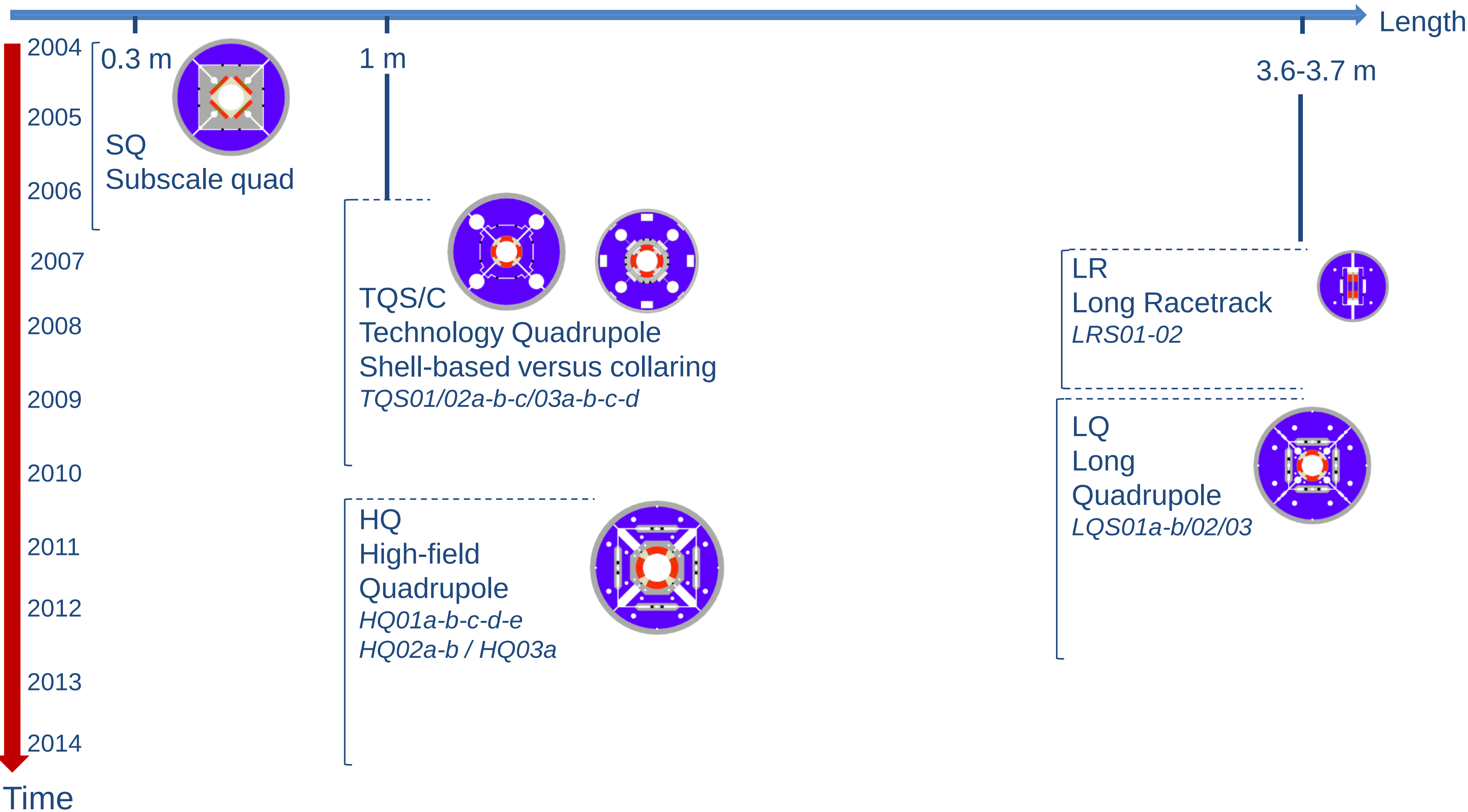
MQXF support structure
An extension of LARP experience

Helene Felice

MQXF Design Review
December 10th to 12th , 2014
CERN

Snapshot of LARP support structure experience



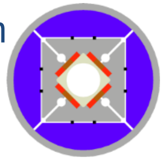
Step-by-step technology demonstration

Length

Time

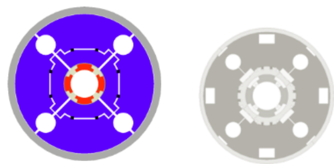
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014

0.3 m



SQ
Subscale quad
Concept

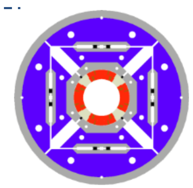
1 m



TQ
Technology Quadrupole
TQS01/02a-b-c/03a-b-c-d
Concept on cos2θ
Technology selection

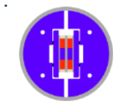
Scale-up & design optimization

HQ
High-field
Quadrupole
HQ01a-b-c-d-e
HQ02a-b / HQ03a
Accelerator quality features
Mechanical alignment

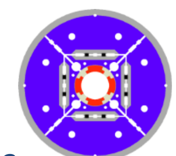


3.6-3.7 m

LR
Long Racetrack
LRS01-02
Length demonstration



LQ
Long
Quadrupole
LQS01a-b/02/03
Some accelerator quality features
Length with cos2θ
Accommodating variability in coil dimension



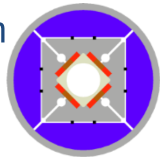
Exploration of the stress limits

Length

Time

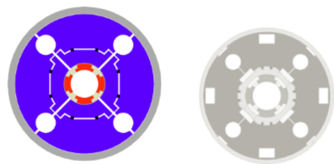
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014

0.3 m



SQ
Subscale quad
Concept

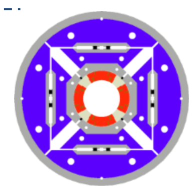
1 m



TQ
Technology Quadrupole
TQS01/02a-b-c/03a-b-c-d
Concept on cos2θ
Technology selection
Ultimate stress exploration

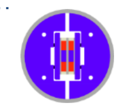
Scale-up & design optimization

HQ
High-field
Quadrupole
HQ01a-b-c-d-e
HQ02a-b / HQ03a
Accelerator quality features
Mechanical alignment
High stress regime

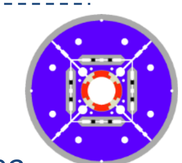


3.6-3.7 m

LR
Long Racetrack
LRS01-02
Length demonstration



LQ
Long
Quadrupole
LQS01a-b/02/03
Some accelerator quality features
Length with cos2θ
Accommodating variability in coil dimension



Magnet Parameters Overview

		TQ		LQ		HQ		MQXF
		Design	TQS03	Design	LQS03	Design	HQ02b	Design
Aperture	mm	90	90	90	90	120	120	150
Gradient	T/m	200	238	200	210	170	195	140
Current	kA	11	13.5	11	11.8	14.6	17.3	17.5
Peak field	T	10.1	12.2	10.1	10.6	11.5	13.5	12.1
Fx	MN/m	1.4	2	1.4	1.5	1.9	2.7	2.6
Fy	MN/m	-1.45	-2.1	-1.45	-1.6	-2.7	-3.8	-3.9

- Performance of actual magnets consistently above design targets
- Design force level in MQXF of the same order than forces reached in HQ

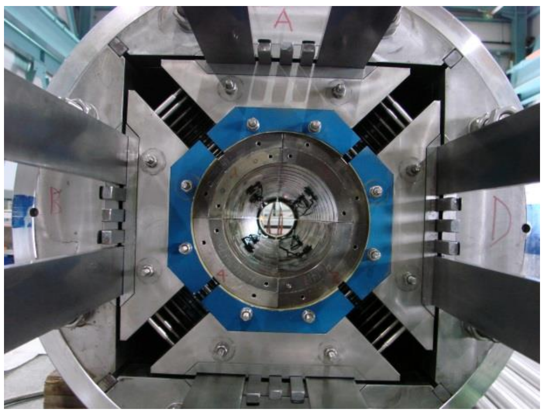
See Gianluca Sabbi's talk

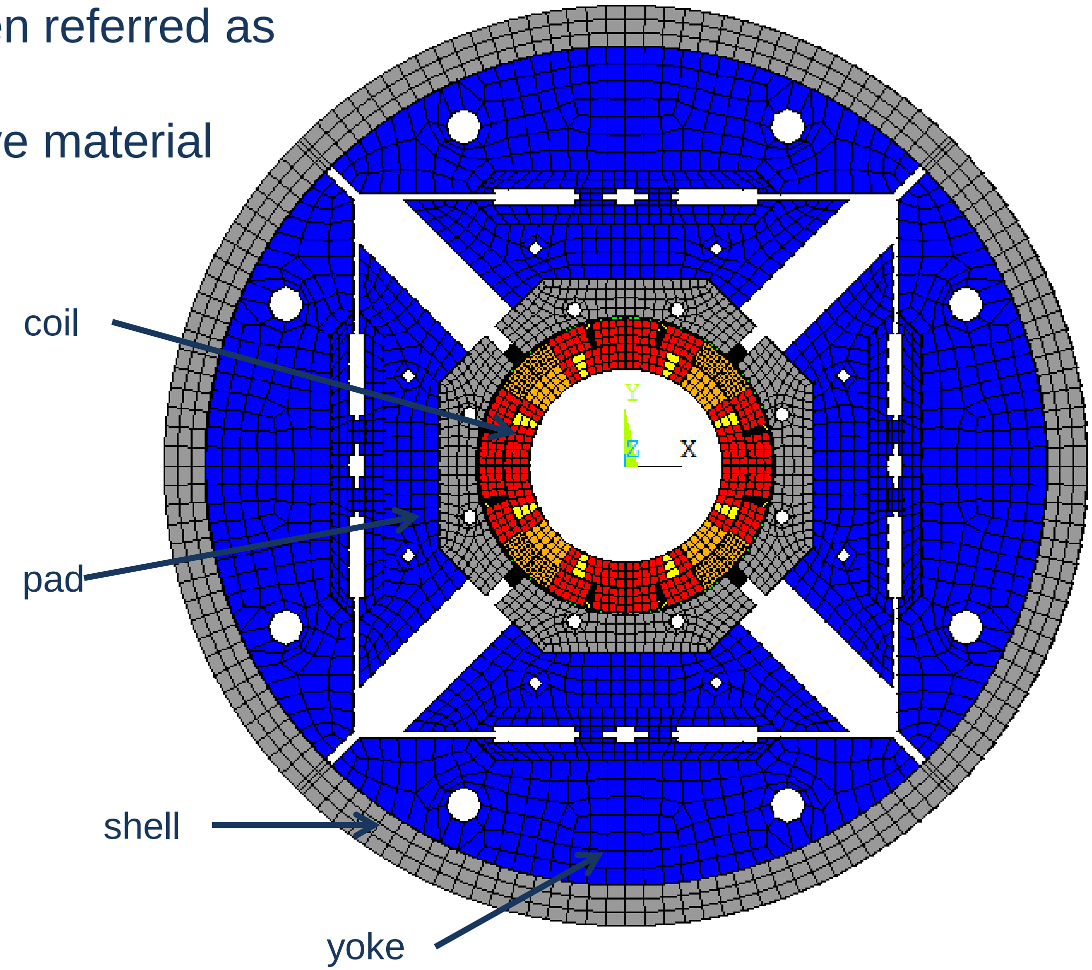
Outline

- Shell-based support structure concept
- Exploring the limits
  - TQ high stress
- Step-by-step technology demonstration
  - Design optimization
  - Length
- MQXF support structure
  - Main features

Shell-based support structure
Motivation and concept

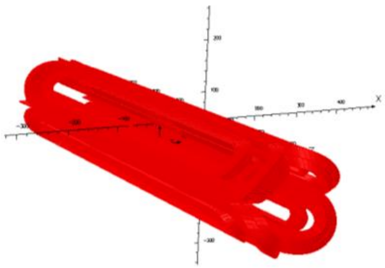
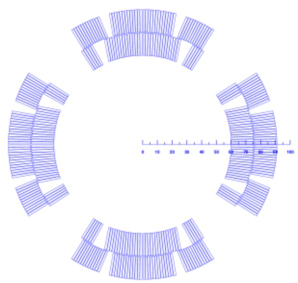
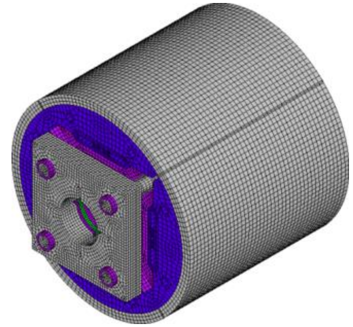
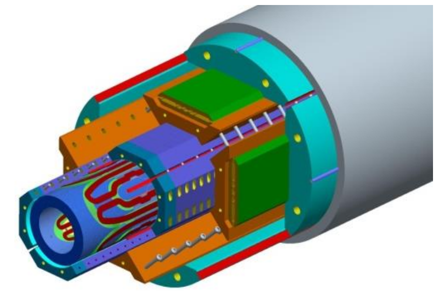
- Shell-based support structure often referred as “bladder and keys” structure developed at LBNL for strain sensitive material



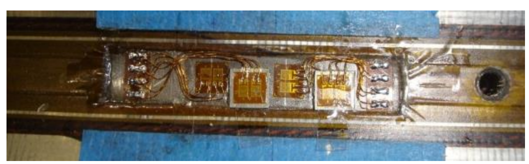
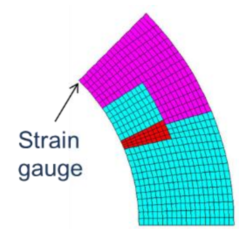


Shell-based support structure
Supporting tools

- Numerical tools: integrated magnetic, mechanical analysis and CAD applied to all LARP magnets and to MQXF

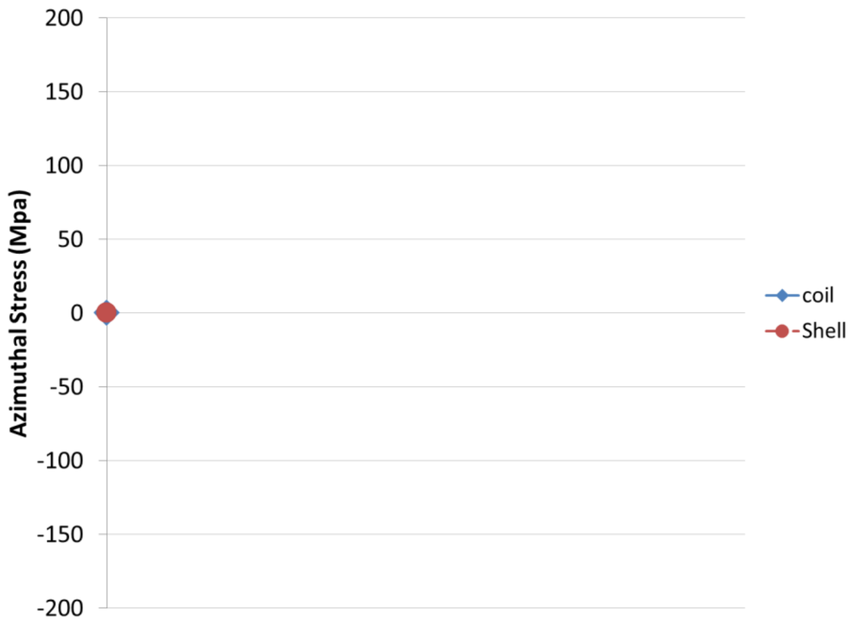
- Instrumentation: strain gauges mounted on coil pole pieces, shell and axial rods

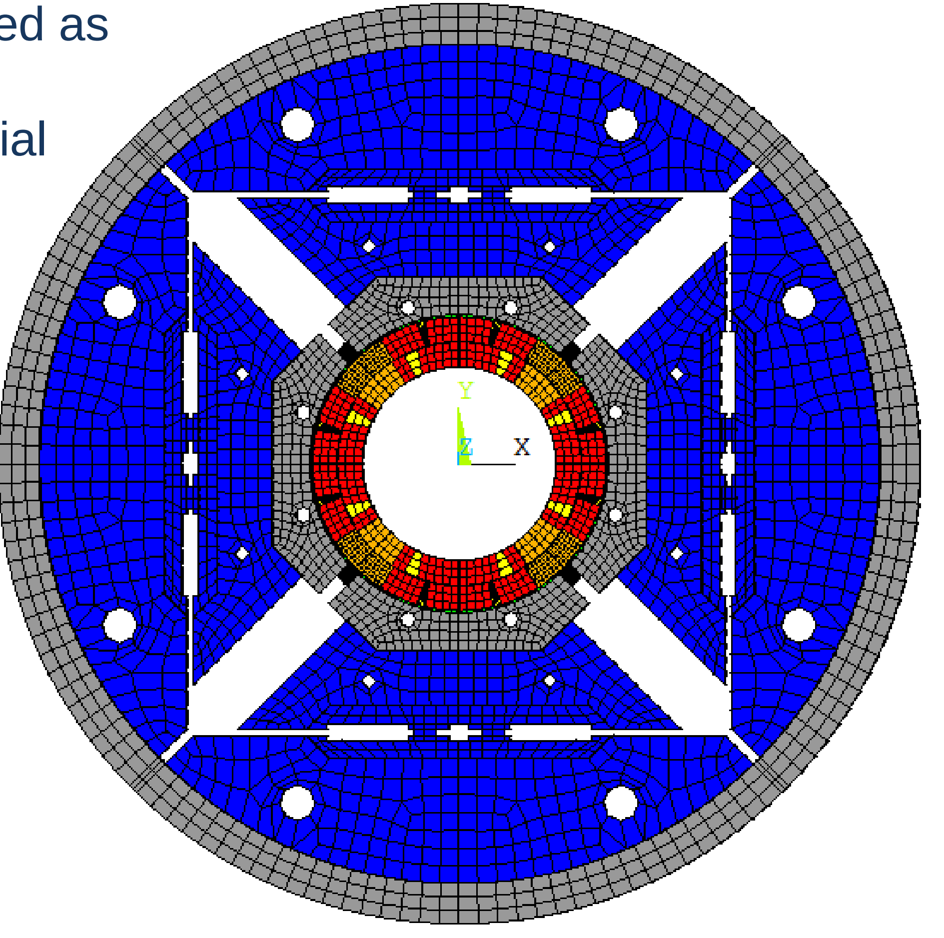




- Same analysis tools used for all LARP magnets and for MQXF
- Assembly and preload target based on analysis
- Control of the pre-stress level
- Constant feedback between SG measurements and model

