Segmented aluminum shells in LARP LR and LQ magnets

P. Ferracin

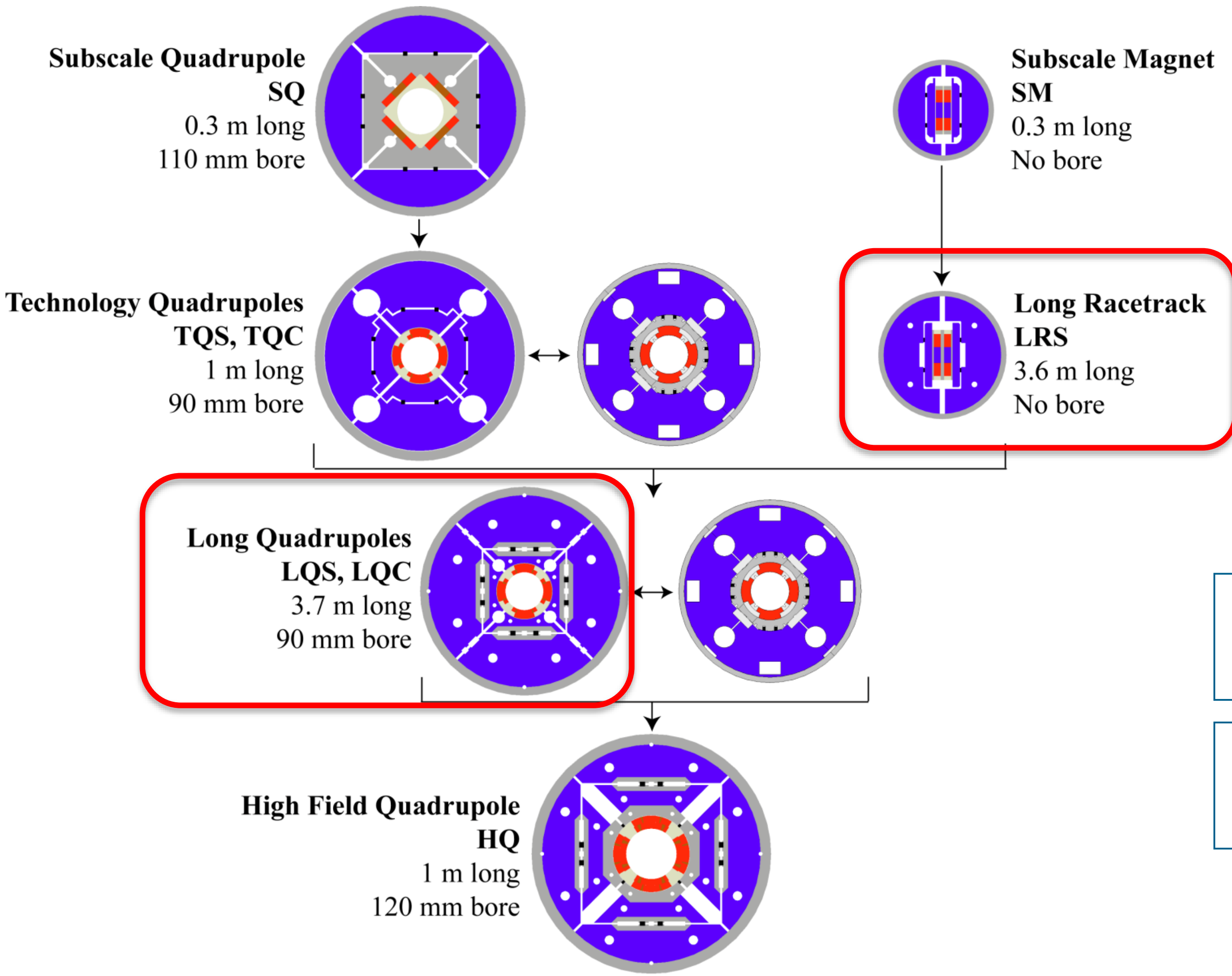
on behalf of the MQXF (*and LARP*) collaboration

Technical meeting on MQXF longitudinal mechanics
April 6th, 2021
LBNL, Berkeley, CA, USA

Outline

- Introduction
- LRS01 and LRS02
- LQS01
- Conclusions

Overview of LARP Program (in 2009)



"**S**": Shell-based support structure

"**C**": Collar-based support structure

Outline

- Introduction
- LRS01 and LRS02
- LQS01
- Conclusions

LRS objectives

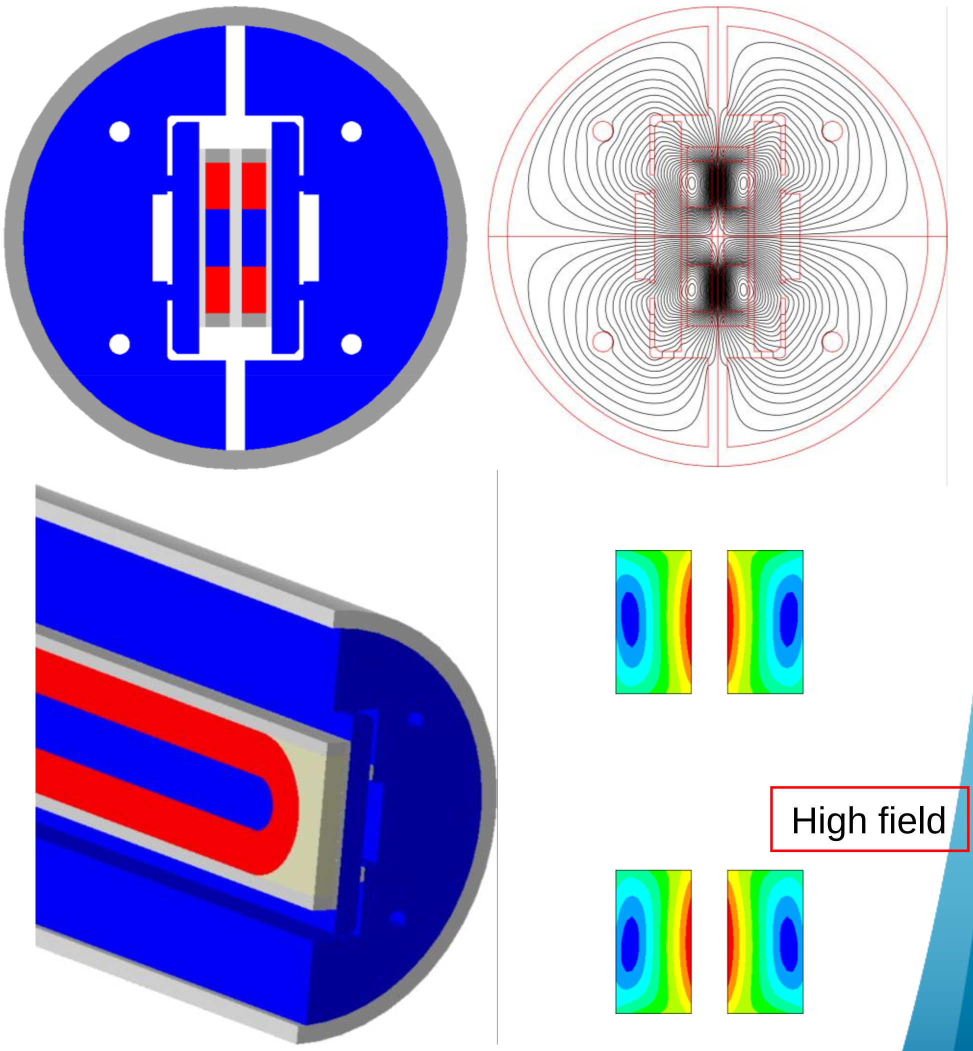
- LHC Accelerator Research Program (LARP)
    - Demonstrate that Nb_3Sn magnets are a viable option for an LHC luminosity upgrade
- LR magnet series
    - 3.6 m long racetrack coils in a shell-based structure
        - Address length issues in Nb_3Sn superconducting coils
        - Investigate shell-based structure scale-up for long magnets

LRS01 magnet design and parameters (I)

- Extension of LBNL SM magnet
- Two double-layer racetrack coils
- “Common-coil” configuration

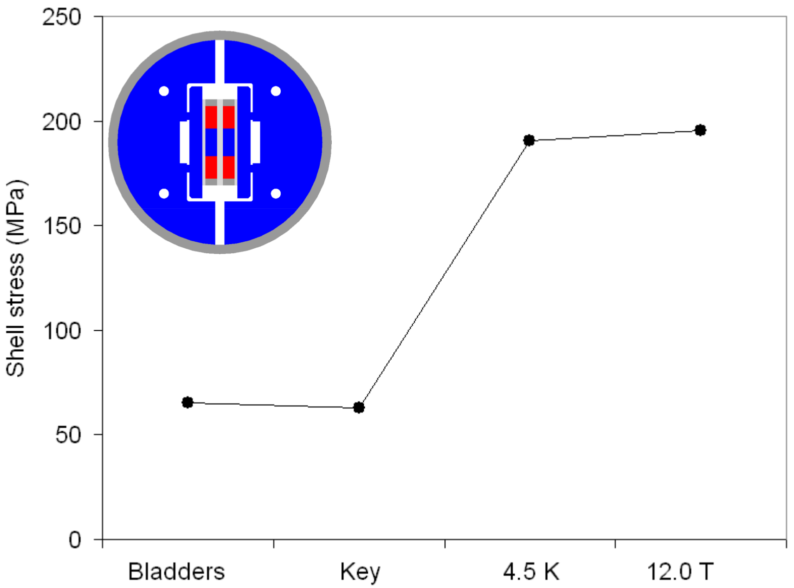
- Coils contained within
  - Iron pads
  - Iron yoke
  - Aluminum shell (3.6 m long)
- 2 bladders and 4 interf. keys for assembly and pre-load

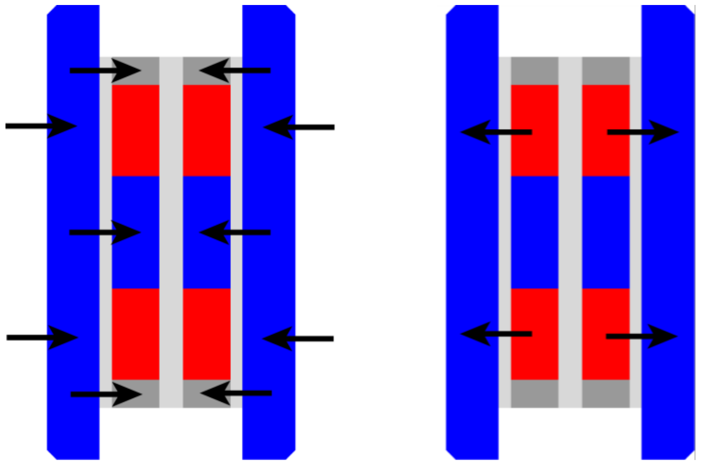
- I_{ss} (4.5 K) = 10.6 kA
- B_{peak} (4.5 K) = 12.0 T
- About 1 T margin in the end



LRS01 magnet design and parameters (II)

- Shell pre-tension
  - 70 MPa after bladder operation
  - 200 MPa at 4.5 K
- Force transferred to coil module
  - Mainly to pole and rails
  - Coil stress at 4.5 K: 30 MPa
- Electro-magnetic forces along *x* axis
  - Coil stress at 12 T: 70-80 MPa
- Target shell stress at 4.5 K (SM tests)
  - 150-250 MPa

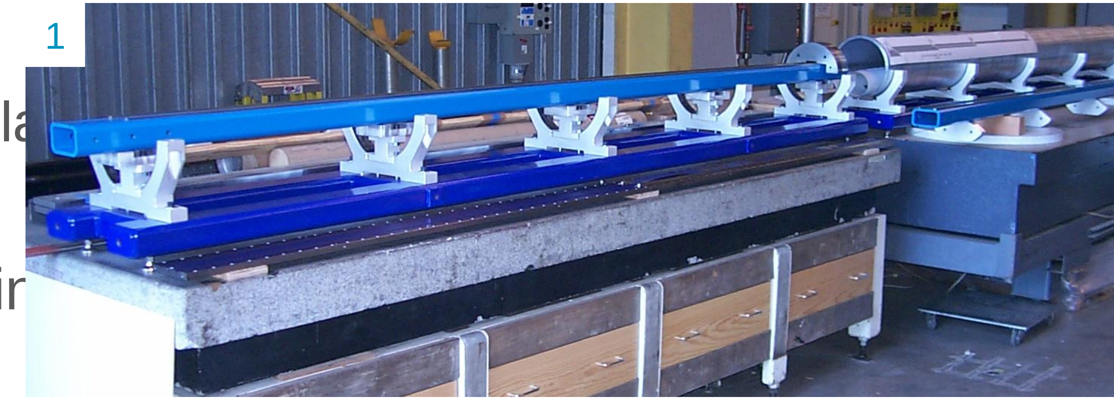


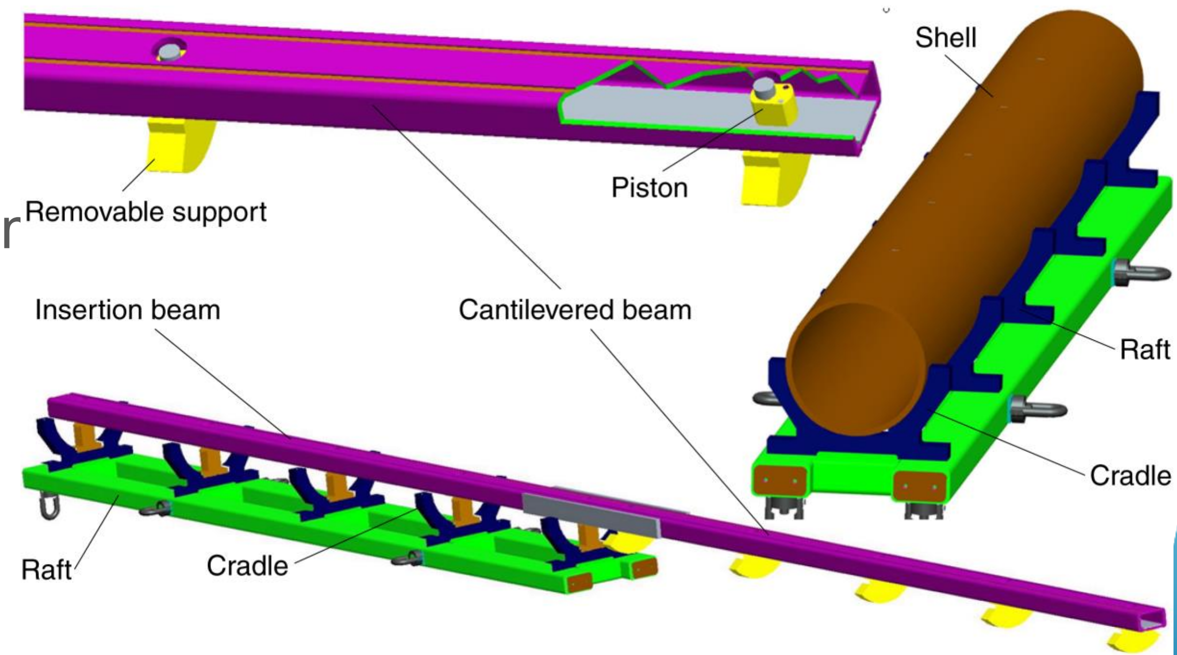


Assembly, pre-loading, and cool-down (I)

