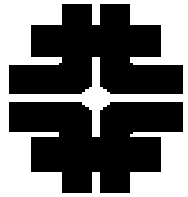
ACADEMIC TRAINING



Technology and applications of high field accelerator magnets

G. Ambrosio

Fermilab – Technical Division

Lesson 4:

- Magnet assembly – II
  Shell-based structures

CERN June 2-6, 2008

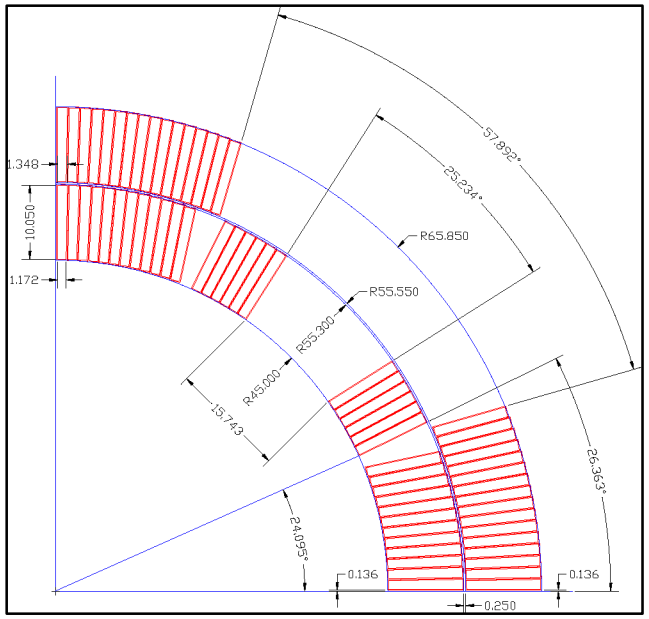
Outline

- Magnet assembly - II
  - Case studies: LARP TQS magnet assembly
    - Technological Quadrupole with Al-shell preloaded by using bladders-&-keys
  - Long magnets with shell-based structures
    - Long Racetrack
    - Long Quadrupole
  - Plan for next lessons

Magnet Assembly

Case study:
LARP TQS
Technological Quadrupole with Shell-based structure

TQ Magnetic Design



Coil layout:

- 2 layers
- 10 mm wide cable
- 1° keystone angle
- 27 strands 0.7 mm diam.

Parameter	Unit	**Collars**	**Shell**
N of layers	-	2	
N of turns	-	136	
Coil area (Cu + nonCu)	cm^2	29.33	
4.2 K temperature			
Quench gradient	T/m	**221**	**233**
Quench current	kA	13.3	13.4
Peak field in the body at quench	T	11.5	11.9
Peak field in the end at quench	T	11.9	11.4
Inductance at quench	mH/m	4.6	4.9
Stored energy at quench	kJ/m	406	439
1.9 K temperature			
Quench gradient	T/m	**238**	**251**
Quench current	kA	14.4	14.5
Peak field in the body at quench	T	12.4	12.9
Peak field in the end at quench	T	12.9	12.4
Stored energy at quench	kJ/m	472	512

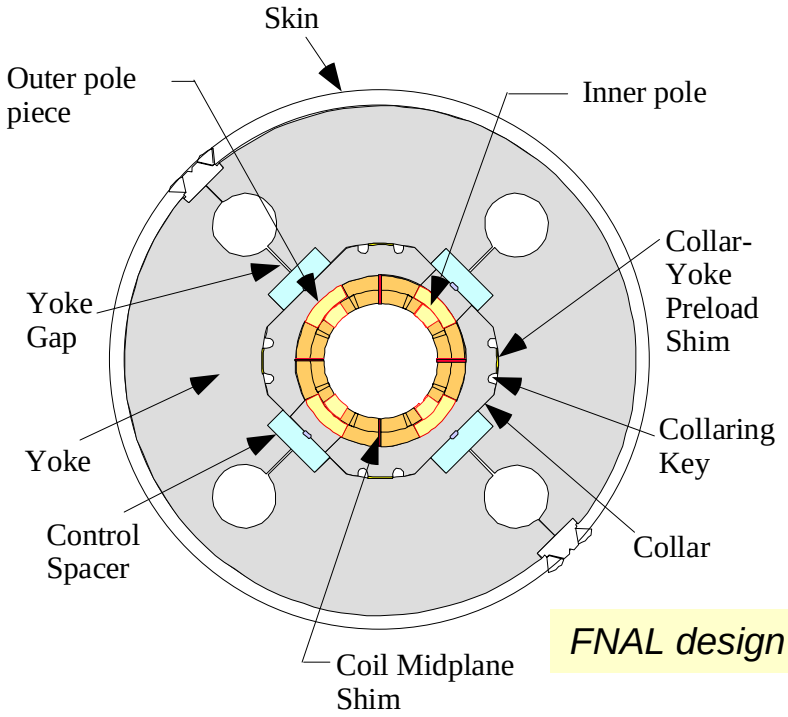
J_c = 2400 A/mm^2 at 12T, 4.2K

TQ Mechanical Designs

Two mechanical designs have been developed

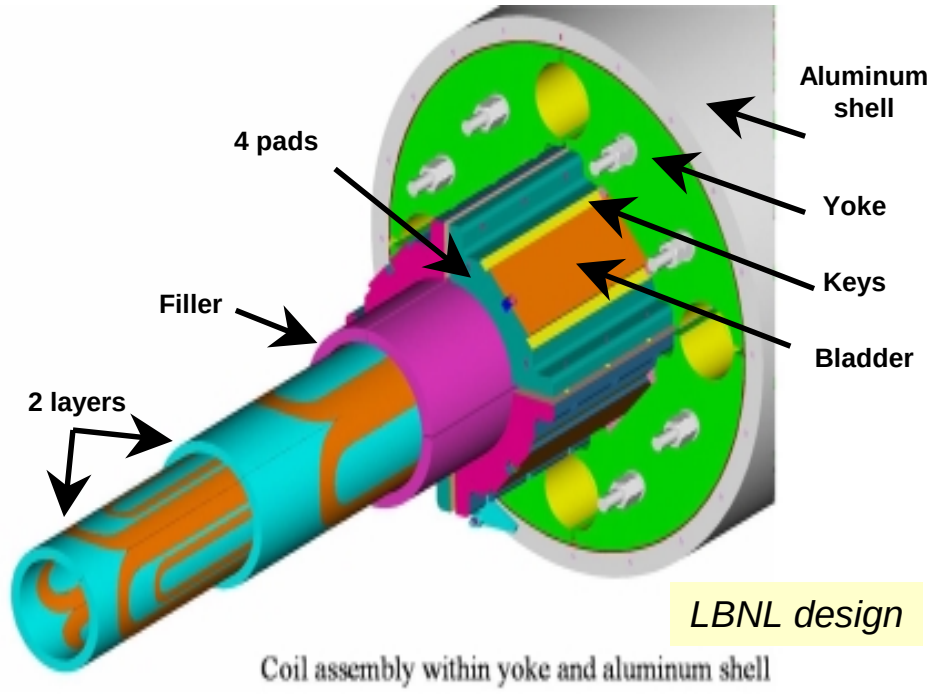
Same coils & Aperture (= 90 mm) & Gradient (> 200 T/m)

TQC: using collars
Collar laminations from LHC-IR quads
1st time applied to Nb_3Sn coils



FNAL design

TQS: using Al-shell
Pre-loaded by bladders and keys
1st time applied to shell-type coils

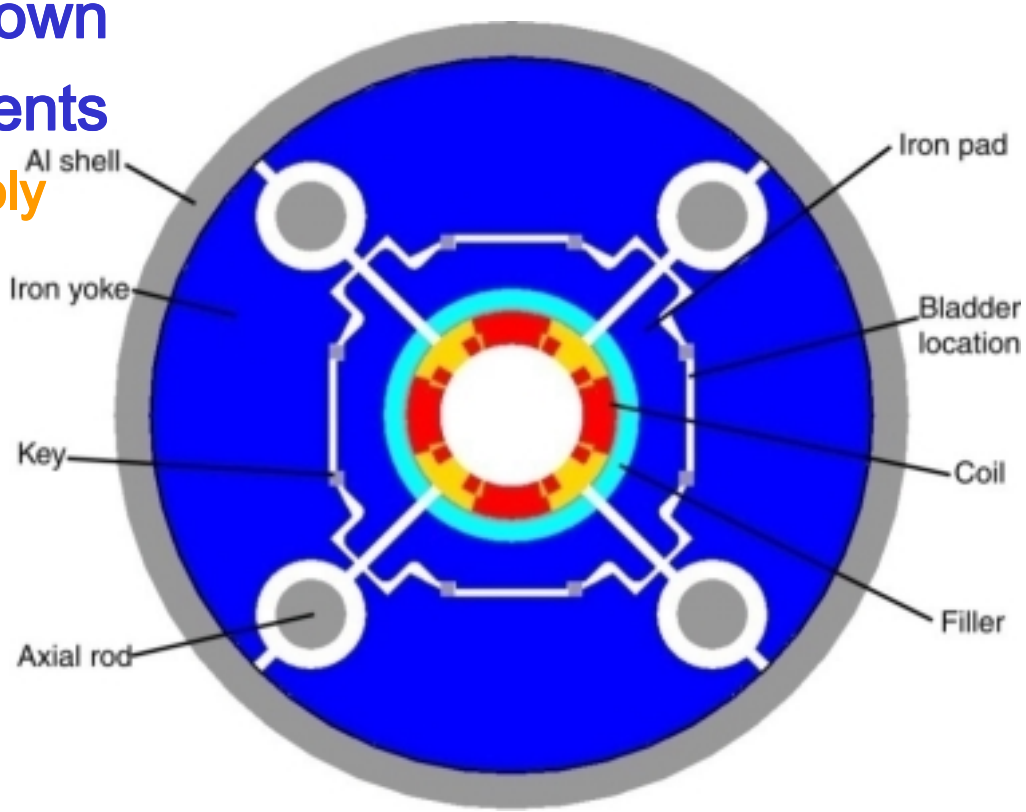


LBNL design

TQS Concept

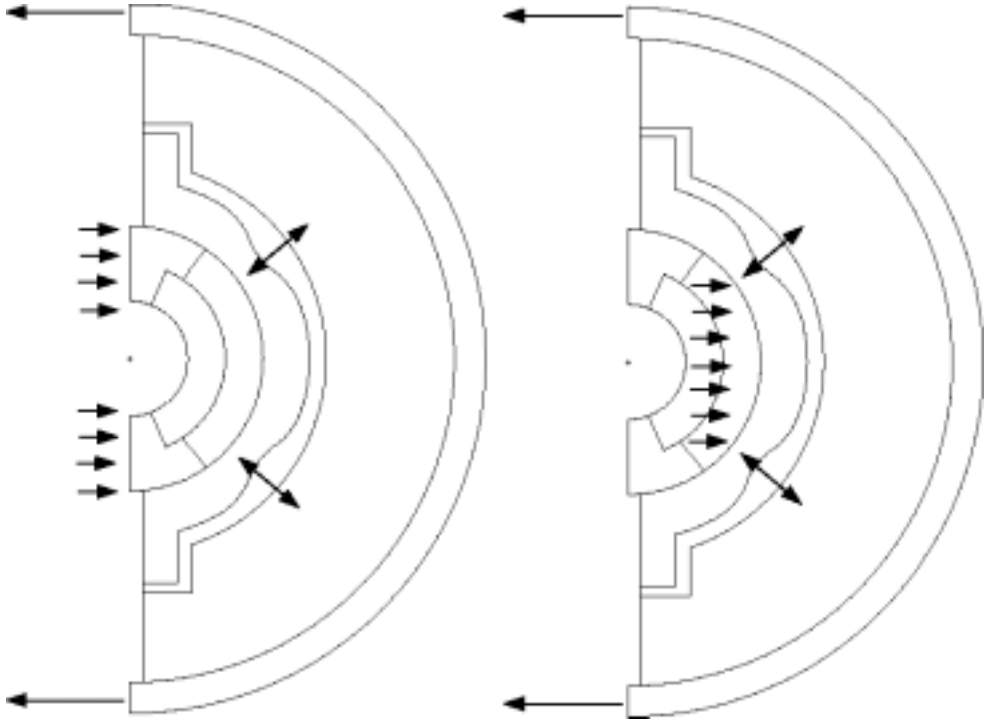
- Low pre-stress during assembly
  - Azimuthal: bladders-&-keys + Al-shell
  - Ends: Aluminum rods
- High pre-stress during cooldown
- Reusable structural components
  - Easy assembly and disassembly

