Longitudinal pre-load of Nb_3Sn magnets

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with feedback and material (mainly) from Paolo Ferracin, Eelis Takala, Emma Gautheron, Manuel Garcia Perez, Giorgio Vallone, Etienne Rochepault.

Outline

- Introduction
- MQXF experience
- 11 T experience
- eRMC/RMM experience
- Few other important 3D features
  - Pole (Titanium vs Bronze)
  - Aluminum shell (Full length vs Segmented)

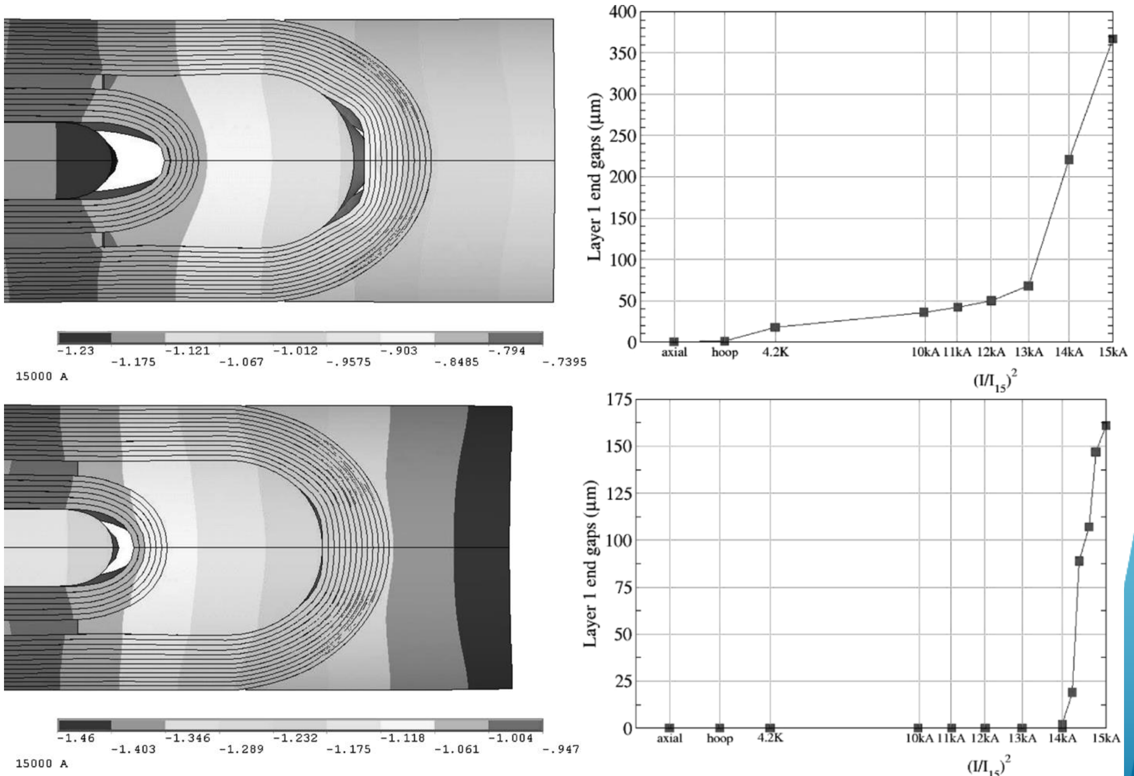
General Statements

- Understanding the 3D mechanical state of SC magnets is complex and requires a dedicate effort.
- Modeling and measuring the reaction process is not a simple task.
- 'Two schools' in terms of longitudinal support, with no consensus on the magnet community:
  - Limit the coil displacements due to electromagnetic forces by having a rigid structure in the longitudinal direction (11 T concept, end-plate welded to the shell)
  - Limit the coil displacements due to electromagnetic forces by having a rigid structure in the longitudinal direction and pre-load coil ends to compensate the axial forces and keep coil end turns under compression (MQXF concept, axial plate and pre-loaded rods)
- My aim is not to judge what is the correct approach, but to show our current understanding.

Force or not force?

- Two type of axial displacements:
  - Relative movement of the coil with respect to the structure. It depends on the overall stiffness of the structure, i.e., independent of the level of pre-load in the ends.
  - Relative movement of the coil ends with respect to the pole. It depends of the level of pre-load.

- This was extensively studied in LBNL, developing the rods - plate axial pre-load system we are currently using for MQXF



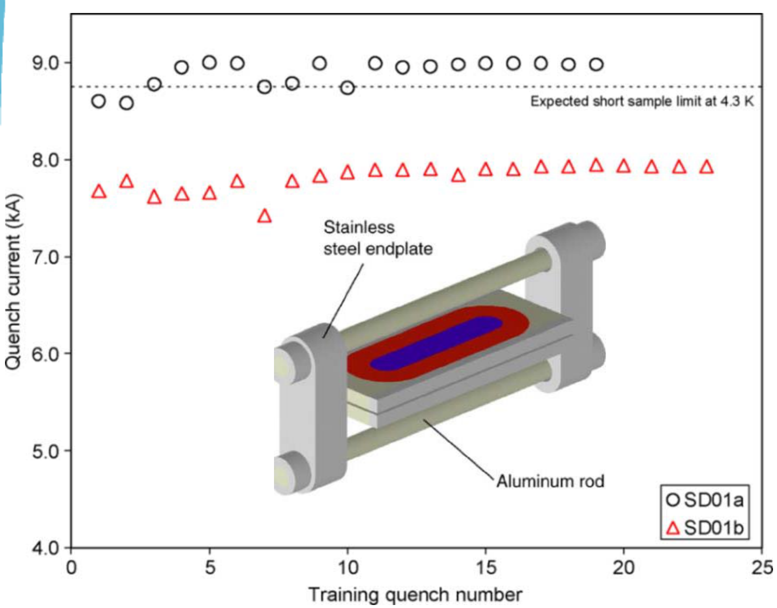
Axial displacements of inner layer's (0.2 friction factor assumed). Limited axial support (top) and full axial support (bottom).

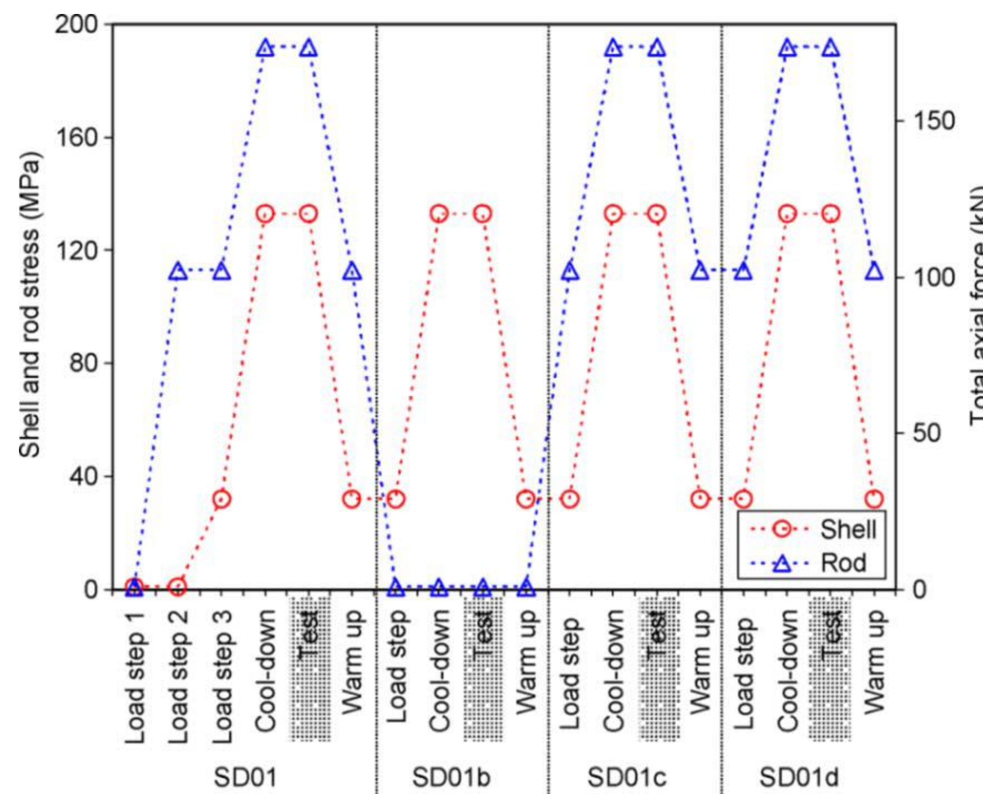
S. Caspi, P. Ferracin., "Towards integrated design and modeling of high field accelerator magnets," IEEE Trans. Appl. Supercond., vol. 16, no. 2, pp. 1298–1303, June 2006.

SQ/SD Experience (LBNL)

- LBNL/LARP intensively studied this problem (FE and experience in sub-scales) .
- SQ02 and SD01 show a clear degradation in training performance with no axial support
  - This is an extreme condition, since both the relative movement coil to structure and relative movement coil to pole were relaxed.

Fz @ Iss = 0.17 MN/end

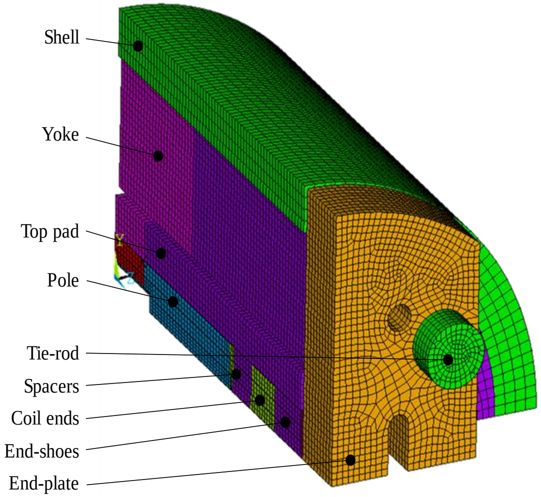




S. Caspi, P. Ferracin., "Towards integrated design and modeling of high field accelerator magnets," IEEE Trans. Appl. Supercond., vol. 16, no. 2, pp. 1298–1303, June 2006.

eRMC/RMM

- Within the FCC effort, eRMC/RMM was designed in order to be able to explore the parameter space:
  - Aluminum and SS rods procured
  - Big rods, thick end plate, in order to have a very rigid structure in the longitudinal direction.