- New procedure
  - Insertion of yoke la
- Two rafts with alumir
- “Insertion” beam
- “Cantilevered” bear
  - Supports
  - Pistons

1



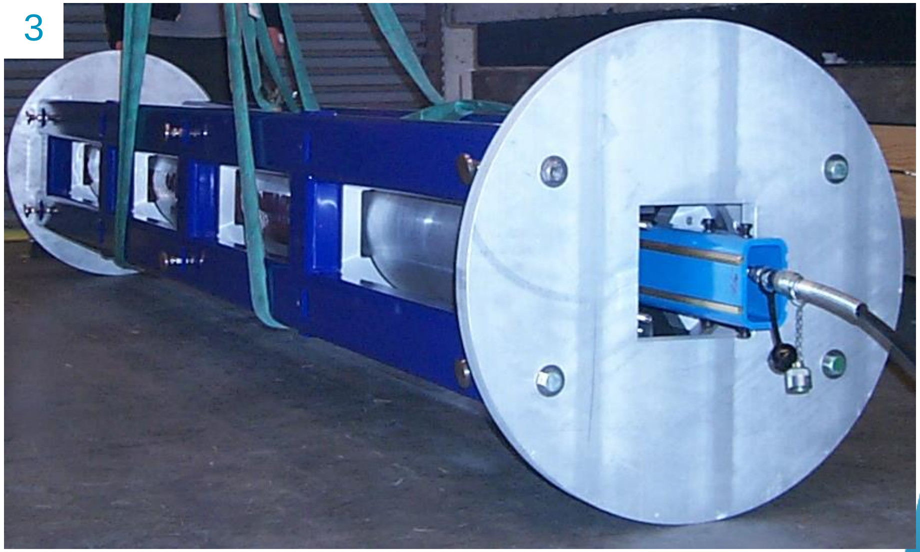


Assembly, pre-loading, and cool-down (II)

- Sliding of first yoke half into the shell
- Pistons pressurization
  - Yoke in contact with shell
- Rotation of the structure
- Yoke resting on bottom surface of the shell
- Configuration for insertion of second yoke half

2

3



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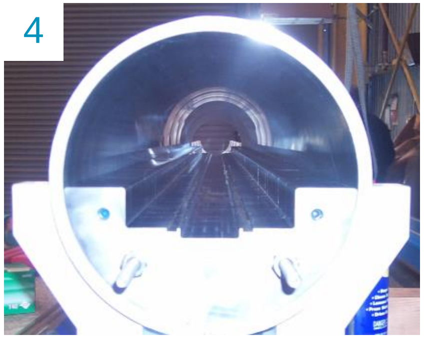

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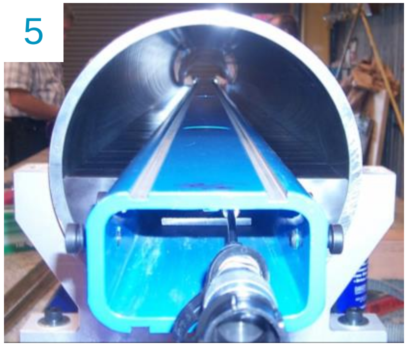
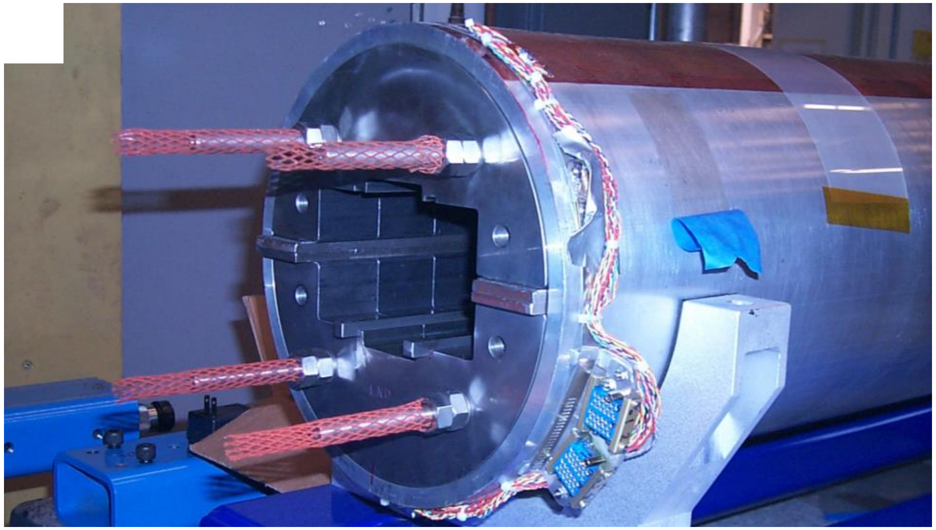
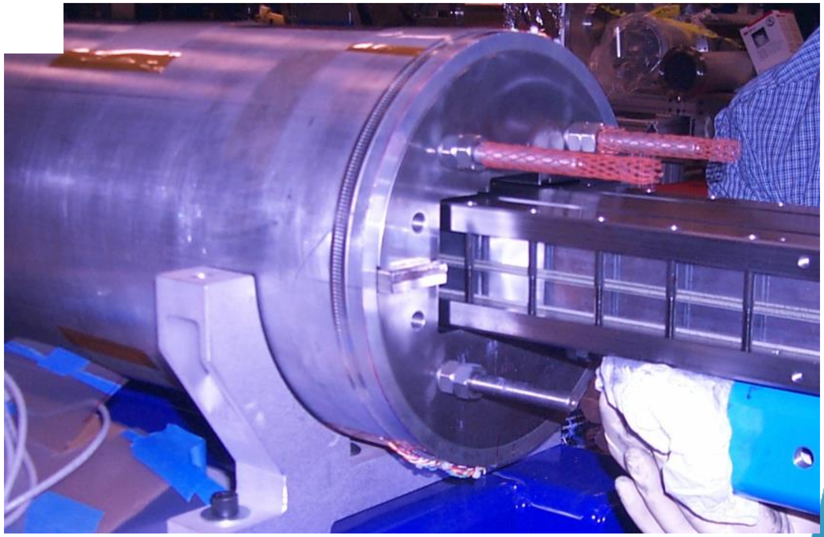


Assembly, pre-loading, and cool-down (III)

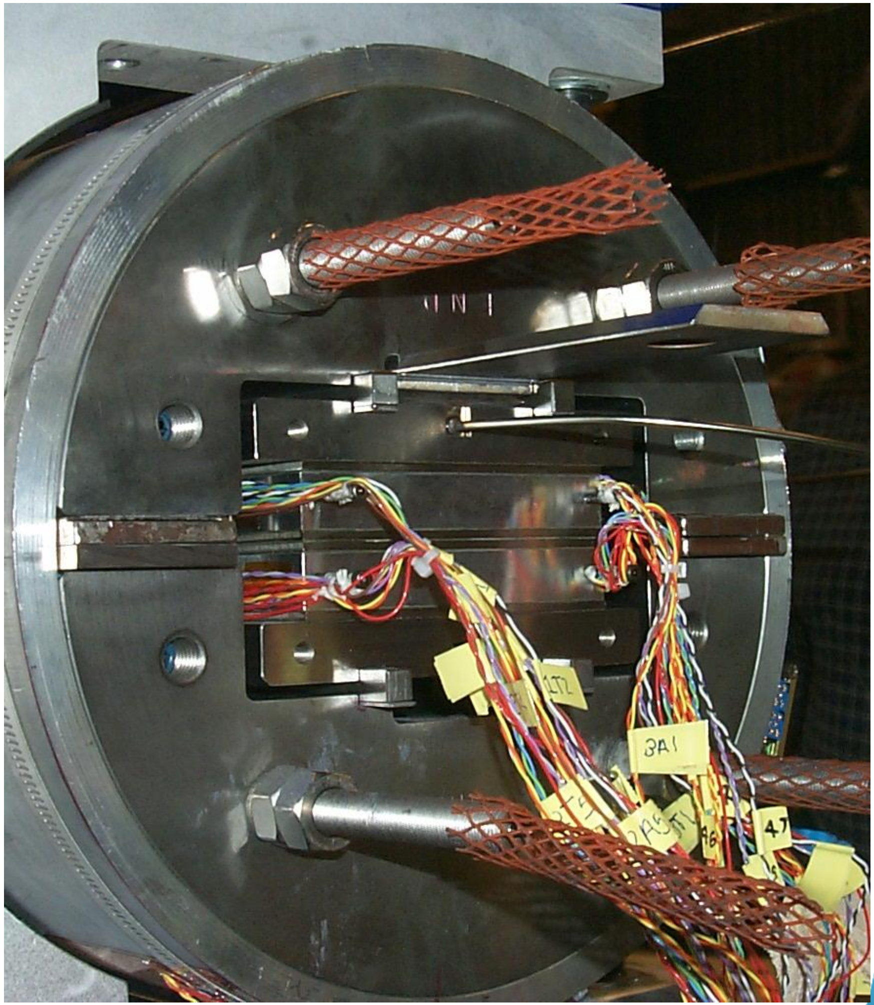
- Sliding of second yoke half into the shell
- Piston pressurization and insertion of gap keys
- Insertion of coil-pack
  - Al plates as dummy coils





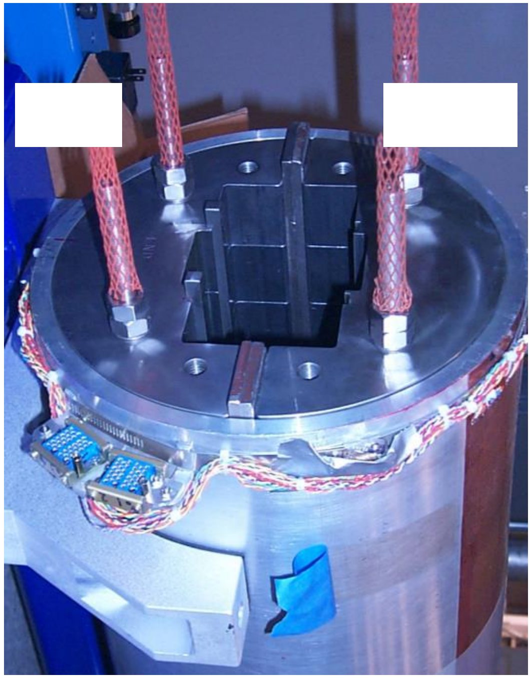
Assembly, pre-loading, and cool-down (IV)

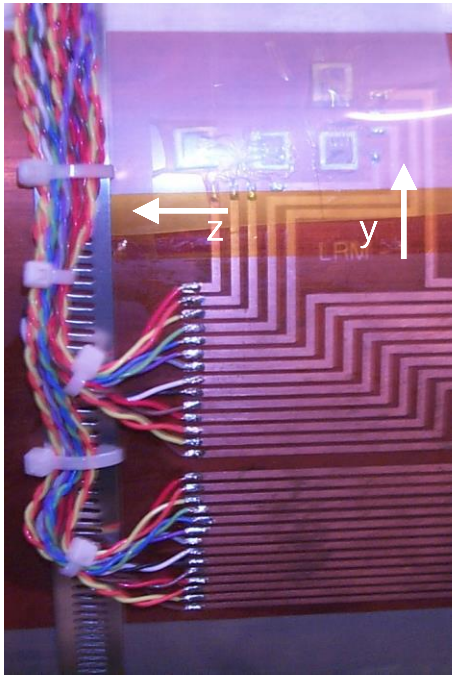
- 1.8 m bladders from both ends
- Bladder pressure up to 55 MPa
- Insertion of interference shims and removal of yoke gap keys
- Bladder deflation and removal
- Cool-down (77 K)
- Reassembly with LRS01 coils
- Final loading and test

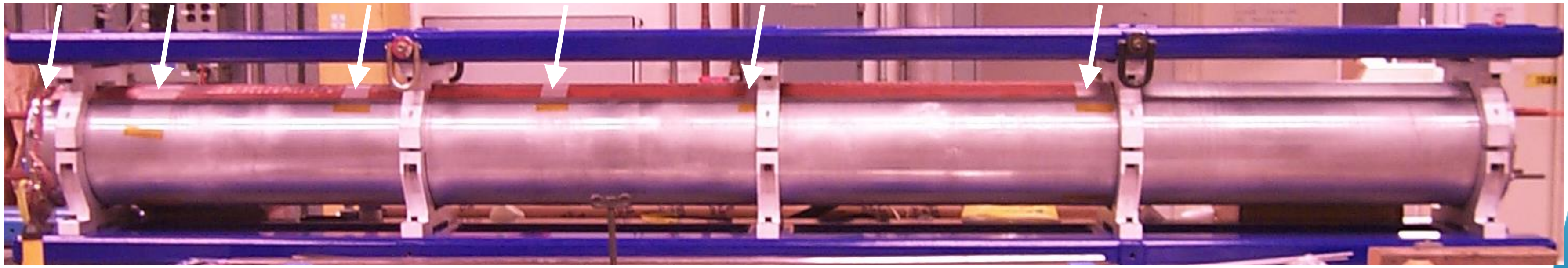


Shell instrumentation

- 24 gauges
  - 6 longitudinal stations
  - Left and right
  - Azimuthal and axial strain with T compens.