TQS Cross-section



Bladders-&-Keys Concept

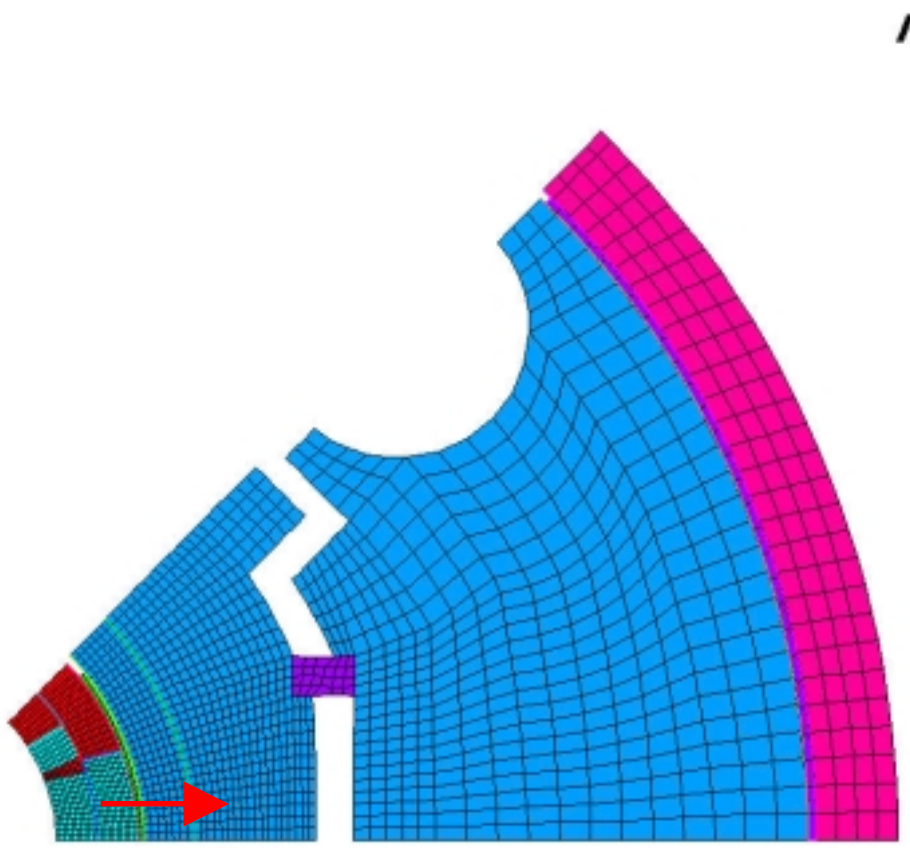
- Assembly
  - Bladders to create a interference and inserting keys to remove them
- Cooldown:
  - Thermal contraction differences to gain pre-stress

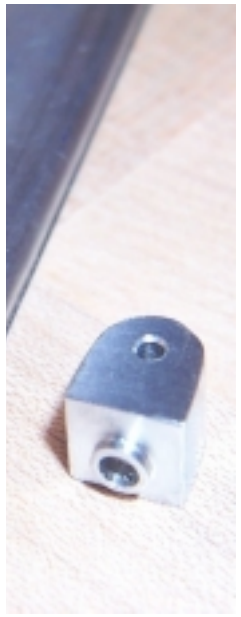


- increase in Lorentz body force = decrease in pole pre-stress
- No coil separation = No change in shell stress (zero net change in force)
- Coil separation = increase in shell stress

Courtesy: S. Caspi

Assembly, cool-down and excitation



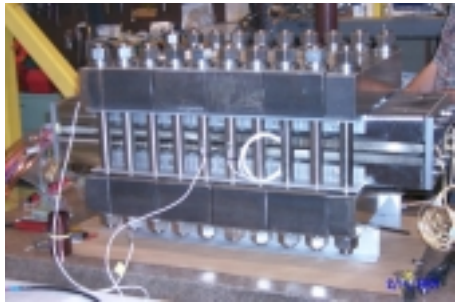


2D mechanical analysis: excitation

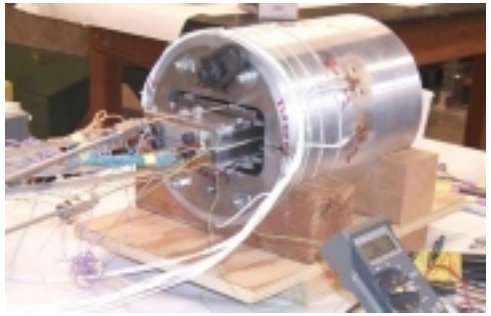
Courtesy: S. Caspi

Shell structure development

RD2 - 6 Tesla

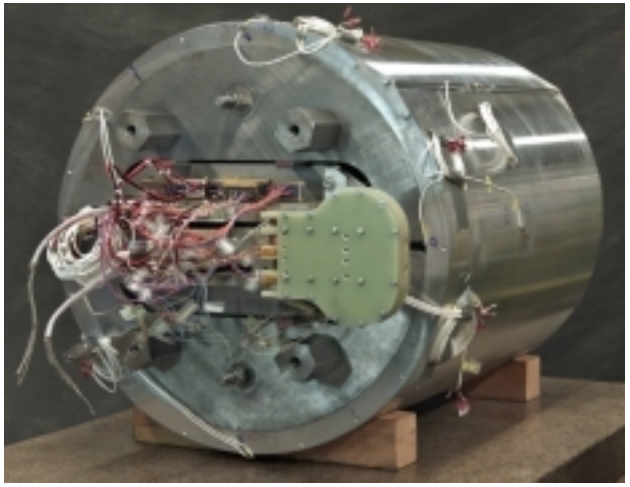


RT1 - 12 Tesla

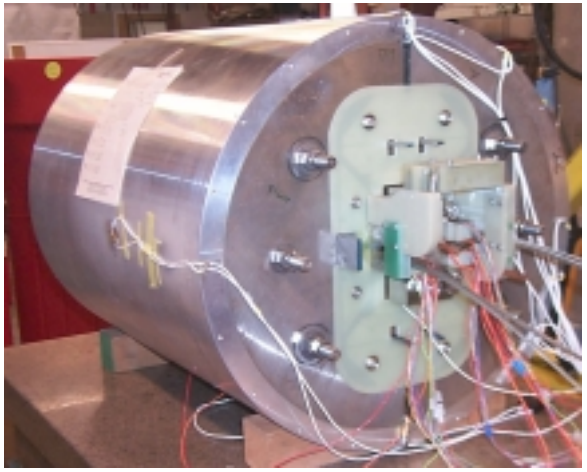


SM-01 - 12 Tesla

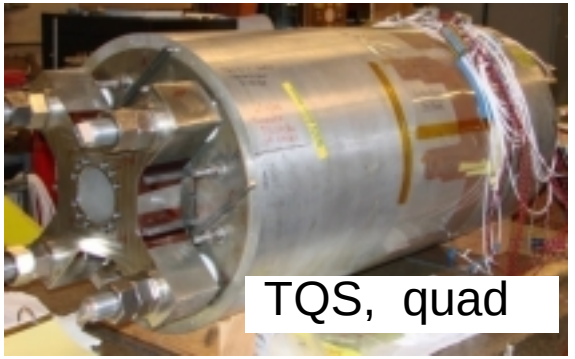
SQ01 short quad

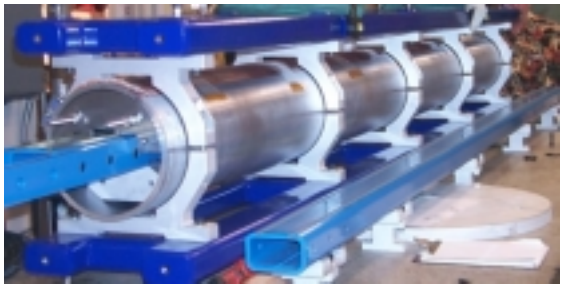


RD3-b - 14.5 Tesla



HD1 - 16 Tesla

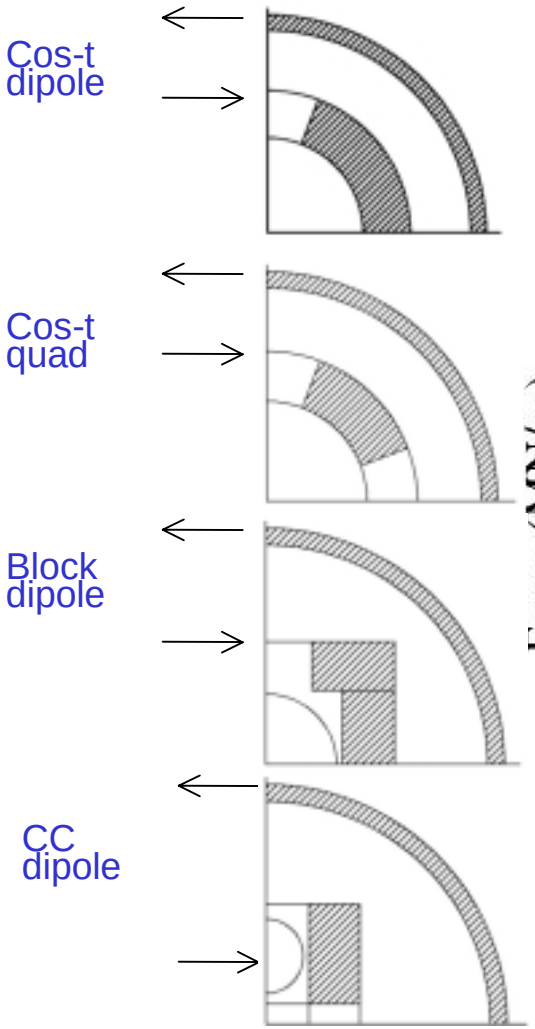


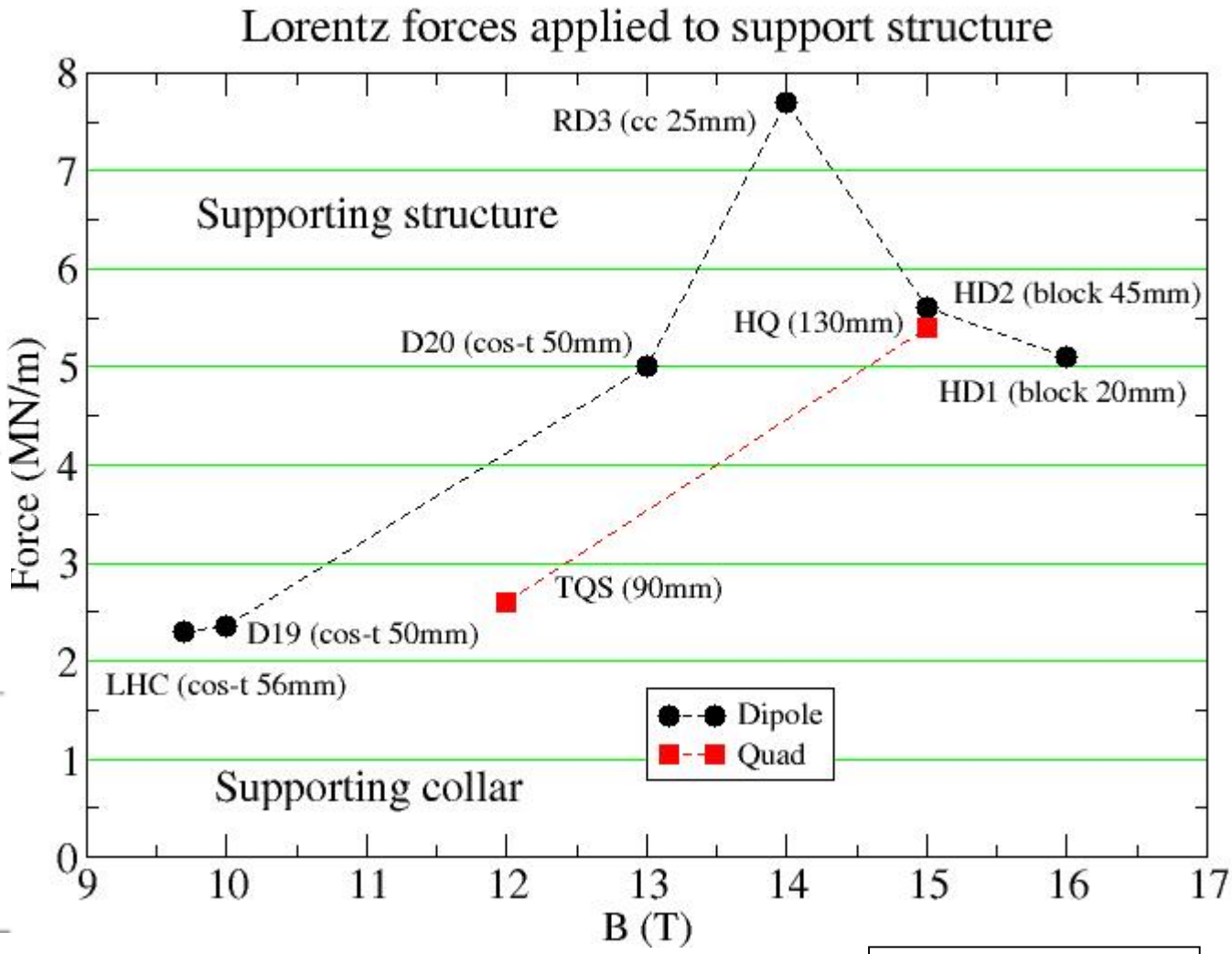


LR01 3.6 m long cc, 11.5 T

Concept developed by LBNL
Small Quadrupoles (SQ), TQS, and Long Racetrack are LARP R&D