Shell-based support structure Concept

- Shell-based support structure often referred as "bladder and keys" structure developed at LBNL for strain sensitive material

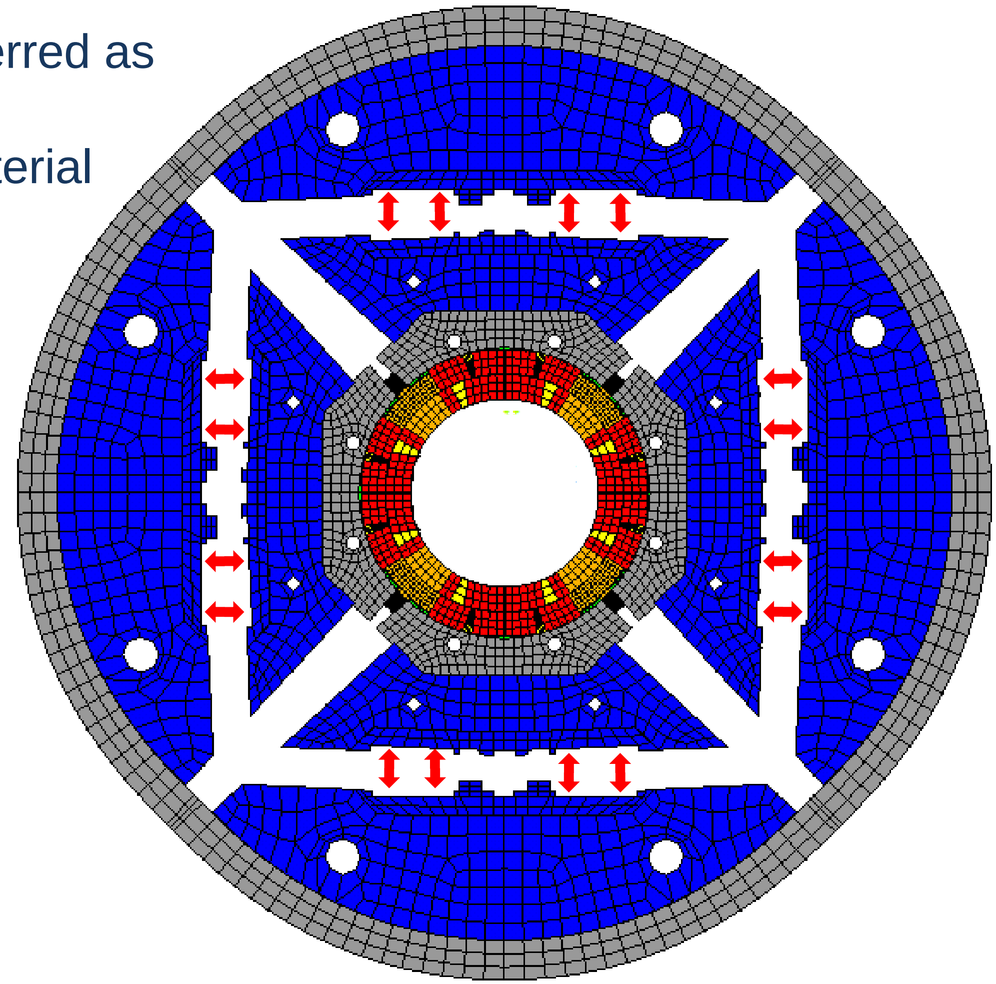




Shell-based support structure Concept

- Shell-based support structure often referred as "bladder and keys" structure developed at LBNL for strain sensitive material

Inflated Bladders



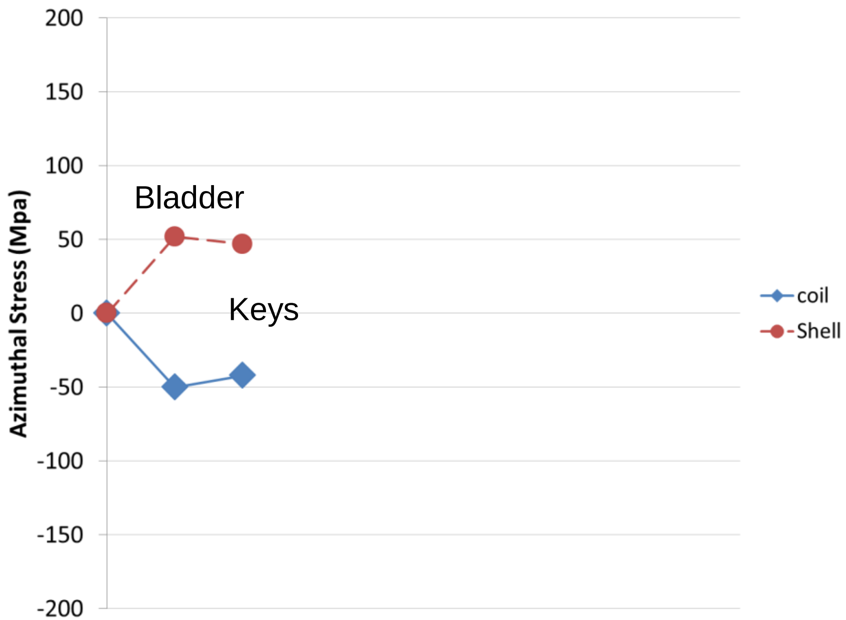
Displacement scaling 30

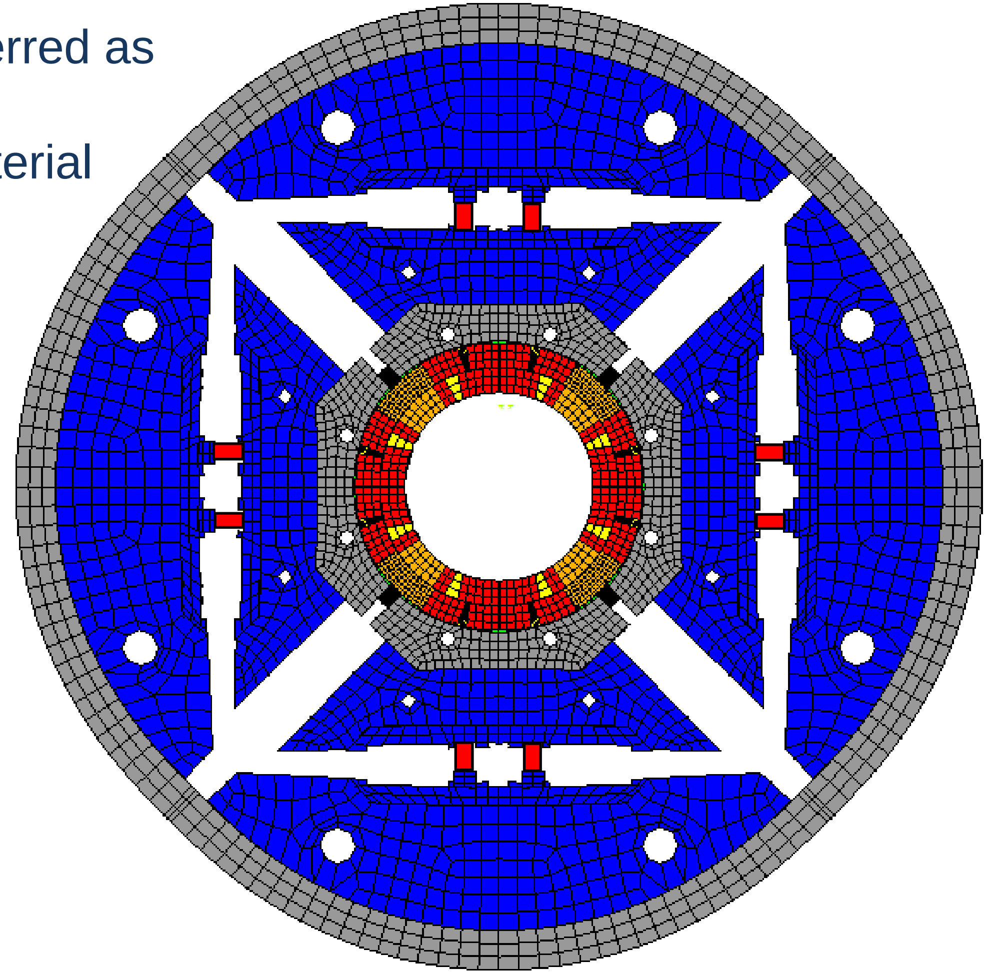
Shell-based support structure Concept

Shimming of the load leys

- Shell-based support structure often referred as "bladder and keys" structure

developed at LBNL for strain sensitive material



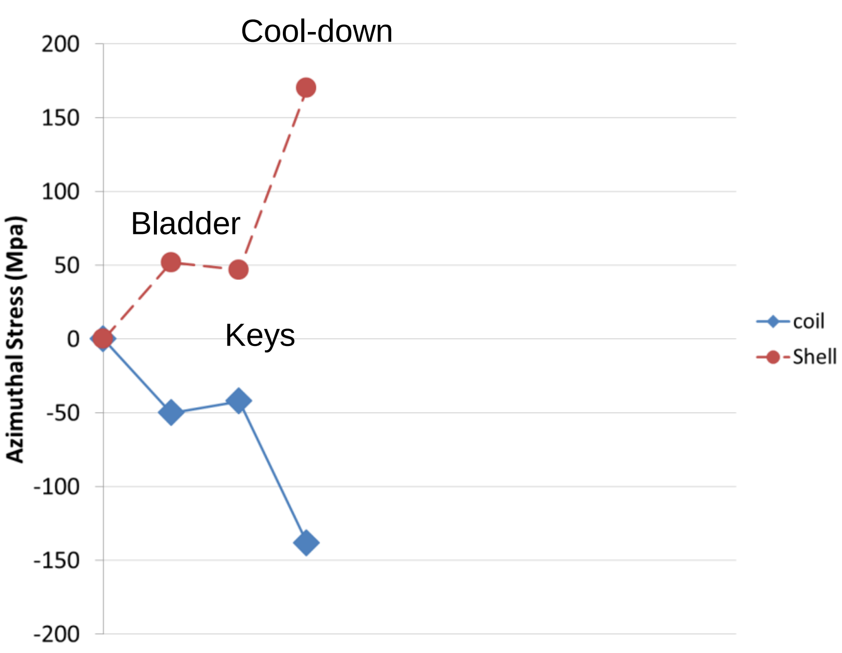


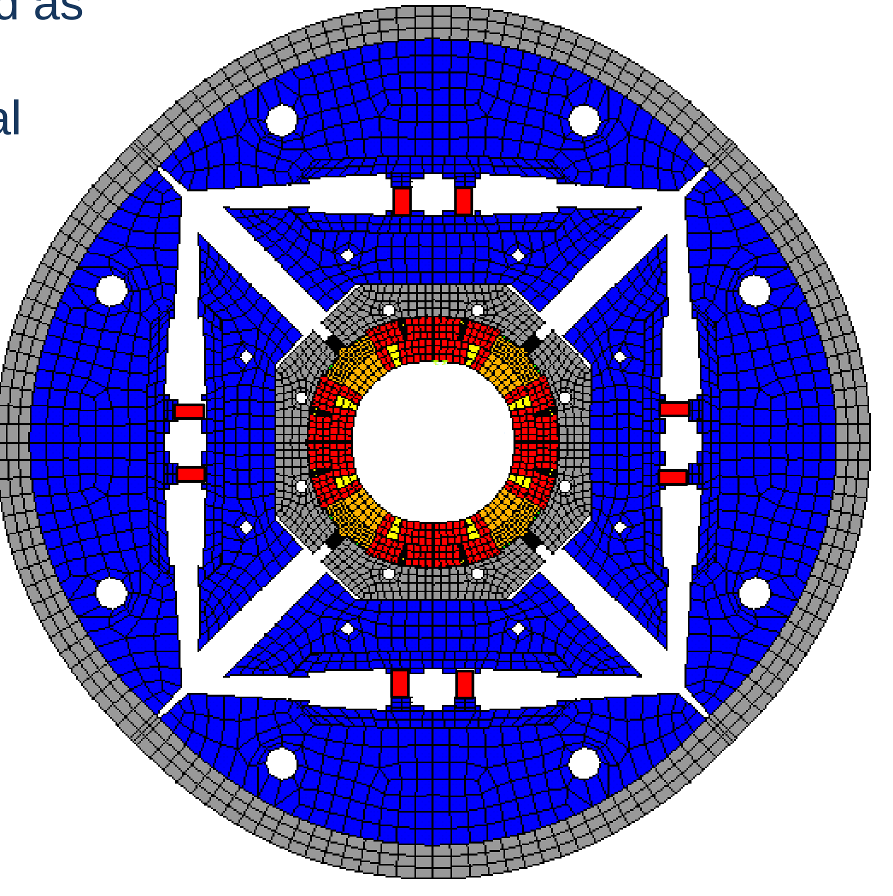
Displacement scaling 30

Shell-based support structure Concept

Cool-down

- Shell-based support structure often referred as "bladder and keys" structure developed at LBNL for strain sensitive material

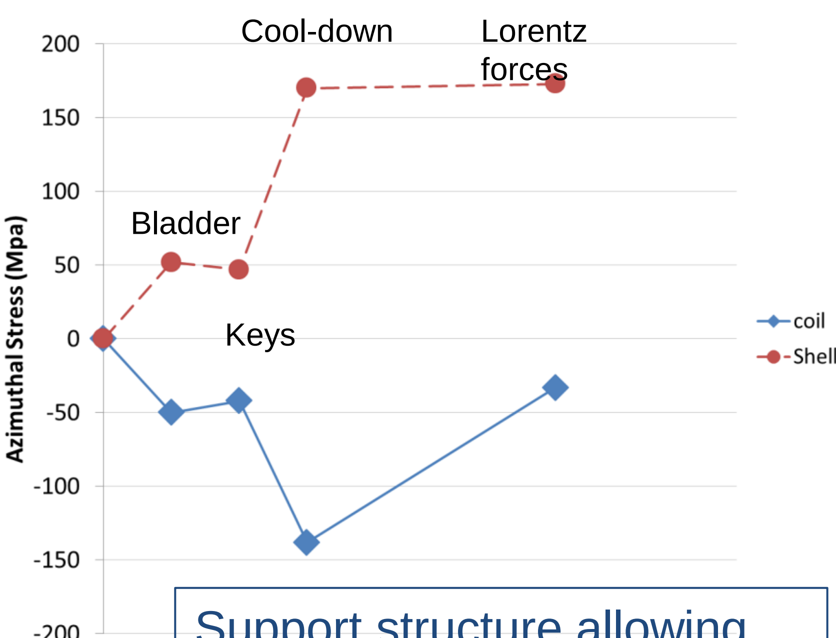




Displacement scaling 30

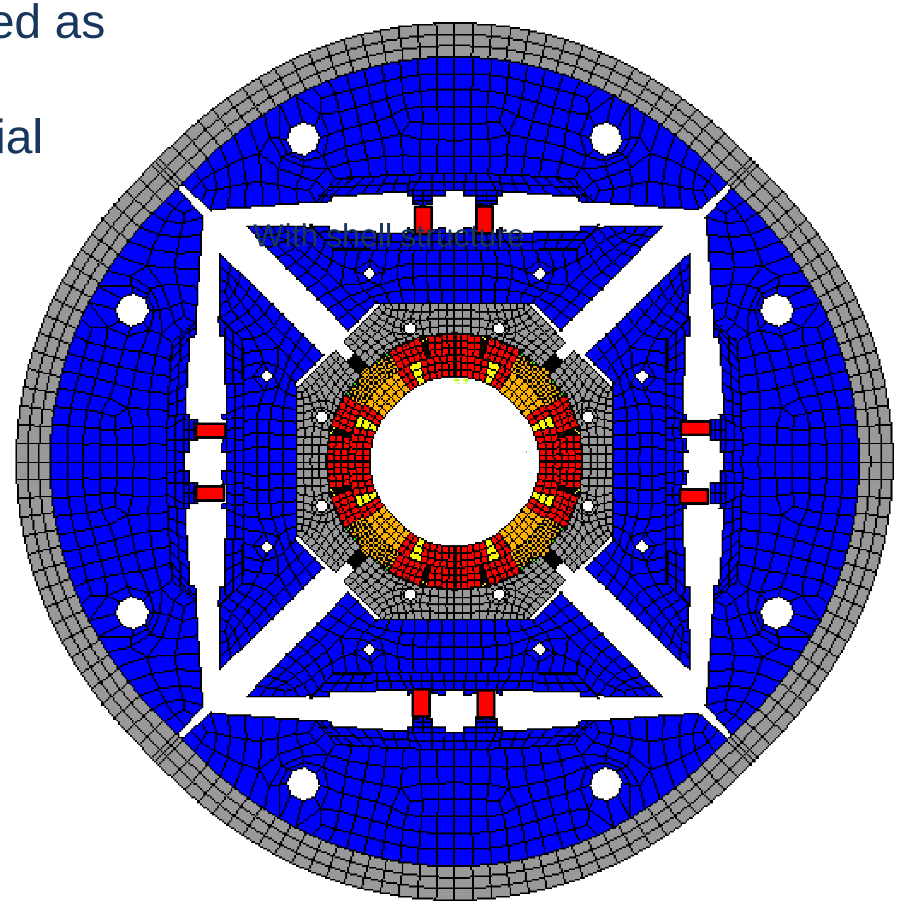
Shell-based support structure Concept

- Shell-based support structure often referred as “bladder and keys” structure
developed at LBNL for strain sensitive material