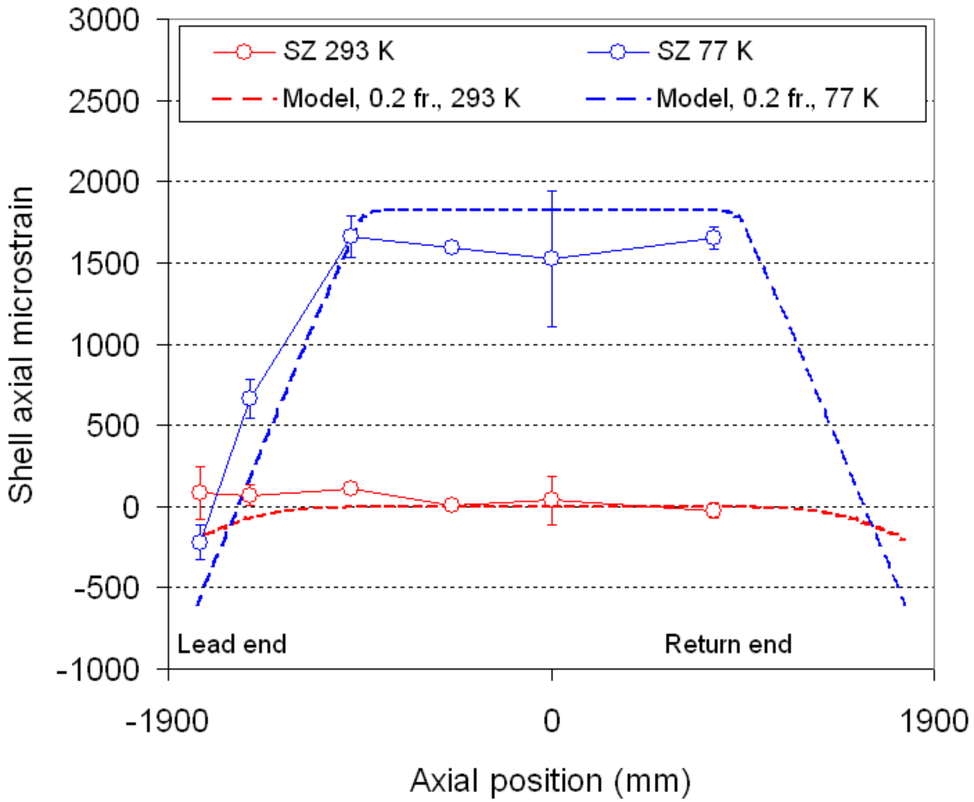






Cool-down with dummy coils

- Shell axial strain in the shell
  - Large variation along z (bell-shaped)
  - High axial tension in the center



Shell - yoke

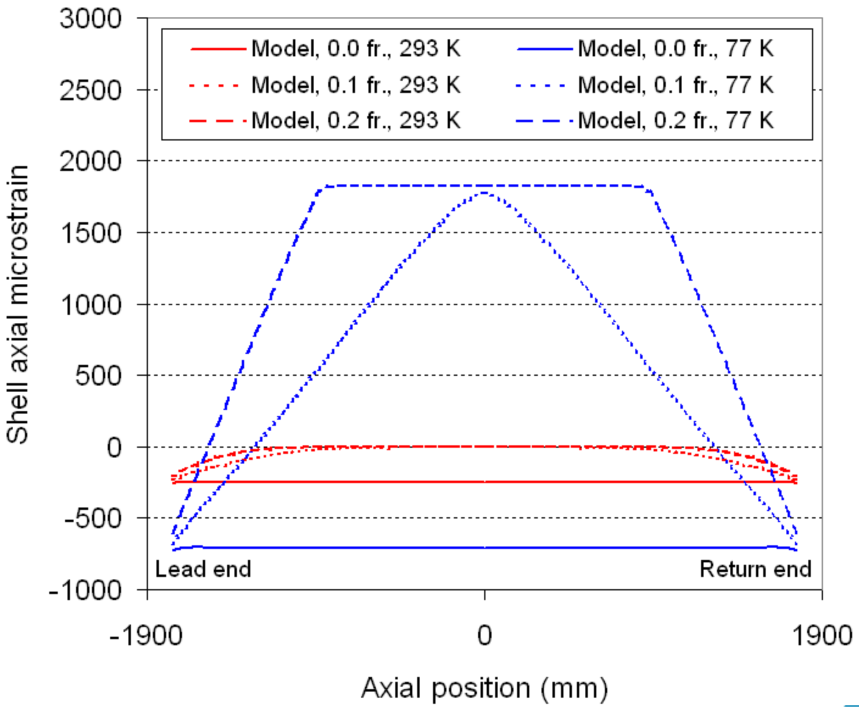
$$\sigma_\theta = \frac{E}{\left(1-\nu^2\right)}\left(\varepsilon_\theta + \nu\varepsilon_z\right)$$

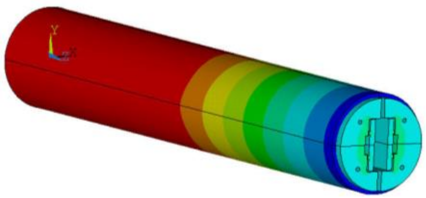
- Shell azimuthal stress $\sigma_\theta \propto$ coil pre-load
- Shell azimuthal strain ε_θ is obtain via keys-and bladders
- If the shell can slide, $\varepsilon_z = -\nu\varepsilon_\theta$
- So, $\sigma_\theta = E\ \varepsilon_\theta$ → basically a 2D problem

Shell - yoke

- But if you have friction between shell and yoke → the shell cannot slide and, in particular at cold, it gets in tension → ε_z
- Bell shape profile: some sliding in the ends, but "glued" to the yoke in the center
  - $\varepsilon_z \sim \Delta\alpha$ → 2000 $\mu\varepsilon$ in z
  - → ~ 50 MPa in θ

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





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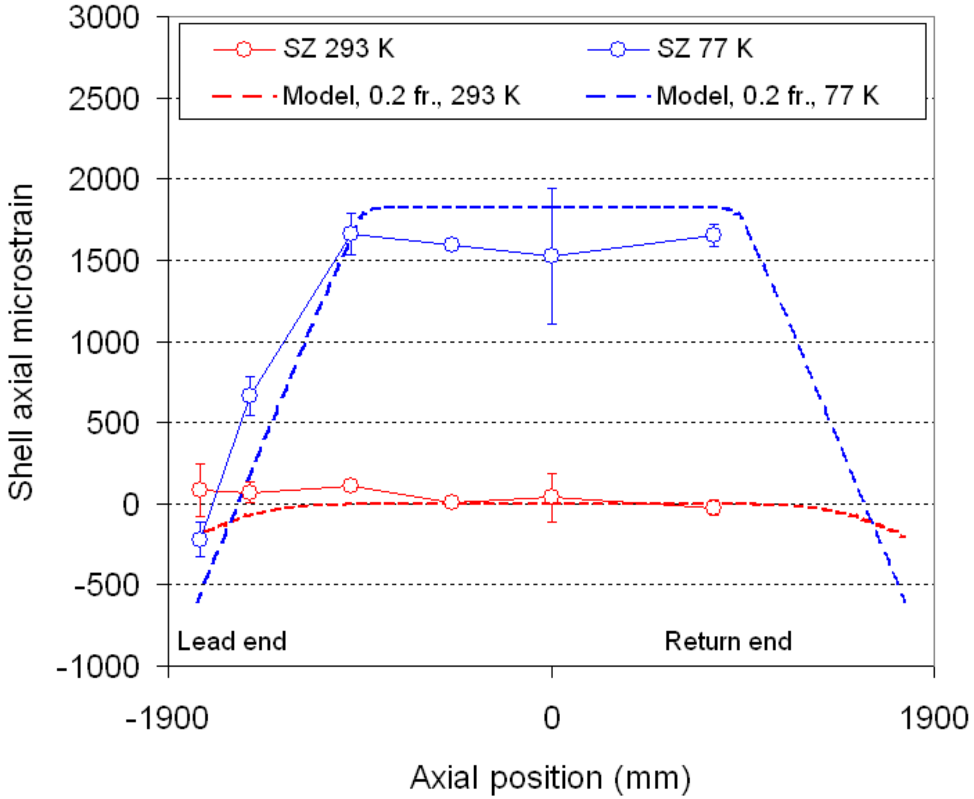
Cool-down with dummy coils

- So,
  - Axial strain → contribution to azimuthal stress
  - Variation of axial strain → variation of azimuthal stress



LRS01 test

- High axial tension → slippage

MURATORE *et al.*: LARP 3.6 m Nb_3Sn RACETRACK COILS SUPPORTED BY FULL-LENGTH SHELL STRUCTURES 1215

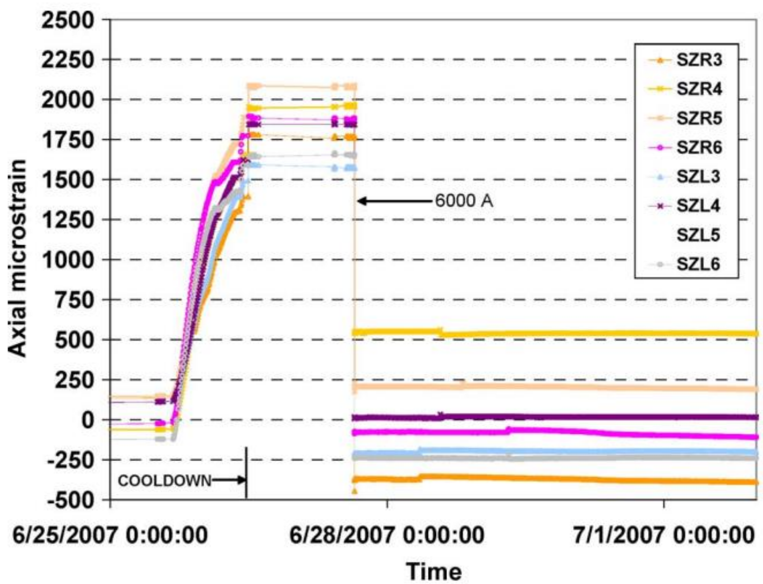


Fig. 4. LRS01 measured axial shell microstrain vs. time during first cool-down and first ramp to 6000 A. Only central stations are plotted (gauge SZL5 appears to be damaged).

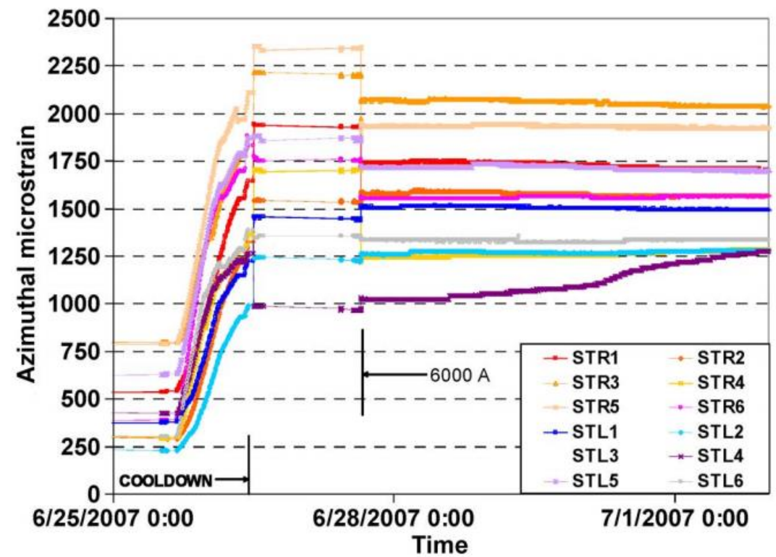
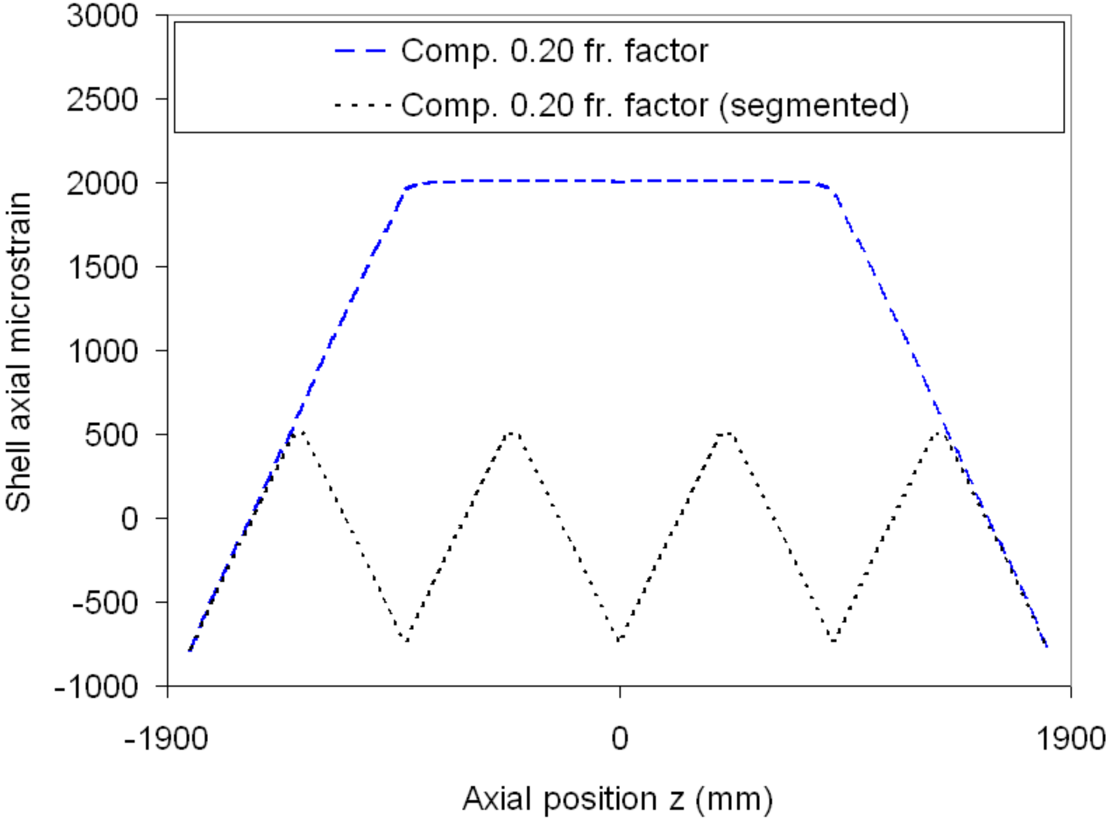


Fig. 6. LRS01 measured azimuthal shell microstrain vs. time during first cool-down and first ramp to 6000 A (gauge STL3 appears to be damaged).