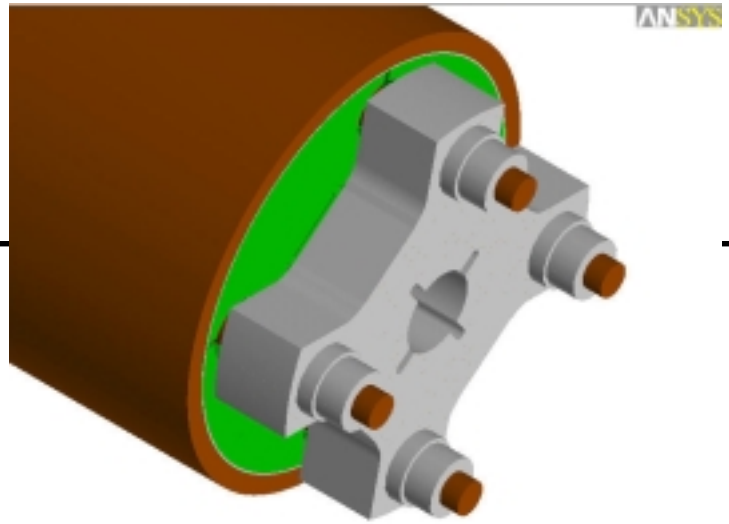
Supporting Structures





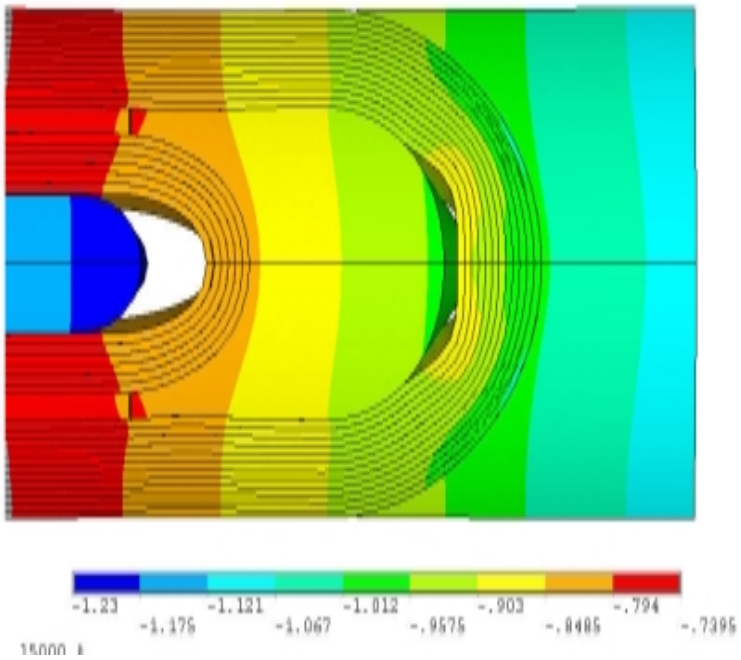
Courtesy: S. Caspi

End load

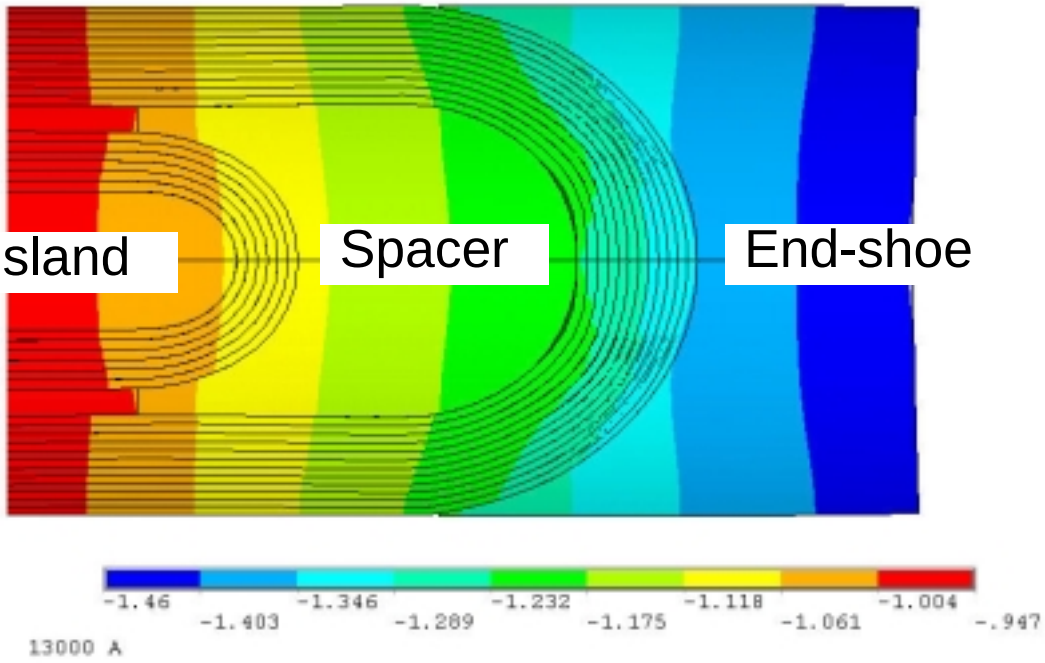


- **Full axial support**
  - ➔ prevent pole-coil gaps

Limited axial support



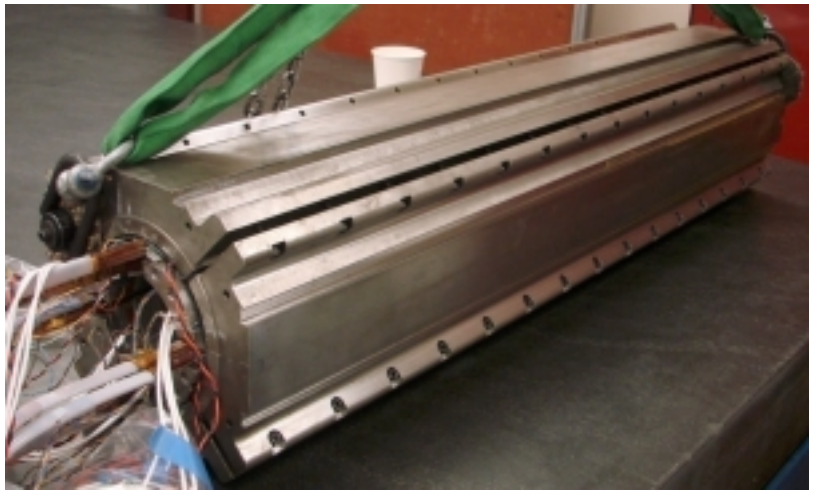
Full axial support ~ 350 kN

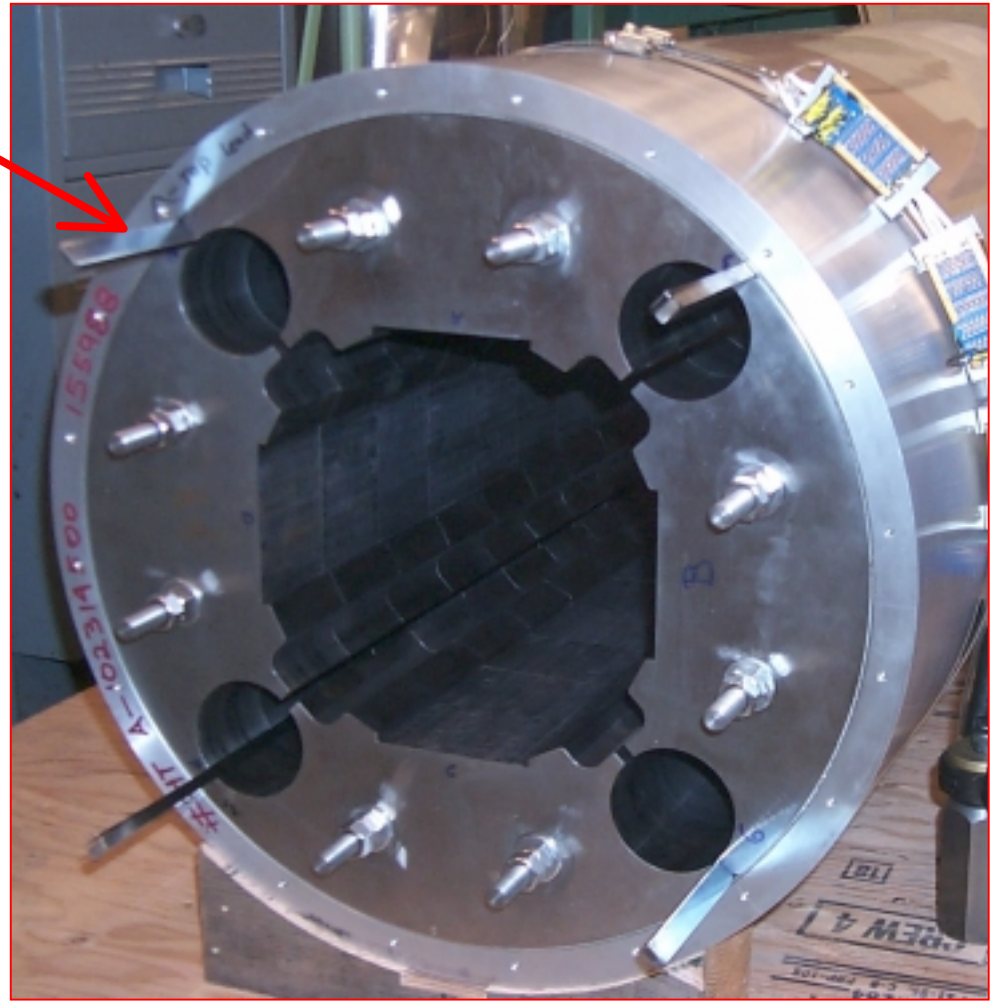


TQS sub-assemblies

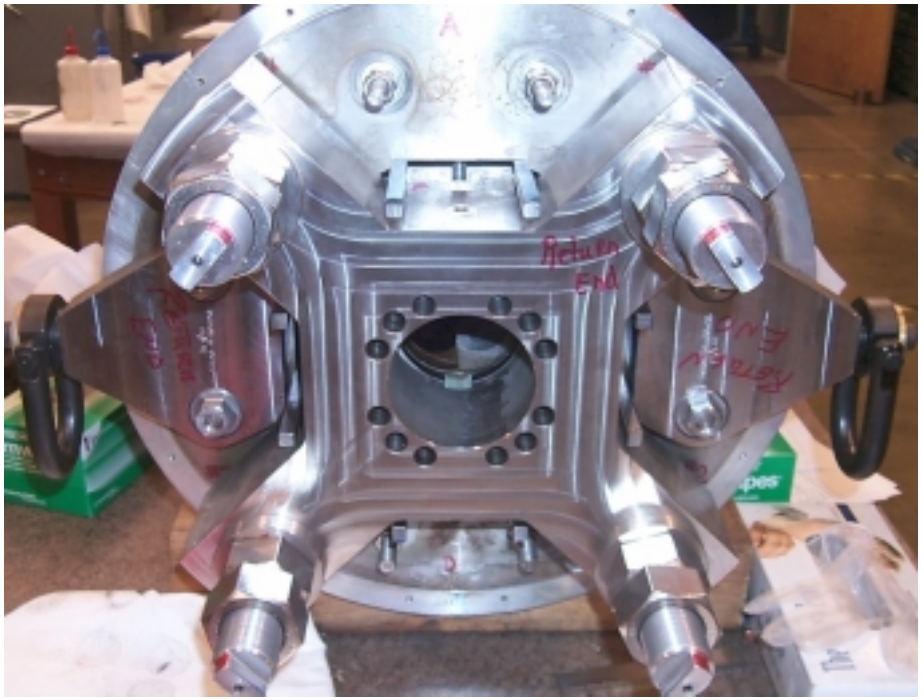
Shell and yoke sub-assembly
Yokes held temporarily with gap keys
Assembled using bladders and dummy coils