- More details later…

Overview on different magnet parameters

Magnet	Longitudinal pre-load system	# of ap.	Field [T] or gradient [T/m]	Fz/ap. [MN]
LHC-MB	? mm thick end-plate, ? mm thick SS shell	2	8.3	0.24
11 T MBHS	43 mm thick end-plate, 12 mm thick SS shell	1	11.2	0.44
11 T MBHD	75 mm thick end-plate, 15 mm SS shell.	2	11.2	0.45
MQXFS	4 x D = 36 mm Al rod, 75 mm thick nitronic50 plates	1	132.6	1.2
MQXFB	4 x D = 35 mm SS rod, 75 mm thick nitronic50 plates	1	132.6	1.2
FRESCA2	4 x D = 60 mm Al rod, 150 mm thick nitronic50 plates	1	13	2.8
eRMC	4 x D = 64 mm Al/SS rod, 100 mm thick nitronic50 plates	1	16	1.5
RMM	4 x D = 64 mm Al/SS rod, 100 mm thick nitronic50 plates	1	16	2.4
HD2		1	13	0.7
HQ		1	219	1.3
LQ	4 x D = 25.4 mm SS rod, 50 mm thick SS plates	1		

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  - **Longitudinal assembly concept**
  - **Experience from short models**
  - **Experience from long magnets**
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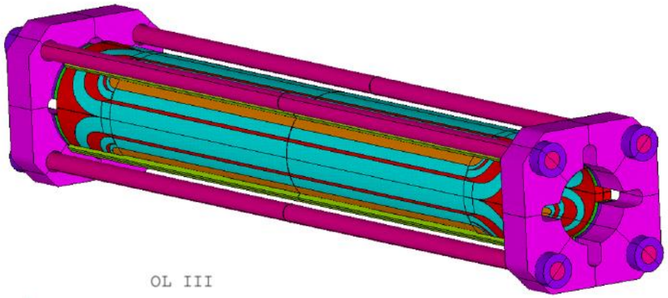
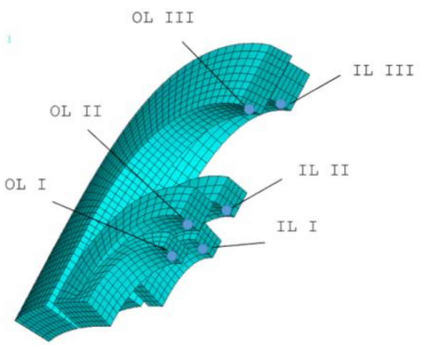
- Few other 3D features in MQXF
  - Pole (Titanium vs Bronze)
  - Aluminum shell (Full length vs Segmented)

MQXF Longitudinal Assembly

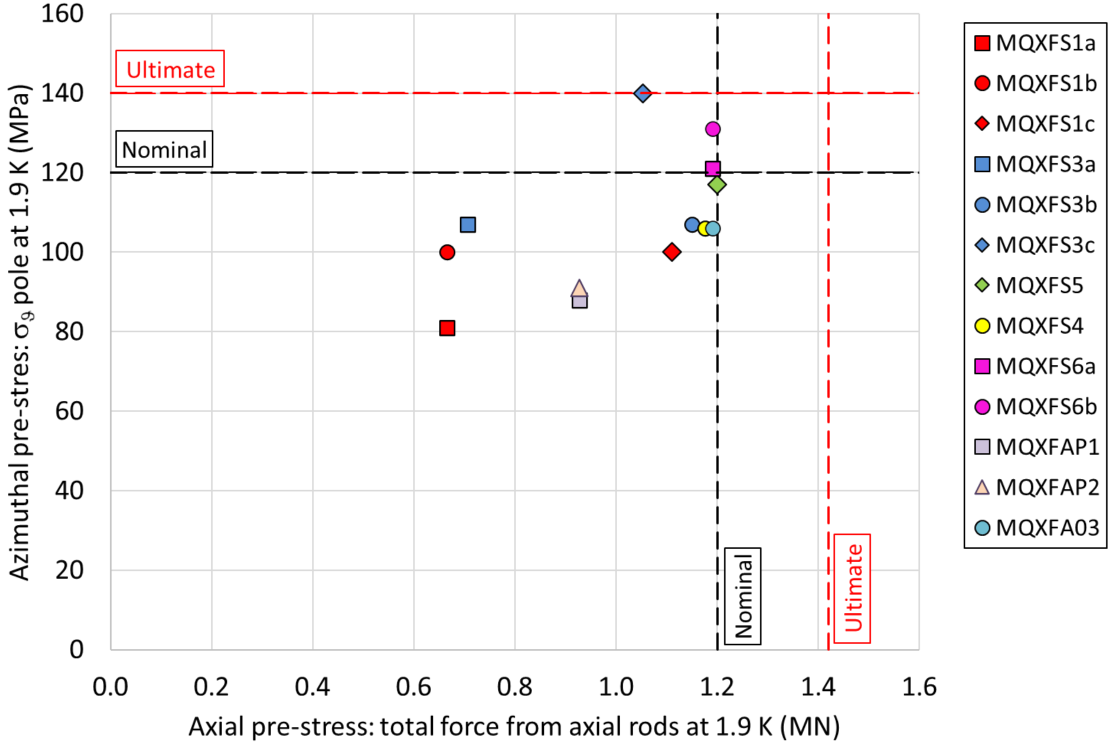
- Direct connection between the motion of the rod and the one of the coil ends
  - Very nice and clean measurements!
- Goal: keep the pole turn under compression during powering.
- Short models (1.2 m):
  - Aluminum rods, 36 mm diameter
  - Nitronic 50 end plate, 75 mm thick
- MQXFA (4.2 m):
  - Stainless steel rods, 32 mm diameter
  - Nitronic 50 end plate, 75 mm thick
- MQXFB (7.15 m):
  - Stainless steel rods, 35 mm diameter
  - Nitronic 50 end plate, 75 mm thick





MQXF – Preload a target

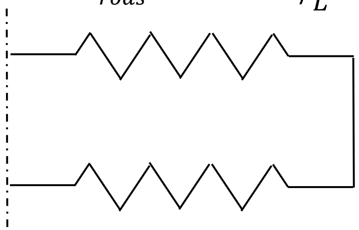
- Started with moderate pre-load 0.6 MN after cool down (50 % F_{em_z})
- Target for series: 1.2 MN after cool down (100 % F_{em_z})



		Rod Strain [με]		Rod Stress [MPa]		Rod Elongation [mm]		Total Force [MN]	
		RT	1.9 K	RT	1.9 K	RT	1.9 K	RT	1.9 K
Target	MQXFS	2450	3800	172	300	3.99	6.19	0.70	1.22
	MQXFA	950	1700	183	357	4.37	7.83	0.59	1.15
	MQXFB	900	1500	174	315	6.80	11.33	0.67	1.21

MQXF – From short to long

$$k_{rods} = {E_{rod}A_{rod}}/{L}$$



$$k_{coil} = \sum {E_i A_i}/{L}$$

- Coil elongation during powering for the 7.2 m magnets:
  - If not supported by the rods: 7.04 mm (0.098 %)
  - With stainless steel rods, no friction: 4.22 mm (0.098 %)
  - With stainless steel rods, friction: 0.28 mm (0.004 %)

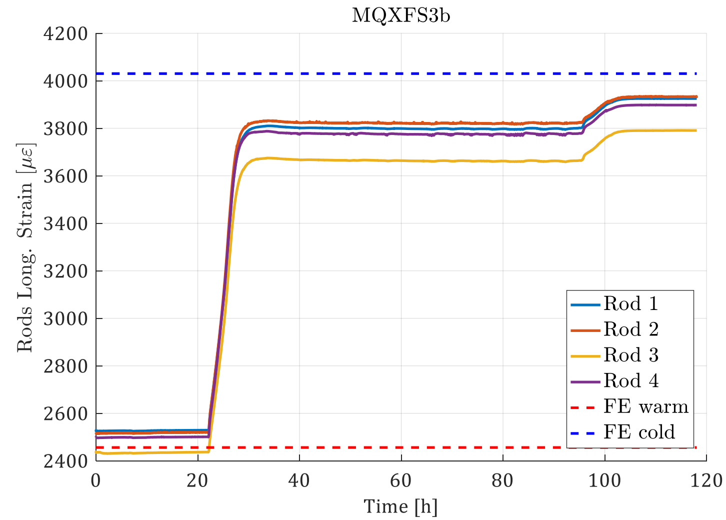
Main Parameters Governing the Longitudinal Motions

Parameter	Unit	MQXFS	MQXFB
e.m. Force Nominal Current	MN	1.2	1.2
Coil Stiffness	MN/mm	0.10	0.17
Al. Rod Stiffness	MN/mm	0.21	0.04
SS. Rod Stiffness	MN/mm	0.53	0.14
Coil Length	m	1.08	7.00
Magnet Length	m	1.55	7.51
Coil Elongation			
No friction, no rods	mm	1.09	7.04
No friction, Al. rods	mm	0.91	5.63
No friction, SS. rods	mm	0.73	4.22
Friction, Al. rods	mm	0.10	0.28
Friction, SS. rods	mm	0.06	0.28
Force Repartition, Coil/Rods/Structure			
Friction, Al. rods	%	10/2/88	4/1/95
Friction, SS. Rods	%	9/5/86	4/3/93

G. Vallone, et. al., Mechanical Design Analysis of MQXFB, the 7.2 m long-β quadrupole for the High-Luminosity LHC Upgrade, *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, 2016.