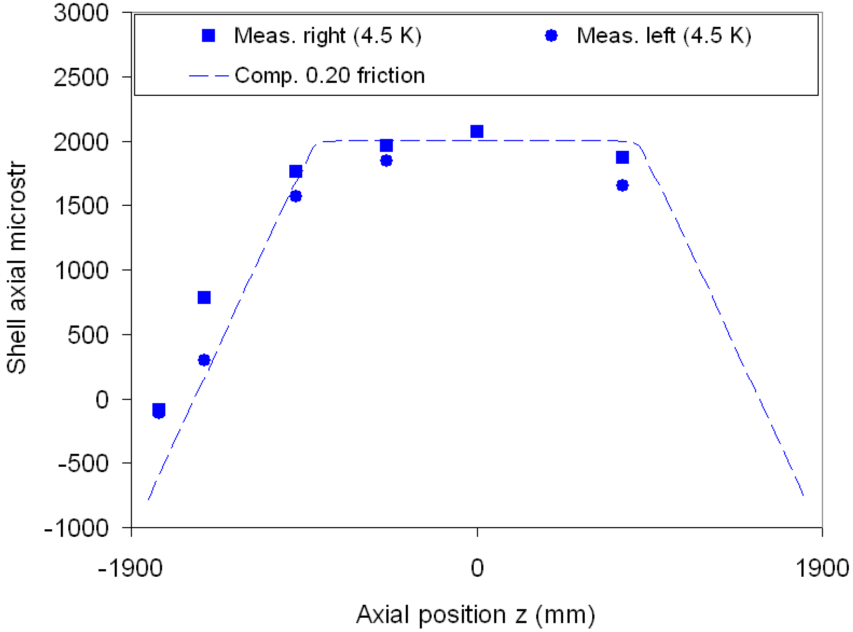
LRS02: shell segmented

- Basically, from a 3D problem to a quasi 2D

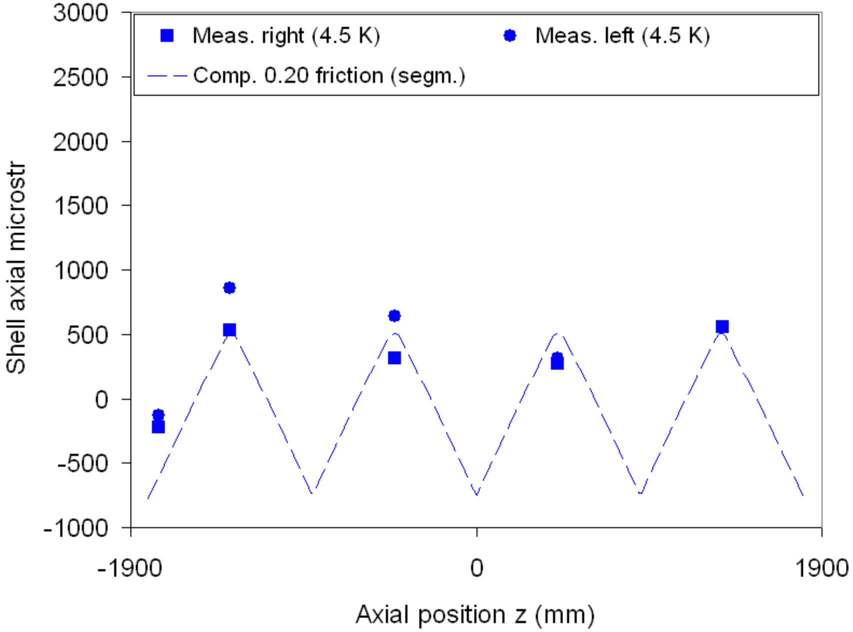


LRS01 vs LRS02

LRS01



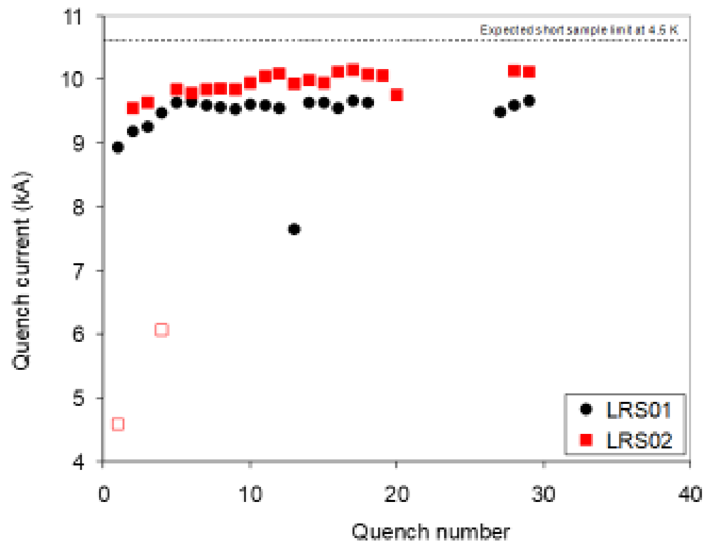
LRS02



Test results

LRS results

- Two tests
  - LRS01 with full shell
  - LRS02 with segm. shell
- LRS02 achieved 96% I_{ss}
  - 11.5 T of peak field
  - Improvement from LRS01 to LRS02
- Demonstrated performance of long Nb_3Sn coil
- Demonstrated assembly and loading procedure of long shell-based structures



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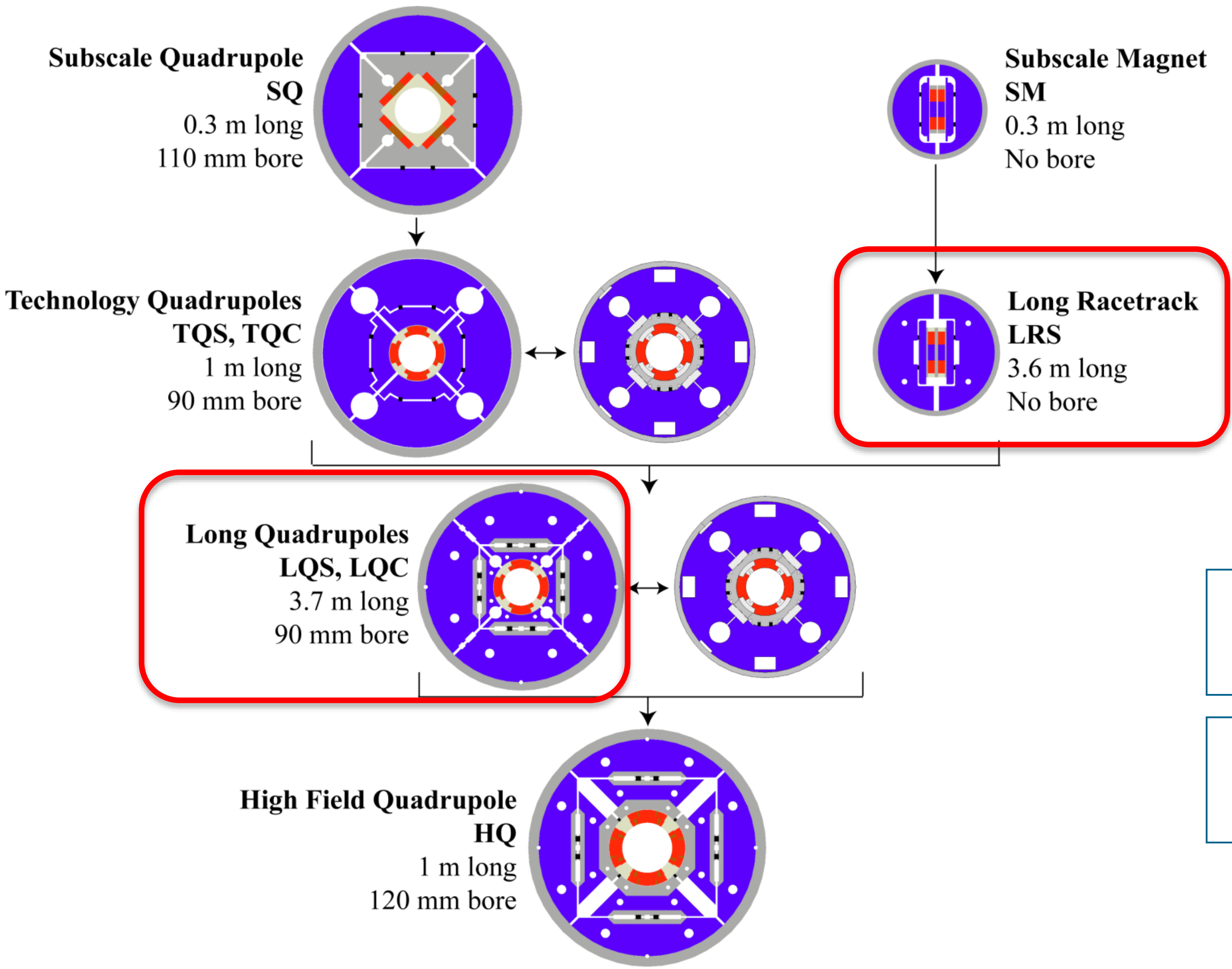
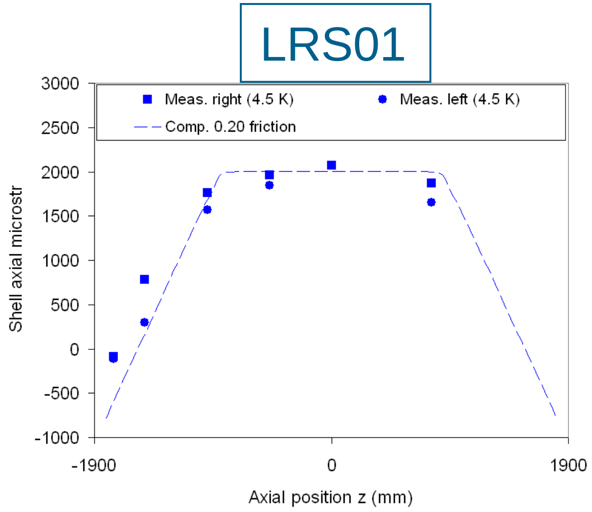
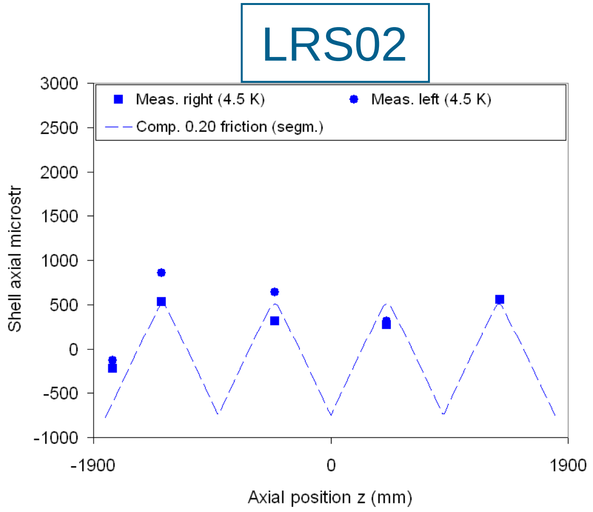


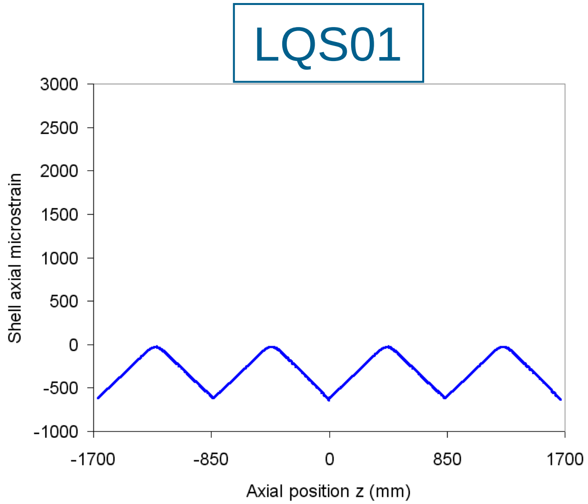
"**S**": Shell-based support structure

"**C**": Collar-based support structure

From LRS to LQ

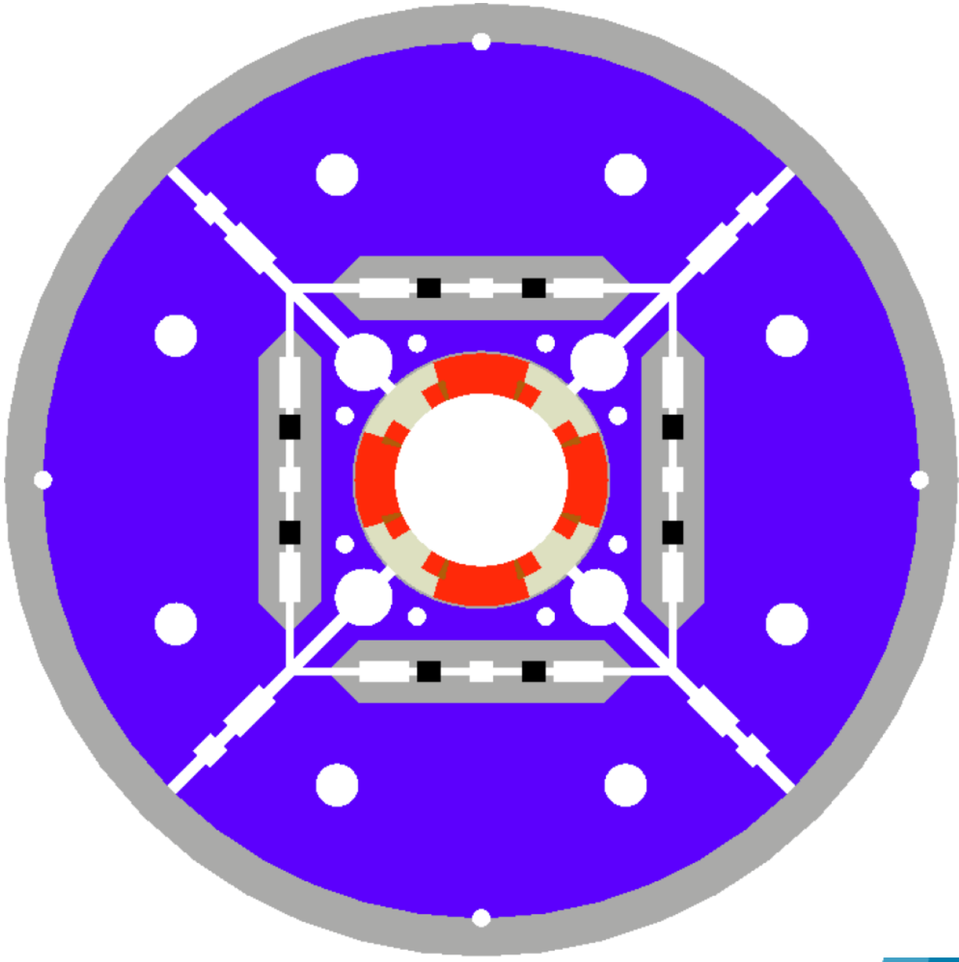






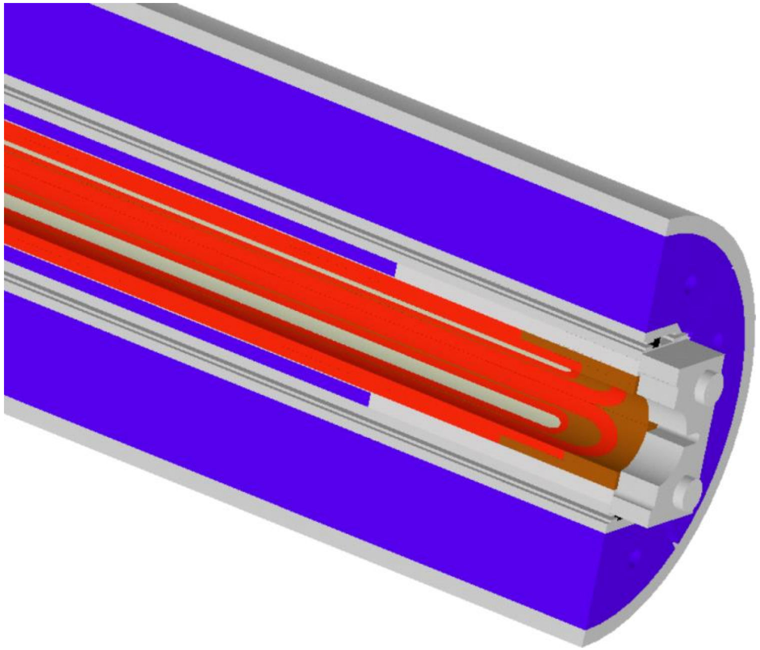
Magnet design
Cross-section

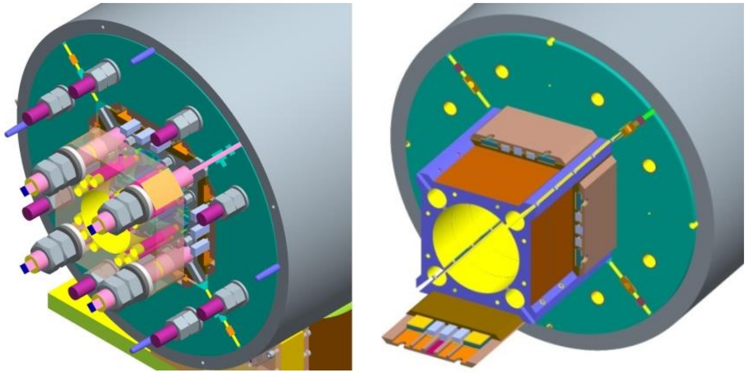
- 20 mm thick Al shell
- 4-split iron yoke
  - Gap keys and auxiliary bladders
  - Holes for tie rods
- Iron pads
  - Holes for coil end support and tie rods
- Iron masters
  - 2 bladders
  - 2 interference keys
- G10 sheet between coil and pad laminations



