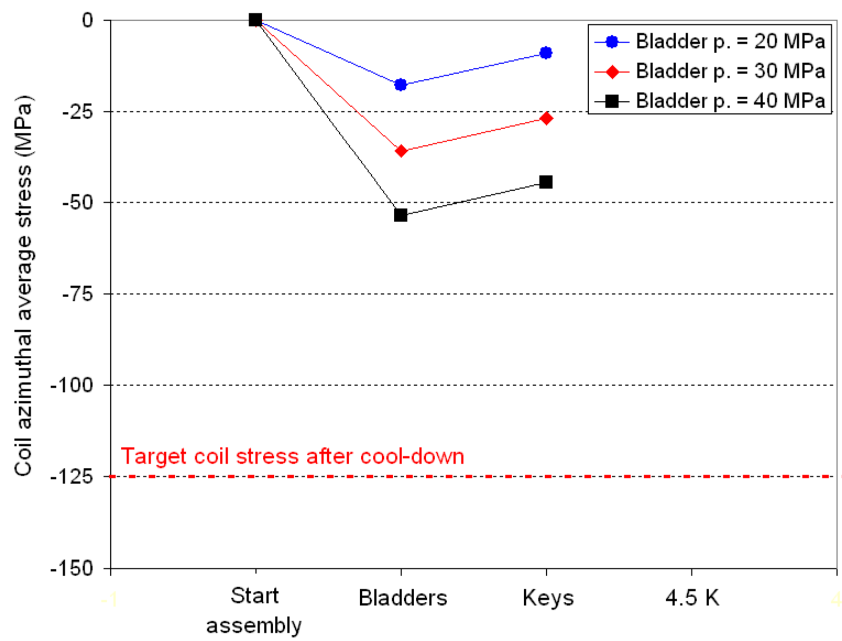
Room temperature pre-load
Key insertion

- Shim inserted between key and pad
  - Clearance (~0.05 mm) required to insert shim
- Bladder deflated => change of coil stress distribution



Deform. shape with displ. scaling = 20

- Choice of total interference – bladder pressure based on
  - Spring back after bladder deflation
  - Required pre-load to reach target coil stress at 4.5 K



Cool-down effect

- All the force transferred to the coil (yoke gaps open)
- Increase of shell stress $\Delta\sigma_{shell} \propto \alpha_{shell} - \alpha_{yoke}$
  - Indipendent on the starting point (offset)
- Total force on the coil $\propto$ shell thickness