MQXFS – Experience from short magnets

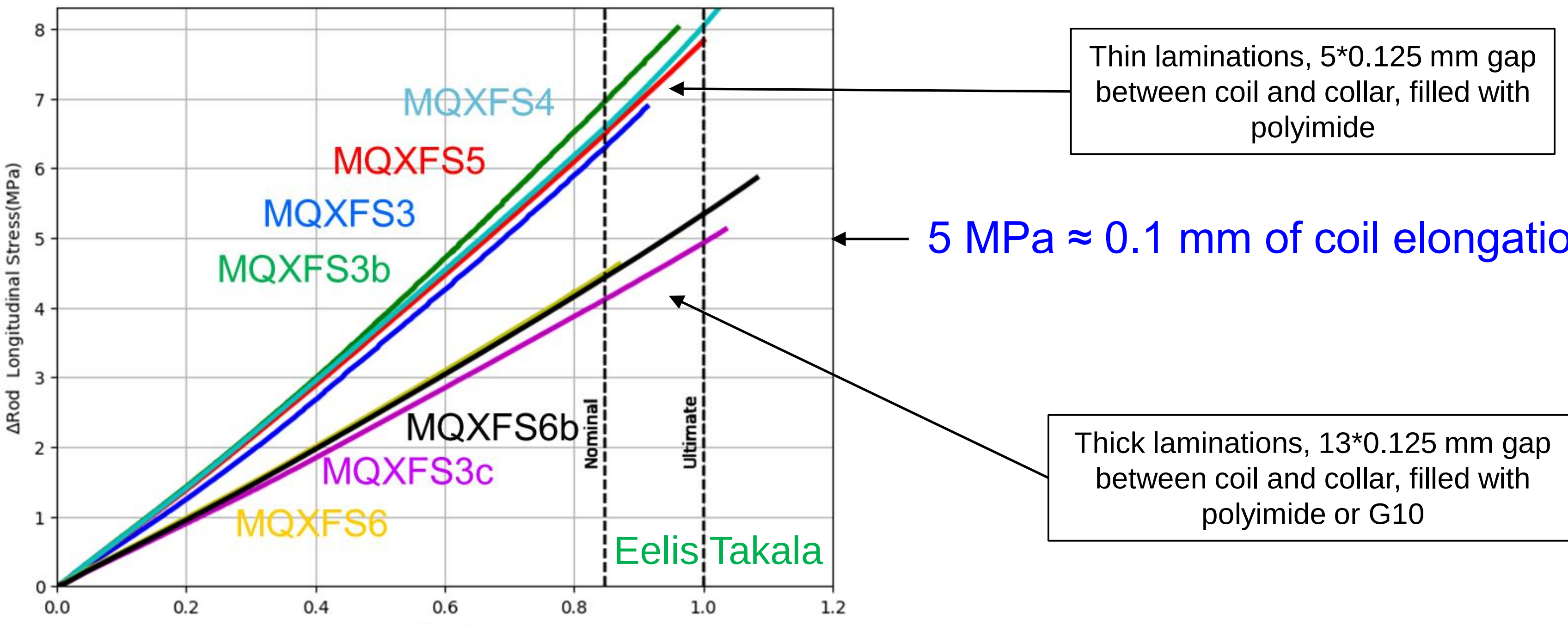
- The model accurately predicts the impact of cool down
- All the four rods are well balanced (+- 30 μstrain to +-100 μstrain for all the tested magnets, both at warm and cold).
- Very consistent behavior in all magnets.



	Rod Strain [με]			Rod Stress [MPa]			Rod Elongation [mm]			Total Force [MN]		
	RT	1.9 K	Δ	RT	1.9 K	Δ	RT	1.9 K	Δ	RT	1.9 K	Δ
MQXFS3	823	2120	1297	58	167	110	1.28	3.29	2.01	0.23	0.68	0.45
MQXFS3b	2492	3576	1084	174	283	108	3.86	5.54	1.68	0.71	1.15	0.44
MQXFS3c	2028	3265	1237	142	258	116	3.14	5.06	1.92	0.58	1.05	0.47
MQXFS4	2427	3818	1391	170	302	132	3.76	5.92	2.16	0.69	1.23	0.54
MQXFS5	2354	3696	1342	165	292	127	3.65	5.73	2.08	0.67	1.19	0.52
MQXFS6	2443	3728	1285	171	295	124	3.79	5.78	1.99	0.70	1.20	0.50
Average Δ Cool Down	1273			119			1.97			0.49		
STD Δ Cool Down	97			9			0.15			0.04		
Max-Min Δ Cool Down	307			24			0.48			0.10		

MQXFS – Experience from short magnets

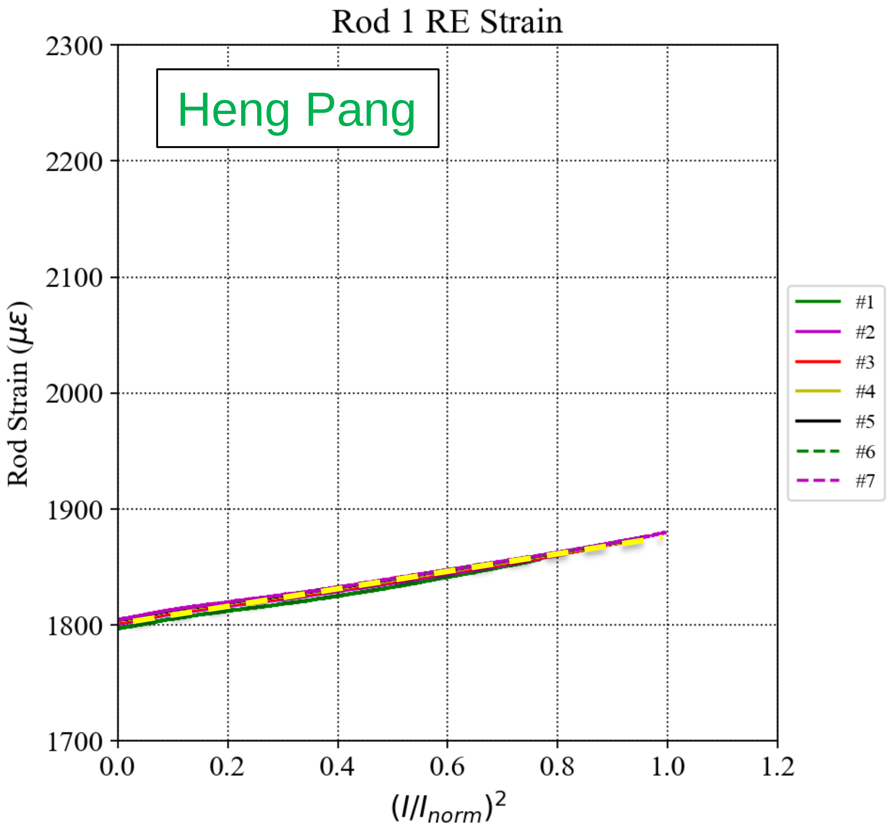
- As expected from the model, the rods only see 2 % for the electromagnetic forces during powering
- Small differences observed in between the two types of structures:
  - Structure 1&2 (thick laminations, large gap coil to collar): 1.4 % of F_{emz} in the rods, 0.16 friction coefficient needed to match the measurements
  - Structure 3 (thin laminations, small gap coil to collar): 2.2 % of F_{emz} in the rods, 0.13 friction coefficient needed to match the measurements
- Measurements confirm that coil elongation is independent of the pre-load level, since it depends on the system stiffness. The effect of the pre-load is to increase the contact pressure coil to pole in the end region.



G. Vallone, et. al., Mechanical analysis of the short model magnets for the Nb_3Sn low-beta quadrupole MQXF, *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, 2016.

MQXFA Experience

- In the first MQXFA magnets (MQXFAP01/01b and MQXAP02), issues with the readings of the SG rods.
- MQXFA03 is the first magnet with reliable measurements:
  - The change of the rod strain during powering to nominal is less than 100 με
  - The four rods have the same behavior → good balance among the rods.



Delta in the rods during powering from 0 to I_{nom}

	Rod Strain [με]	Rod Stress [MPa]	Force [MN]	% of F_{em} at I_{nom}	Rod elongation [mm]
MQXFS	75	6	0.02	2	0.12
MQXFA	80	17	0.05	4	0.37

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- Few other 3D features in MQXF
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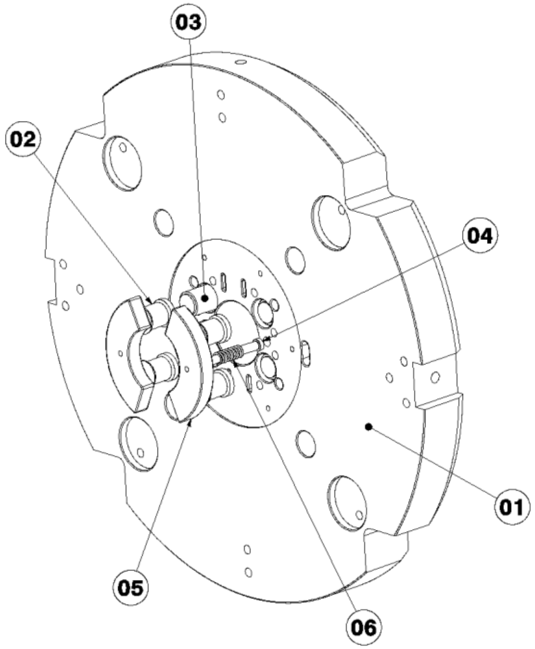
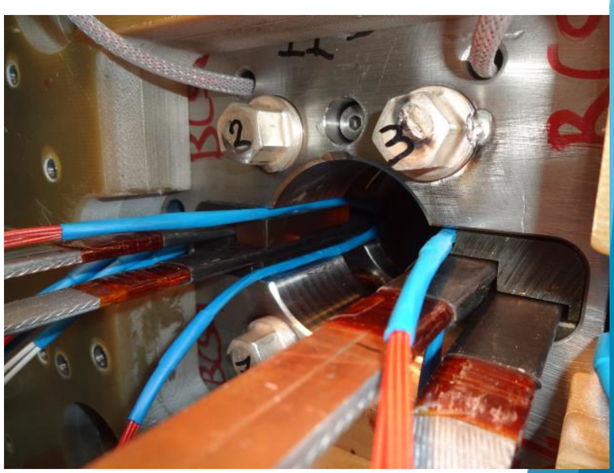
11 T Longitudinal Assembly

- Slight pre-load at room temperature, to guarantee that there is still contact coil to end plate at 1.9 K.
- Goal: limit the coil displacements providing a rigid lateral support
- 1in1 models:
  - 43 mm thick end-plate, 12 mm stainless steel shell.
- 2in1 models:
  - 75 mm thick end-plate, 15 mm stainless steel shell.