Magnet design
3D components

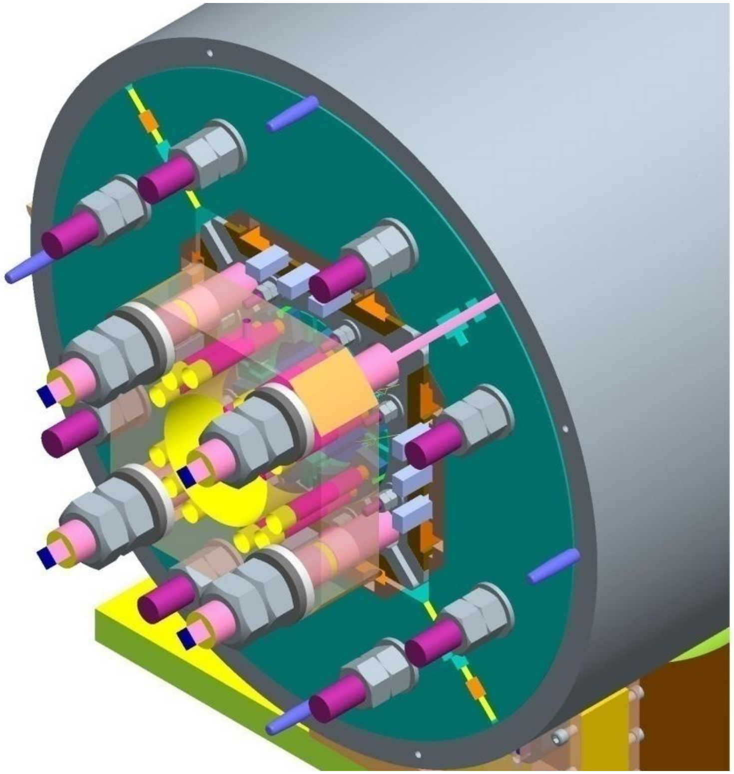
- 4 shell segments, 0.85 m long
- Yoke laminations, 50 mm thick with 3.4 m long tie rods
- Iron pad laminations, 50 mm thick with 3.4 m long tie rods
- Iron masters, 2 x 1.7 m long
  - Easy insertion and removal of coil pack (large clearance)
  - Continuous surface
  - Pad-yoke alignment
  - Improved tolerances

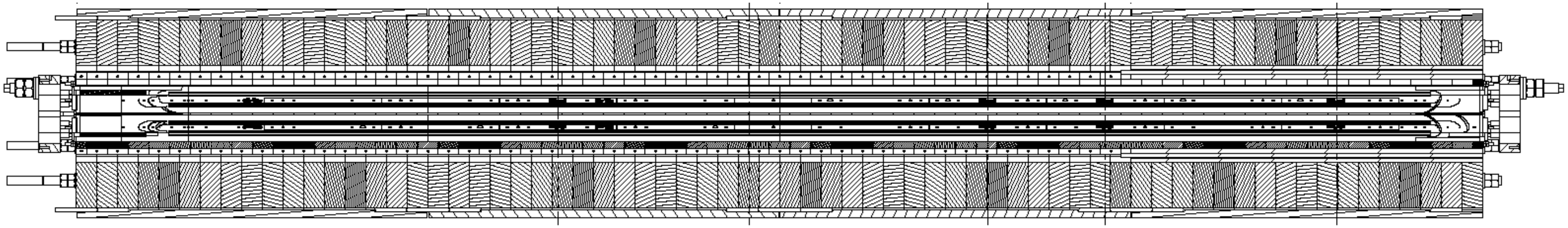




Magnet design
Axial support

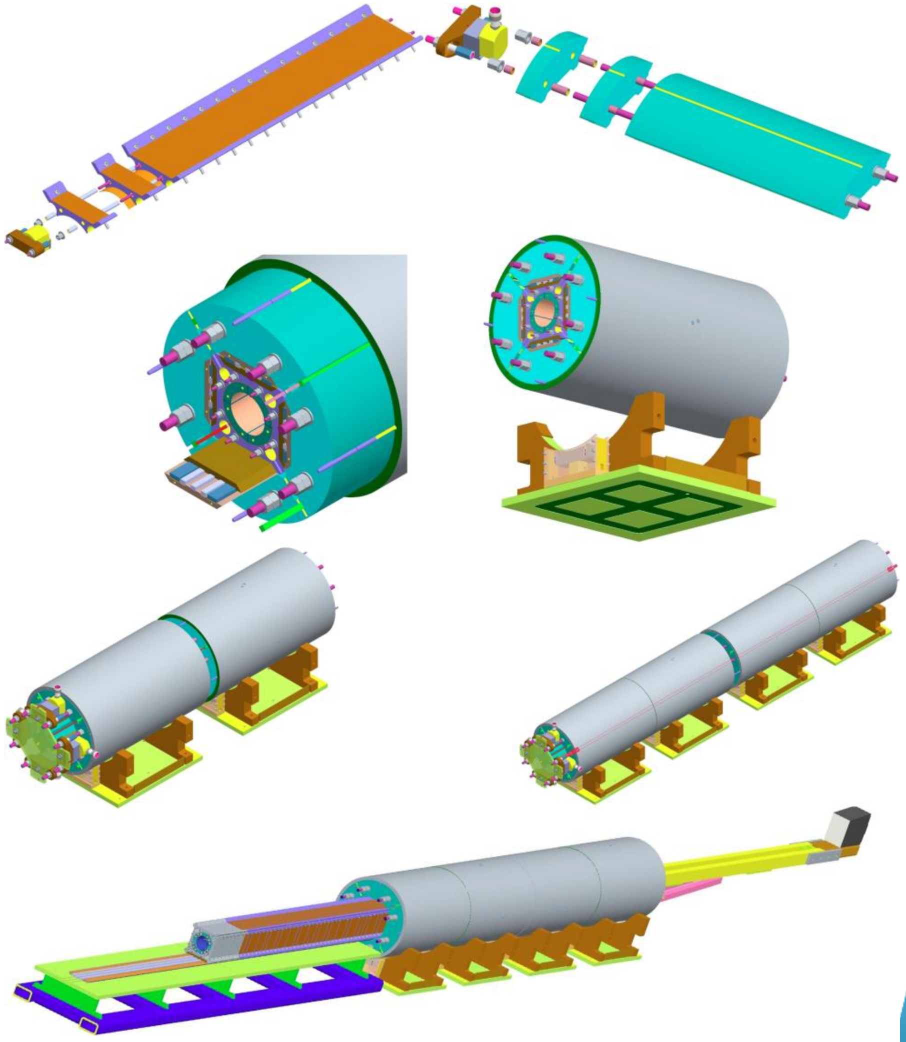
- Stainless steel end plate
  - 50 mm thick
- Stainless steel axial rods
  - 24.5 mm diameter
- Axial pre-load provided by piston



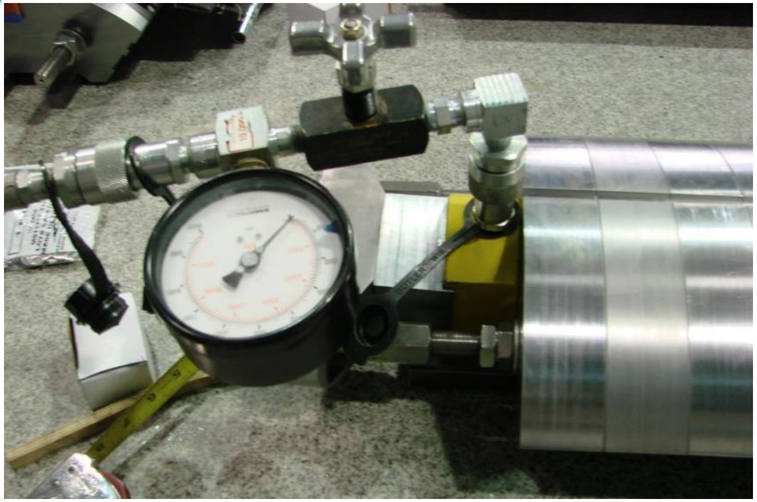


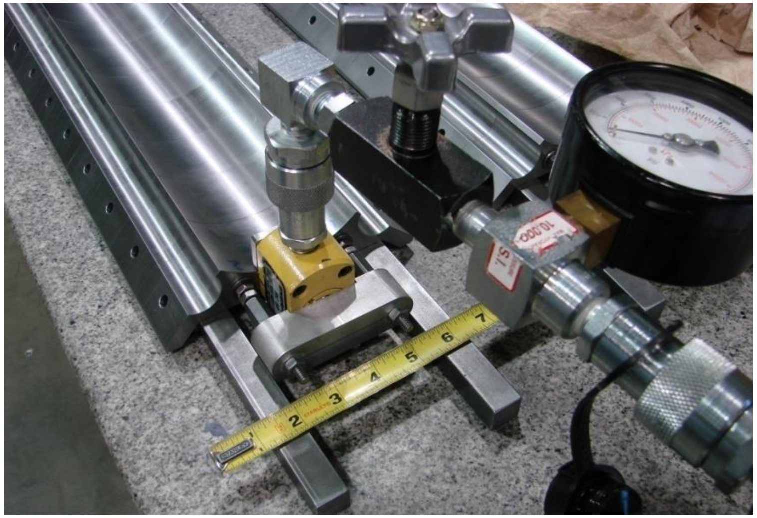
Magnet design
Assembly procedure

- New procedure to be developed
  - Assembly of 850 mm long segments
  - Joining of segments with air pallets
  - Insertion of coil-pad sub-assembly with masters



Assembly and loading of 850 mm long segment
Stacking pad and yoke laminations





- Yoke rod tension: 330 MPa
- Force on yoke stack: 190 kN

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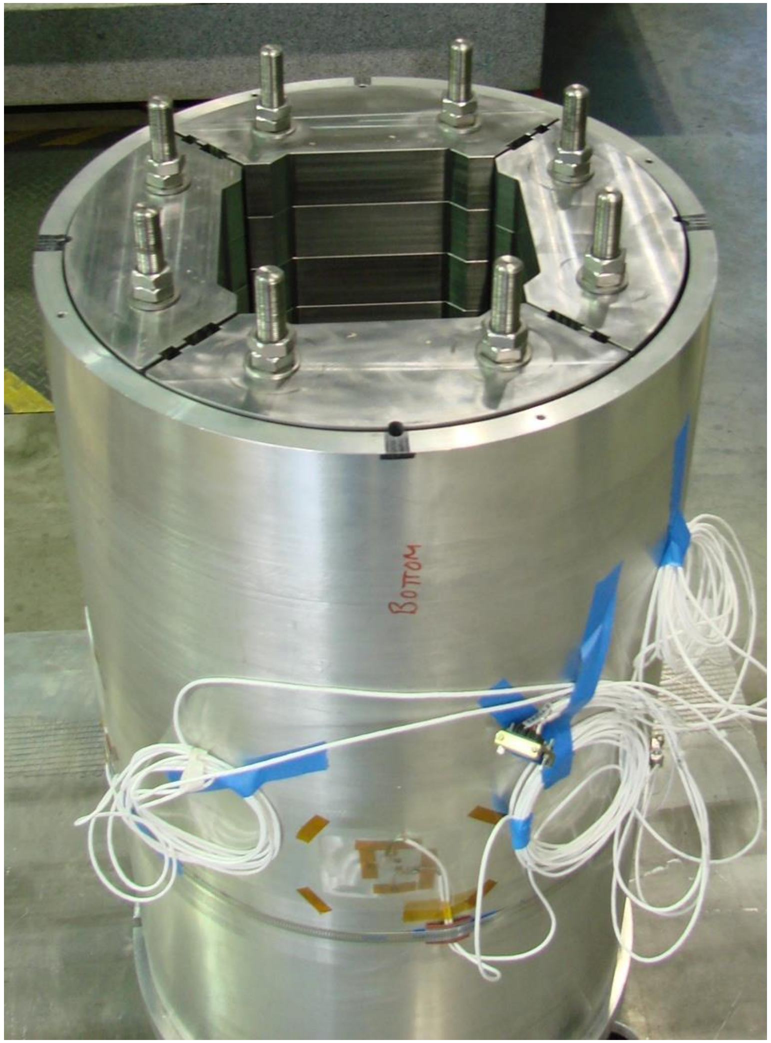
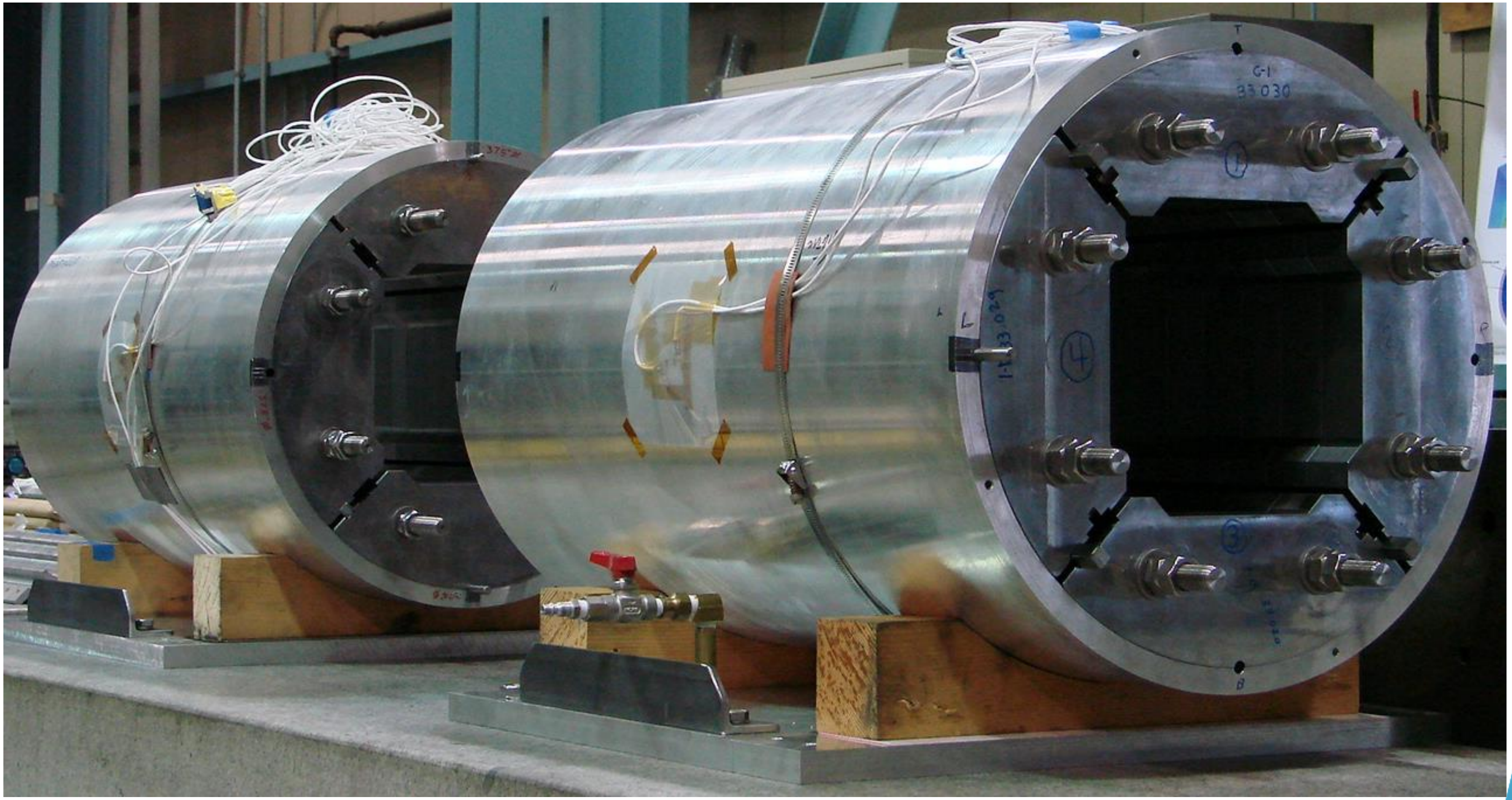
Assembly and loading of 850 mm long segment
Insertion of yoke stacks in shell