Coil and pad sub-assembly
Pads held by bolts

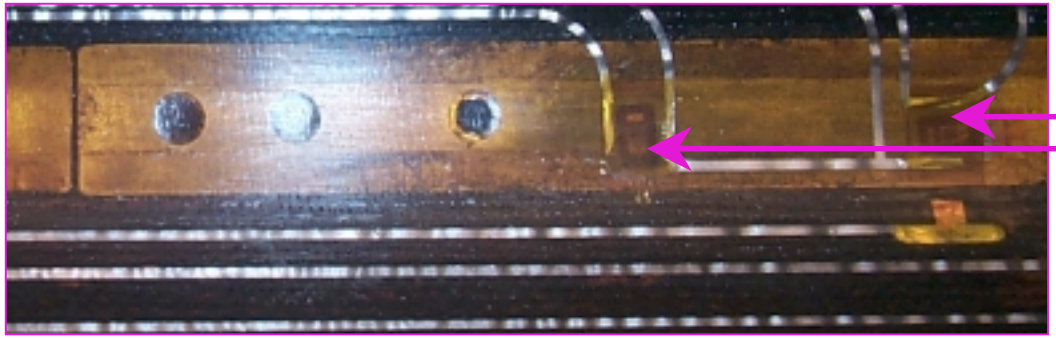




TQS Final assembly



Coil Island instrumented
to monitor stresses



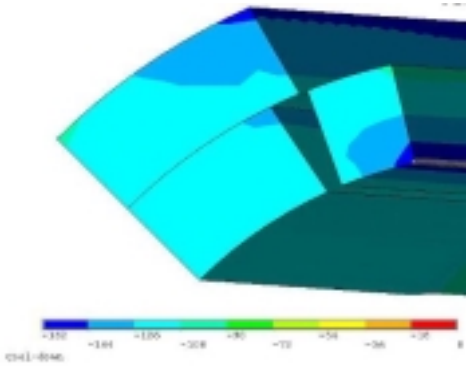
Azimuthal pre-stress (bladder operation)

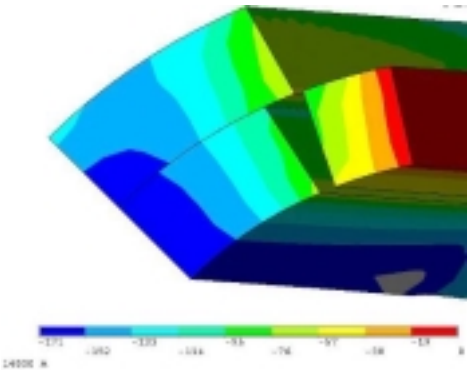
Bladders are inserted than pressurized with water

FEM analysis

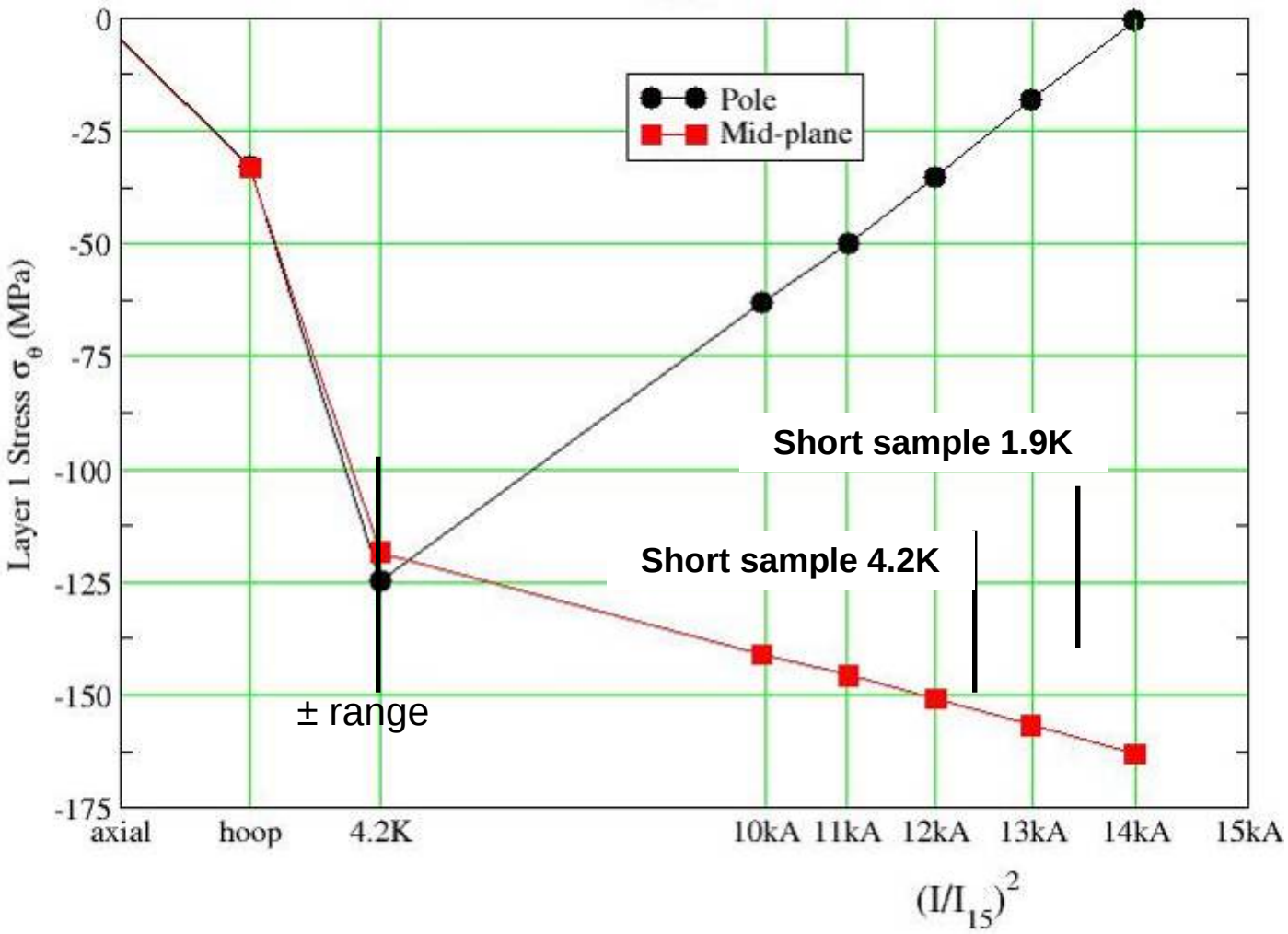
- **Azimuthal stress in layer 1 (Bronze pole with friction)**

4.2 K





14kA



TQS01/02 Strain/Stress at 4.4K

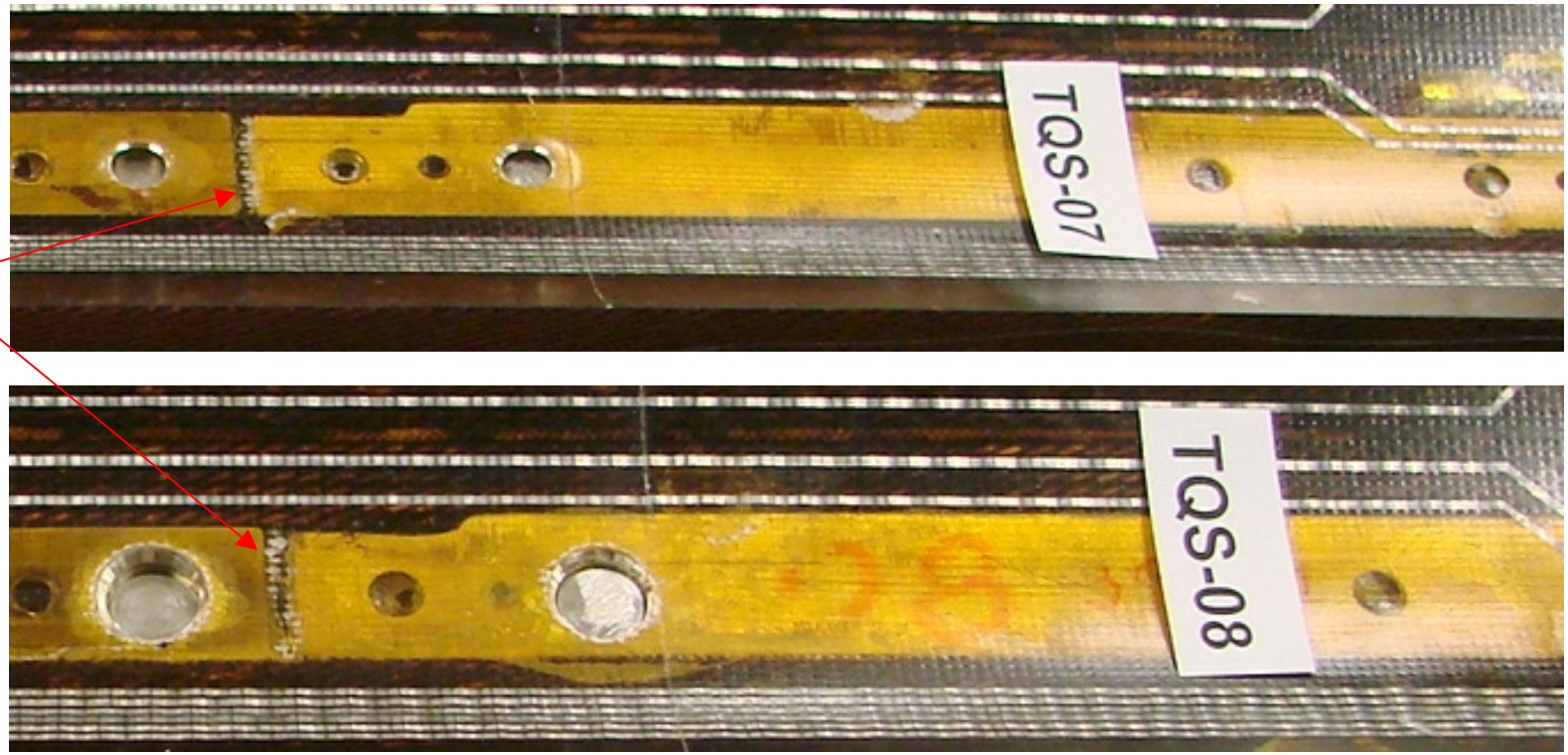
	Bronze - with axial support	Titanium- with axial support
Island Strain $\mu\varepsilon_\theta$	-1900	-750
Island Strain $\mu\varepsilon_z$	+760	-520
Island Stress σ_θ	-215	-129
Island Stress σ_z	+25	-105
Coil Strain $\mu\varepsilon_\theta$	-3300	-3100
Coil Strain $\mu\varepsilon_z$	+1000	+1000
Coil Stress* σ_θ	-150	-134
Coil Stress σ_z	+12	+30

**Outer layer azimuthal stress with Ti pole: 180-190 MPa*

TQS01c post test inspection

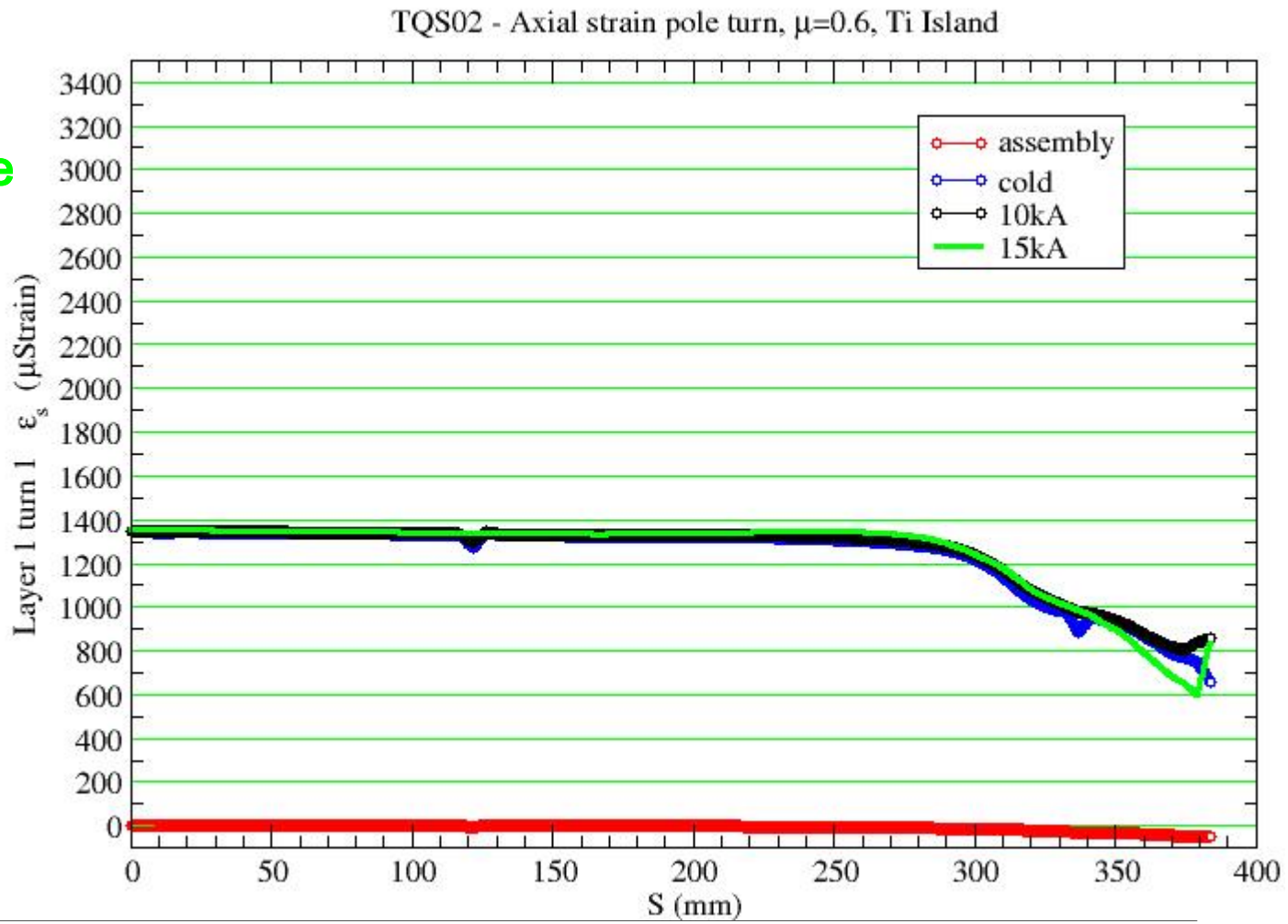
- Signs of high tensile strain in the pole gaps
  - Caused by the different contraction of coil and iron pads
    - under high pre-stress (no sliding)
  - Possible damage in the coil because of high tensile strain