Support structure allowing fine tuning of the pre-stress

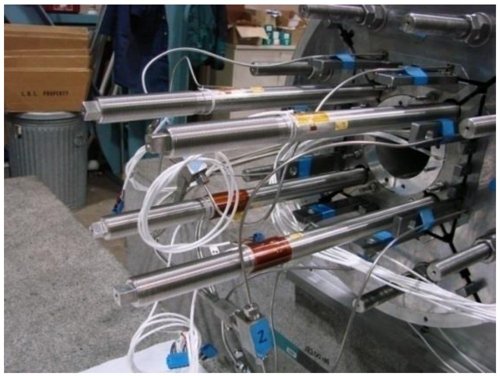
Energized

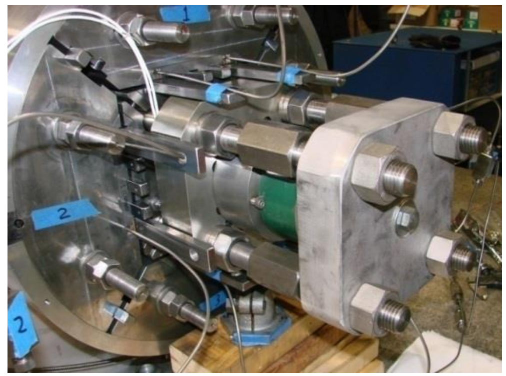


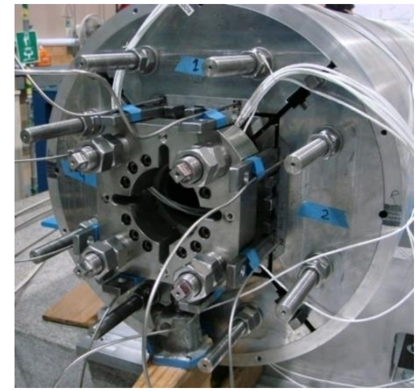
Displacement scaling 30

Axial support

- Provided by axial (aluminum or stainless) rods pre-tensioned at room temperature using a hydraulic piston and rod shrinkage during cool-down

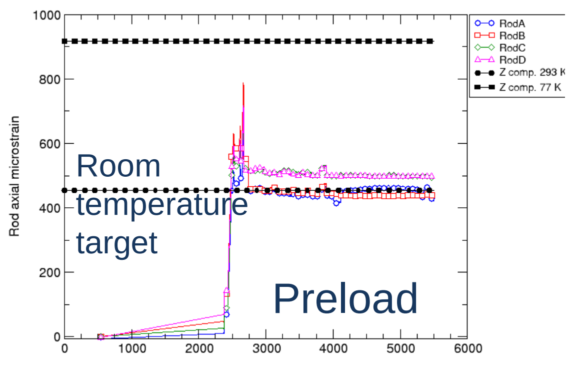


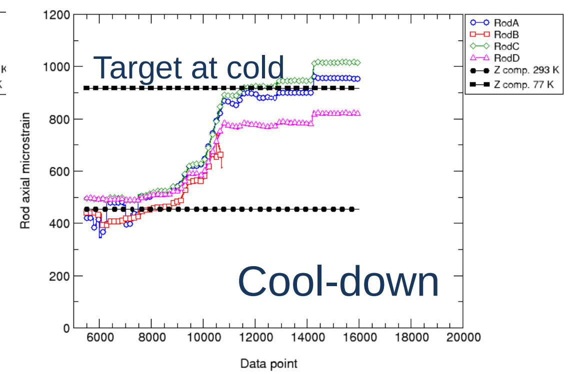




- Preloading supported by analysis and monitored with strain gauges

Typical strain gauges readings





Shell based structure allows adjustable / tunable azimuthal and axial preload

Shell-based support structure
Key features

- Gradual application of the preload:
  - Axially and Azimuthally
- Tunable preload
  - During assembly
  - In between tests
- Reversible assembly process
  - Allowing fast replacement of a defective coil if needed
- Correlation between models and strain gauges measurements

Outline

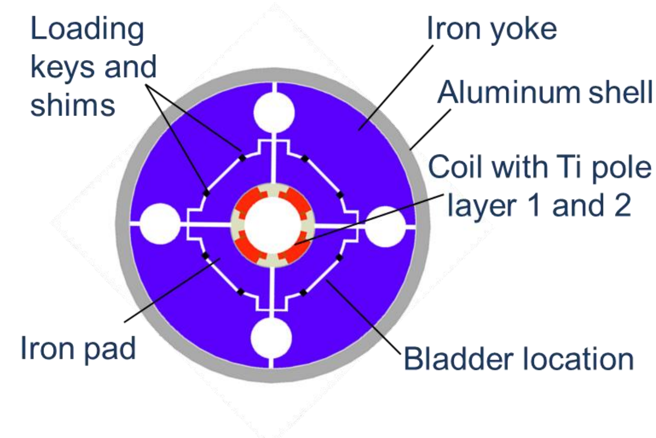
- Shell-based support structure concept
- Exploring the limits
  - TQ high stress
- Step-by-step technology demonstration
  - Design optimization
  - Length
- MQXF support structure
  - Main features

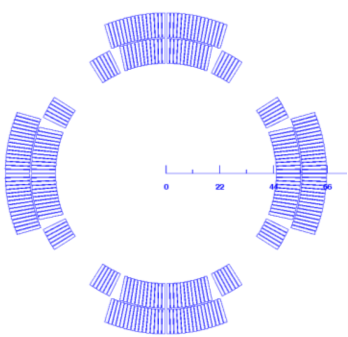
Stress limits: defining an acceptable range TQS03 program

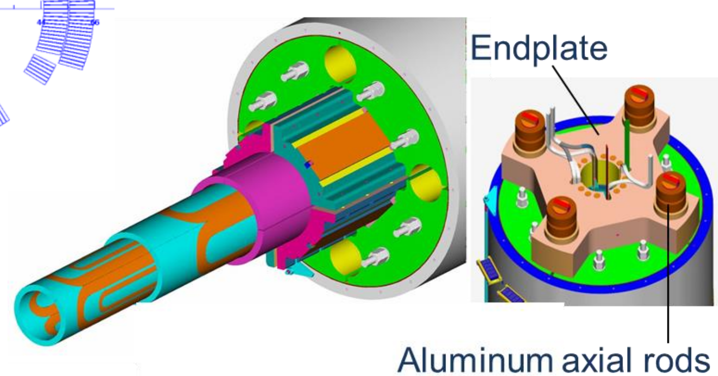
CONDUCTOR

- OST RRP 108/127 strand
- High RRR
- 54 % Cu fraction
- Jc (12T, 4.3 K) 2770 A/mm^2
- 27 strands cable
- 1.26 mm mid-thickness bare
- 10 mm width bare
- 0.125 mm insulation

	TQS03 parameters	
	4.3 K	1.9 K
I_{ss} (kA)	13.2	14.5
$B_{peak\ ss}$ (T)	12	13
G_{ss} (T/m)	234	254







4 tests: TQS03 a, b, c and d

- performed with variable pre-stress
  - TQS03a: 120 MPa*
  - TQS03b: 160 MPa*
  - TQS03c : 200 MPa*
  - TQS03d: 120 MPa *

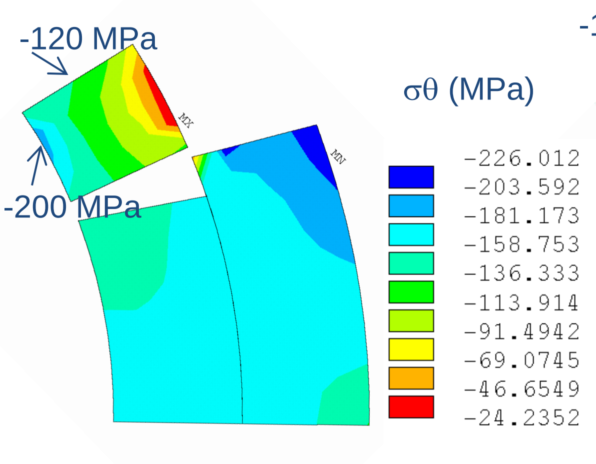
  * Average value at pole turn

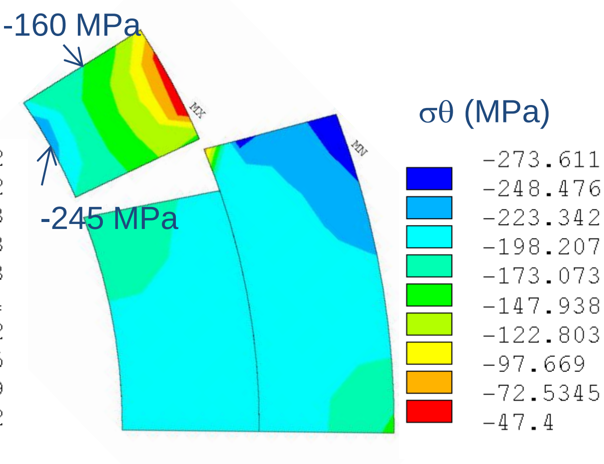
- by increment of load shims
- supported by ANSYS analysis