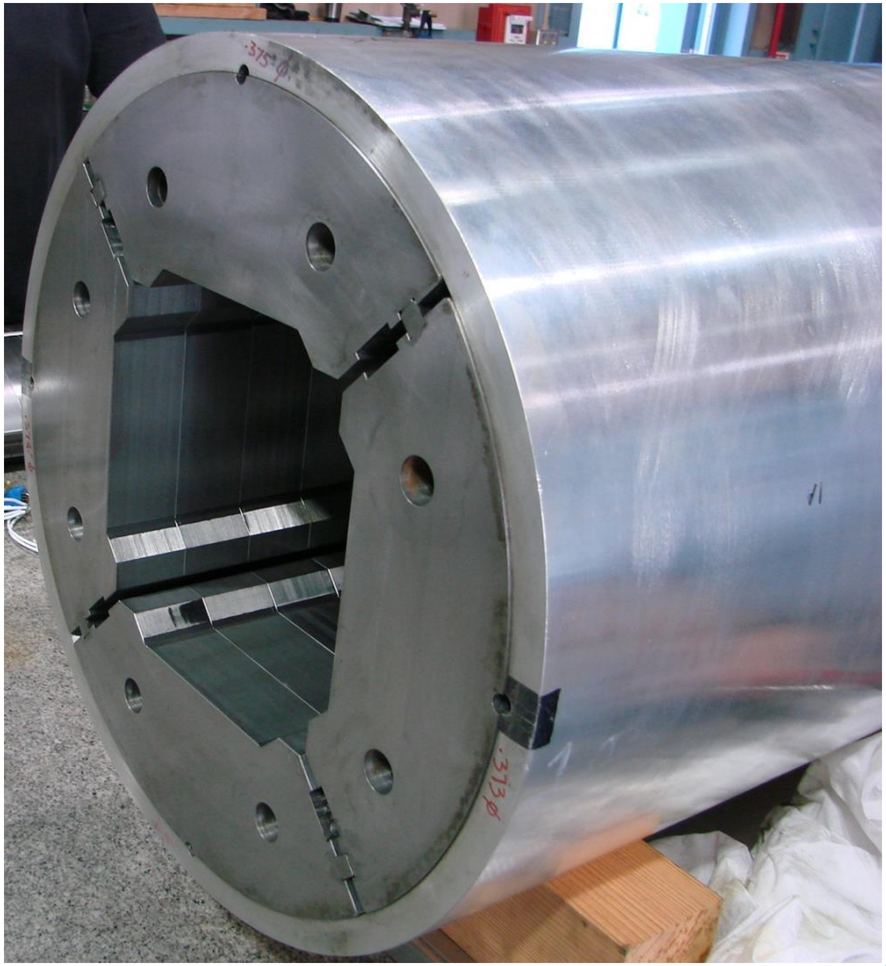


- 4 azimuthal and 4 axial gauges
- Locations
  - longitudinal center of the shell
  - quadrupole mid-planes

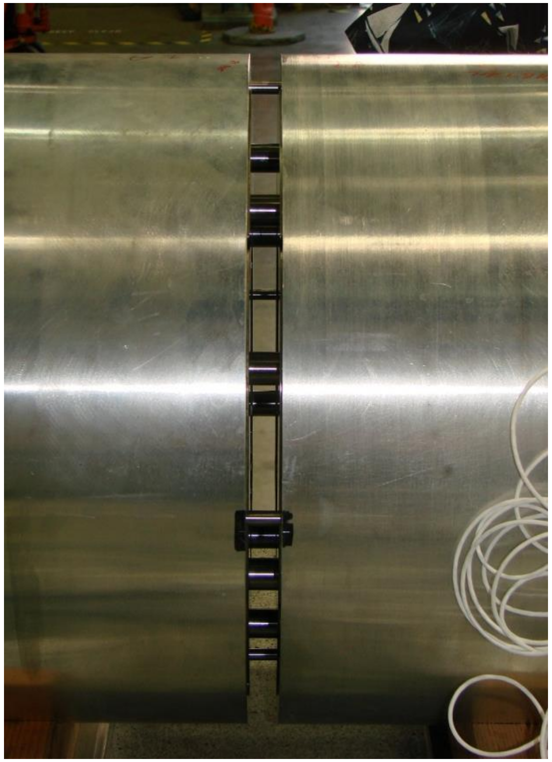
Assembly of 1.7 m long structure
Section 1 and 2 before joining operation

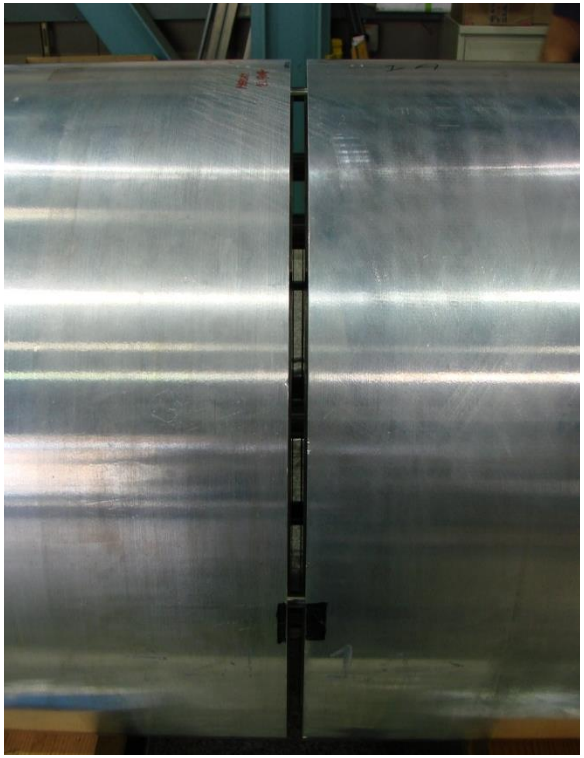


Assembly of 1.7 m long structure
Preparation of alignment pins and bushings

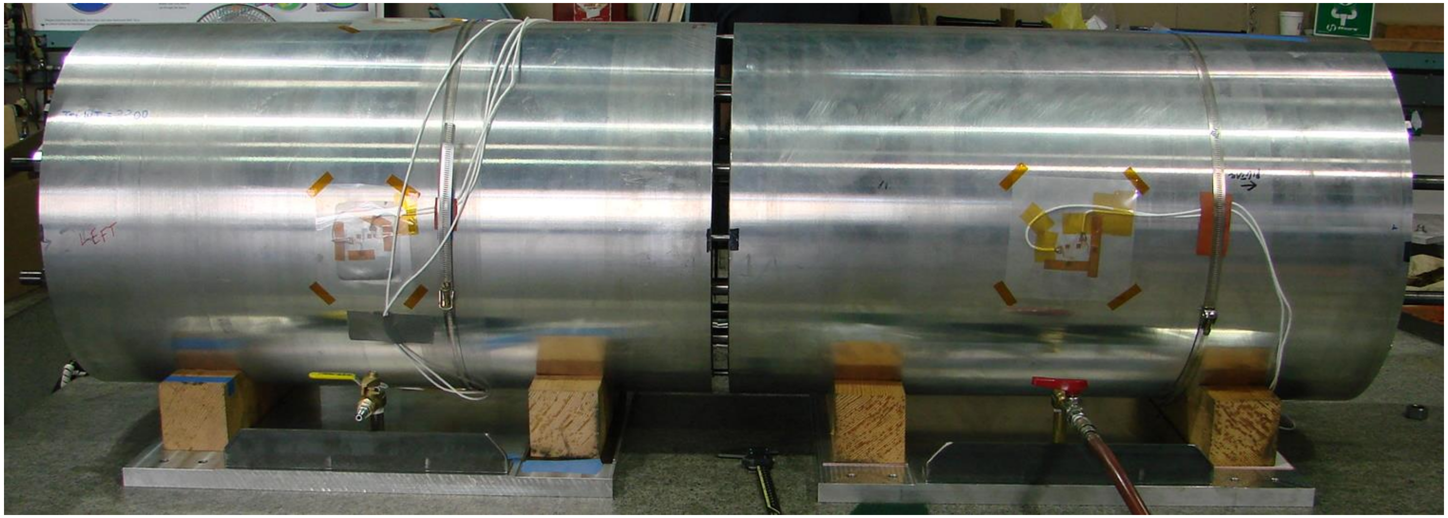


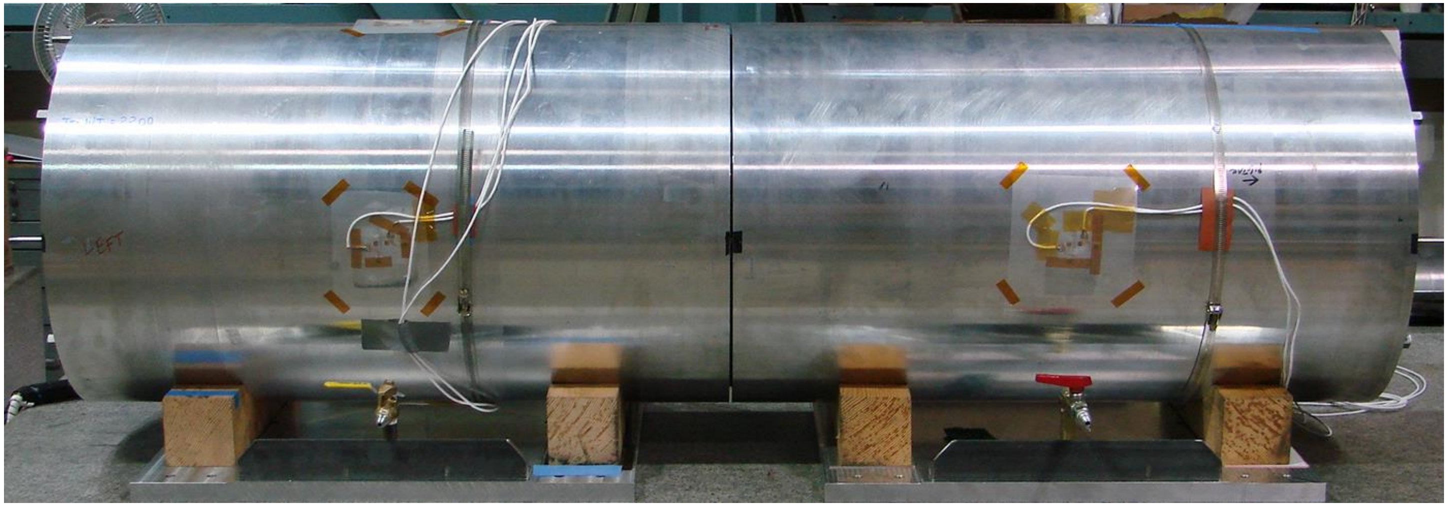
Assembly of 1.7 m long structure
Joining operation of 2 segments (I)



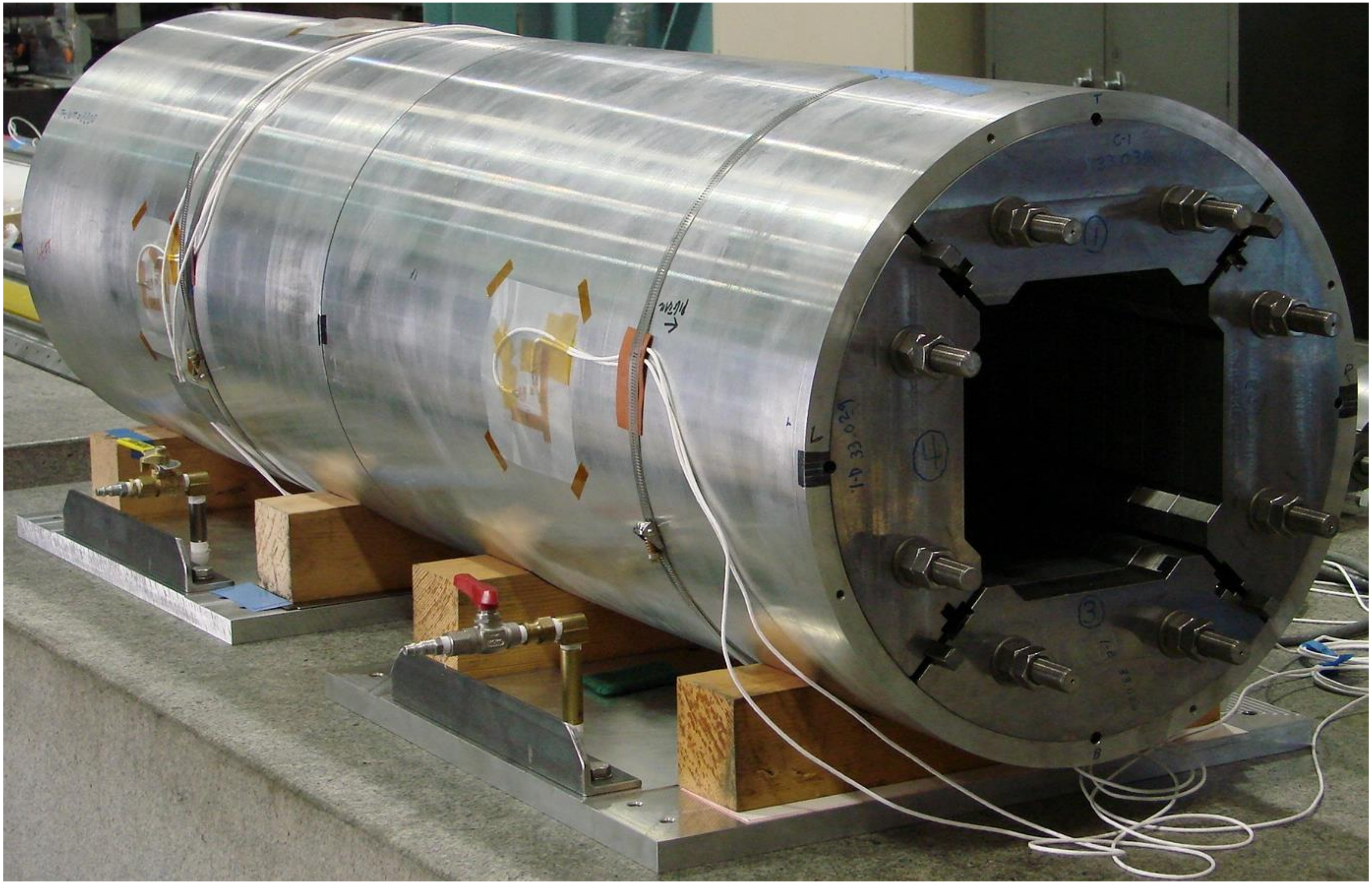


Assembly of 1.7 m long structure
Joining operation of 2 segments (II)