High strain discoloration



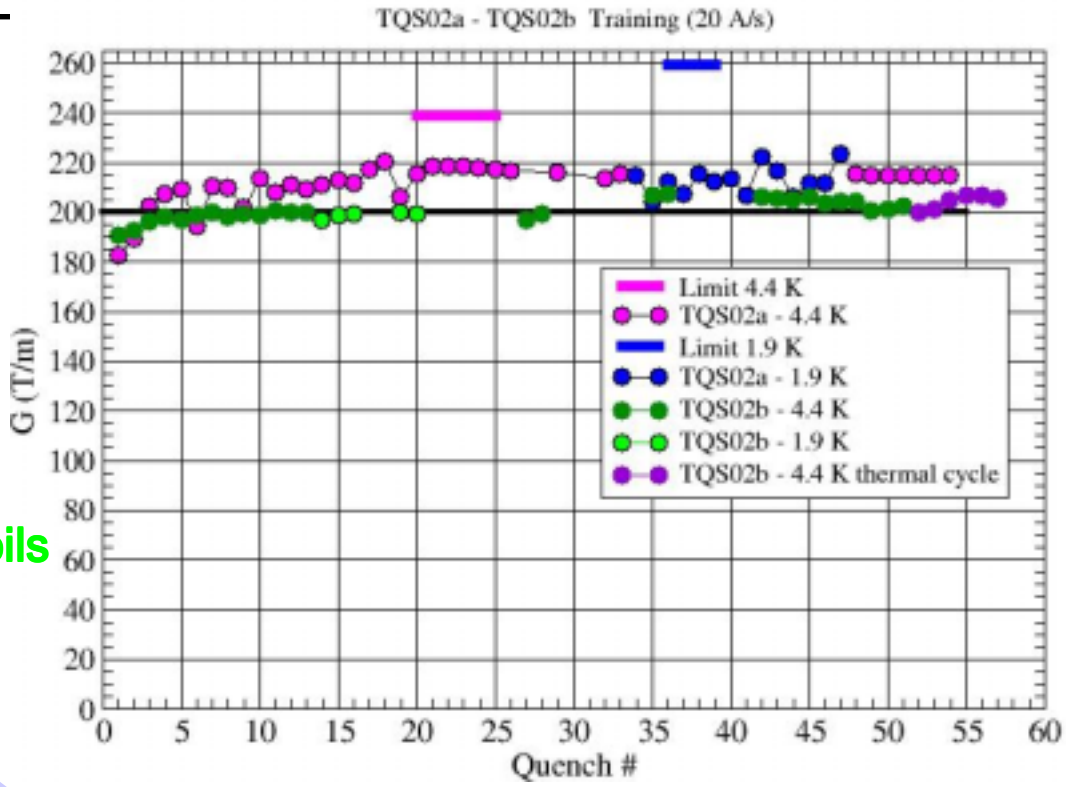
Axial strain in turn 1 (ANSYS)

- Possible high longitudinal strain after cooldown
  - Iron pads
  - Pole:
    - Al-bronze
    - Ti-Al-V



TQS Results

- TQS01 (MJR)
  - 89% SSL at 4.5K
  - 200 T/m at 3.2K
- TQS01b (MJR)
  - 84% = 182 T/m at 4.5K
    - Reassembly w 2 new coils
- TQS01c (MJR)
  - 85% = 183 T/m at 4.5K
  - 80% = 192 T/m at 1.9K
    - Reassembly w best used coils
- TQS02a (RRP 54/61 – Ti pole)
  - 91% = 219 T/m at 4.5K
  - 84% = 221 T/m at 1.9K
    - 4 new coils
      - **No improvement at 1.9K**
- TQS02b (RRP 54/61 – Ti pole)
  - ~207 T/m at 4.5K
  - 200 T/m at 1.9K
    - Reassembly w 2 new coils
      - **Damaged coil?**



Magnet assembly:

- *Al-shell w bladders&keys can provide prestress and support for these forces*
- *Very short assembly time*

Further development

Next steps to demonstrate possible use of Al-shell with bladders-&-keys concept for accelerator magnets:

Long magnets:

➔ **Long Racetracks** and **quadrupoles (LQ)** addressing long magnet issues

LRs have two flat racetrack coils, B_{coil} > 11 T, 3.6 m long coils
- NO aperture

LQs have same features of TQs, B_{coil} > 12 T, 3.5 m long coils
- 90m aperture, 200 T/m grad, NO coil alignment

Coil alignment:

➔ **High gradient quadrupoles (HQ)** to explore performance limits

1 m long, 90-130 mm aperture, G_{nom} > 250 T/m, B_{coil} > 15 T

Others: helium containment (additional ss shell), heat transfer

LARP Long Racetrack

The goals of the Long Racetrack (LR) are:

- to fabricate and test long Nb_3Sn racetrack coils — *Performed at BNL*
- to test an Al-shell-based supporting structure — *Developed at LBNL*

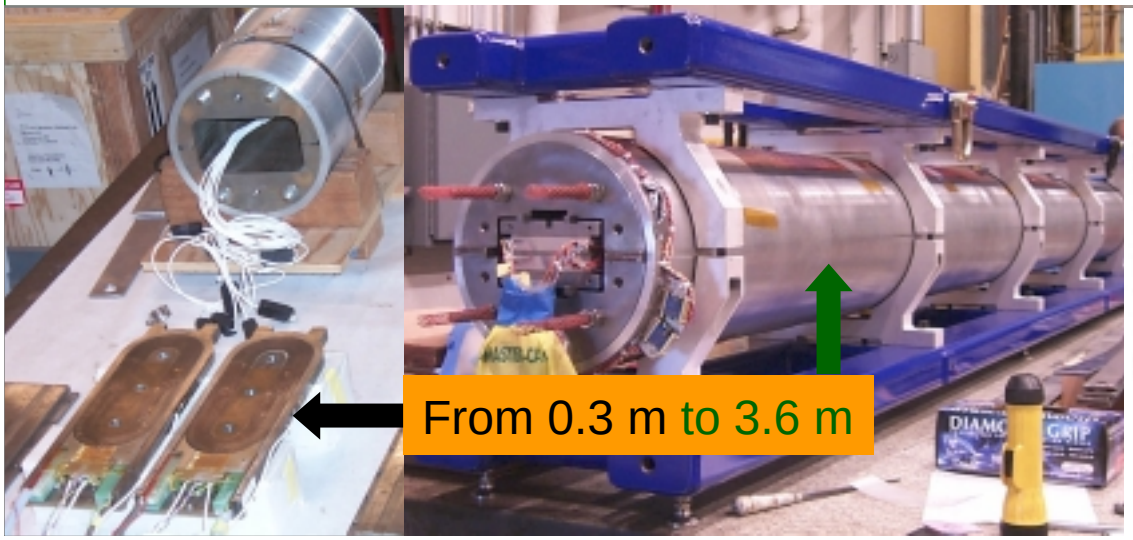
(preloaded using bladders and keys)

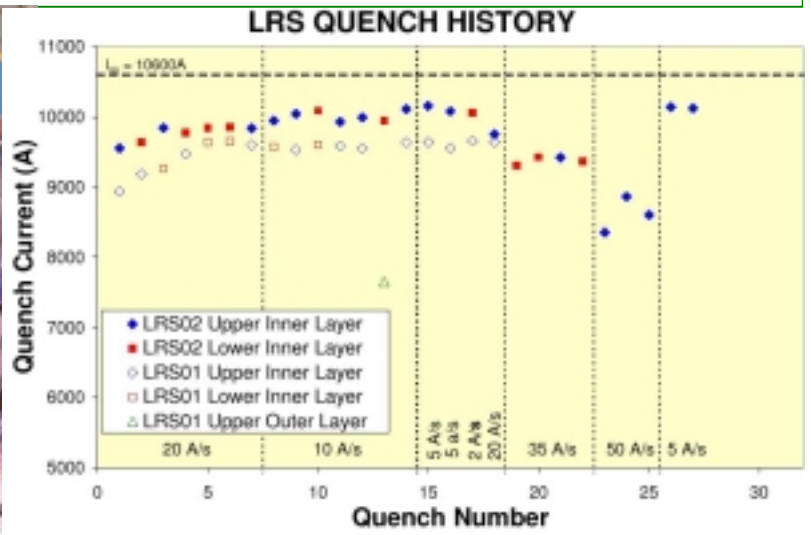
Project coordination — *Fermilab*

Results:

- **1st test: I_q= 90% ssl; 2nd test with segmented shell: I_q~ 96% ssl**
- **Shell stress variation during 1st test ➔ Shell should be segmented**

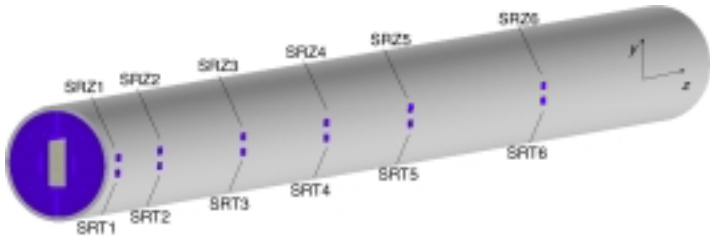
Coil layout: two flat double-layer racetrack coils
Technology developed at LBNL, modified at FNAL, successfully transferred to BNL

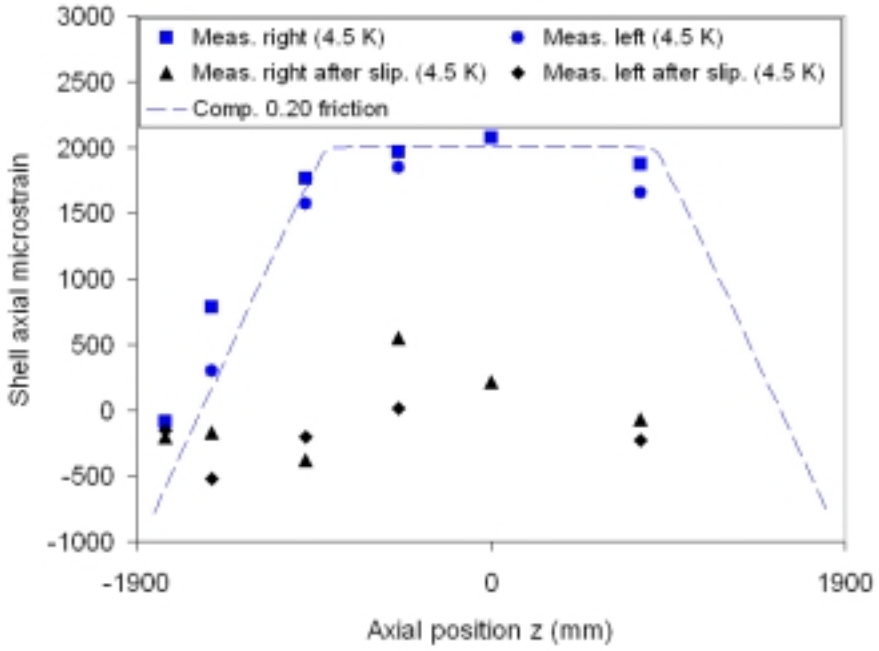


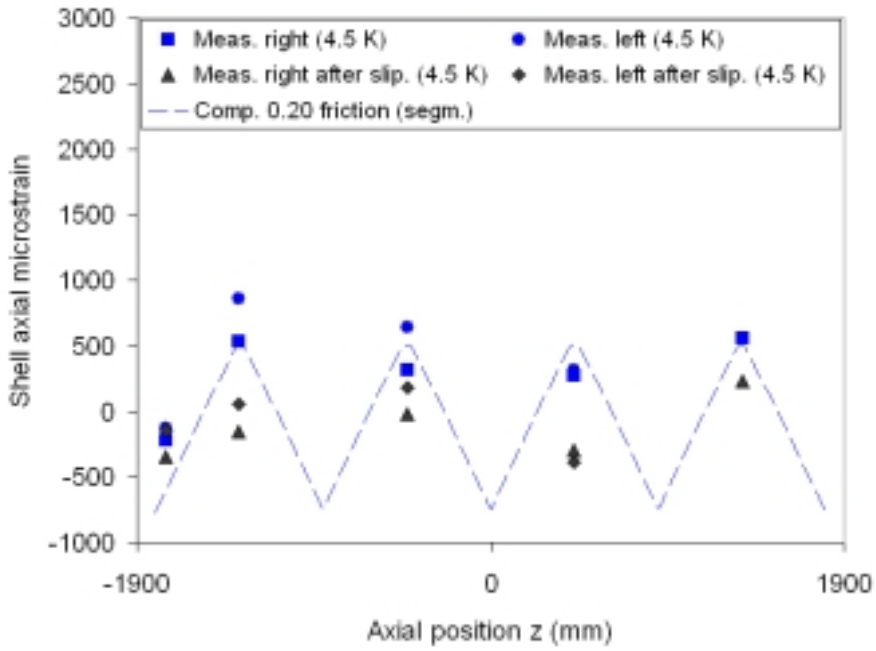


3D mechanical analysis
Full length or segmented shell

- LRS01
  - High axial strain meas. in LRS01
  - Slippage shell-yoke
- LRS02 (with segmented shell)
  - Reduced axial strain