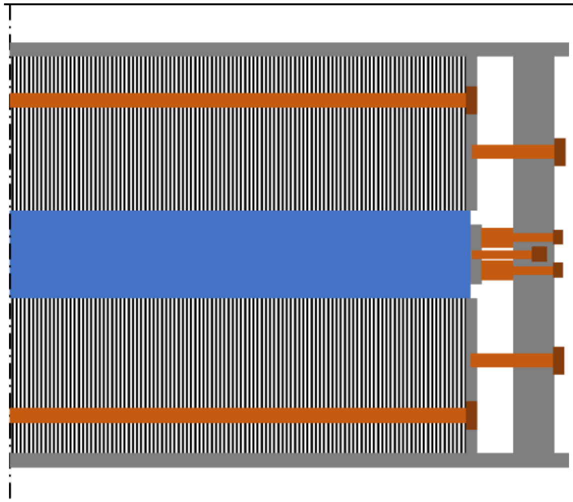




11 T Longitudinal Assembly – Short models

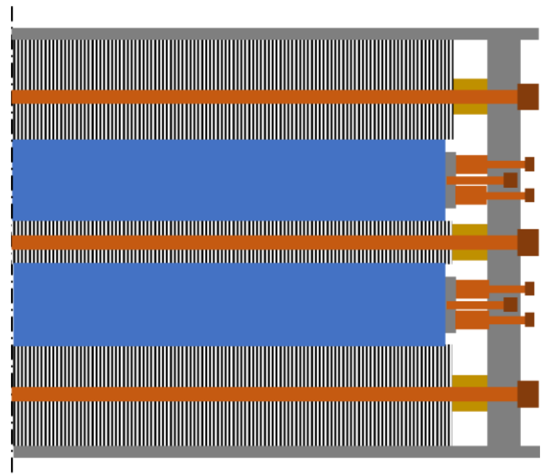
- Details on the longitudinal assembly of 11 T short model are different.
  - The thinking is that these rods have a negligible impact on the longitudinal stiffness of the assembly, but it would be good to verify through FE.

Single aperture (SP10X)



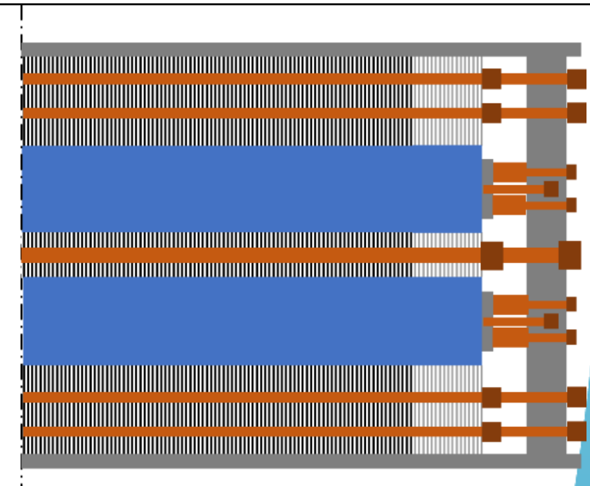
100 % packing factor of the yokes
43 mm thick SS end-plate
12 mm SS shell.
4x 35/M24 mm rods end yoke through yoke
4x M20 mm screws end plate to end yoke
Yoke OD = 510 mm

1st Double Aperture (DP101)



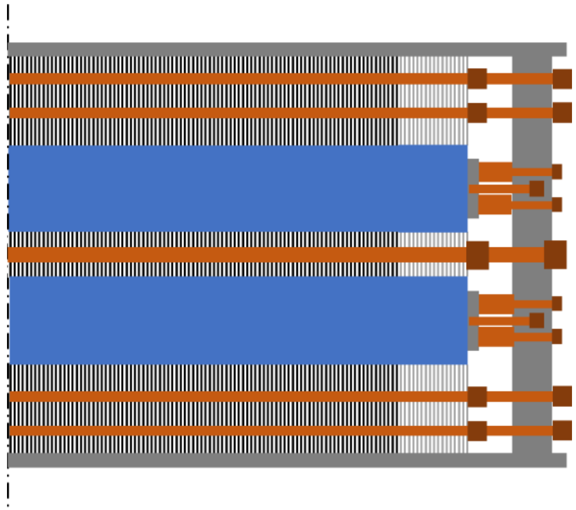
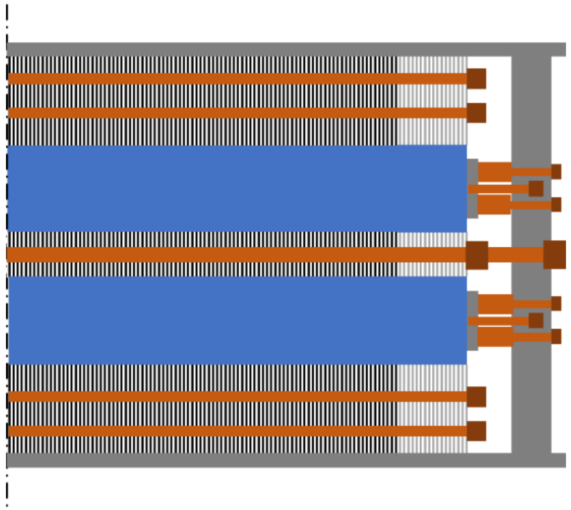
98 % packing factor (washers between laminations)
75 mm thick SS end-plate
15 mm SS shell.
4x 32/M24 mm rods end plate through the external yoke
2x 25/M24 mm rods end plate through the yoke between apertures
Yoke OD = 550 mm

2nd&3th Double Aperture (DP102&DP201)



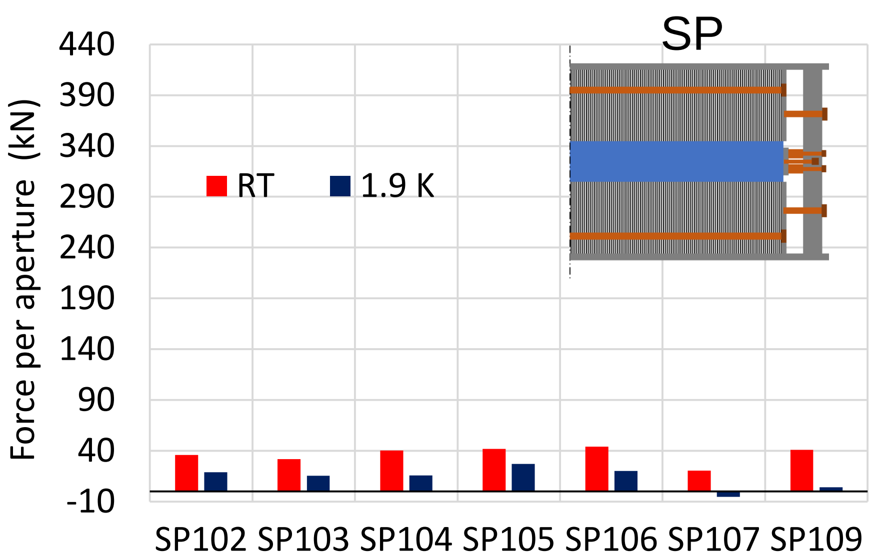
98 % packing factor (laminations bended)
75 mm thick SS end-plate
15 mm SS shell.
8x 12/M12 mm rods end plate through the external yoke
2x 25/M24 mm rods end plate through the yoke between apertures
Yoke OD = 540 mm
Non-magnetic laminations in the ends.

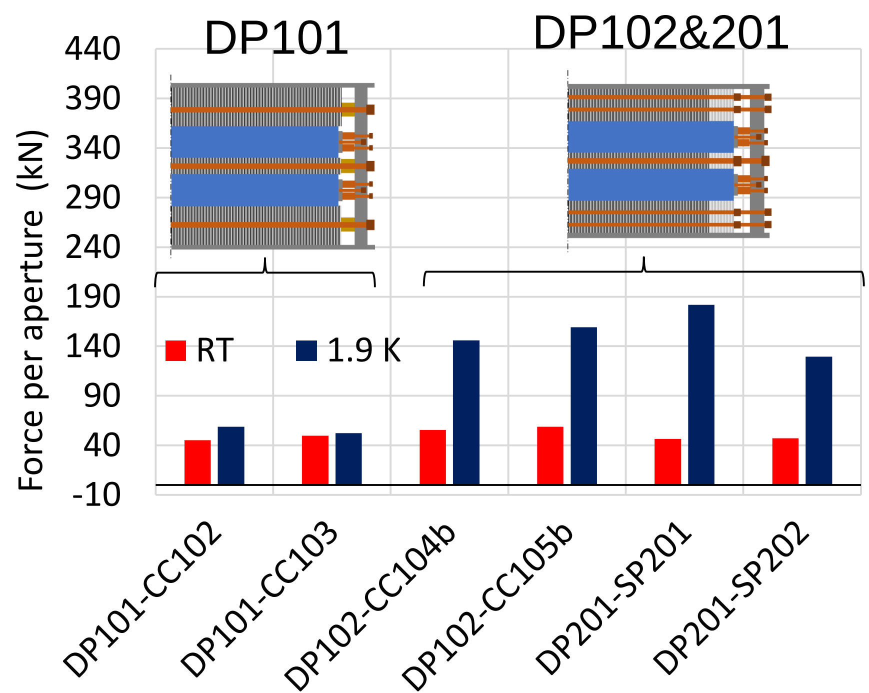
11 T longitudinal assembly – From short to long magnets

2^{nd}&3^{th} Double Aperture Short Models (DP102&DP201)	Series magnets
	
98 % packing factor (laminations bended) 75 mm thick SS end-plate 15 mm SS shell. 8x 12/M12 mm rods end plate through the external yoke 2x 25/M24 mm rods end plate through the yoke between apertures Yoke OD = 540 mm Non-magnetic laminations in the ends.	98 % packing factor (laminations bended) 75 mm thick SS end-plate 15 mm SS shell. 8x 12/M12 mm rods through the external yoke 2x 25/M24 mm rods end plate through the yoke between apertures Yoke OD = 540 mm Non-magnetic laminations in the ends.

11 T : Experience from short models

- Bullets are loaded at RT with 20-60 kN/aperture, which corresponds to less than 10 % of the Lorentz forces at nominal current (440 kN/aperture).
- During cool down, very different behavior in single and double aperture magnets.
  - In the single aperture, we loose most of the applied pre-load
  - In the first double aperture design, ≈ same after cool down
  - In the final double aperture design, significant increase of the load in the bullets during cool down (+ 80-140 kN/aperture, i.e., 25 % of the Lorentz forces at nominal).
- The reason for the different behaviour is not understood yet.