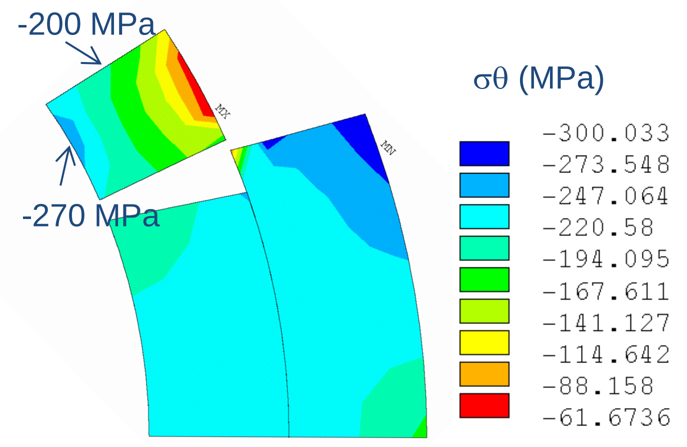
Azimuthal stress from 3D analysis

TQS03a/d	TQS03b	TQS03c

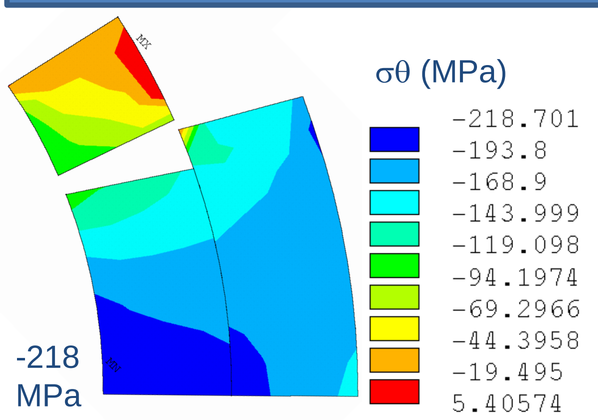
At cold

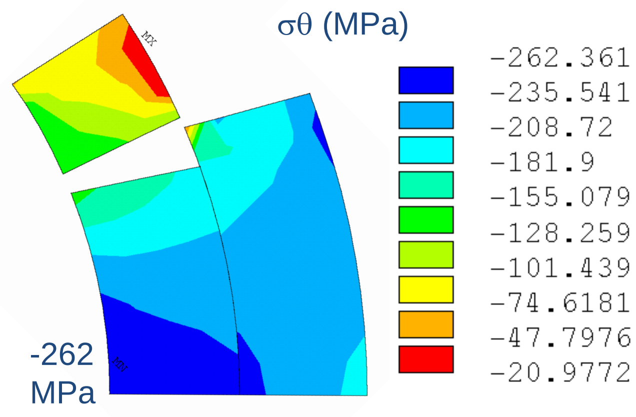


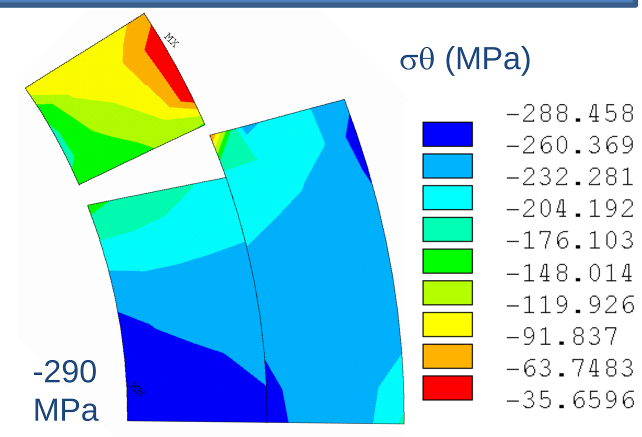




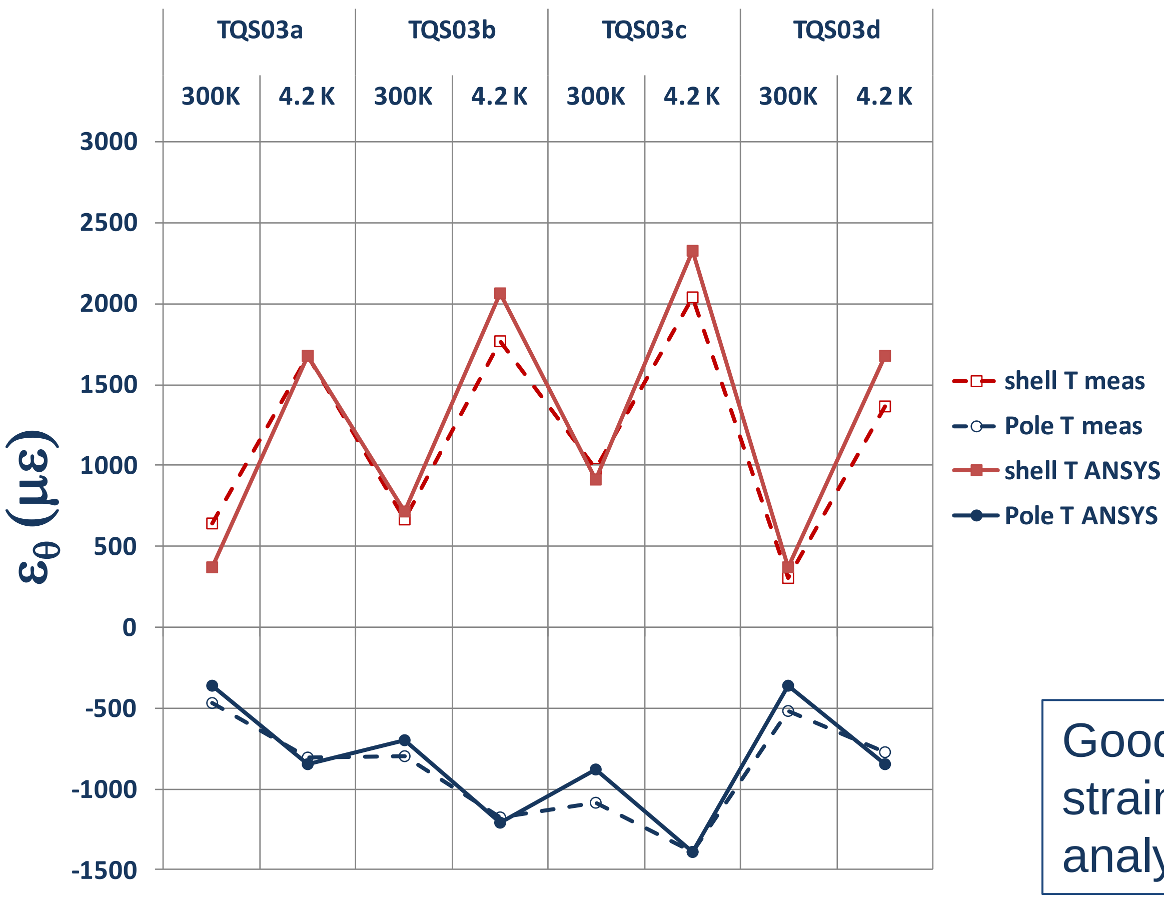
At 13 kA



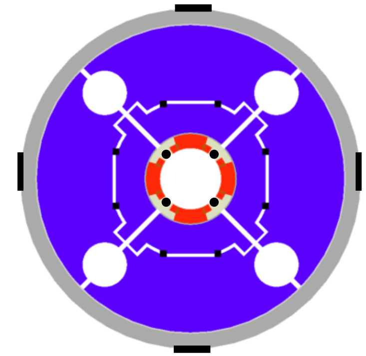


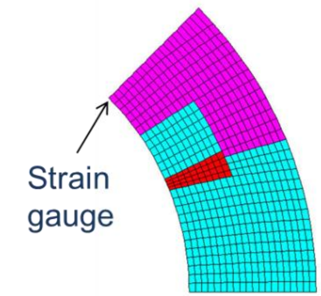


Azimuthal Strain
Comparison with Strain Gauges measurements



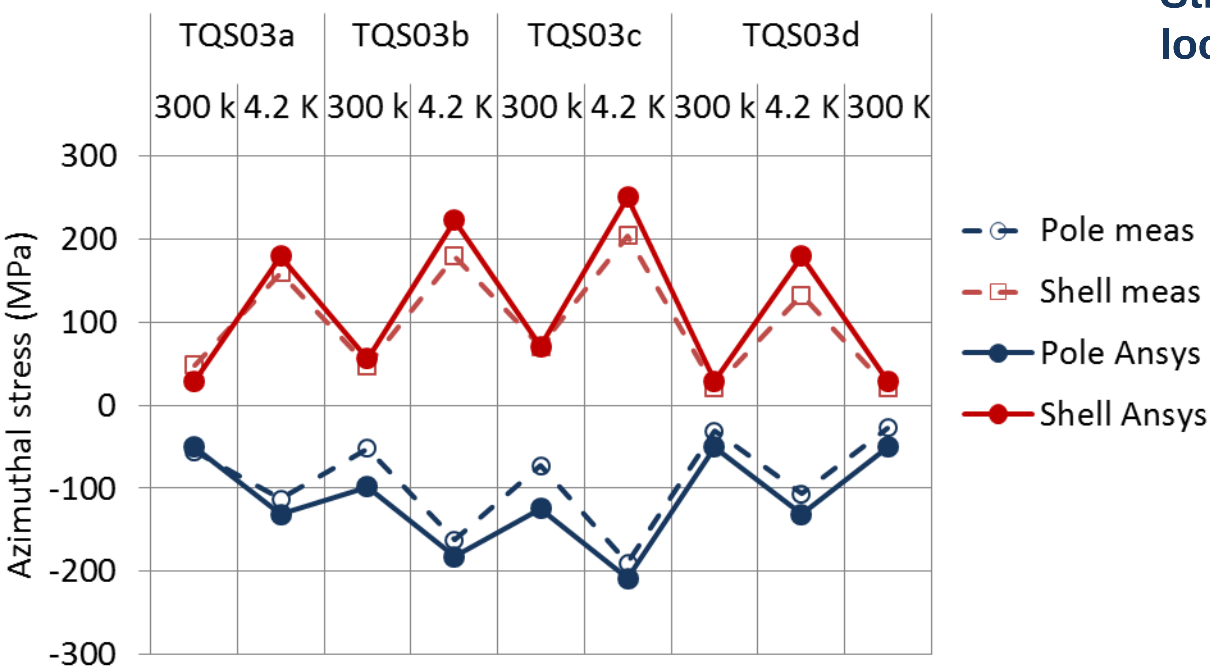
Strain gauges location



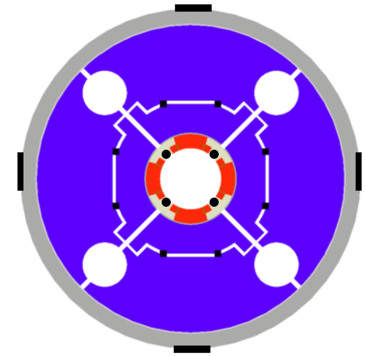


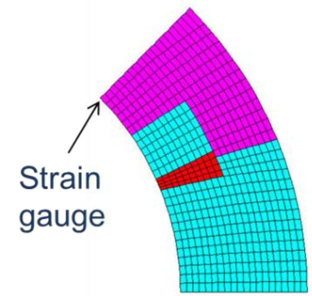
Good agreement between azimuthal strain measurements and ANSYS analysis

Azimuthal Stress
Comparison with Strain Gauges measurements



Strain gauges location



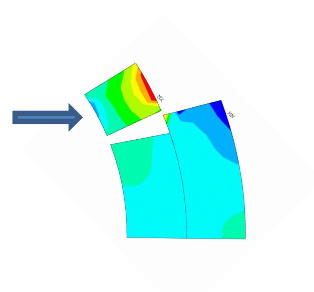


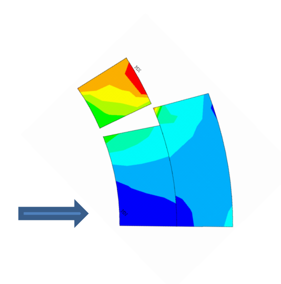
$$\sigma_\theta = \frac{E}{(1-\nu^2)}(\varepsilon_\theta + \nu \varepsilon_z)$$

- Axial strain more difficult to control
- Cold preload within 10 % of the ANSYS computed preload

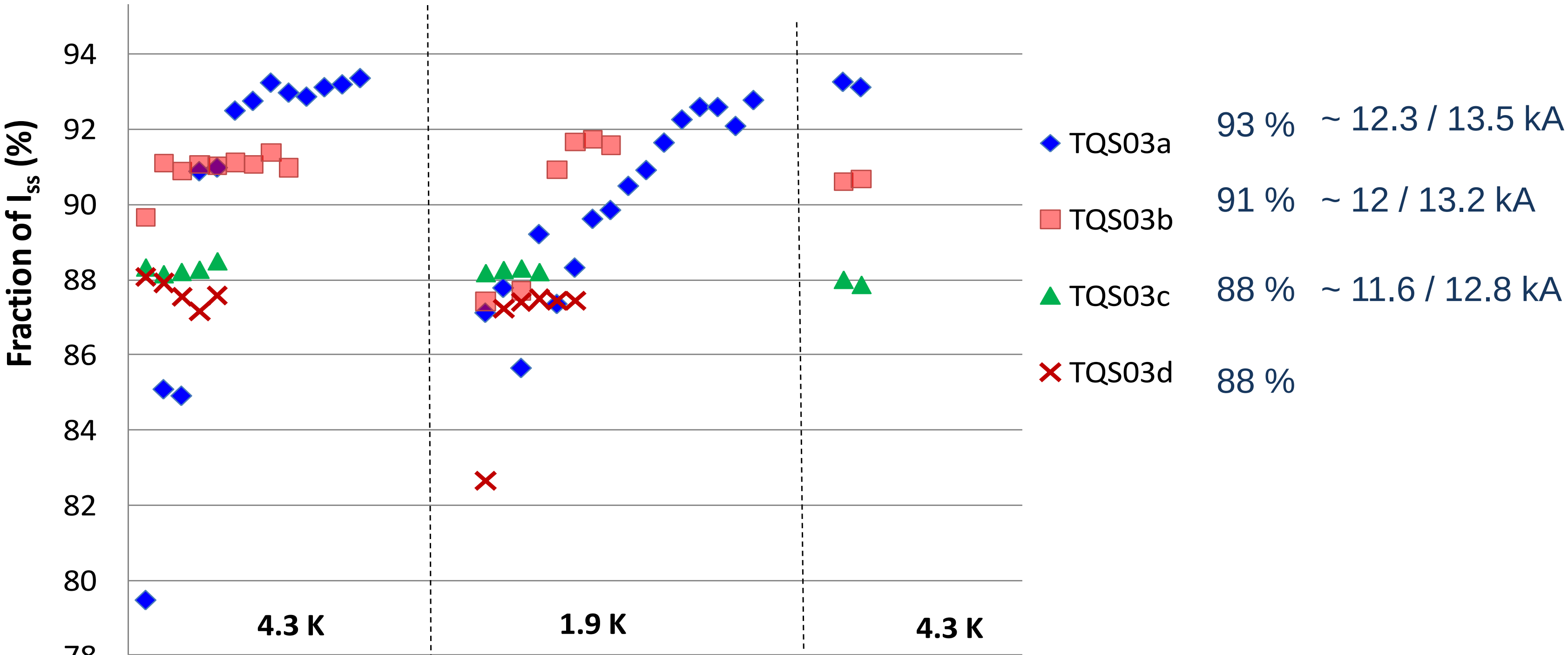
TQS03 series
Estimated stress overview

	ANSYS peak stress at cold	Estimated peak stress at cold based on pole SG meas.	ANSYS peak stress with Lorentz forces	Estimated peak stress with Lorentz forces
TQS03a	-200	**-180**	-220	**-200**
TQS03b	-245	**-220**	-260	**-240**
TQS03c	-270	**-250**	-290	**-270**
TQS03d	-200	**-180**	-220	**-200**
MQXF	-176	NA	-142	NA





Training performance



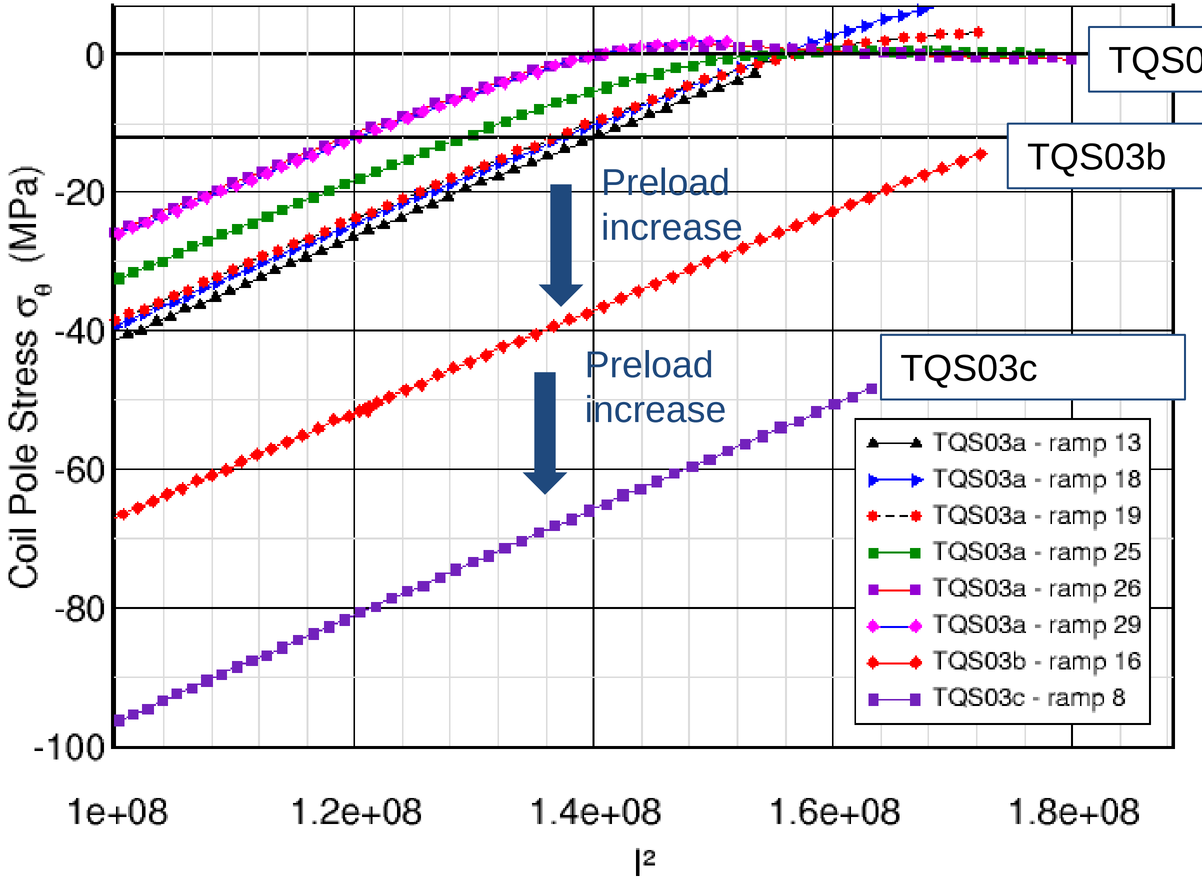
- Only 5 % degradation from TQS03a to TQS03c
- TQS03d did not recover => Permanent degradation

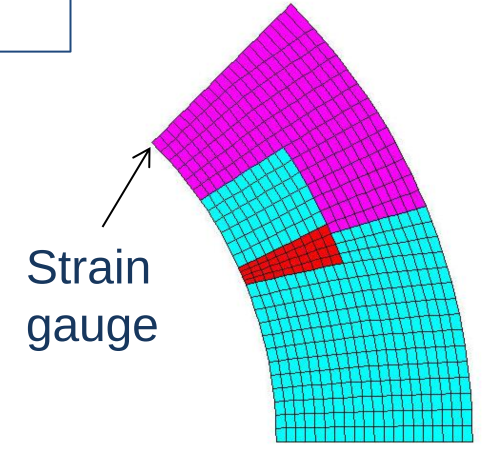
TQS03 series summary

	Estimated peak stress at cold based on SG meas. (MPa)	**Estimated peak stress with Lorentz forces (MPa)**	**Fraction of Iss reached (%)**
TQS03a	**-180**	**-200**	93
TQS03b	**-220**	**-240**	91
TQS03c	**-250**	**-270**	88
TQS03d	**-180**	**-200**	88
MQXF	-176 (design)	-142 (design)	NA

- TQS03: performance above 90% reached with 220-240 MPa of estimated compressive azimuthal stress in the high field region

Experience of tension in the pole



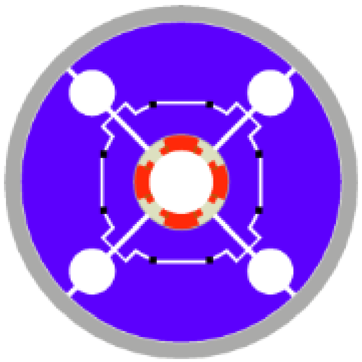


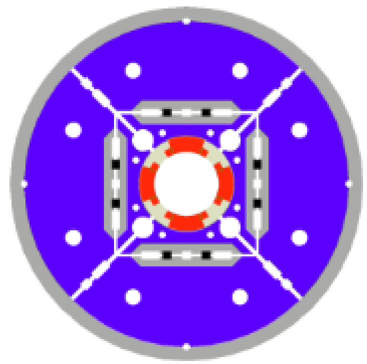
In TQS03a, some tension at the pole did not impact the magnet performance.

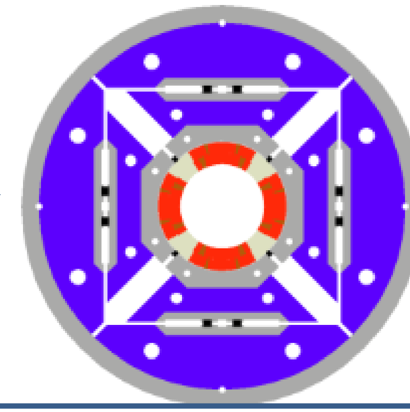
Outline

- Shell-based support structure concept
- Exploring the limits
  - TQ high stress
- Step-by-step technology demonstration
  - Design optimization
  - Length
- MQXF support structure
  - Main features

From TQ to HQ
Design optimization







	TQ	LQ	HQ

Field and stress	• Stainless steel insert to lower peak field in the end	• Optimization of the design
		  • load key positon
		  • Pad extremity in stainless steel to lower peak field in the end
			• Cross-section optimization considering force distribution among layers
			• Stainless steel pad ends

Alignment	• No alignment features	• Implementation of alignment features from pad to shell	• Alignment features between coil and pads: aluminum collars and key

From TQ to HQ
Design optimization

Azimuthal stress σ_θ : design values

TQ

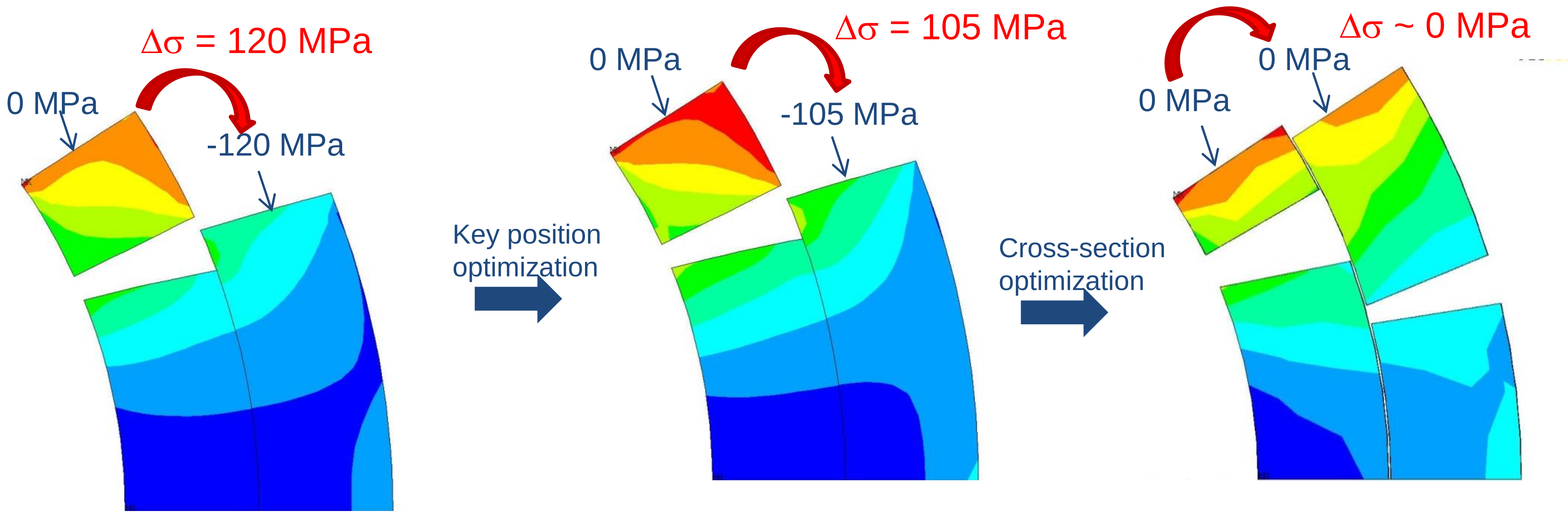
- 90 mm aperture
- 240 T/m (12.5 T – 13.8 kA)
- F_θ Layer 1 = -1.5 MN/m
- F_θ Layer 2 = -1.02 MN/m

LQ

- 90 mm aperture
- 240 T/m (12.5 T – 13.8 kA))
- F_θ Layer 1 = -1.5 MN/m
- F_θ Layer 2 = -1.02 MN/m