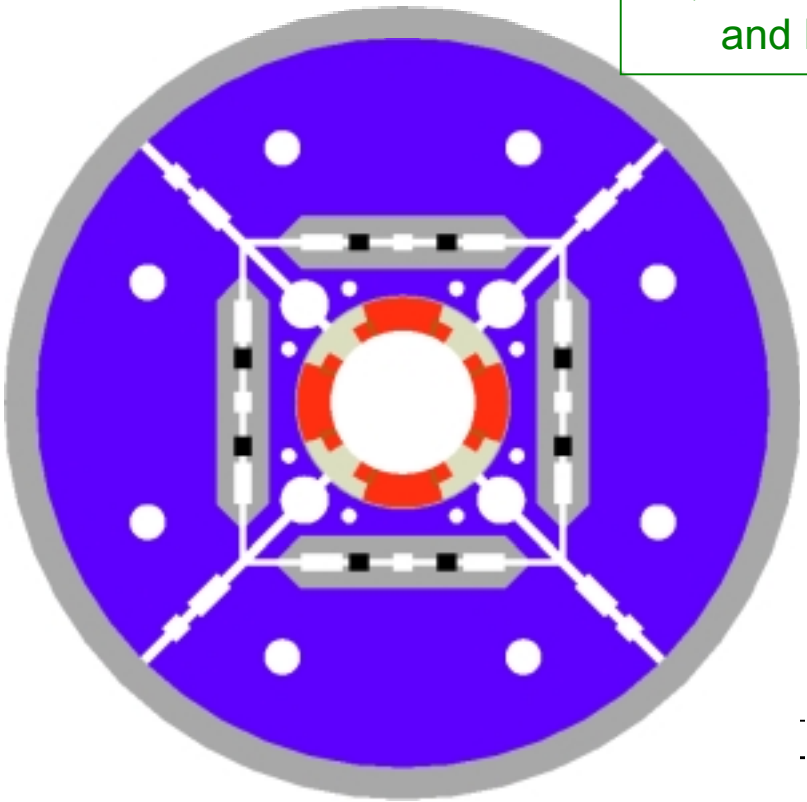


LARP Long Quadrupole

The goals of the Long Quadrupole (LQ) are:

- G > 200 T/m in 3.8m long quad with 90-mm aperture using Nb_3Sn coils
- to test both structures:
  - Al-shell-based structure (preloaded using bladders-&-keys)
  - Collar structure with support from yoke and welded skin

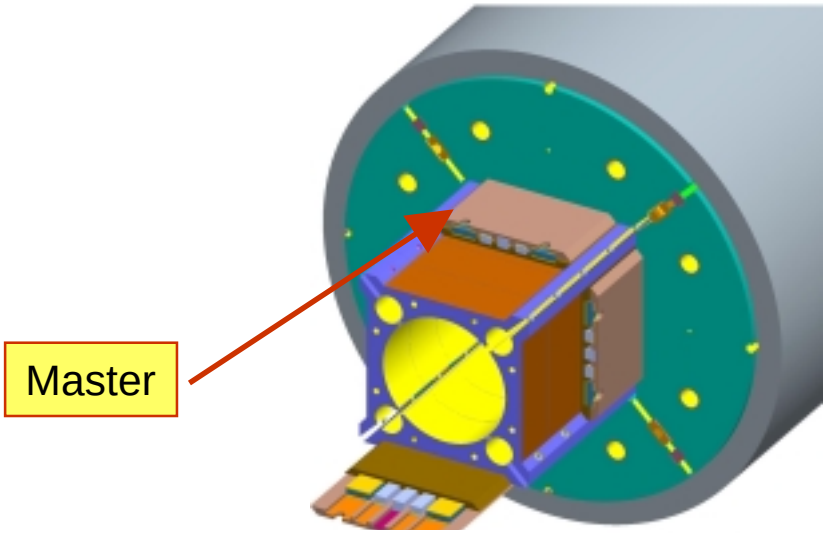
LQS01 is based on TQS magnets and LRS02



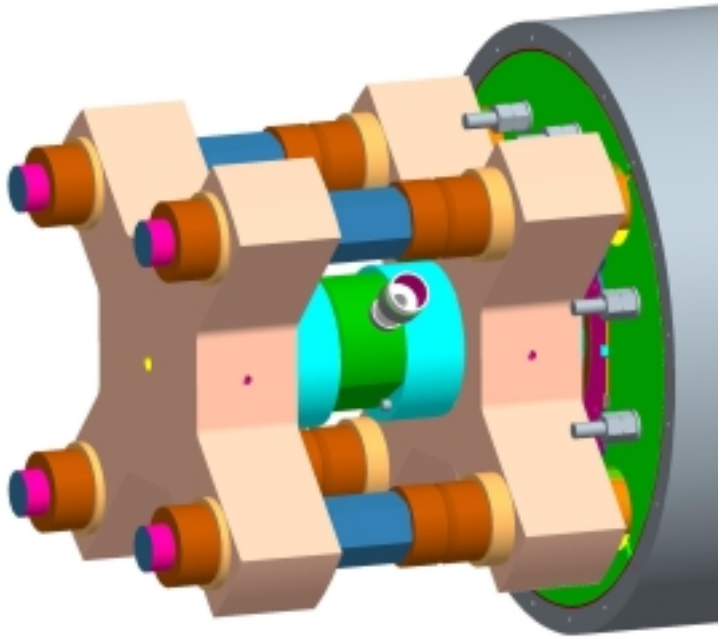
- 20 mm shell
- 4-split iron yoke
  - Gap keys and auxiliary bladders
  - Holes for tie rods
- Iron pads
  - Holes for coil end support and tie rods
- Iron masters
  - 2 bladders
  - 2 interference keys
- Stainless steel sheet between coil and pad laminations

LQS design
3D components

- 4 shell segments, 0.8 m long
- Yoke laminations, 50 mm thick with 3.3 m long tie rods
- Iron pad laminations, 50 mm thick with 3.3 m long tie rods
- Iron masters, 2 x 1.6 m long



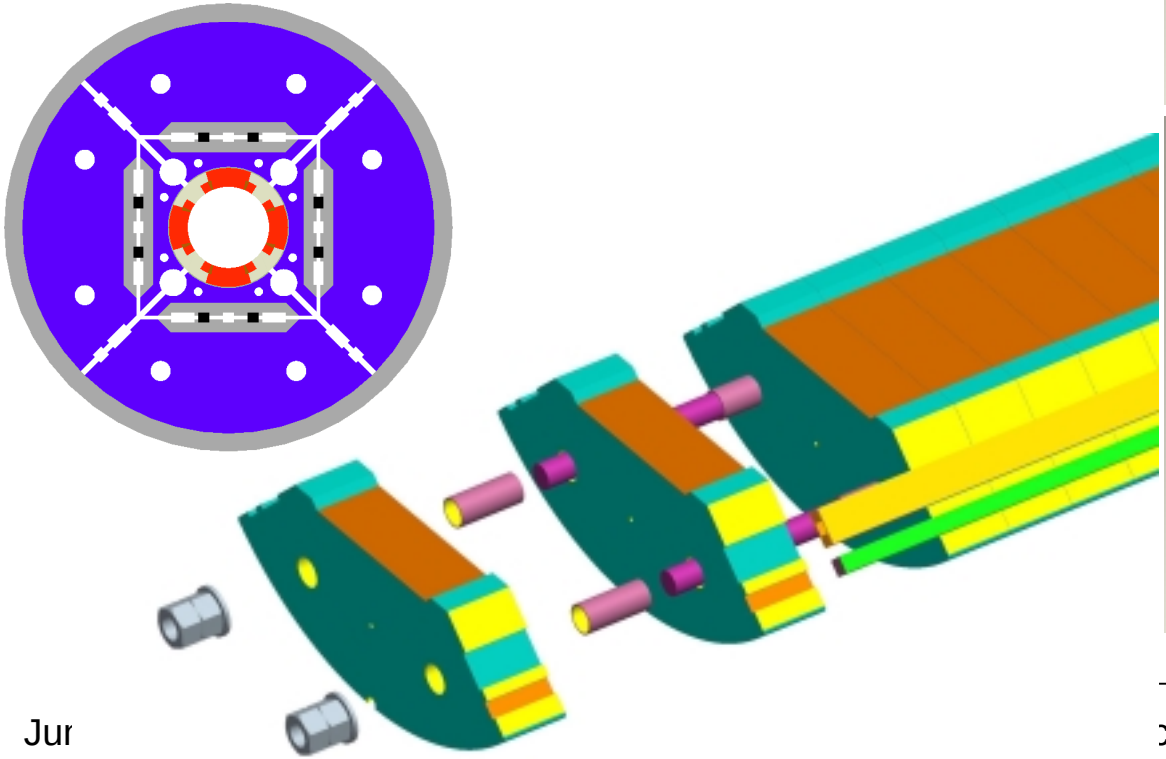
- Stainless steel axial rods
  - 24.5 mm diameter
- Axial pre-load provided by additional plate and piston

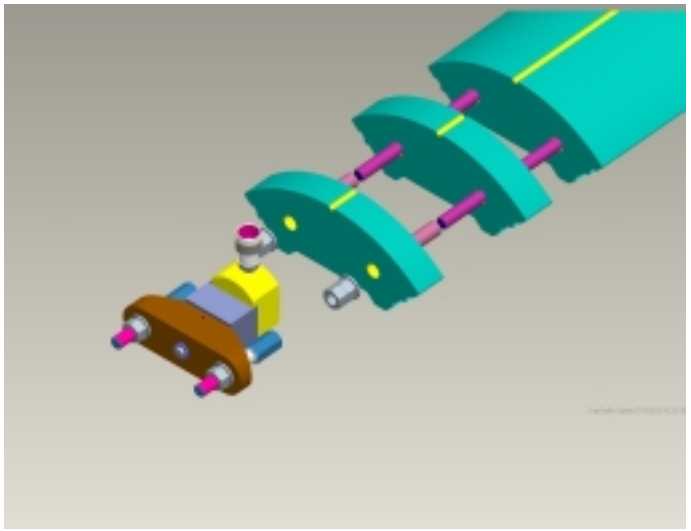


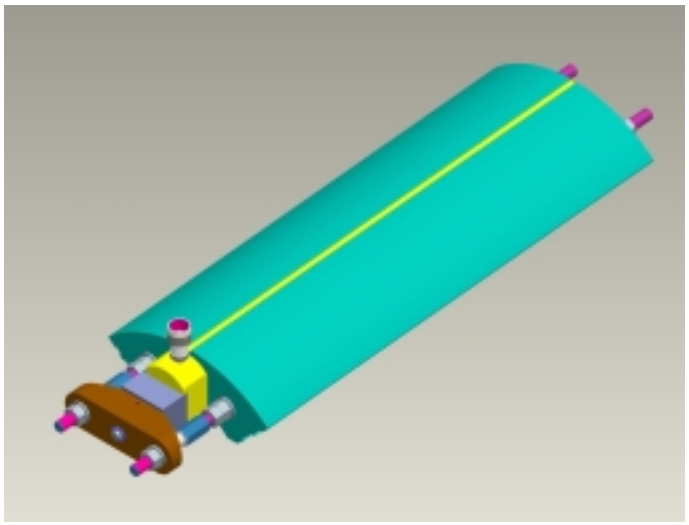
Assembly: Yoke and pads lamination stacking

0.8m sections assembly:

- Alignment of laminations with bushings
- Insertion of tie rods
- Pre-tension of tie rods with piston