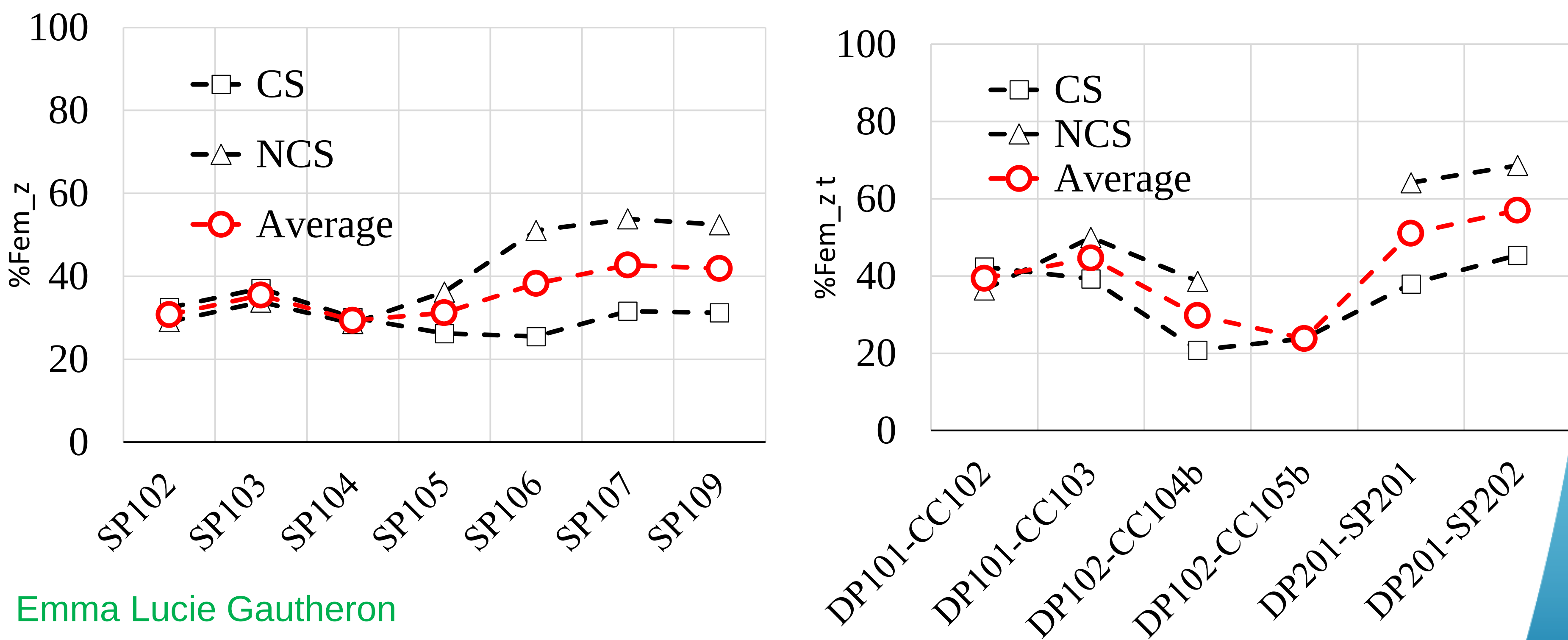




11 T : Experience from short models

- During powering, similar behavior in all magnets → 30-60 % of the electromagnetic forces are transferred to the bullets
  - One order of magnitude larger than MQXF case (2 % in MQXFS, 4 % in MQXFA)

Force transferred to the bullets during powering



Emma Lucie Gautheron

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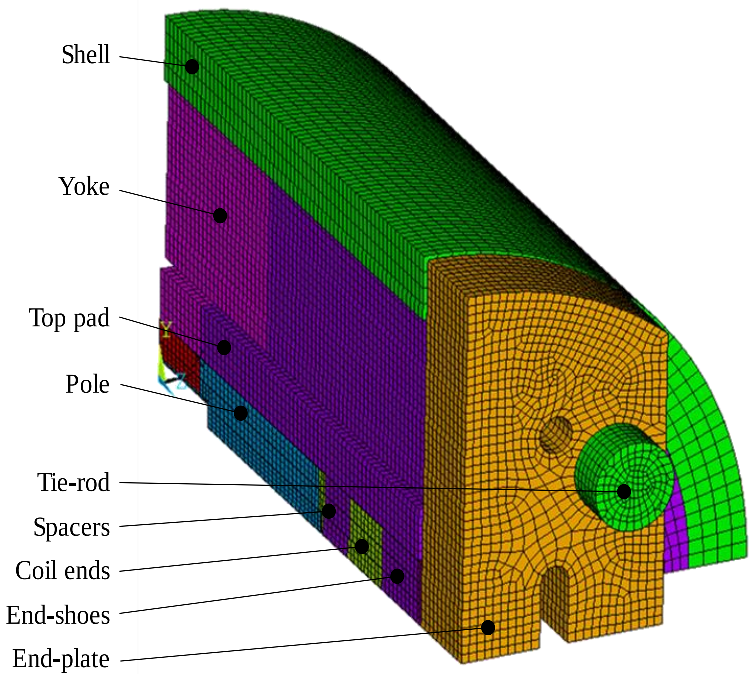
RMM: Longitudinal stiffness

- The optimization was guided by designing a system as rigid as possible:
  - Rods for longitudinal loading shall be as close as possible to the coil to minimize bending of the end plate (becomes hard in blocks coil if when one needs to leave the space for the flared ends).



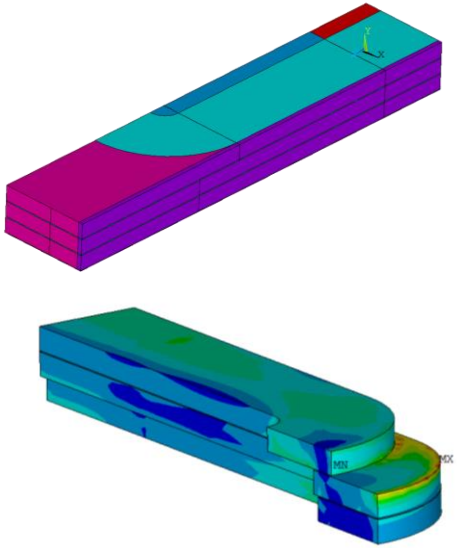
	11 T	MQXFS – Al rods	RMM-Al rods	RMM-SS rods
e.m. force per aperture at nominal field [MN]	0.44	1.2	2.4	
Coil length [mm]	1.6	1.1	0.97	
Magnet length [mm]	2	1.55	1.5	
Rod diameter [mm]	n.a.	36	64	
End-plate thickness [mm]	43	75	100	
Coil Stiffness [MN/mm]	1.40	1.10	4.06	4.06
Rod Stiffness [MN/mm]	n.a.	0.21	0.78	2.08
Coil elongation				
No friction, no rods [mm]	0.31	1.09	0.59	
No friction, rods* [mm]	n.a.	0.92	0.51	0.41

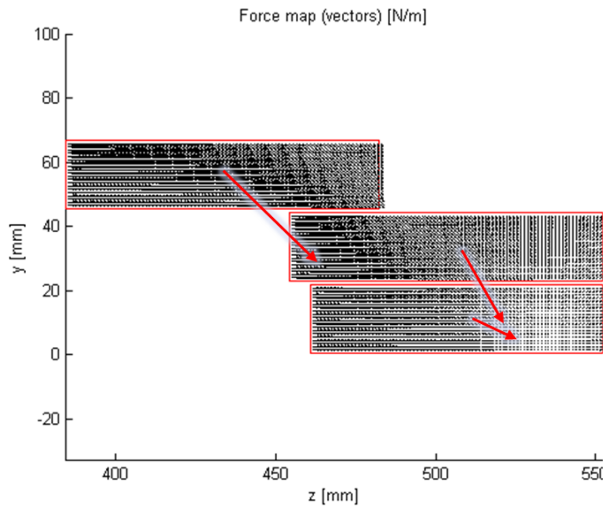
*Assuming infinitely rigid end-plate

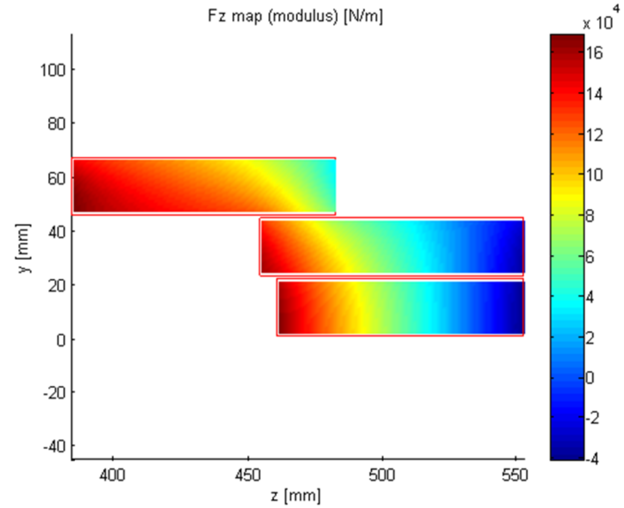
RMM – Coil end design

- First coil design:
  - G11 end saddles
  - Shifted layers without end spacer, since you can decrease the field without the complexity of adding end parts
  - Drawback: large unbalance of the forces in the coil ends.