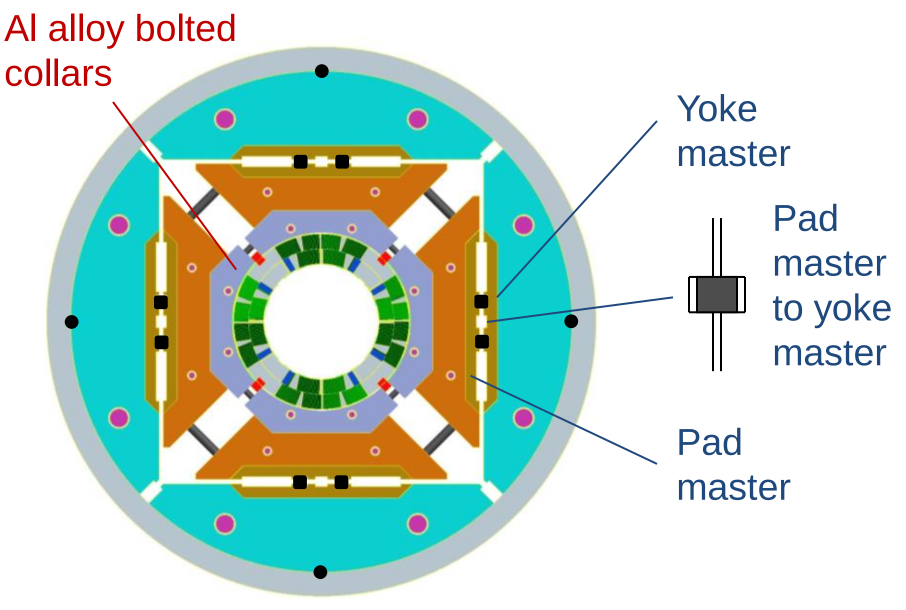
HQ

- 120 mm aperture
- 220 T/m (15 T - 19.6 kA)
- F_θ Layer 1 = - 2.1 MN/m
- F_θ Layer 2 = - 2.6 MN/m



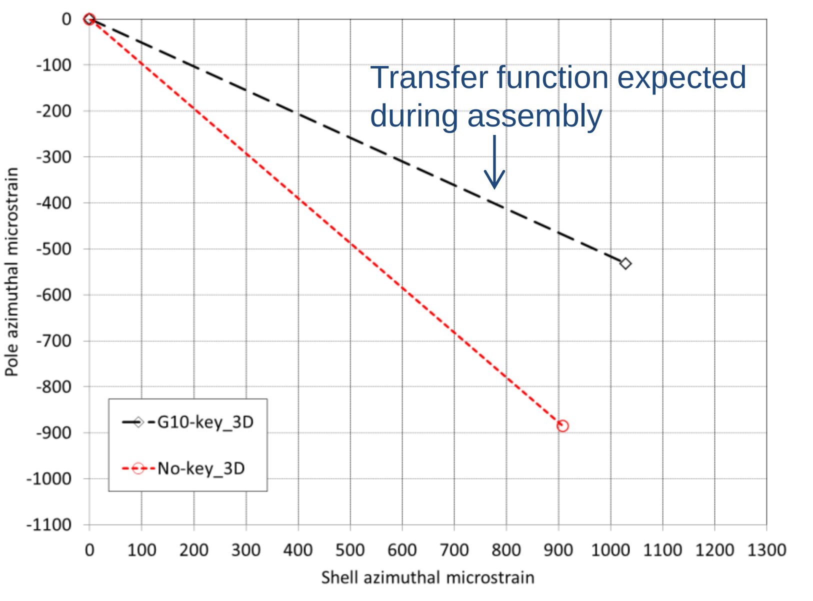
Design optimization led to more homogenous stress distribution in the coil cross-section

HQ the closest relative to MQXF
Support structure overview



Alignment features

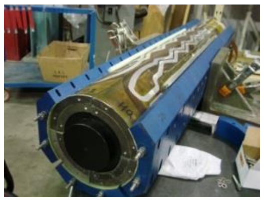
- From pad to shell: demonstrated in LQ
- From coil to pad: new bolted collar features
  - Alignment purpose only
  - No preload applied by the collar
  - Interception of part of the preload



Coil to pad alignment features introducing a new pre-stress regime

Stress distribution in HQ02b Straight section

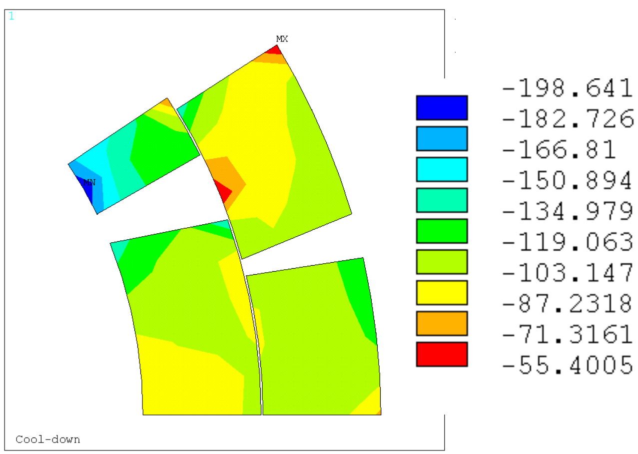
2010 HQ01a-b-c
2011 HQ01d-e
2012
2013 HQ02a-b
2014 HQ03



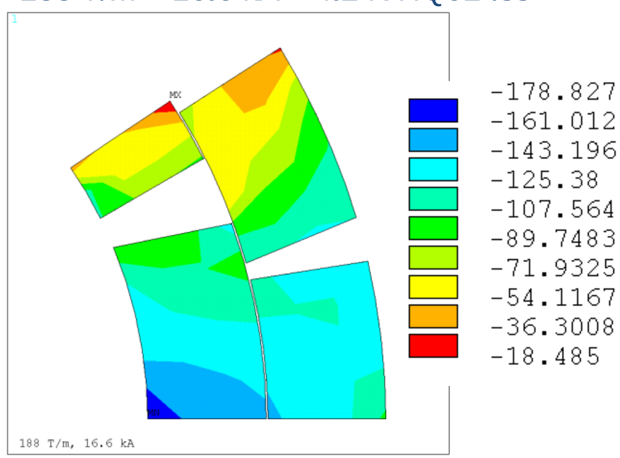
Coil to pad alignment features introducing a new pre-stress regime

Focus on HQ02 with 2nd generation coils

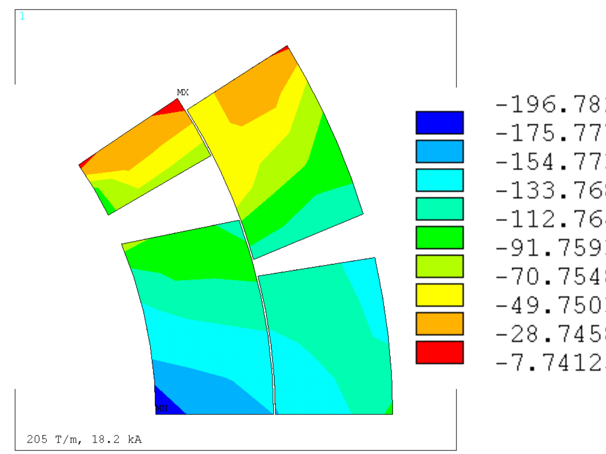
Azimuthal stress (MPa)
4.2 K



Azimuthal stress (MPa)
188 T/m – 16.6 kA – 4.2 K HQ02 Iss

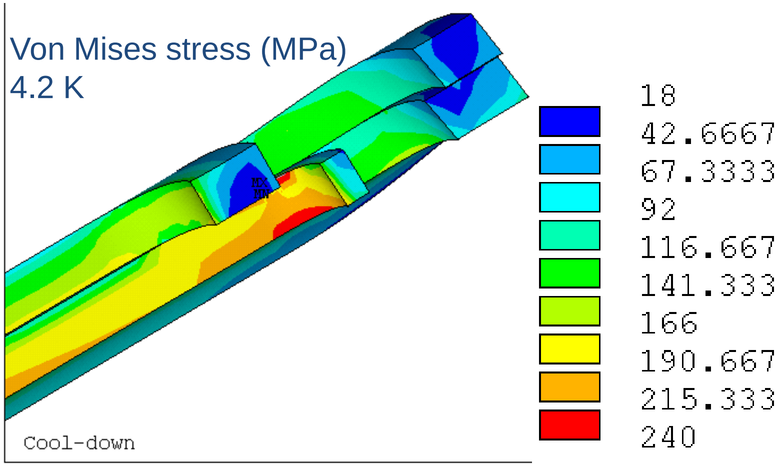


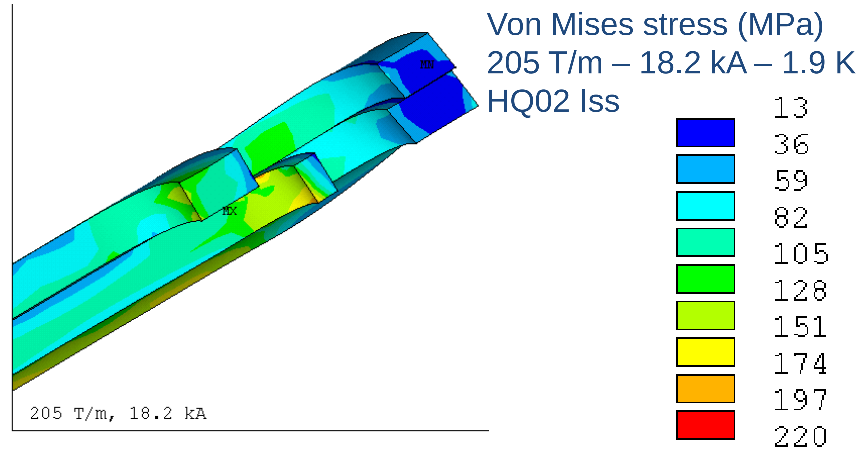
Azimuthal stress (MPa)
205 T/m – 18.2 kA – 1.9 K HQ02 Iss

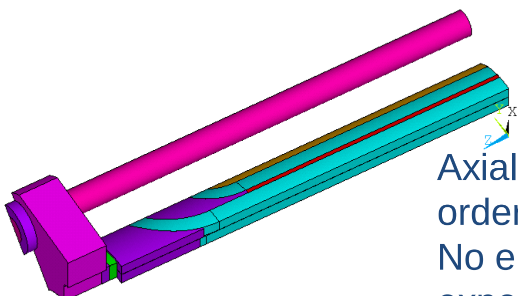


Azimuthal stress in HQ02b of the order of 200 MPa

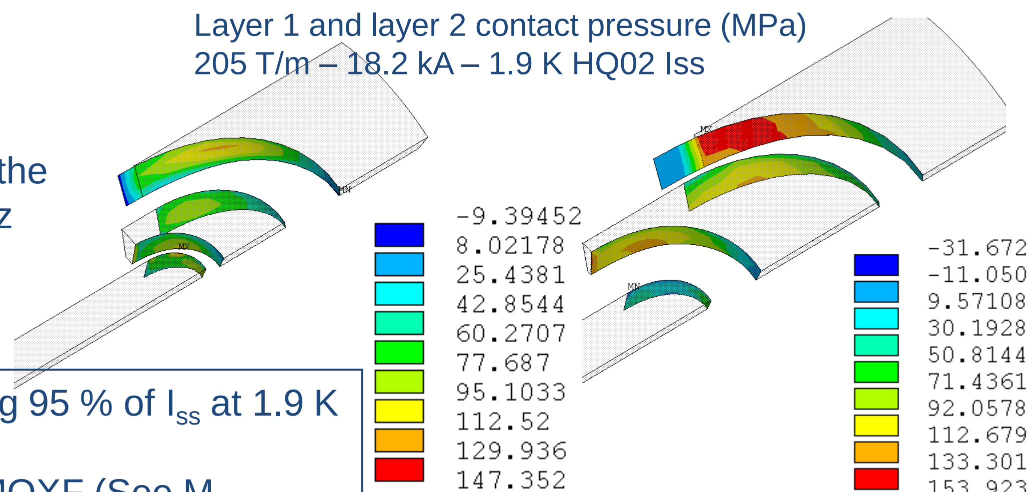
HQ02: End region





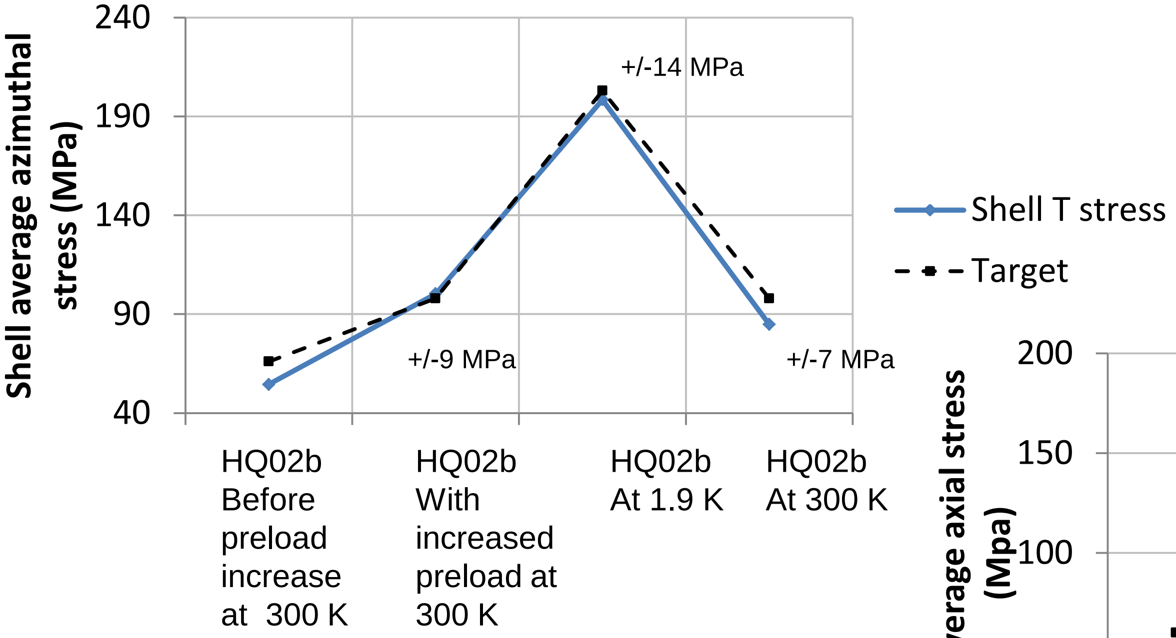


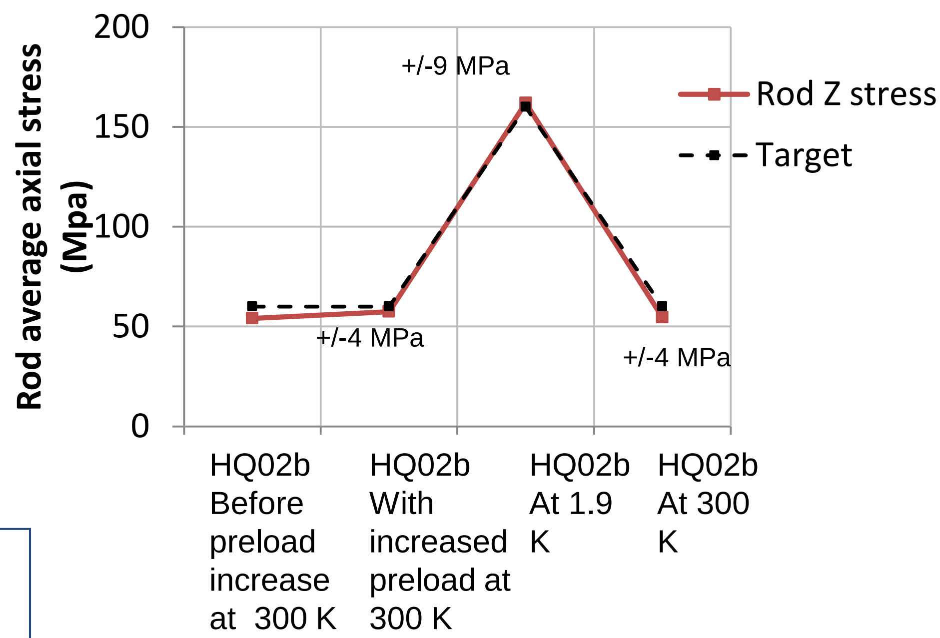
Axial preload applied of the order of 500 kN ~ 50% Fz
No end quenches ever experienced



- Pre-stress condition in HQ02b allowed reaching 95 % of I_{ss} at 1.9 K
- No quenches in the end
- Higher stress range (beyond 180 MPa) than MQXF (See M. Juchno talk)

HQ02b: strain gauges data



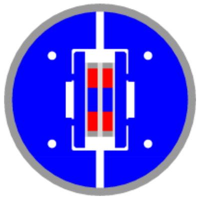


- Preload on shell and rods consistent with ANSYS target

Outline

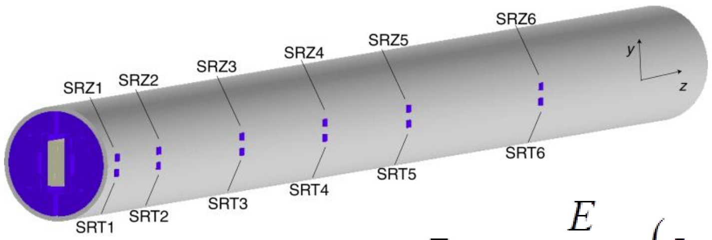
- Shell-based support structure concept
- Exploring the limits
  - TQ high stress
- Step-by-step technology demonstration
  - Design Optimization
  - Length
- MQXF support structure
  - Main features