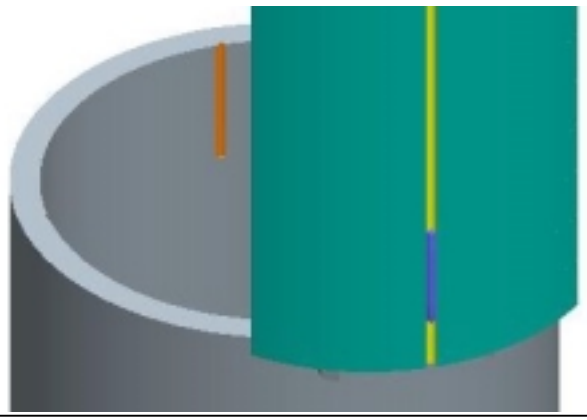


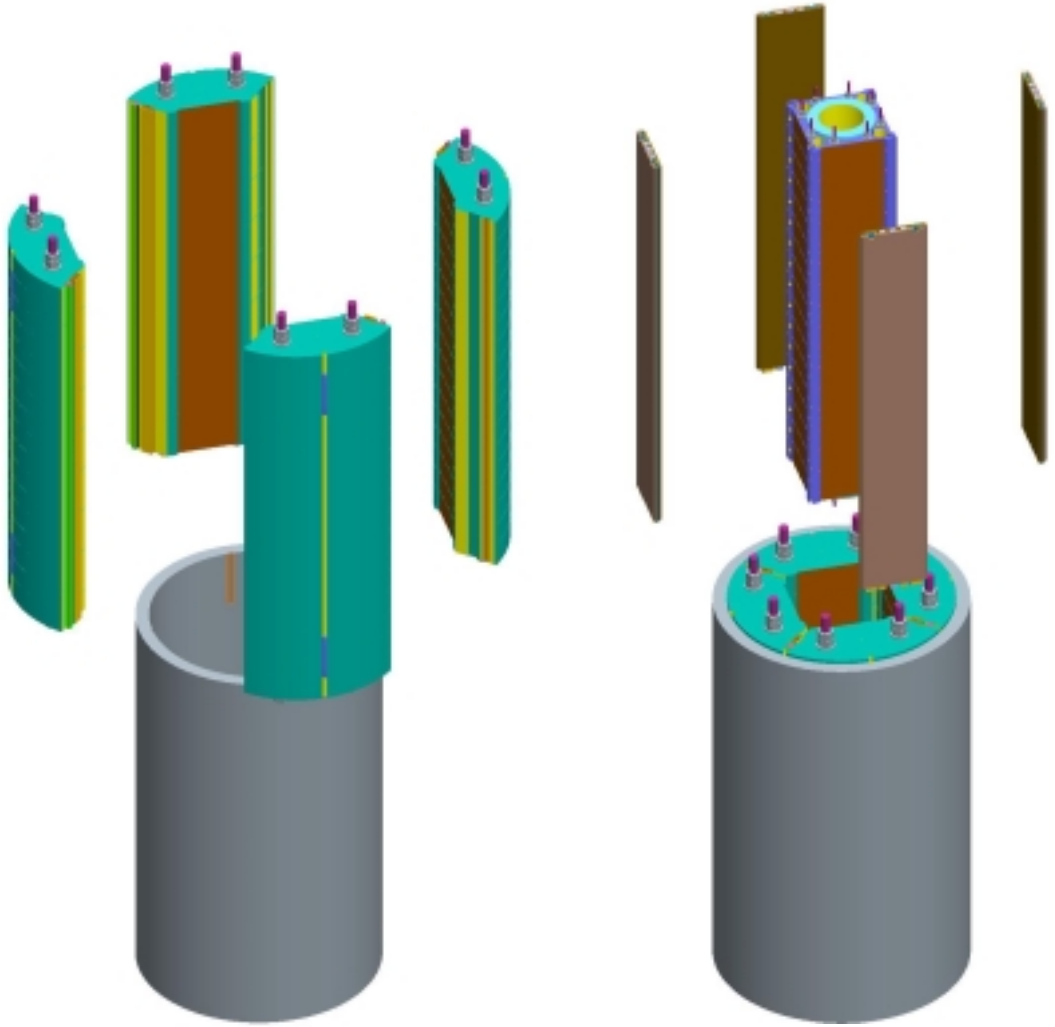




Assembly: Single shell-yoke sub-assembly

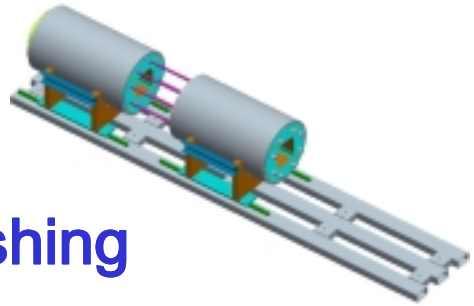
- Insertion of yoke stacks
  - Alignment by shell-yoke pins
- Insertion of dummy coil-pad sub-assembly with masters
- Shell pre-tensioning with bladders
- Insertion of gap keys
- Removal of coil-pad sub-assembly and masters

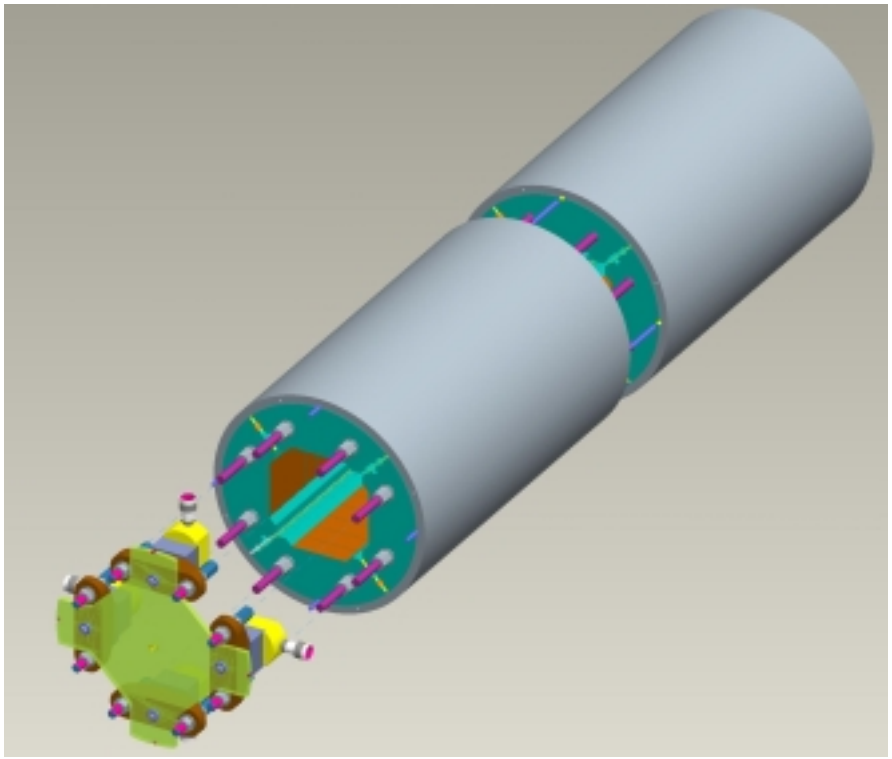


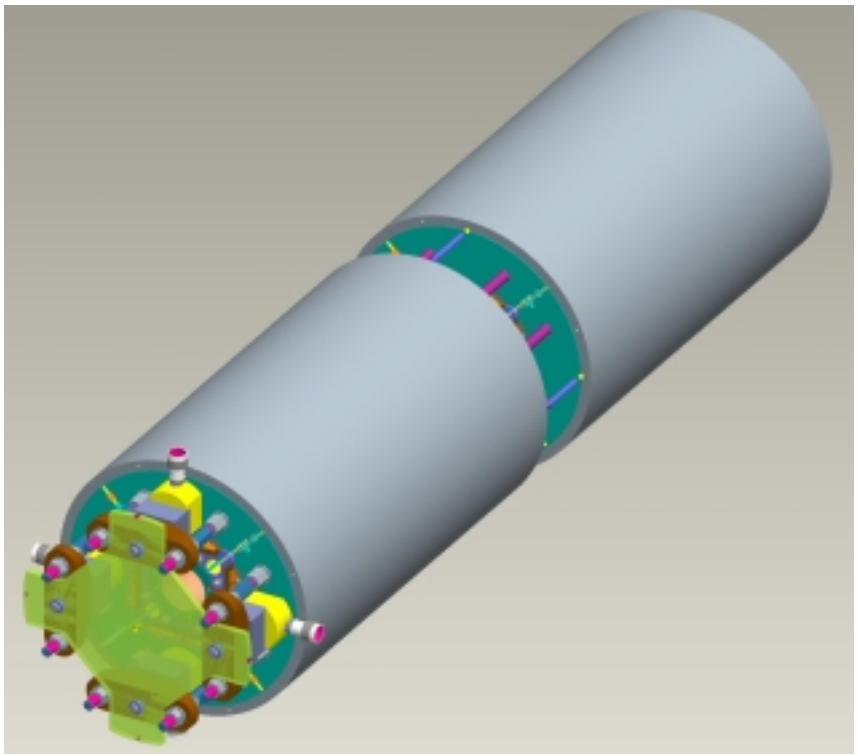


Assembly:
Yoke/shell pair - assembly

- System of linear rails for assembly
- Pretension of tie rods with pistons
- Alignment by yoke-shell pins and yoke-yoke bushing

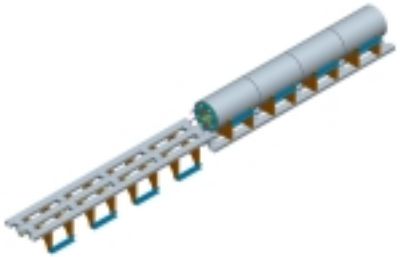


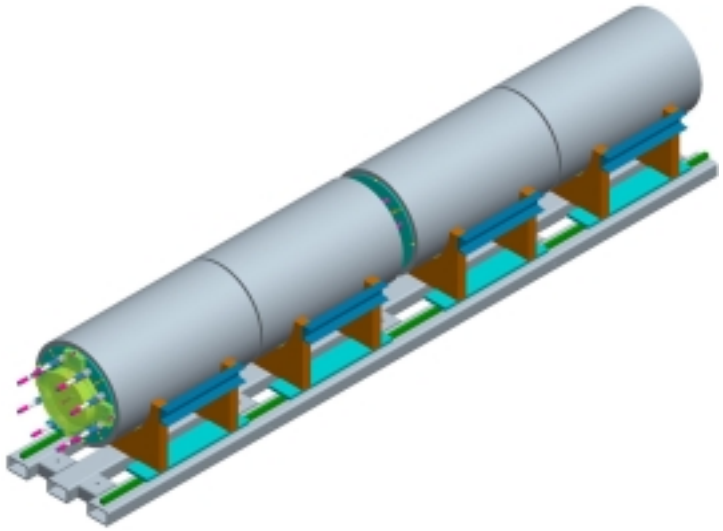


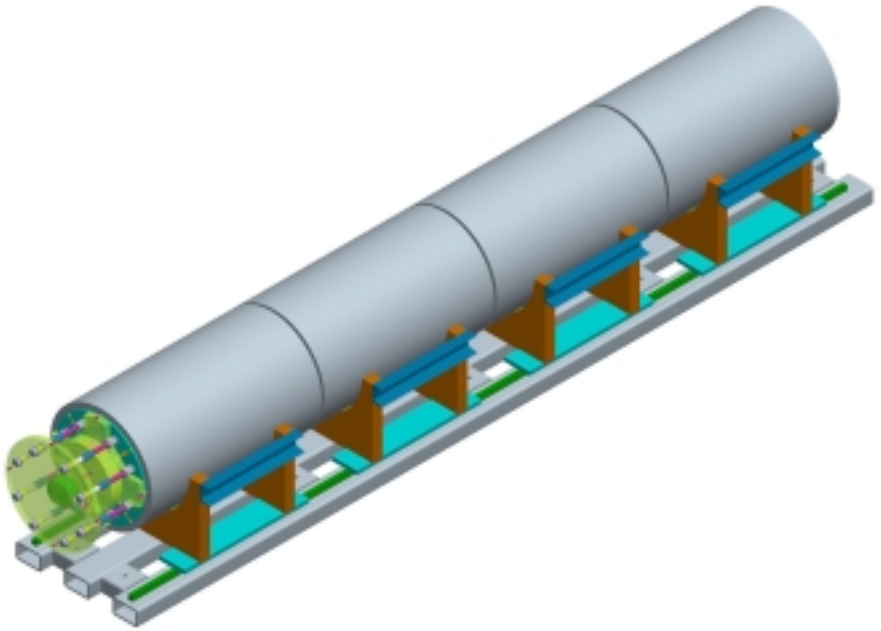


LQ Assembly: Final yoke-shell assembly

- Same operation as yoke-shell pair assembly
- Final status
  - Yoke laminations inserted in the shell segments and compressed together
  - Shell segments partially pre-tension by gap keys
  - Yoke-shell sub-assembly ready for insertion of coil-pad sub-assembly