	Fy		Fz	
layer	**[kN]**	**[MN/m]**	**[kN]**	**[MN/m]**
3	-350	-55.5	**362**	**204**
2	-280	-69.6	158	96.5
1	-80	-20.1	168	96.8



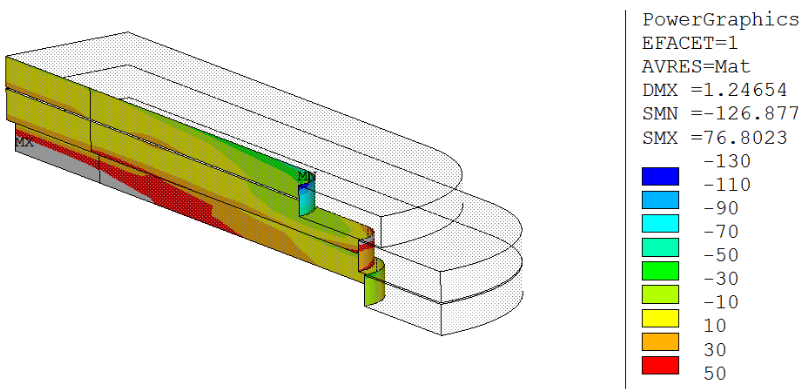




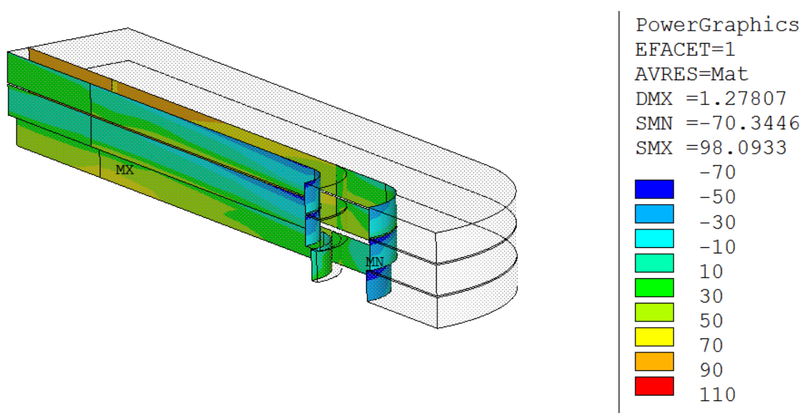
RMM – Coil end design

- Final design:
  - The handling of the longitudinal forces was found as a showstopper for the shifted layers solutions → moved to the traditional solution of aligned blocks with end spacers.
  - Stainless steel end saddles instead of G11 to limit the coil displacement in the coil ends during powering.

<u>*Shifted layers*</u>



<u>*Aligned layers*</u>

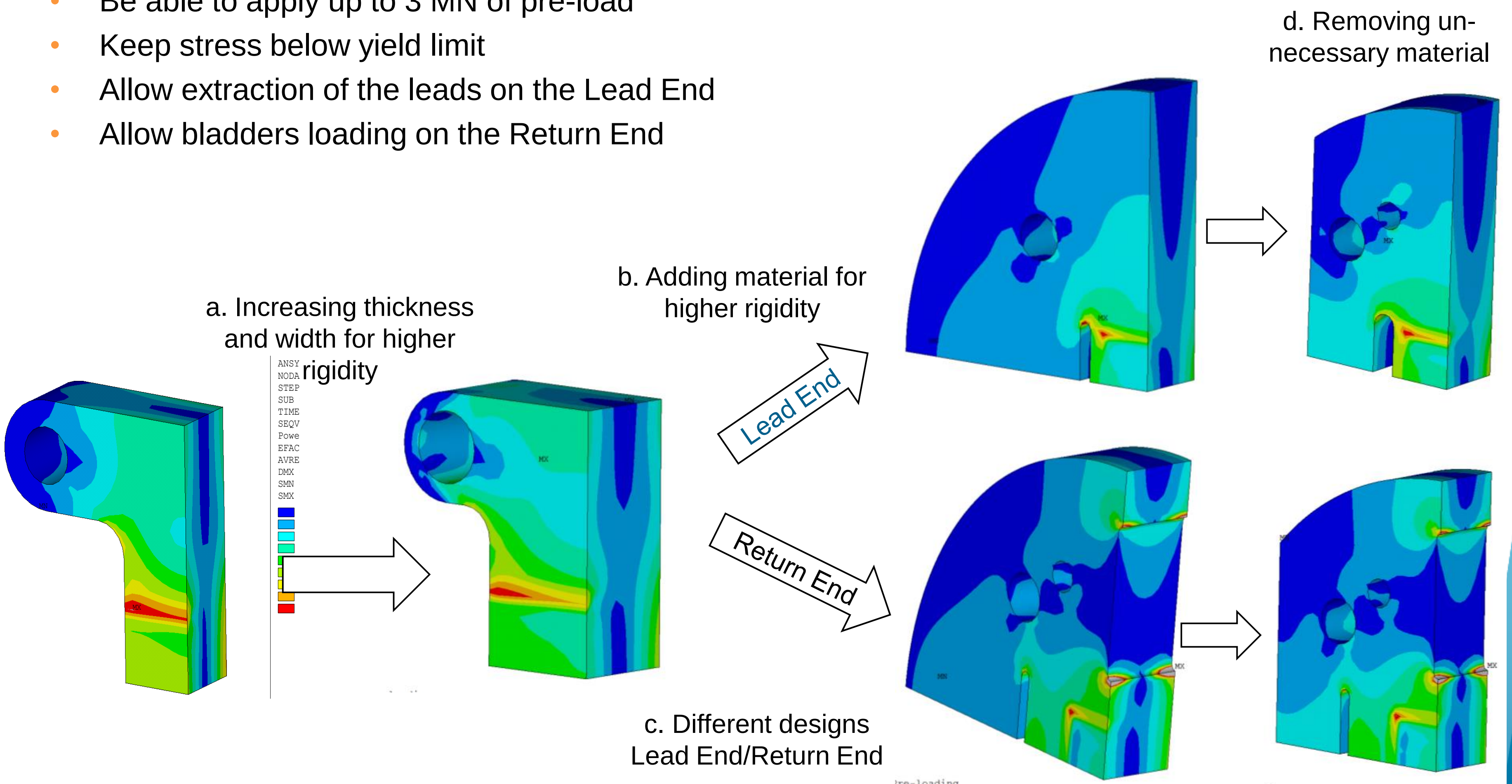


https://indico.cern.ch/event/610114/

RMM: End-plate design

Goals:

- Provide enough rigidity to the system, limiting coil displacements
- Be able to apply up to 3 MN of pre-load
- Keep stress below yield limit
- Allow extraction of the leads on the Lead End
- Allow bladders loading on the Return End



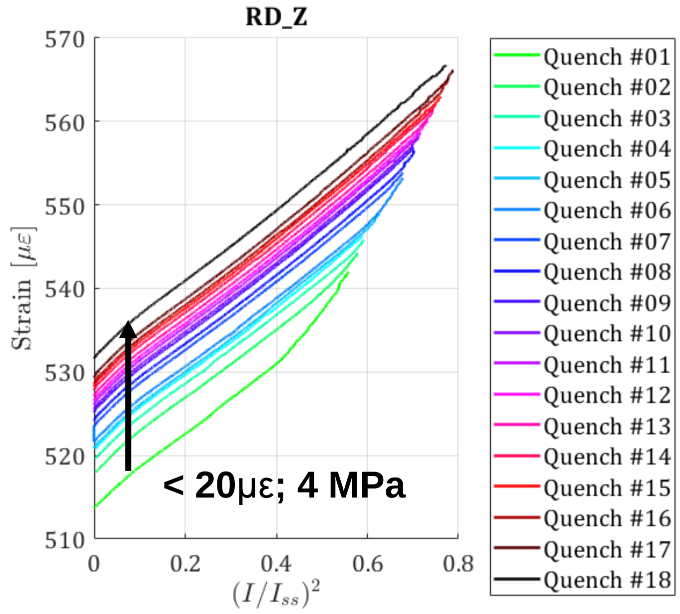
eRMC – Feedback from experience

- eRMC1a was assembled with stainless steel rods.
- Target pre-load level: 60 MPa in the rods at RT (50 % F_{em} @ 16 T),80 MPa at 1.9 K (70 % F_{em} @ 16 T),
- As in all the rest of magnets loaded longitudinally with this concept, good fitting between measured and FEA.

- The model (including friction) predicts 10 % of electromagnetic forces going to the rods, very consistent with measurements.

Delta in the rods during powering from 0 to 16 T

	Rod Strain [με]	Rod Stress [MPa]	Force [MN]	% of F_{em} at I_{nom}	Rod elongation [mm]
eRMC	35	6	0.02	10	0.12



Assembly report EDMS 2333771

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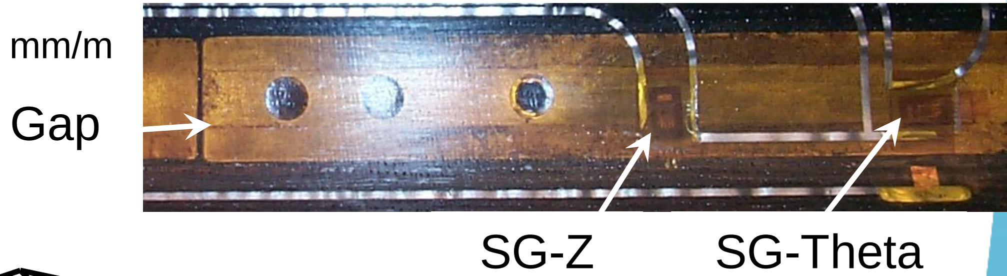
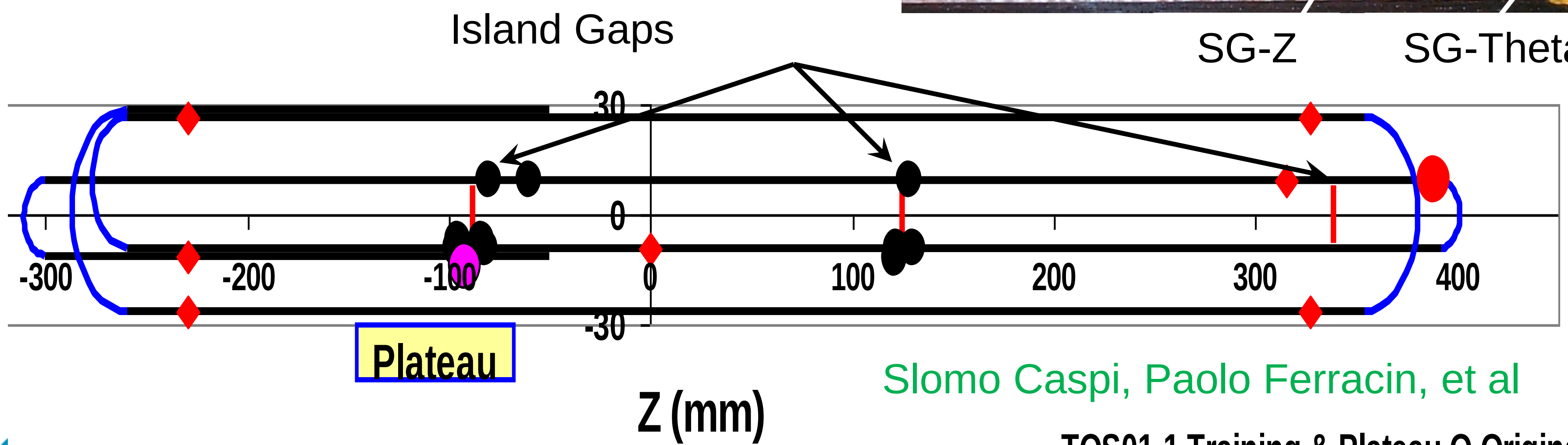
Conductor axial strain