1st long shell based structure: the Long Racetrack LR

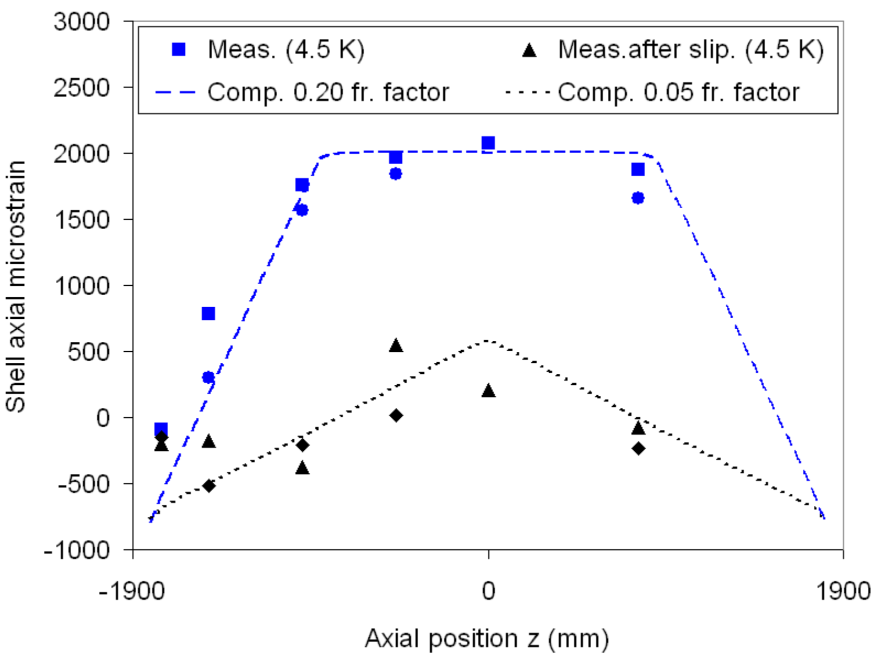


	LRS parameters
	4.5 K
I_{ss} (kA)	10.6
$B_{peak\ ss}$ (T)	12

- LRS01: full length shell (3.6 m)
- Friction limits the shell contractions
    - Central part locked
- Strain at 4.5 K consistent with 0.2 friction model results
- Slippage occurred during the test

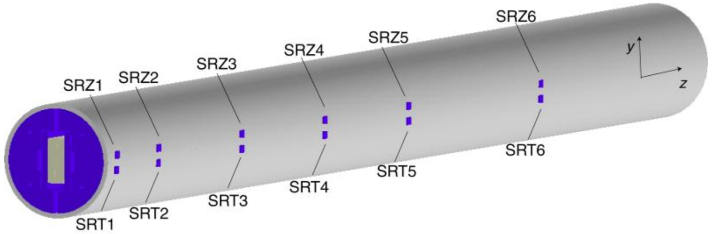


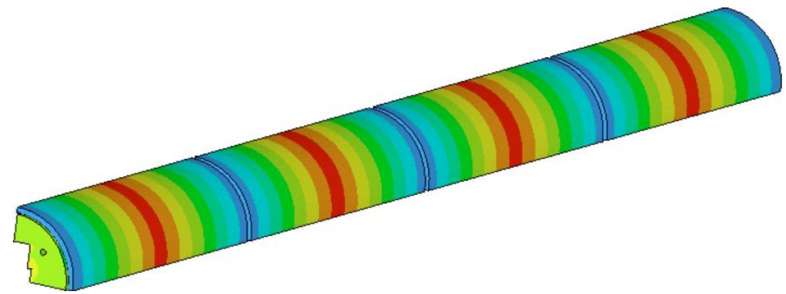
$$\sigma_\theta = \frac{E}{(1-\nu^2)}(\varepsilon_\theta + \nu\varepsilon_z)$$

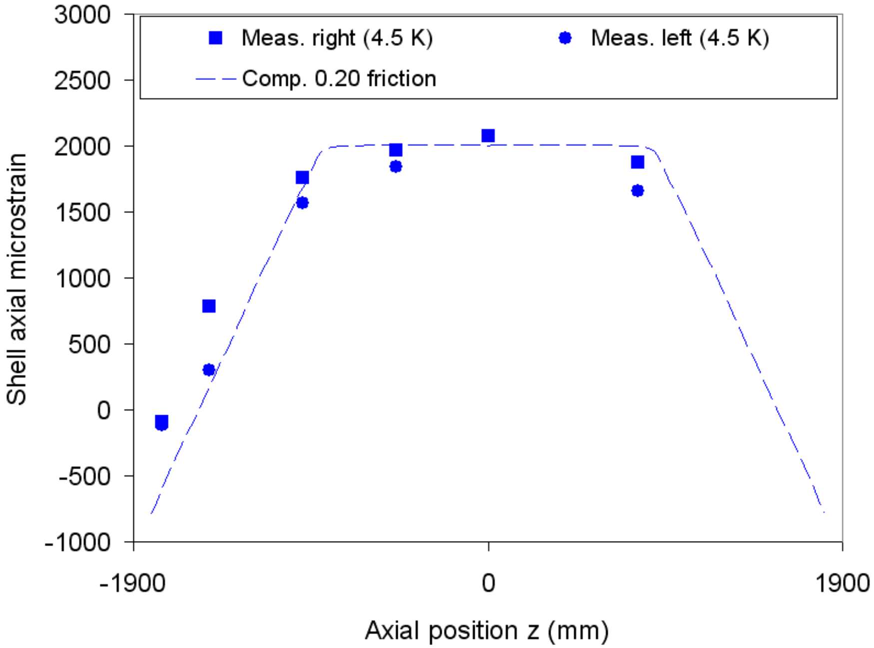


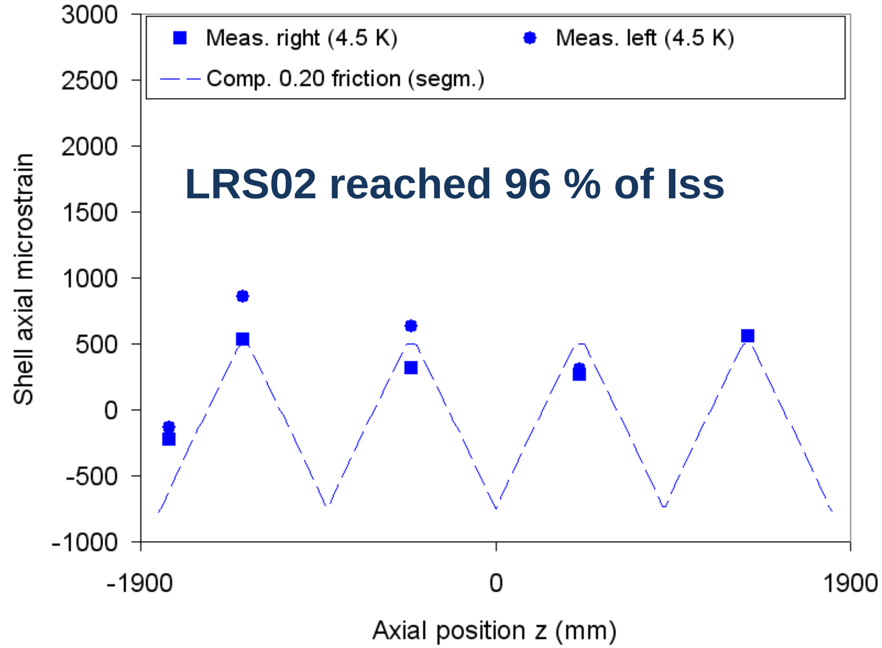
- In LRS01: shell slippage occurred during test due to high axial tension in the shell

From full length shell to segmented





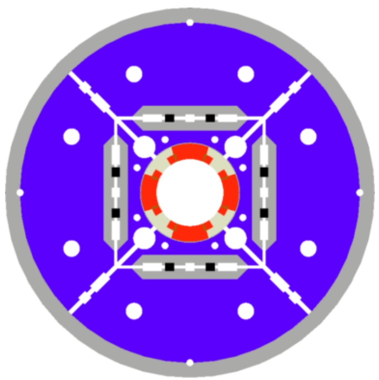




Shell segmentation demonstrated in LR to ensure reliable azimuthal preload

Length demonstration on a cos2θ magnet: the Long Quad LQ

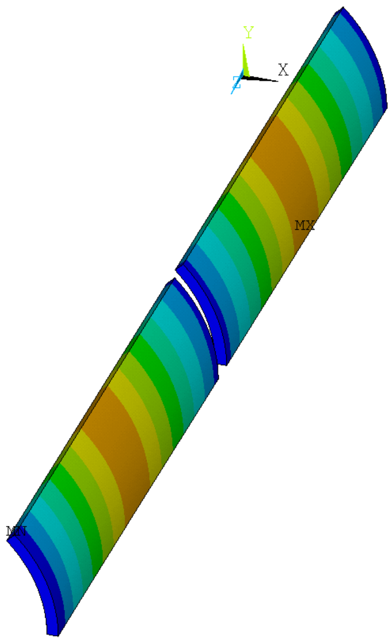
- 90 mm aperture
- TQ coil scale-up
- Magnet/coil length: 3.7/3.4 m



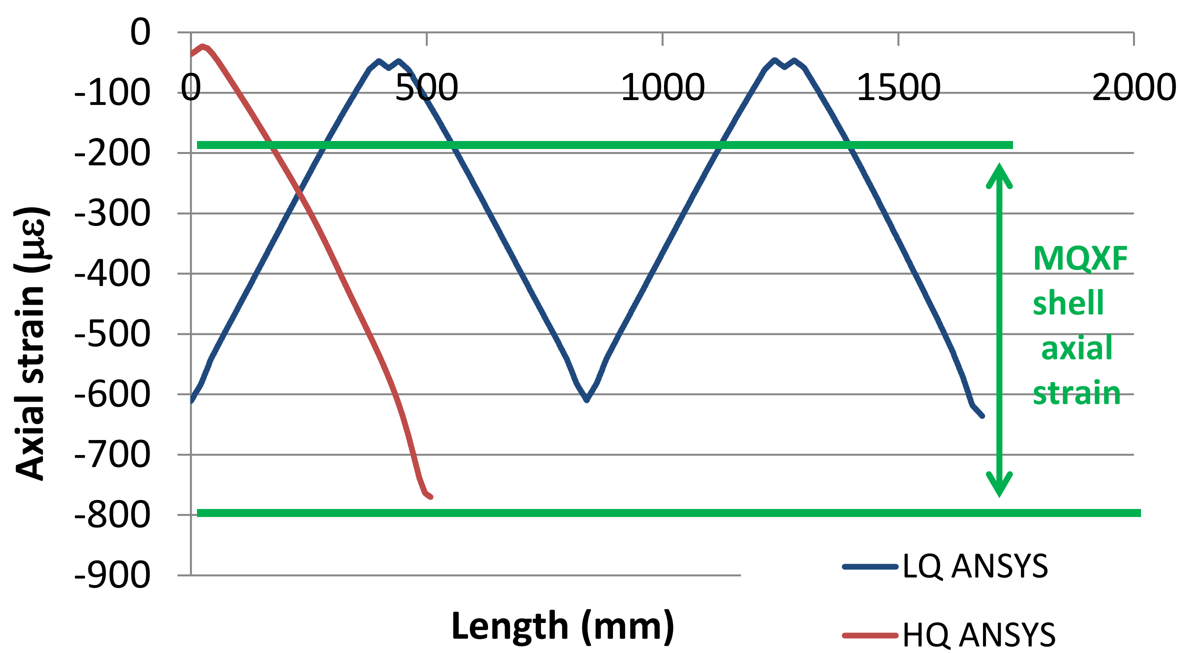
	LQS01-2 parameters		LQS03 parameters	
	4.5 K	1.9 K	4.5 K	1.9 K
I_{ss} (kA)	13.8	15.4	12.9	14.4
$B_{peak\ ss}$ (T)	12.3	13.6	11.5	12.8
G_{ss} (T/m)	240	267	227	250

- **Based on LR results, LQ shell was segmented**
- **4 complete assemblies: LQS01a/b and LQS02 and 3**

LQ Shell Axial strain



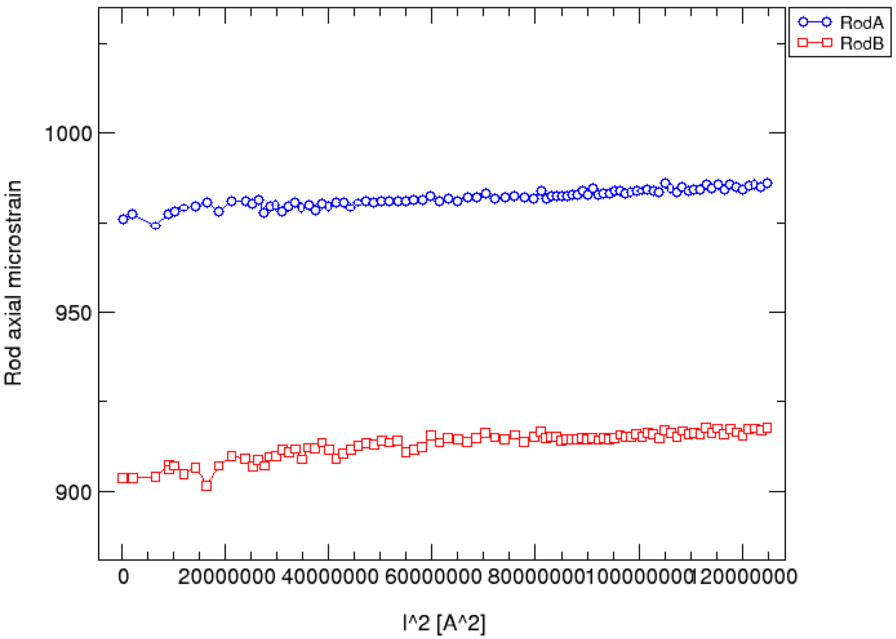
After cool-down

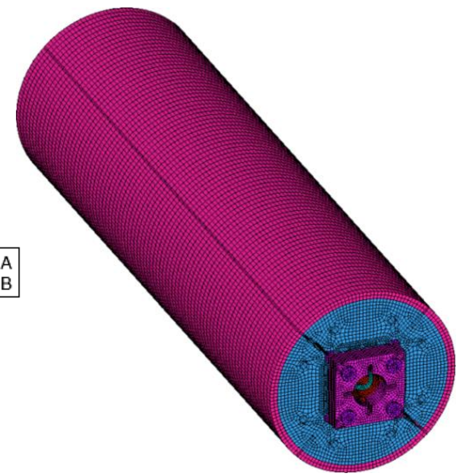


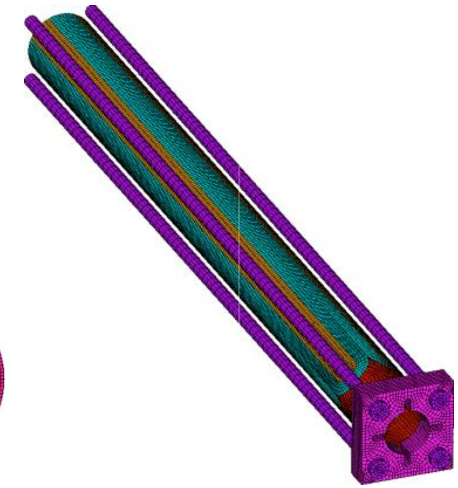
- LQ: Axial strain value consistent with LRS02 shell strain values
- No slippage monitored during test
- LQ, HQ and MQXF have consistent shell axial strain values

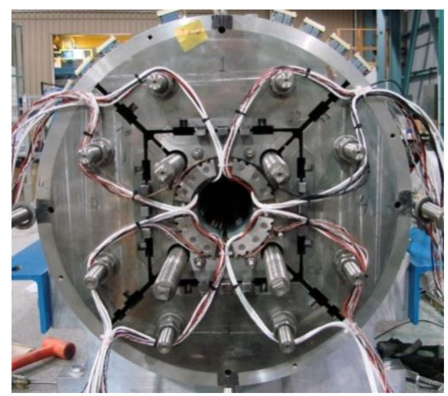
LQ: Axial motion during excitation

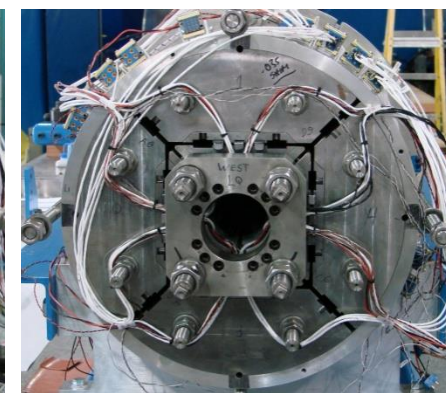
- Variation of rod axial strain
  - +10 microstrain
- Elongation of the coil
  - 34 micron (with 330 kN, 33 t)