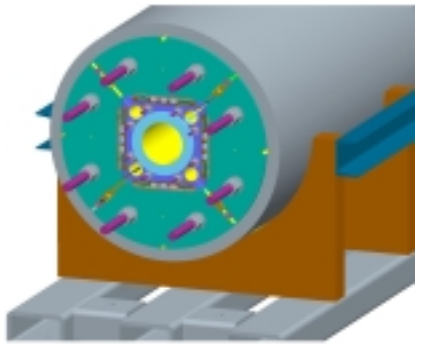


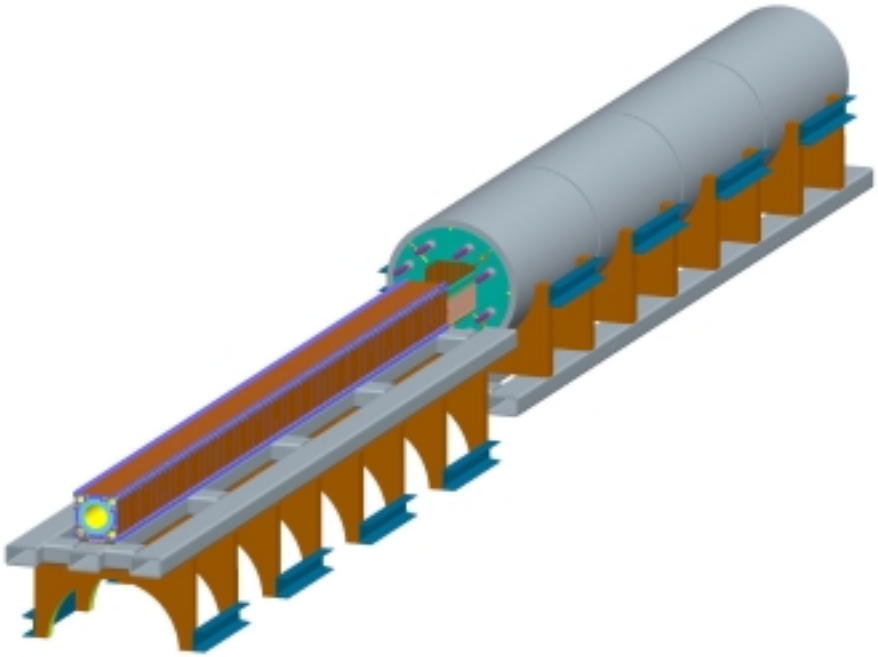


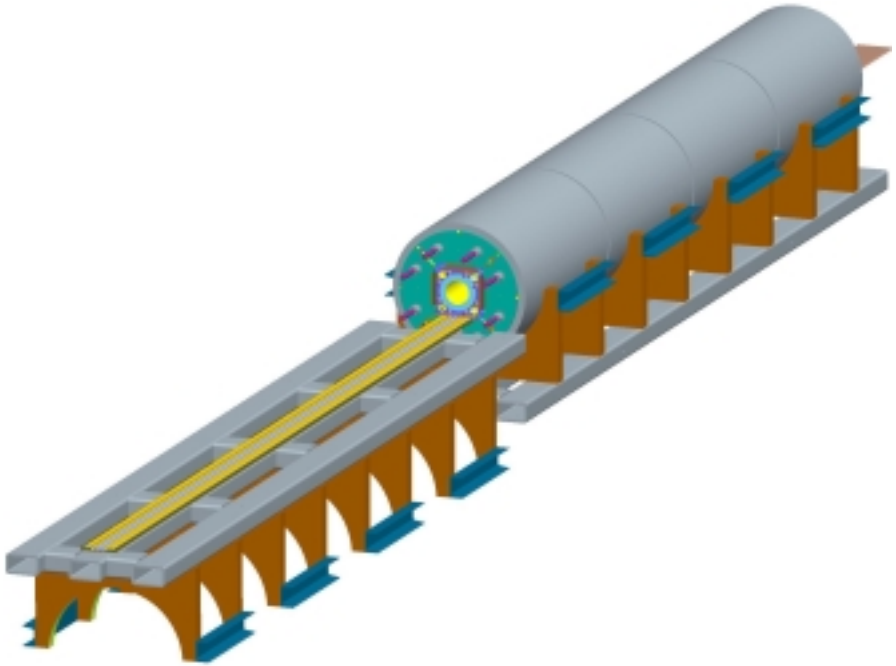


Assembly:Insertion and pre-load of coil-pad sub-assembly

- Coil-pad sub-assembly placed on raft
- Sliding of coil-pad sub-assembly inside yoke-shell sub-assembly
- Insertion of masters and bladder pressurization



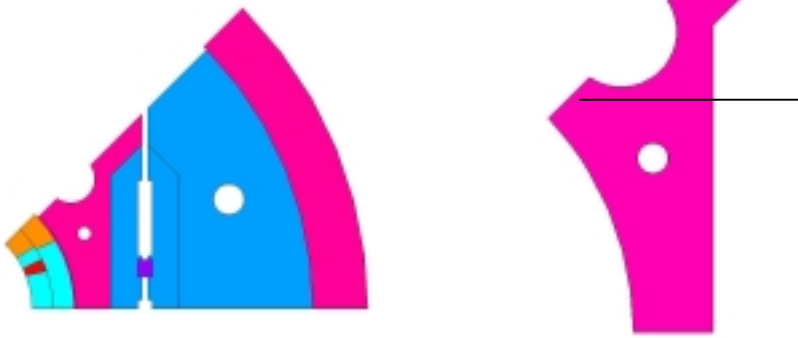




Shell structure with coil alignment

- Coil alignment goals:
  - Assure straightness of coils inside mechanical structure
  - Provide magnetic field alignment with respect to external reference points

Structure 1



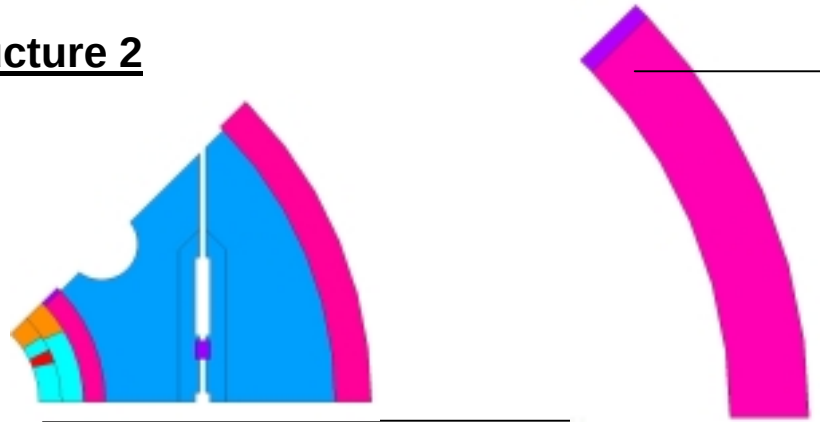
Compression at 45 degrees

-during assembly

-during cool-down

- during excitation

Structure 2



Full contact between ring and pole key

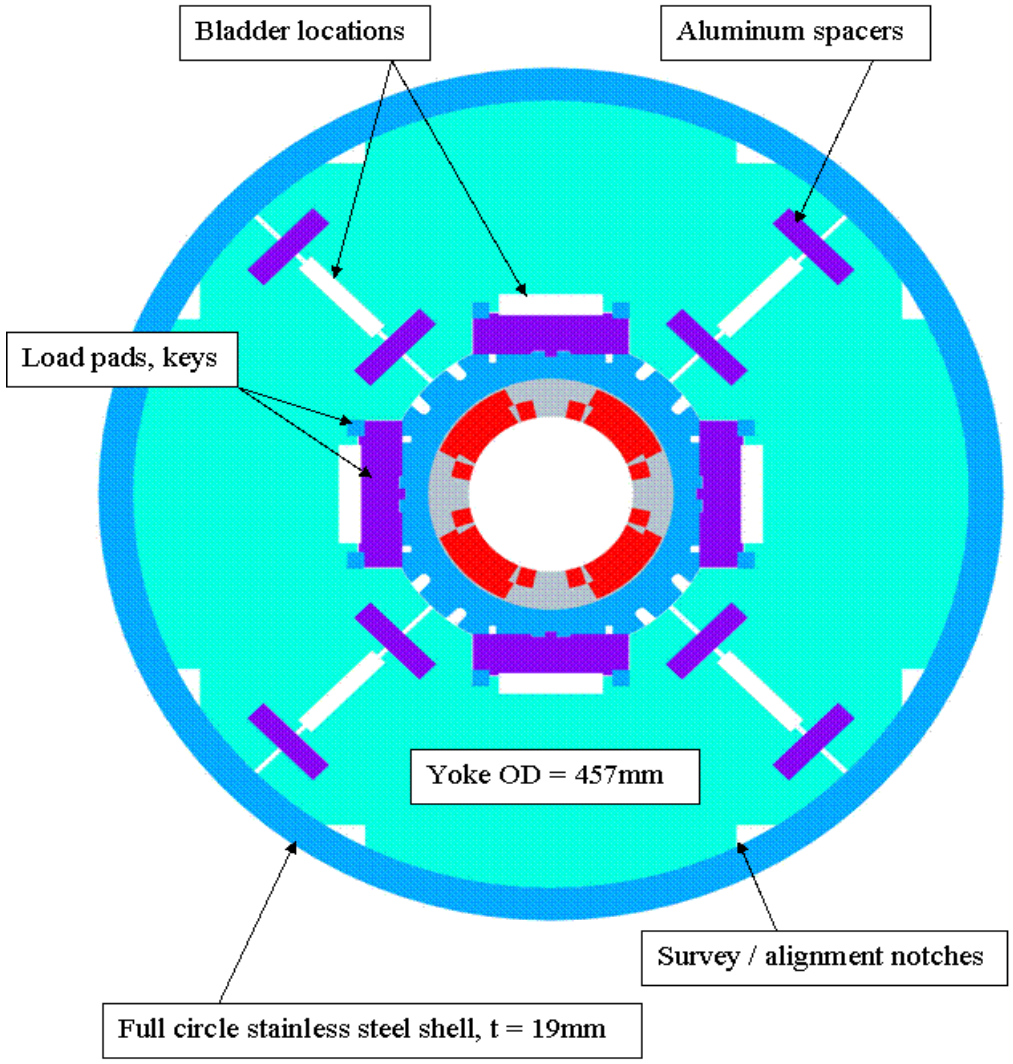
-during assembly

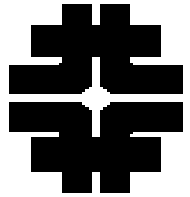
-during cool-down

Contact with 2.5 μm gap on the outer edge during excitation

Hybrid Design

- Main features:
  - Alignment features and reliability of collar style assembly
  - Avoids possible distortions due to welding
  - Limited coil stresses required during assembly
    - by using the bladders-&-keys technology

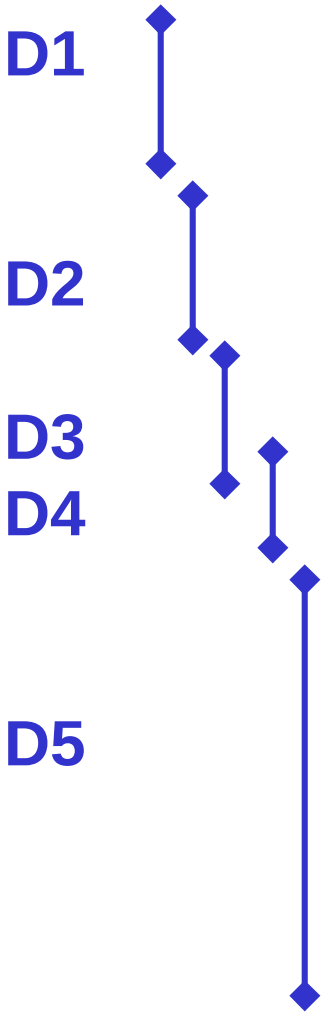




Test of shell-based structure for long quadrupoles (3.8m)
LQS01 test: Feb 09

Test of shell-based structure with alignment features (1m)
2nd test of HQ: TDB

Outline of the lessons



- Introduction
- Conductors
- Magnetic design
- Mechanical design
- Coil fabrication technology
- Magnet assembly
  - Long magnets
- Quench protection design
- Cryogenic design
- Magnet test and analysis
- Lifetime issues
- Next steps

Acknowledgement

Fermilab

N. Andreev, E. Barzi, R. Bossert, G. Chlachidize

V.V. Kashikhin, F. Nobrega, I. Novitsky, A.V. Zlobin

BNL

M. Anerella, A. Ghosh, J. Schmalzle, P. Wanderer

LBNL

S. Caspi, D. Dietderich, P. Ferracin, H. Felice,

A. Lietzke, G.L. Sabbi,

Texas A&M University

A. McInturff , P. McIntyre

CERN

L. Rossi, E. Todesco