- Thermal contraction from RT/1.9 K among coil and pole/wedges play a role on the axial strain. The coil contracts ≈ 3-4 mm/m longitudinally.
- Typical materials we use:
  - Pole:
    - Bronze (HD1/TQ times): 3.2 mm/m --> magnet performance limited in the pole transitions.
    - Titanium (HQ, MQXF, 11 T…): 1.7 mm/m
    - Iron (FRESCA2): 2 mm/m
  - Wedges:
    - Bronze (MQXF AUP): 3.2 mm/m
    - ODS Copper (11T, MQXF CERN): 3.5 mm/m
    - Stainless steel (FNAL): 2.8 mm/m



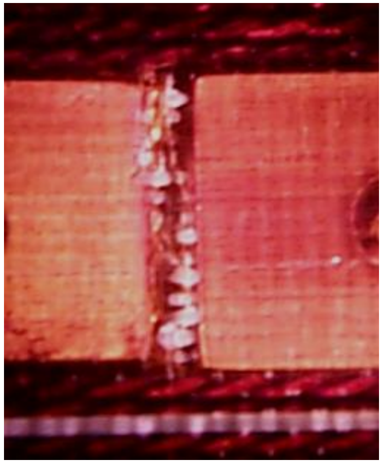


Slomo Caspi, Paolo Ferracin, et al

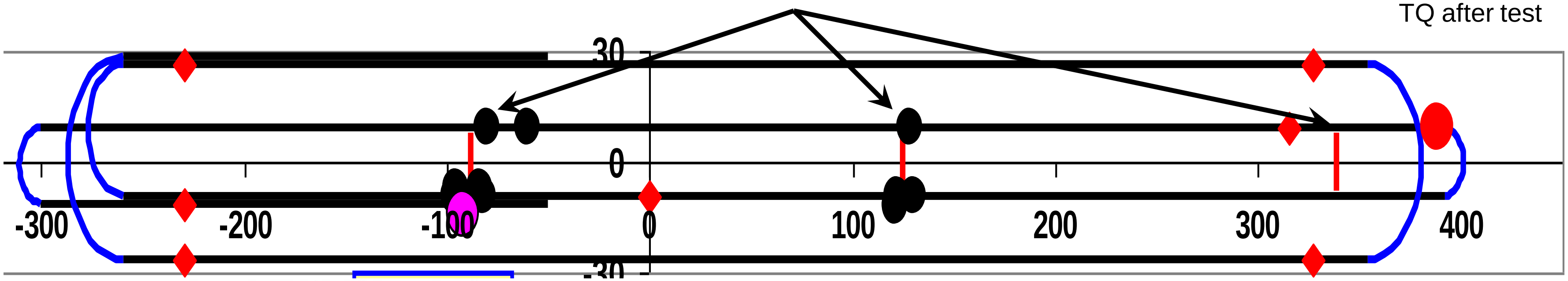
TQS01-1 Training & Plateau Q-Origins

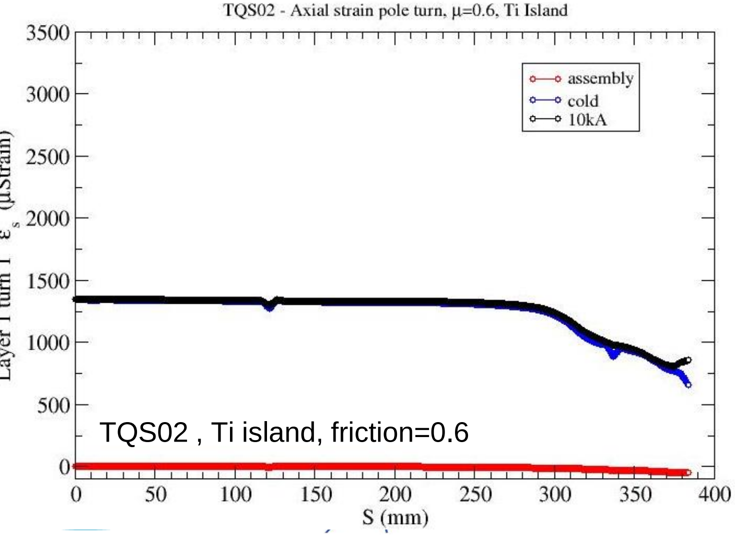
Conductor axial strain

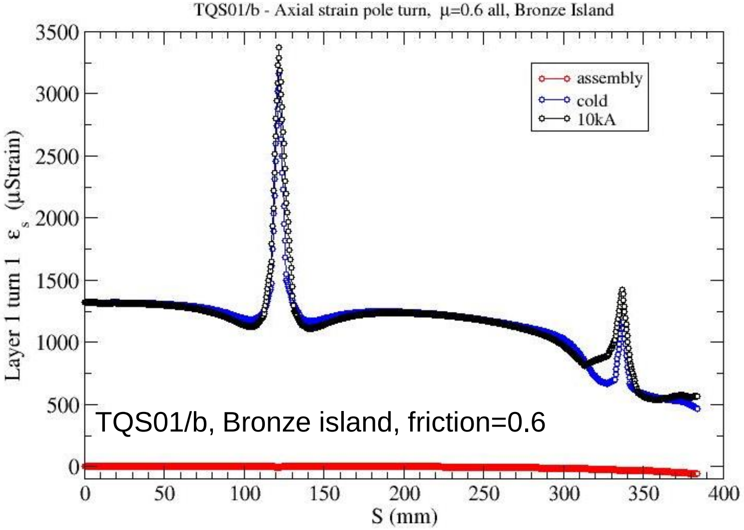
- Axial tension in bronze islands, a source of localize strain near gaps (after cold tests, sign of delamination in that region)
- Based on simulations, this effect disappears when using titanium pole.



TQ after test







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

Slomo Caspi, Paolo Ferracin, et al

Aluminum Shell Segmentation

- Shell shrinks more than the yoke, friction limits the shell contractions
- Strain at 4.5 K consistent with 0.2 friction model results
- During excitation e.m. forces induced slippage.
- This was studied in LRS (long racetrack quadrupole).
  - In LRS01 High axial tension, with sudden slippages over the course of the test, and variations in azimuthal strain were recorded by gauges mounted on the shell

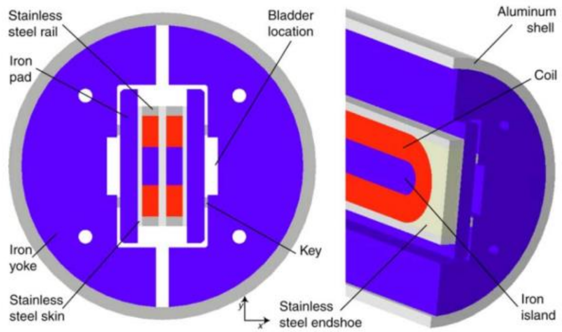
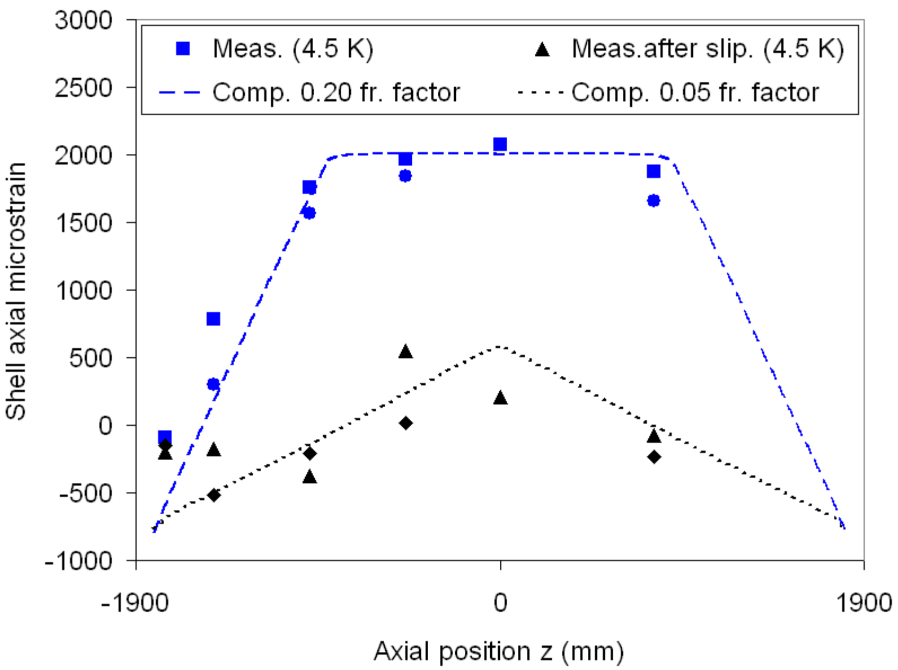


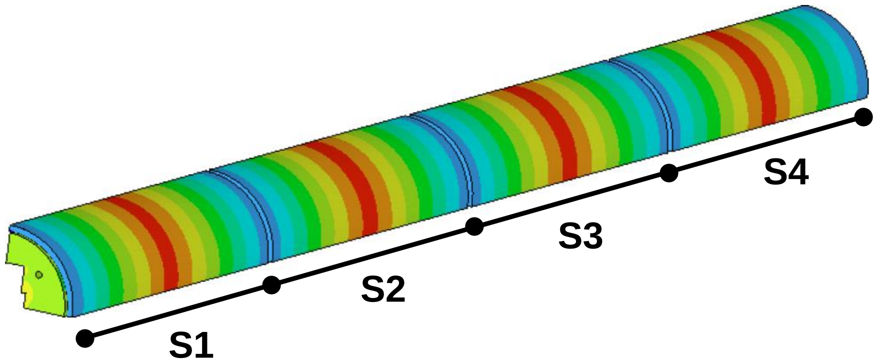
Fig. 1. LRS01 cross section (left) and end design (right).