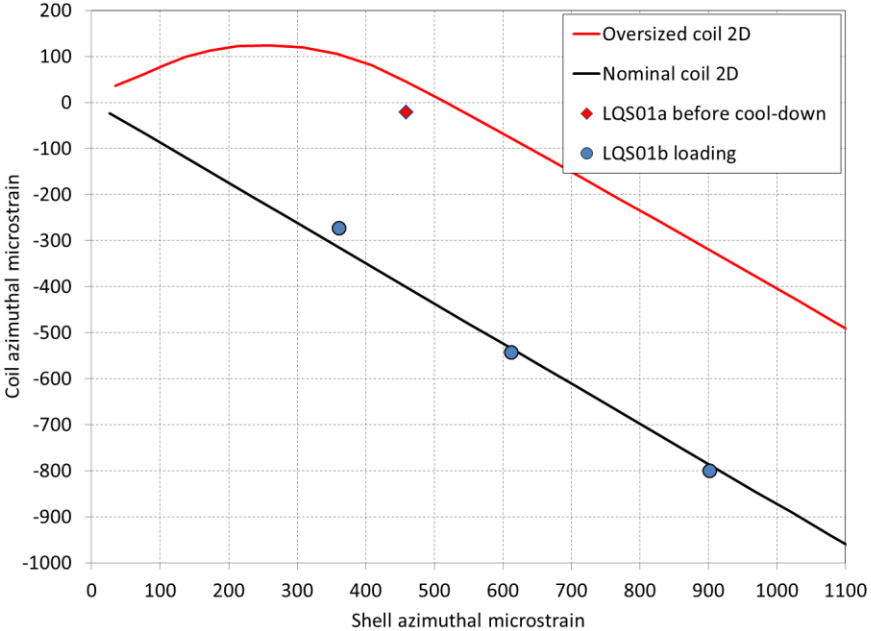


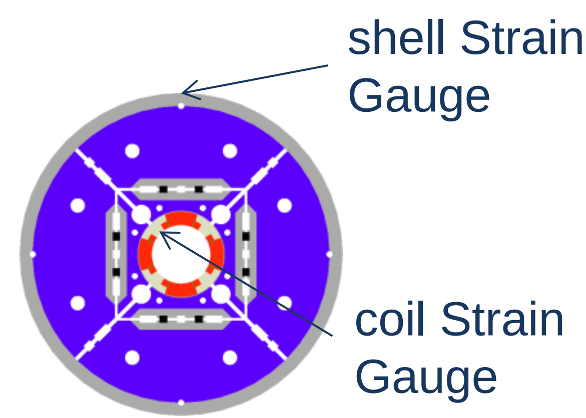


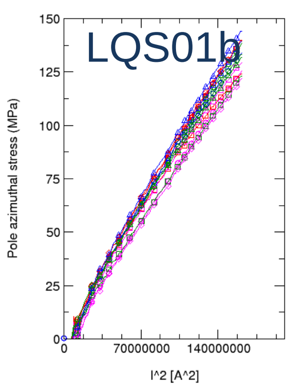


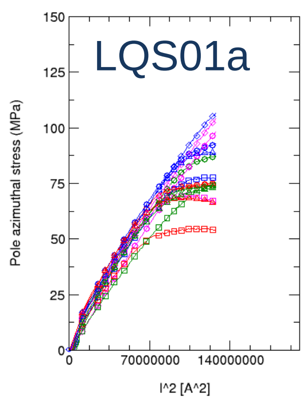
Axial rigidity of the structure was demonstrated with LQ

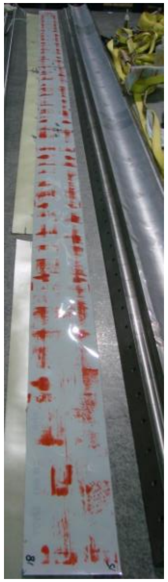
LQ: assembly optimization

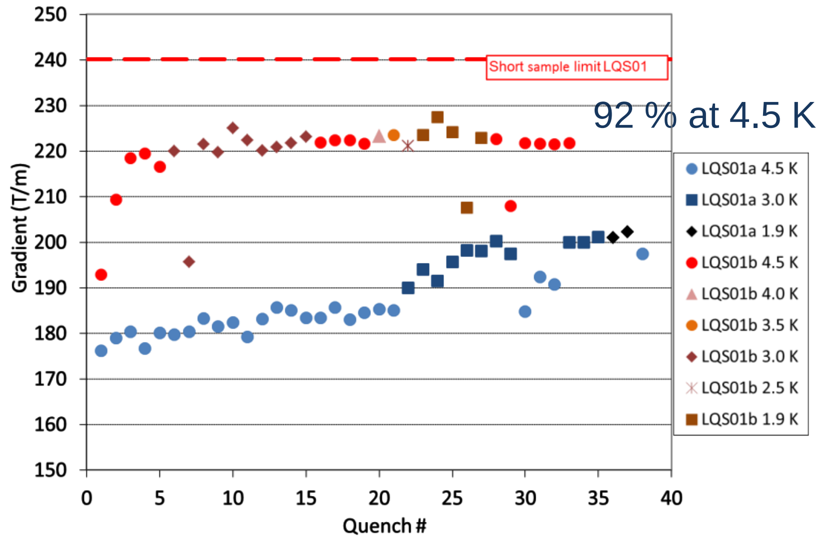












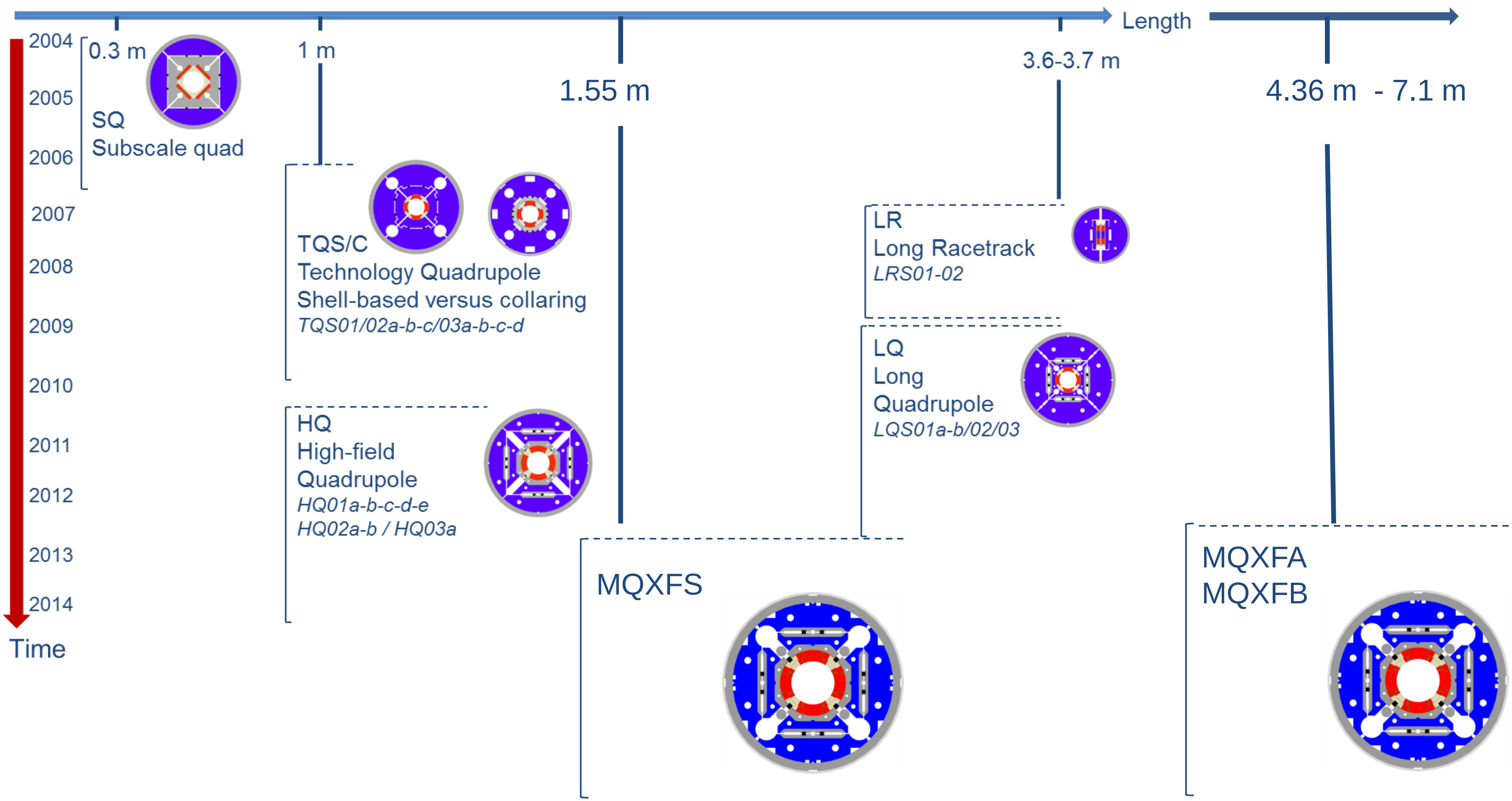
Summary

- Stress limits were explored with the TQ program and showed that stresses as high as 240 MPa in the winding were compatible with performance above 90%
- From SQ to HQ, LARP demonstrated that the shell-based support structure:
  - Can be used in long magnets with a segmented shell
  - Can provide alignment between coil and structure
  - Can accommodate oversized coils
- Same assumptions applied to LARP magnets and MQXF analysis
- HQ experienced stresses beyond the stress level of MQXF
- The support structure features demonstrated by LARP are now implemented in the MQXF design

Outline

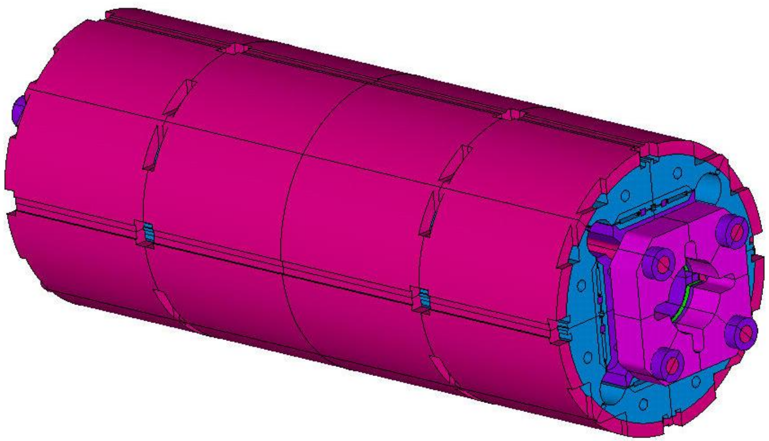
- Shell-based support structure concept
- Exploring the limits
  - TQ high stress
- Step-by-step technology demonstration
  - Alignment features
  - Length
- MQXF support structure
  - Main features

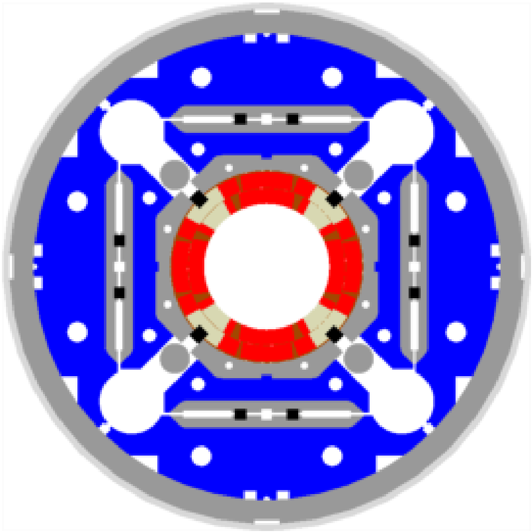
From LARP to MQXF



MQXF support structure overview

- Alignment components similar to HQ
- Similar axial support
- Segmented shell
- Level of stress below past LARP experience



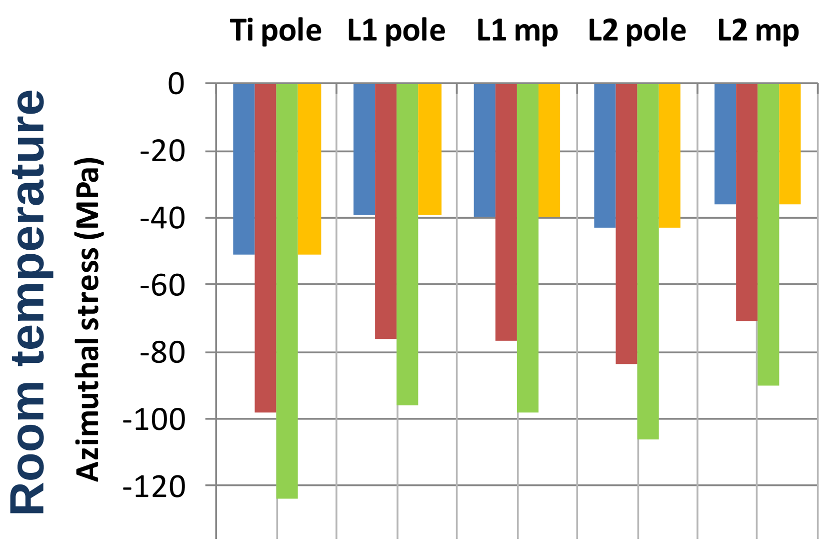


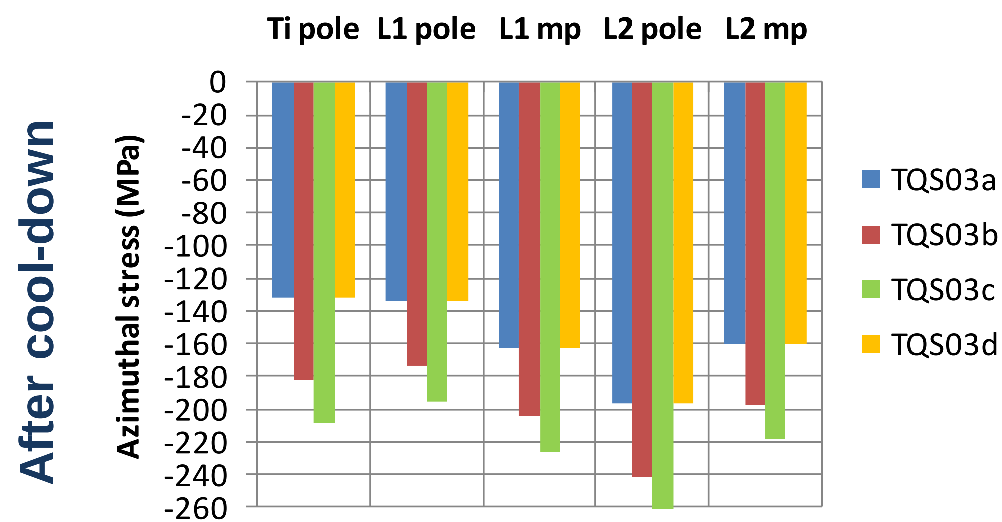
- MQXF support structure includes features for cooling and cold mass assembly