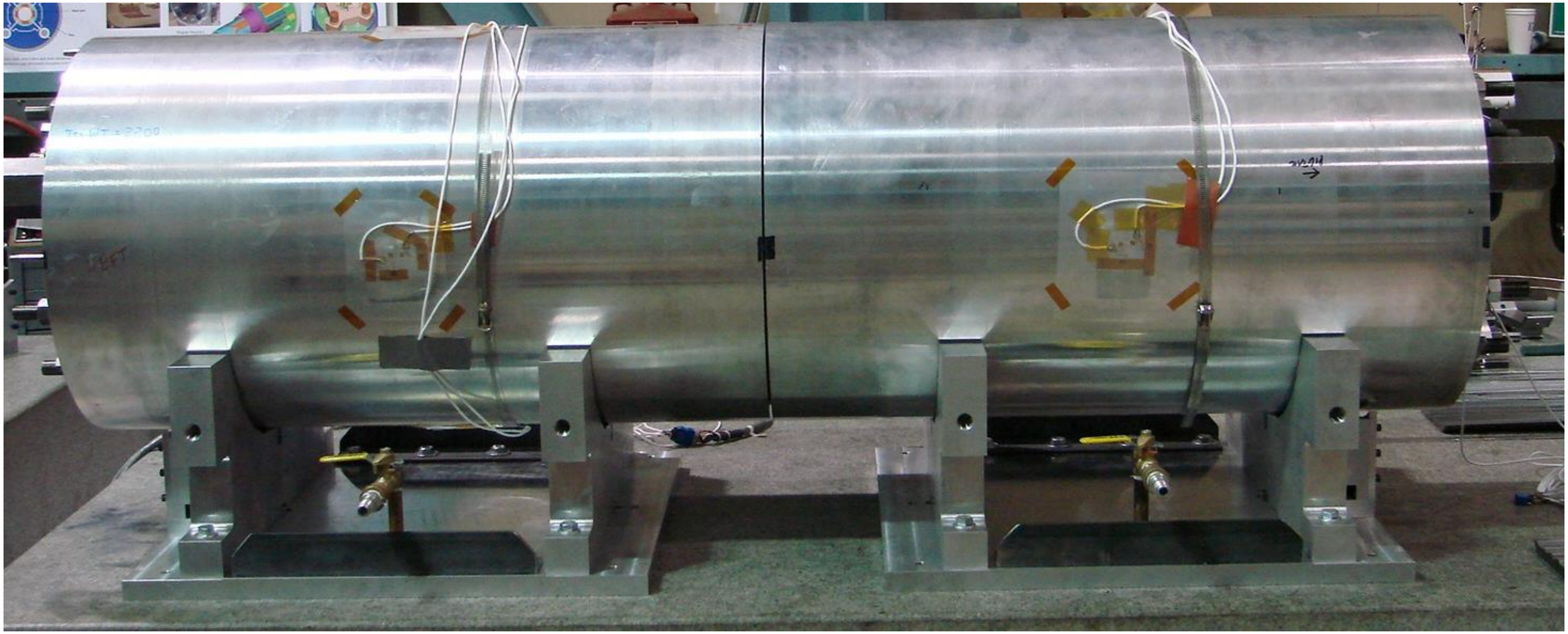




Assembly of 1.7 m long structure
Section 1 and 2 after joining operation

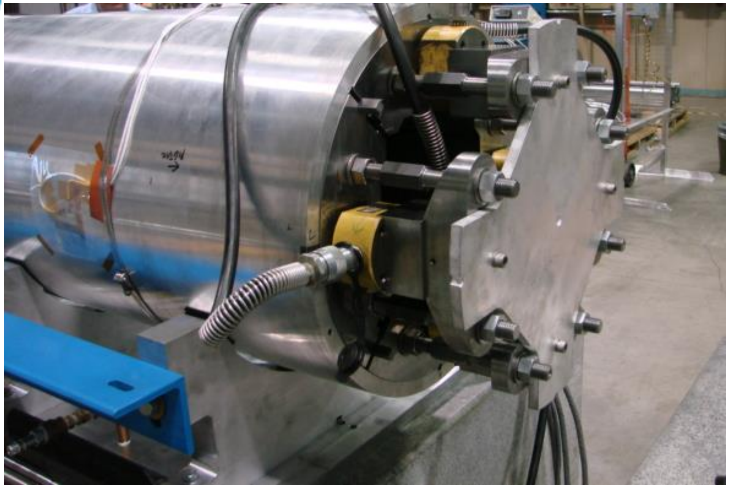


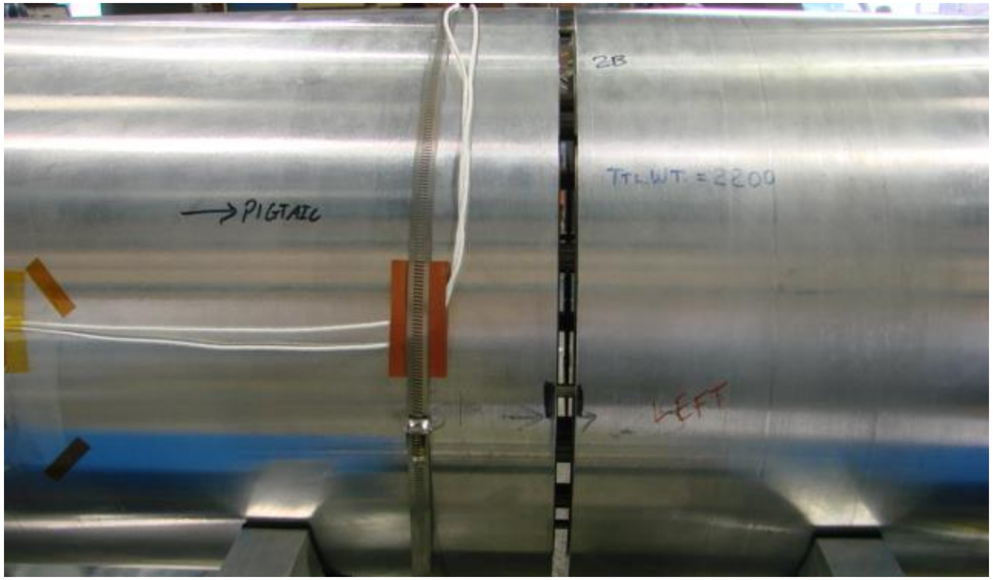
Assembly of 1.7 m long structure
Section 1 and 2 connected

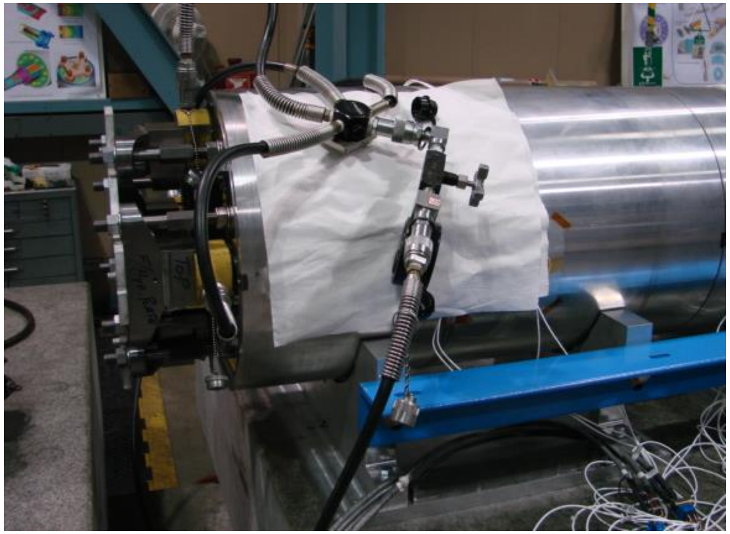


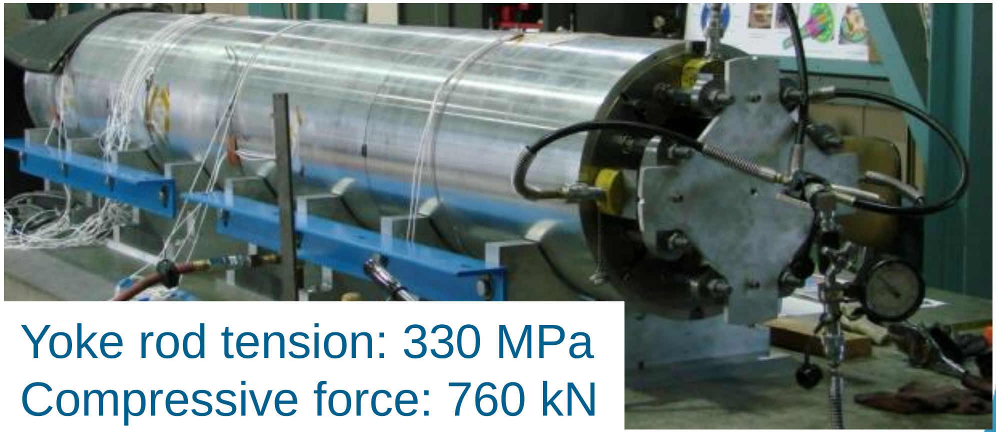
Assembly of 1.7 m long structure
Assembly of second segment pair