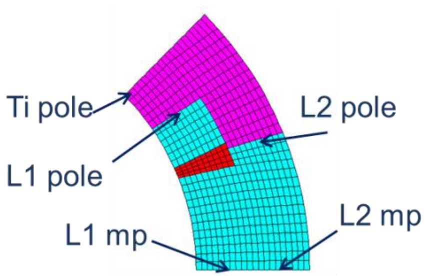
See Mariusz Juchno's talk

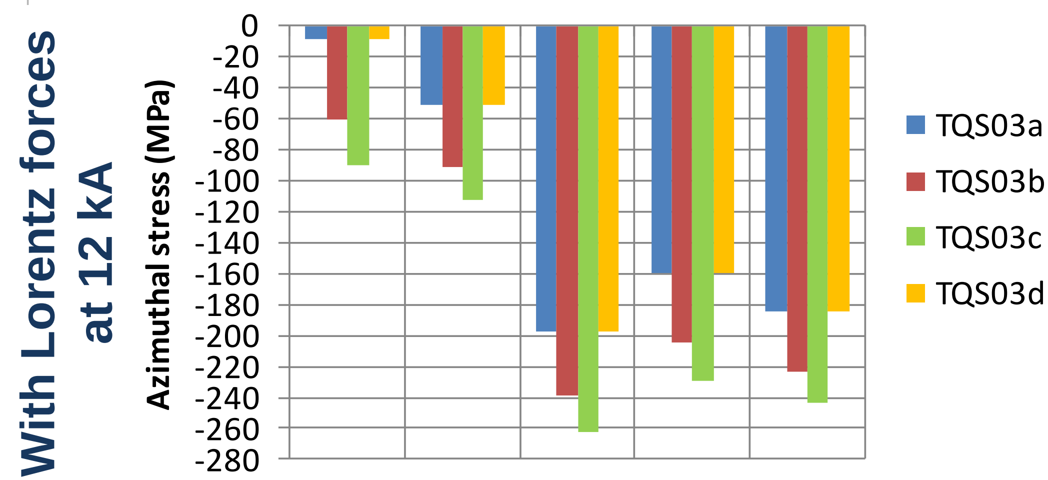
APPENDIX

Stress limits – TQS03 program
Predicted Azimuthal stress



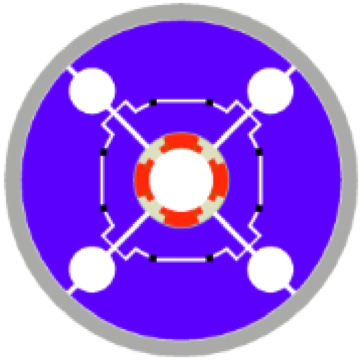




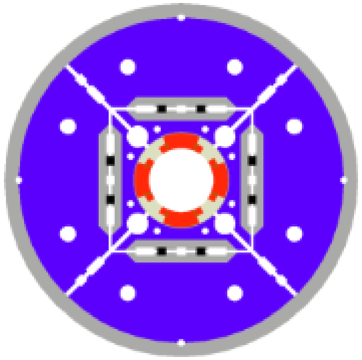


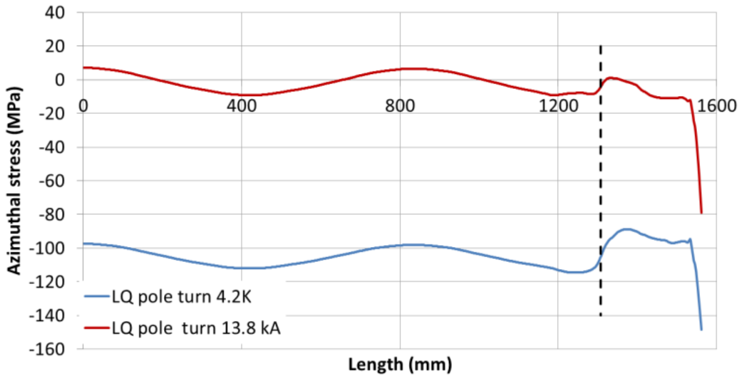
From TQ to HQ
Design optimization

TQ



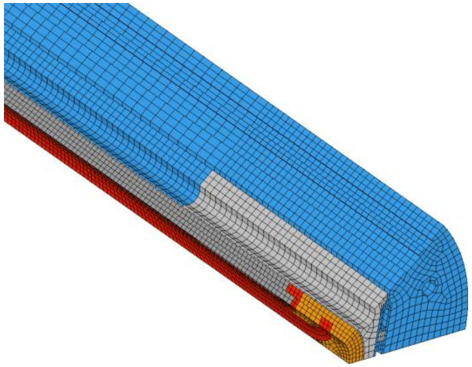
LQ



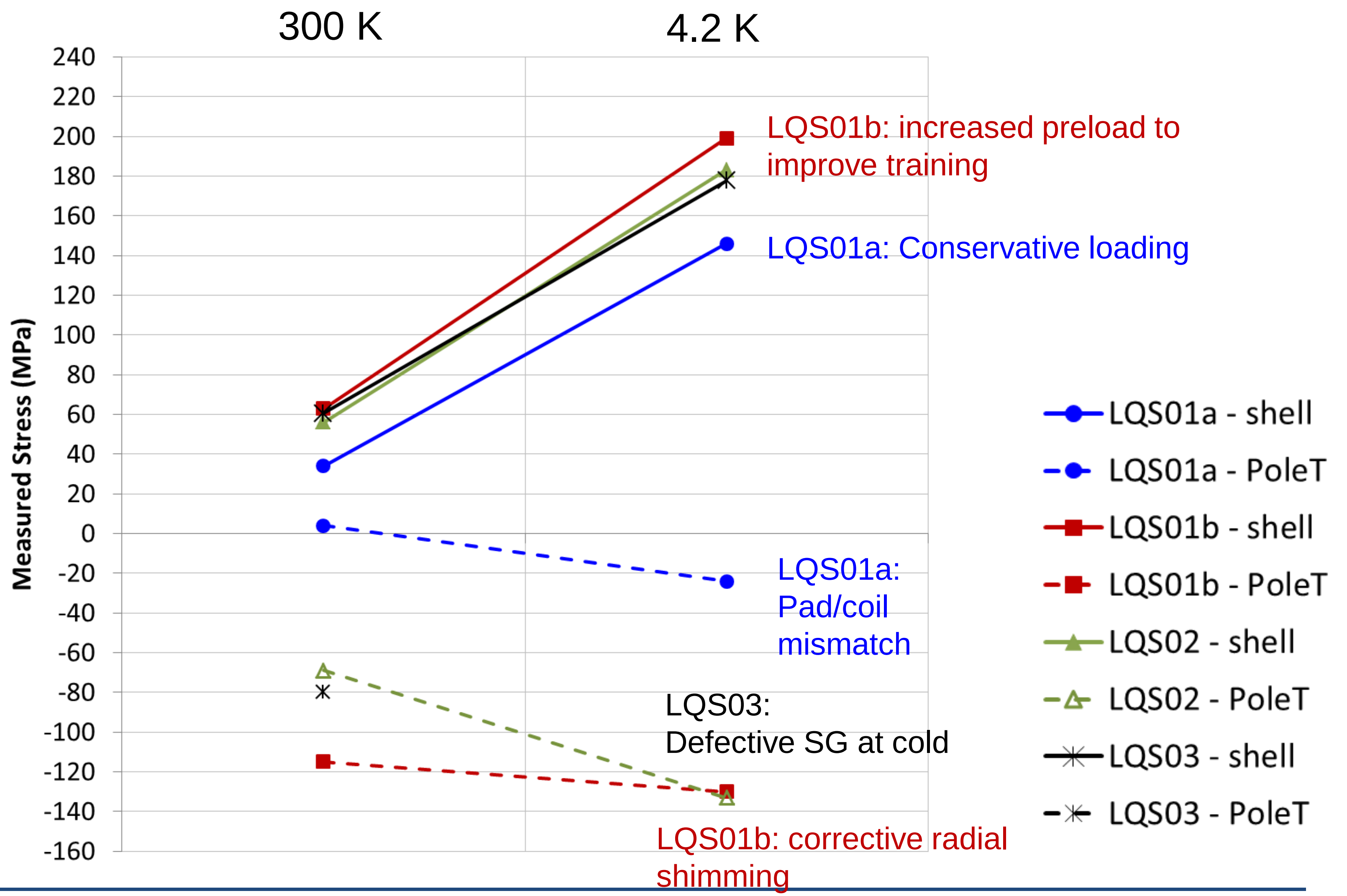


- Pad extremities in stainless steel to lower the peak field in the end region
- No alignment features

- Optimization of the design
  - load key positon
  - Pad extremity in stainless steel
- Implementation of alignment features from pad to shell:
  - Key, masters and pins



LQ series preload overview



Mechanical Analysis
Typical Stress distribution

Shell

Preload for 260 T/m

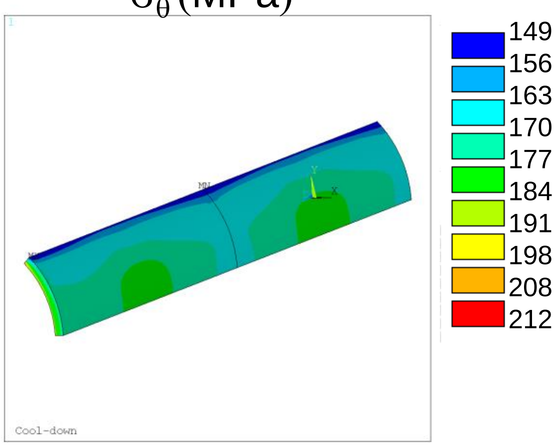
σ_θ and ε_θ at 300 K

- target (3D): + 56 MPa
+ 750 $\mu\varepsilon$

σ_θ and ε_θ at 4.3 K

- target (3D): + 183 MPa
+2080 $\mu\varepsilon$

σ_θ (MPa)



Pole

Preload for 260 T/m

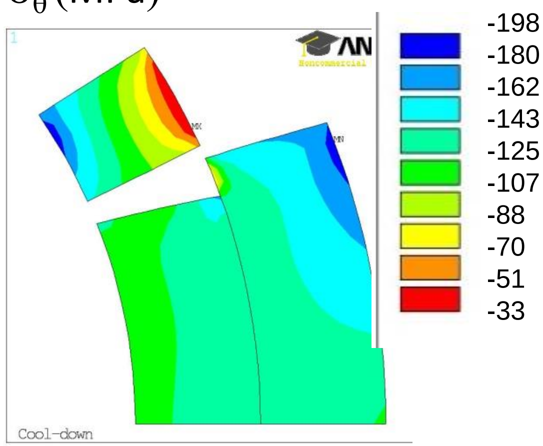
σ_θ and ε_θ at 300 K

- target (3D): -82 MPa
-580 $\mu\varepsilon$

σ_θ and ε_θ at 4.3 K

- target (3D): -157 MPa
-1031 $\mu\varepsilon$

σ_θ (MPa)



Rod

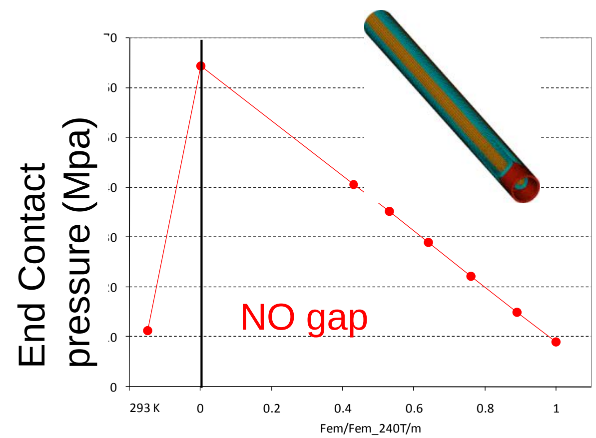
Preload for 240 T/m: 471 kN

σ_z and ε_z at 300 K

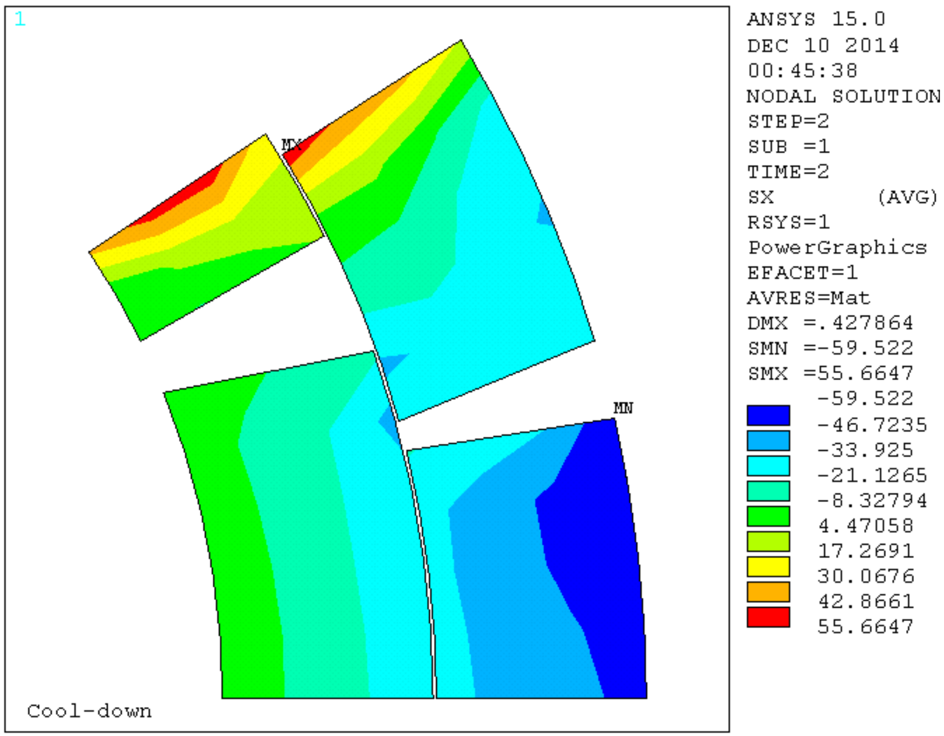
- target (3D): +88 Mpa (178 kN)
+455 $\mu\varepsilon$

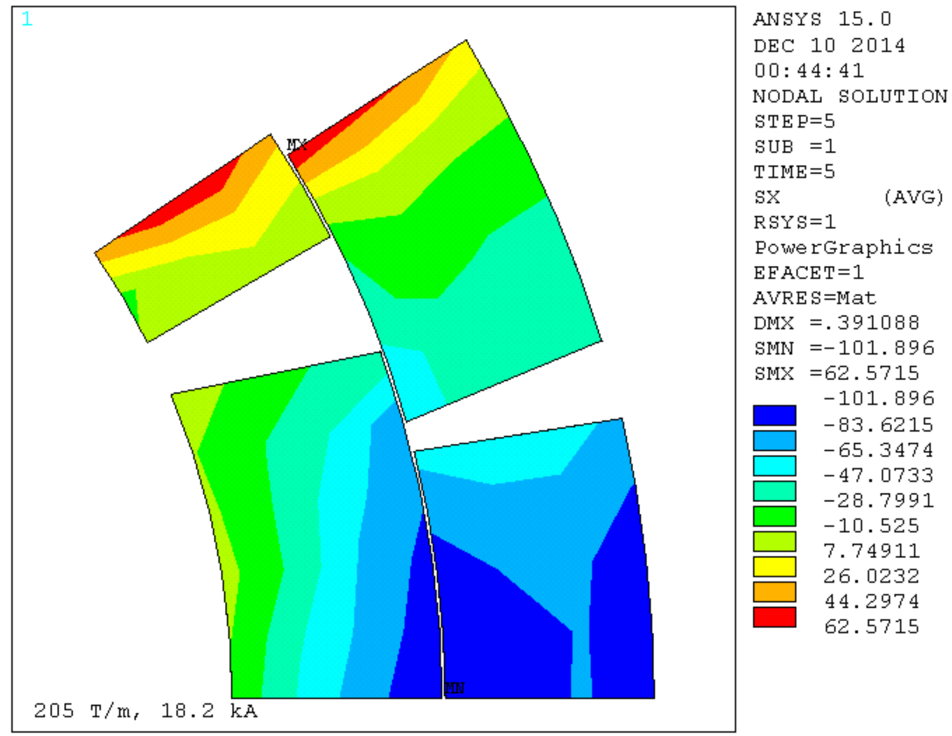
σ_z and ε_z at 4.3 K

- target (3D): + 239 MPa
+ 1138 $\mu\varepsilon$

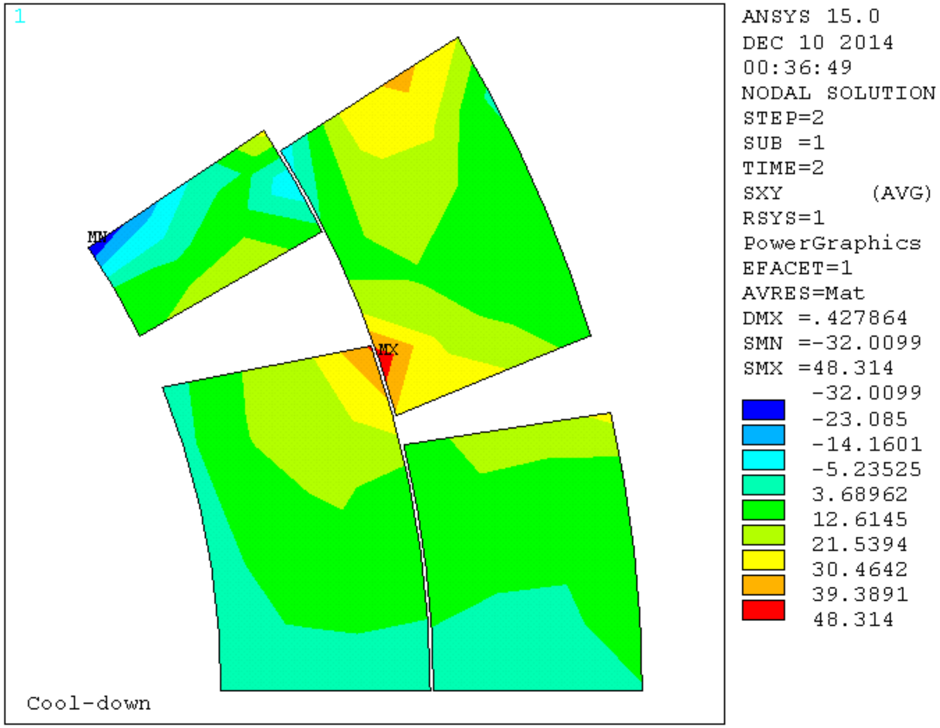


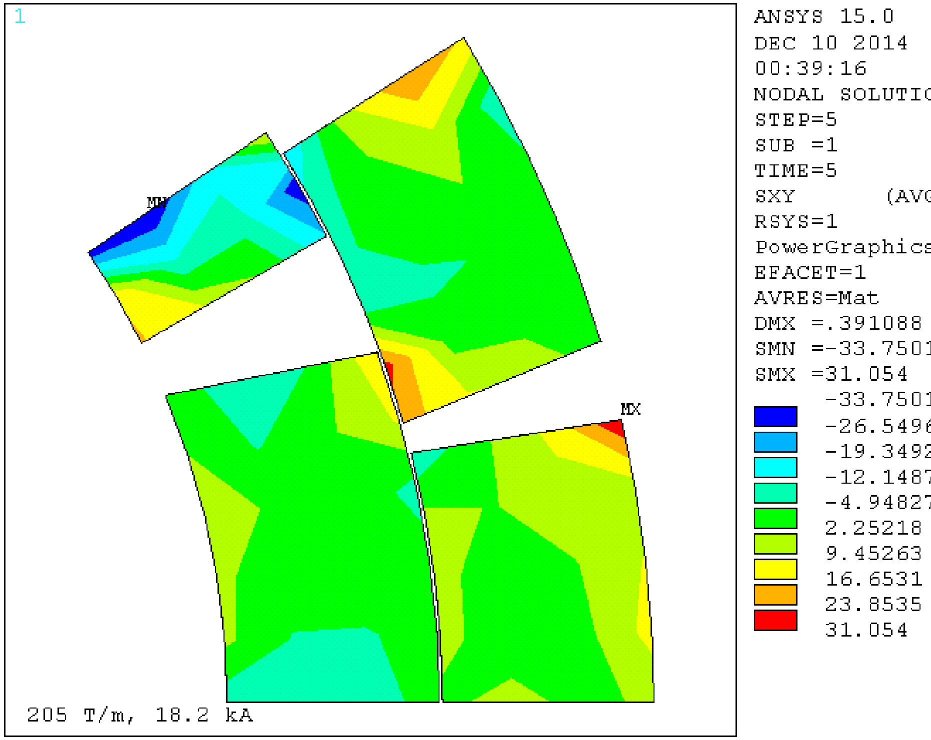
HQ02b – radial stress (MPa)





HQ02b – Shear stresses (MPa)





HQ02b – axial stress (MPa)