Assembly of full-length structure
Joining operation of 2 segment pairs



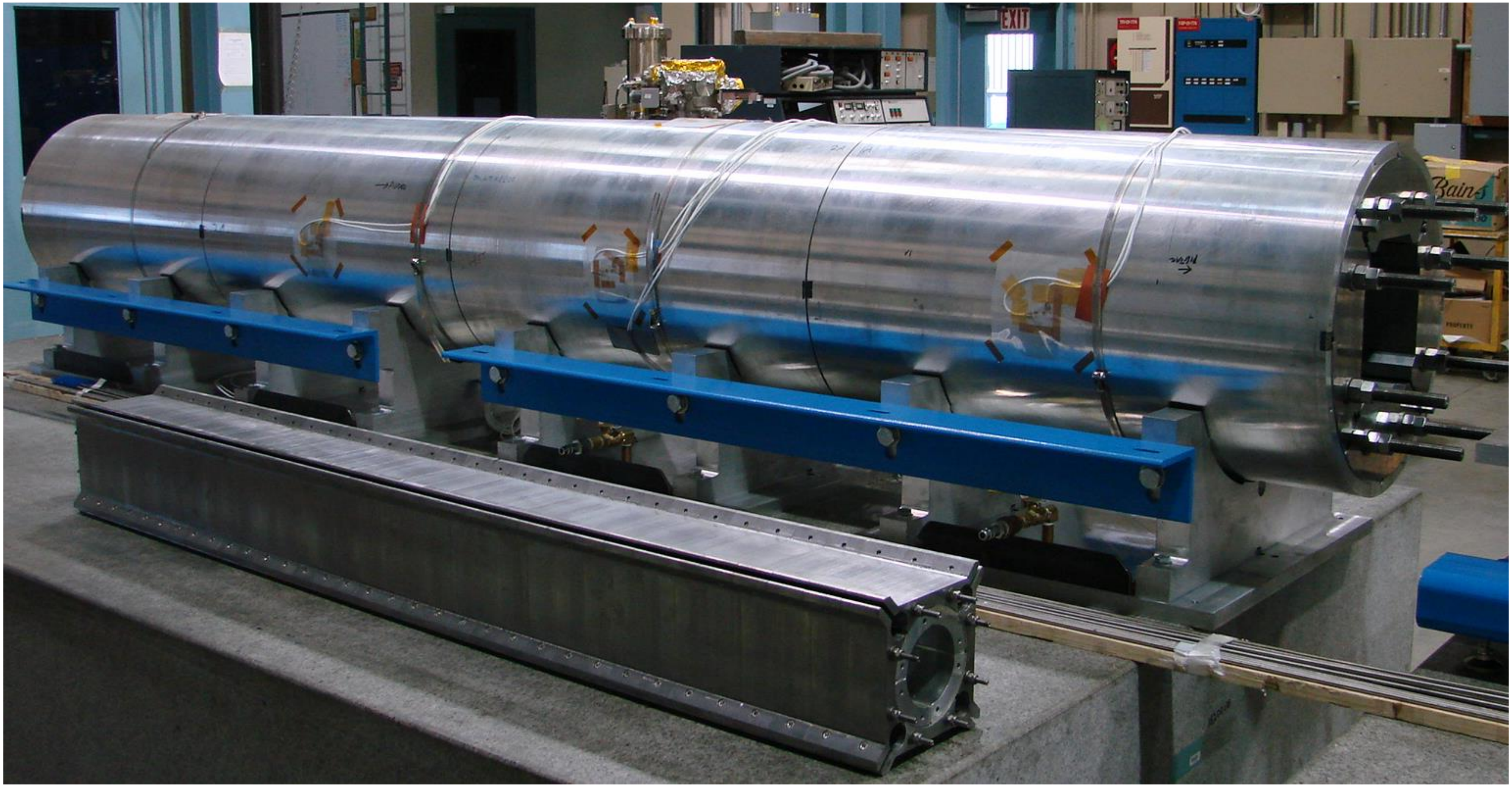




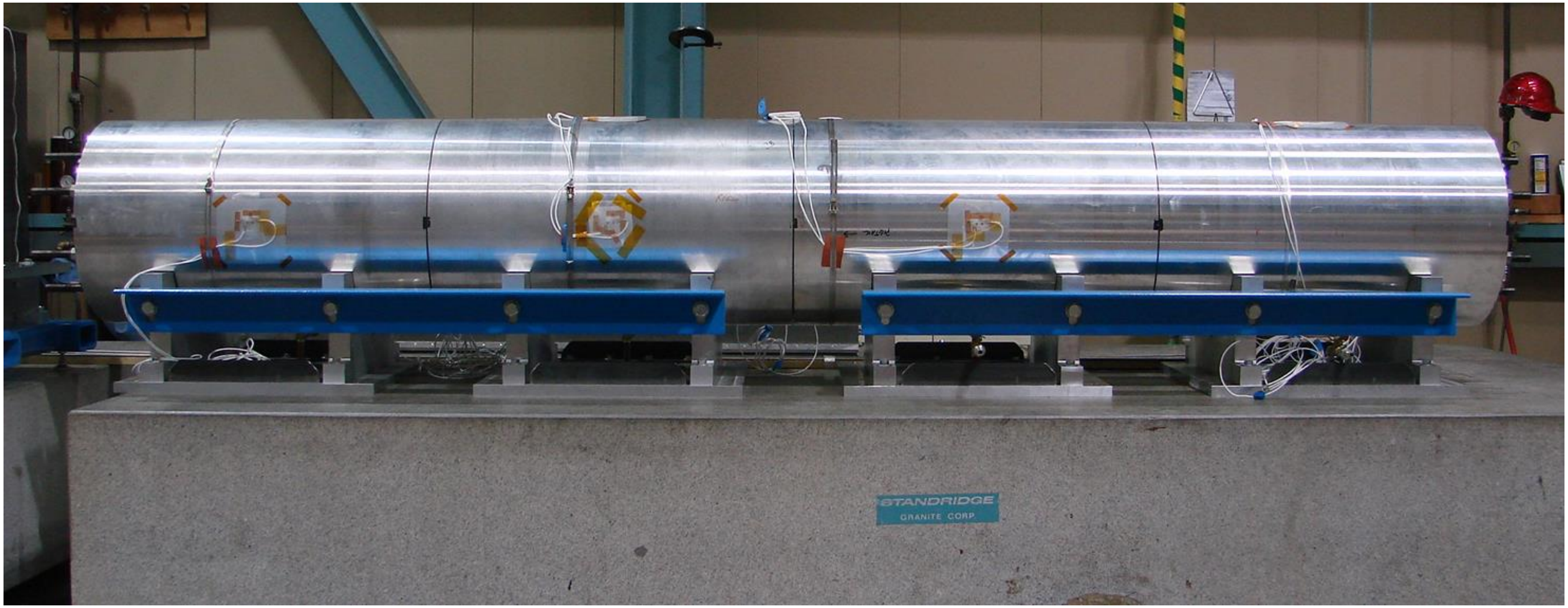


Yoke rod tension: 330 MPa
Compressive force: 760 kN

Assembly of full-length structure
3.4 m long yoke-shell sub-assembly

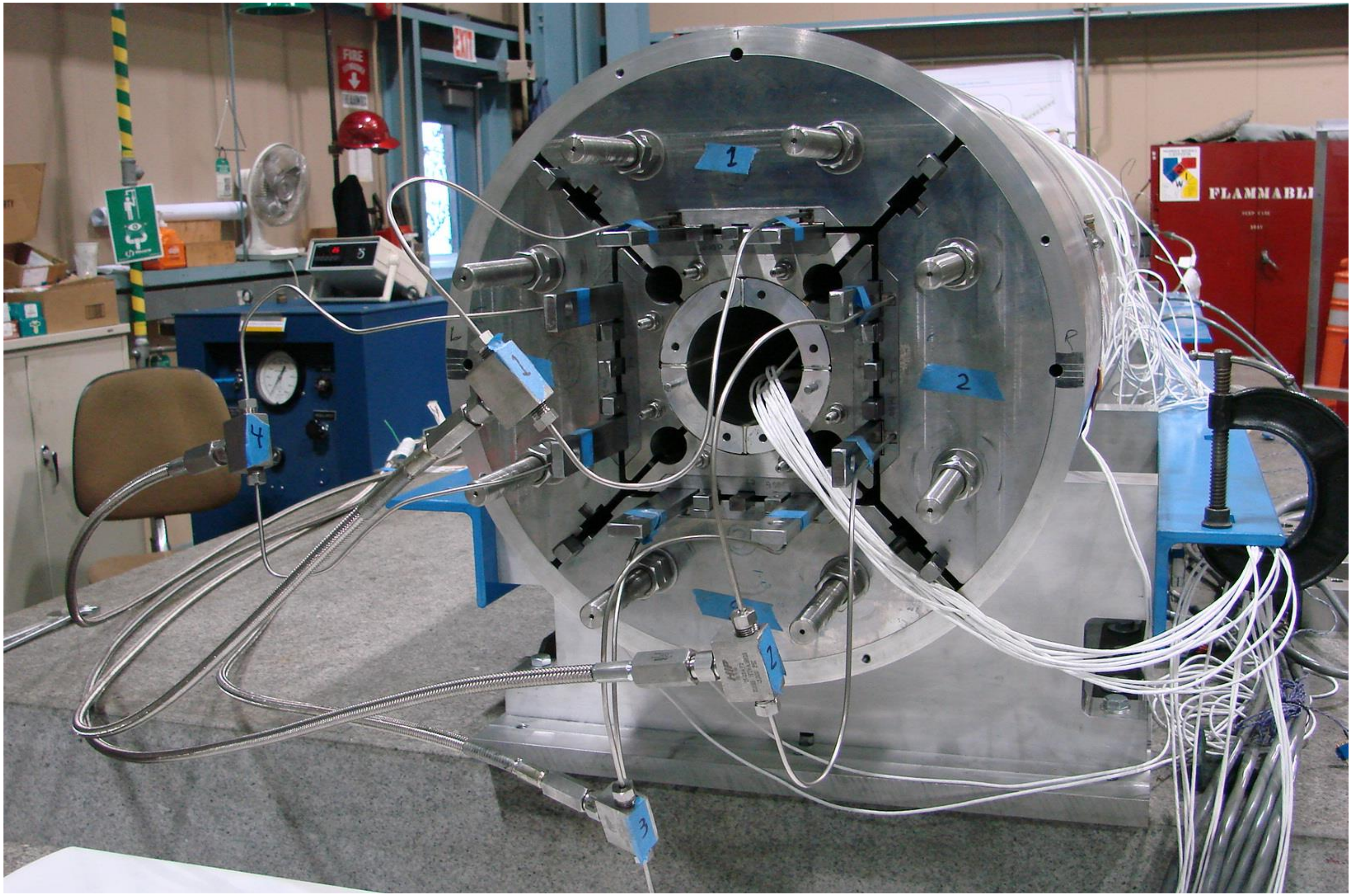


Assembly of full-length structure
3.4 m long yoke-shell sub-assembly

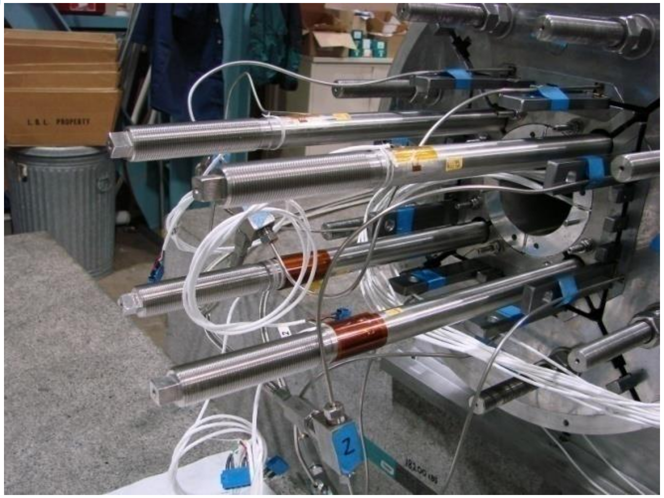


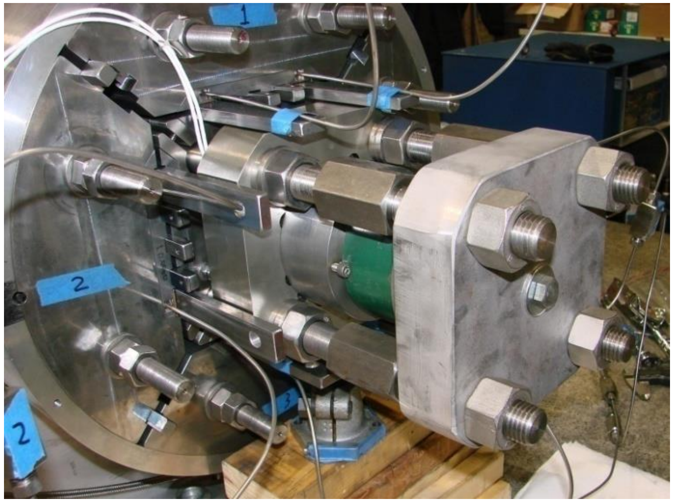
Assembly of full-length structure
3.2 m long coil-pack sub-assembly

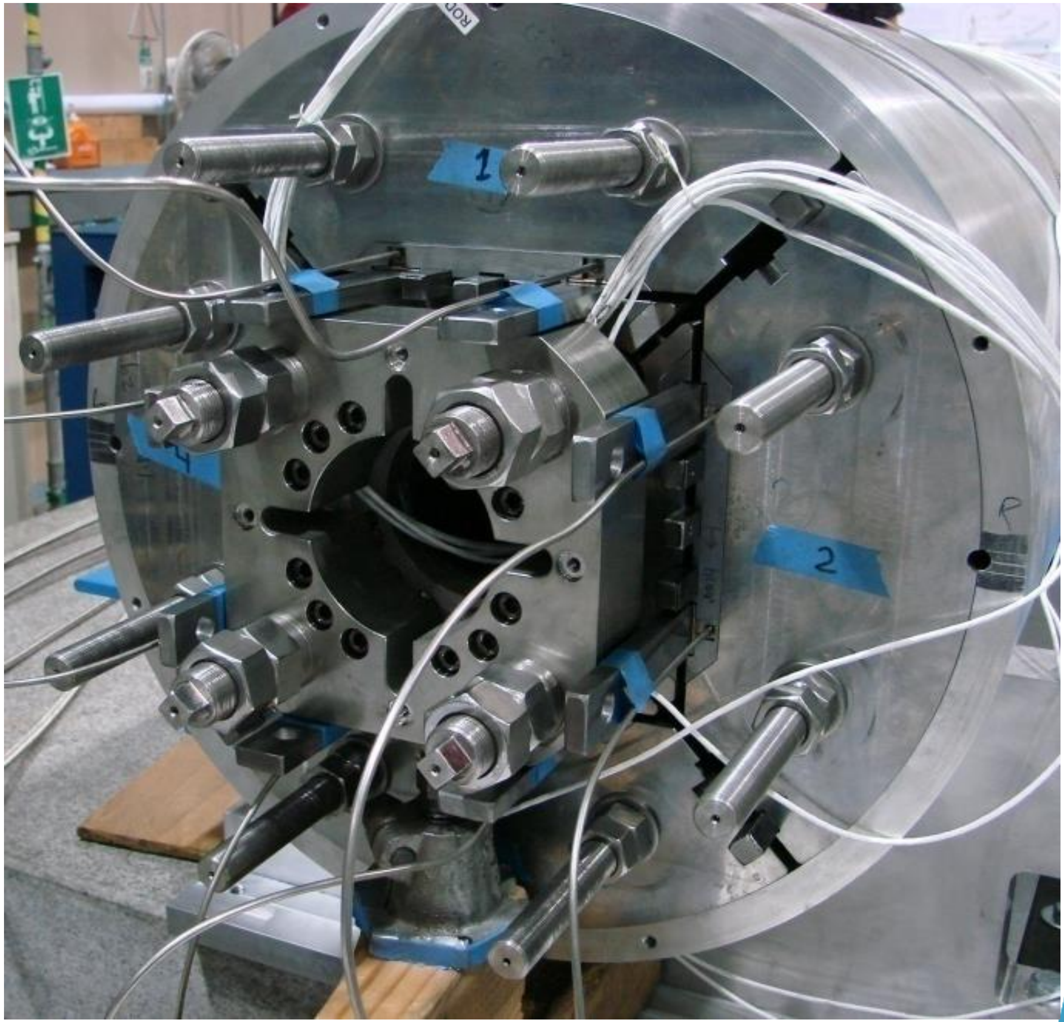
Loading of full-length structure
Bladder operation



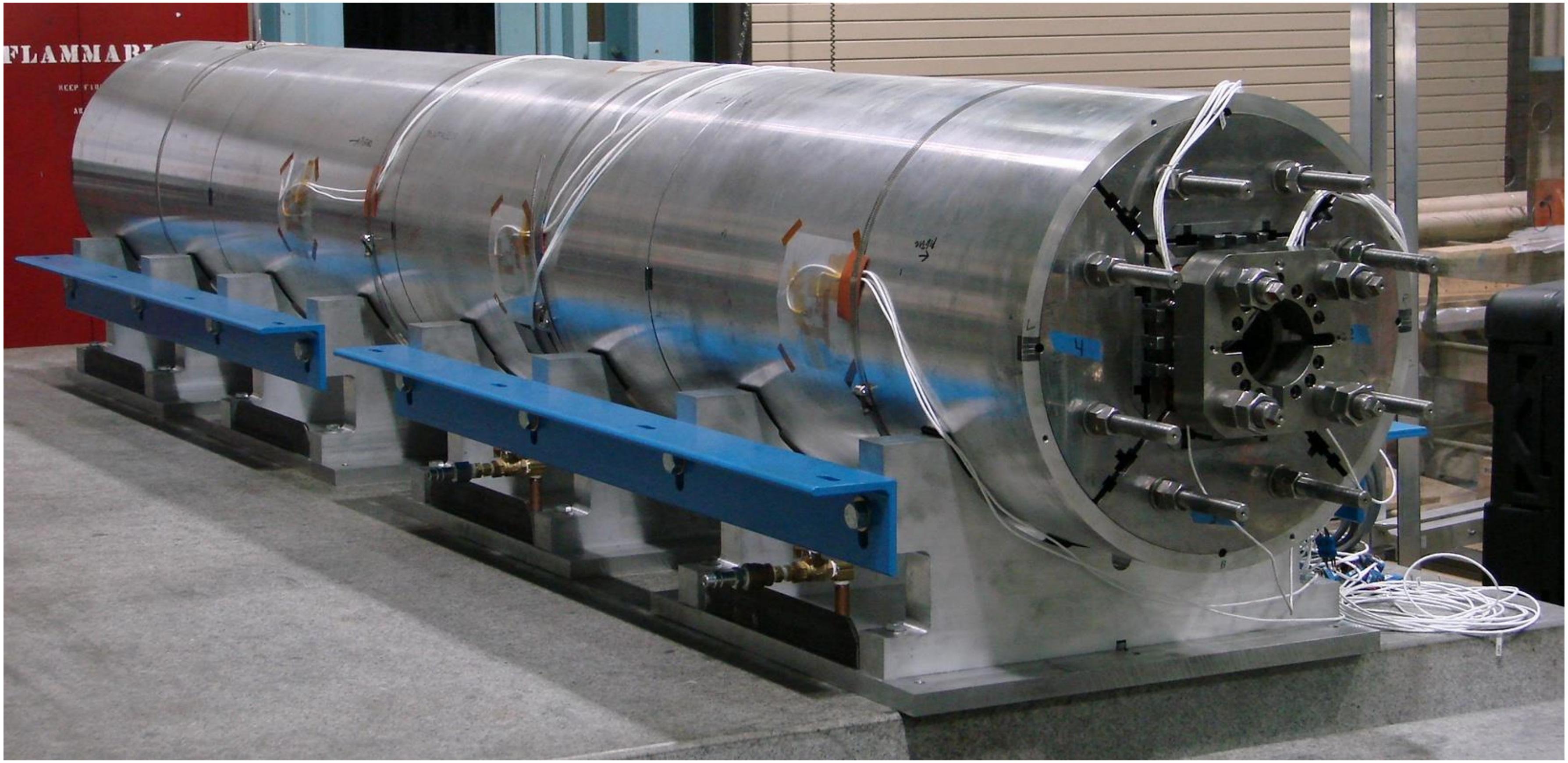
Loading of full-length structure
Axial loading operation







LQSD pre-loaded



Outline

- Introduction
- LRS01 and LRS02
- LQS01
- Conclusions

Conclusions

- The aluminum shell segmentation was implemented in the first long racetrack magnet to
  - Minimize axial tension on the shell
    - Reduce possibility of sudden slippage shell wrt yoke
  - Minimize variation of axial strain
    - Reduce resulting variation of azimuthal stress

- With a four piece yoke of a quadrupole, the shell segmentation required the definition of a new assembly procedure based on shell-yoke modules