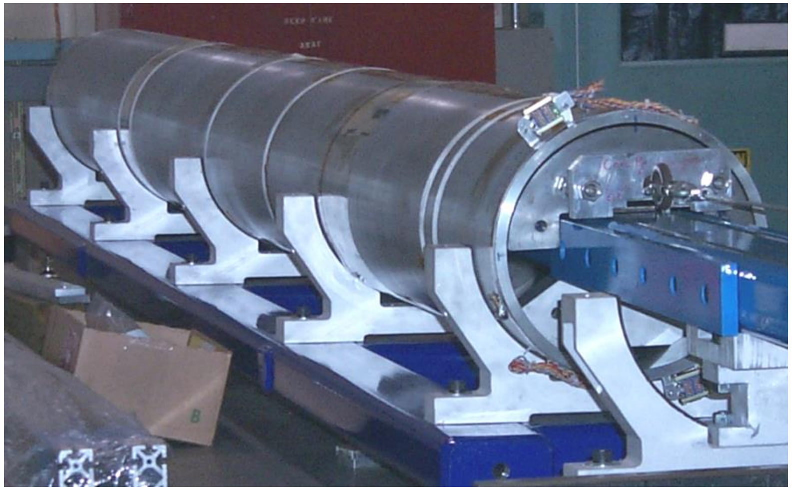


P. Ferracin , Assembly and Test of a Support Structure for 3.6 m Long Nb3Sn Racetrack Coils IEEE Transactions on Applied Superconductivity Year: 2008 | Volume: 18, Issue: 2

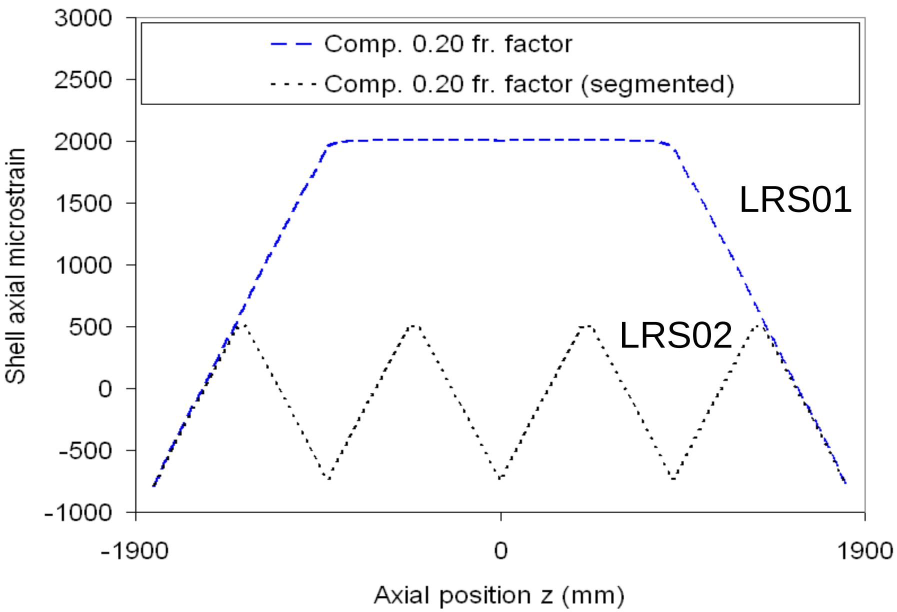
Aluminum Shell Segmentation

- Shell was divided in 4 segments
- No axial strain accumulation
- Required for very long shells
- Factor of 2 improved homogeneity
- Increased field and no slippage
- 96% SSL with minimal training
  - LRS01 reached 91 % of SSL





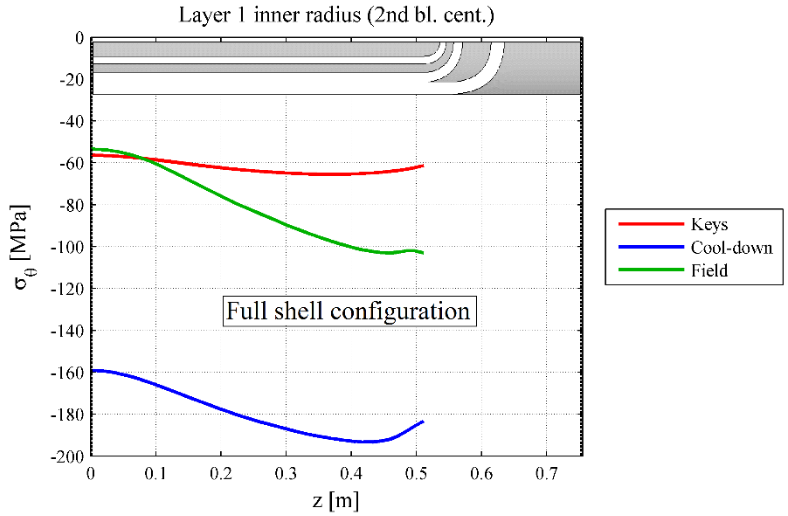
Structure re-assembly with segmented shell

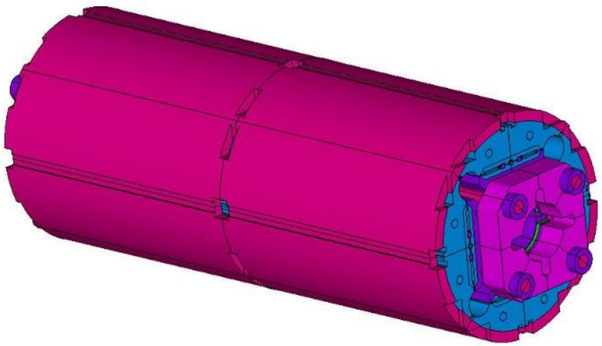


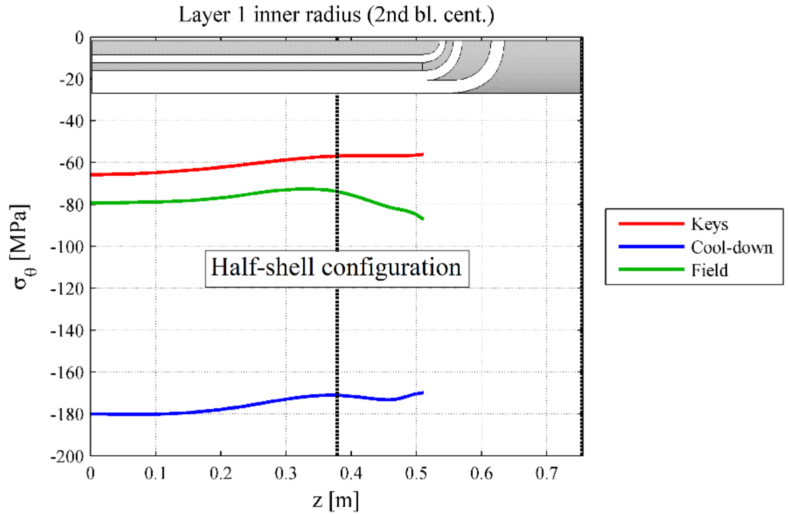
Joseph F. Muratore , Test Results of LARP 3.6 m Nb3Sn Racetrack Coils Supported by Full-Length and Segmented Shell Structures, IEEE Transactions on Applied Superconductivity, 2009 | Volume: 19, Issue: 3

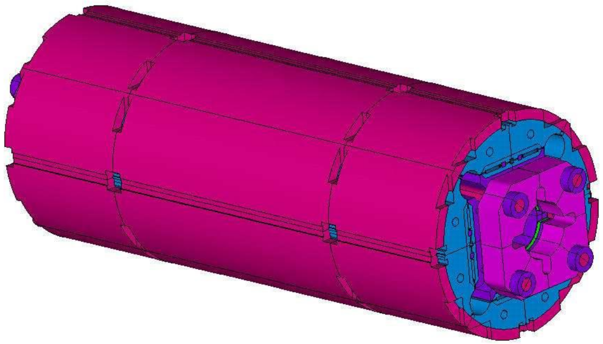
Aluminum Shell in MQXF

- In order to smooth the stress in the coil ends, the aluminum shell is half length in the extremities.









Summary

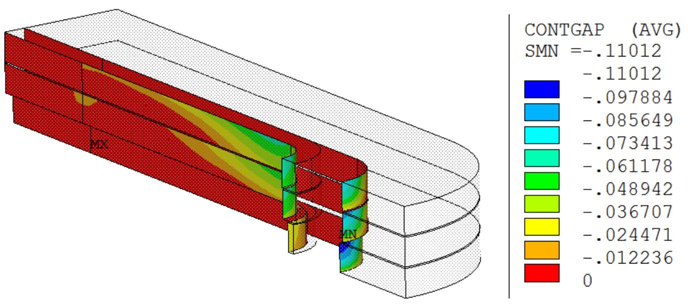
- 'Two schools' in terms of longitudinal support, with no consensus on the magnet community:
  - Limit the coil displacements due to electromagnetic forces by having a rigid structure in the longitudinal direction (11 T concept, end-plate welded to the shell)
  - Limit the coil displacements due to electromagnetic forces by having a rigid structure in the longitudinal direction and pre-load coil ends to compensate the axial forces and keep coil end turns under compression (MQXF concept, axial plate and pre-loaded rods)
- Understanding the 3D mechanical state of SC magnets is complex and requires a dedicate effort → modeling and measurements have to go together.
- We have a good understanding of the end-plate-rods system, developed within LARP, tested up to 4.5 m length magnets. In the coming weeks we will have the first results for 7.5 m length magnet.

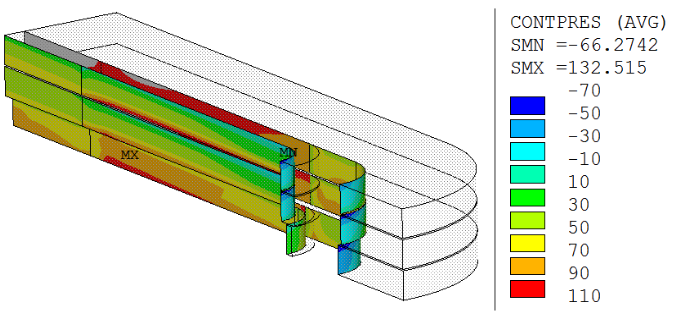
HiLumi
HL-LHC PROJECT

CERN

RMM: coil-pole contact

- Main difficulty on the end design: keep the pole turn under compression during powering.
  - Only 20% of the pre-load force applied in the rod reaches the coil-pole contact (assuming a friction coefficient of 0.2)

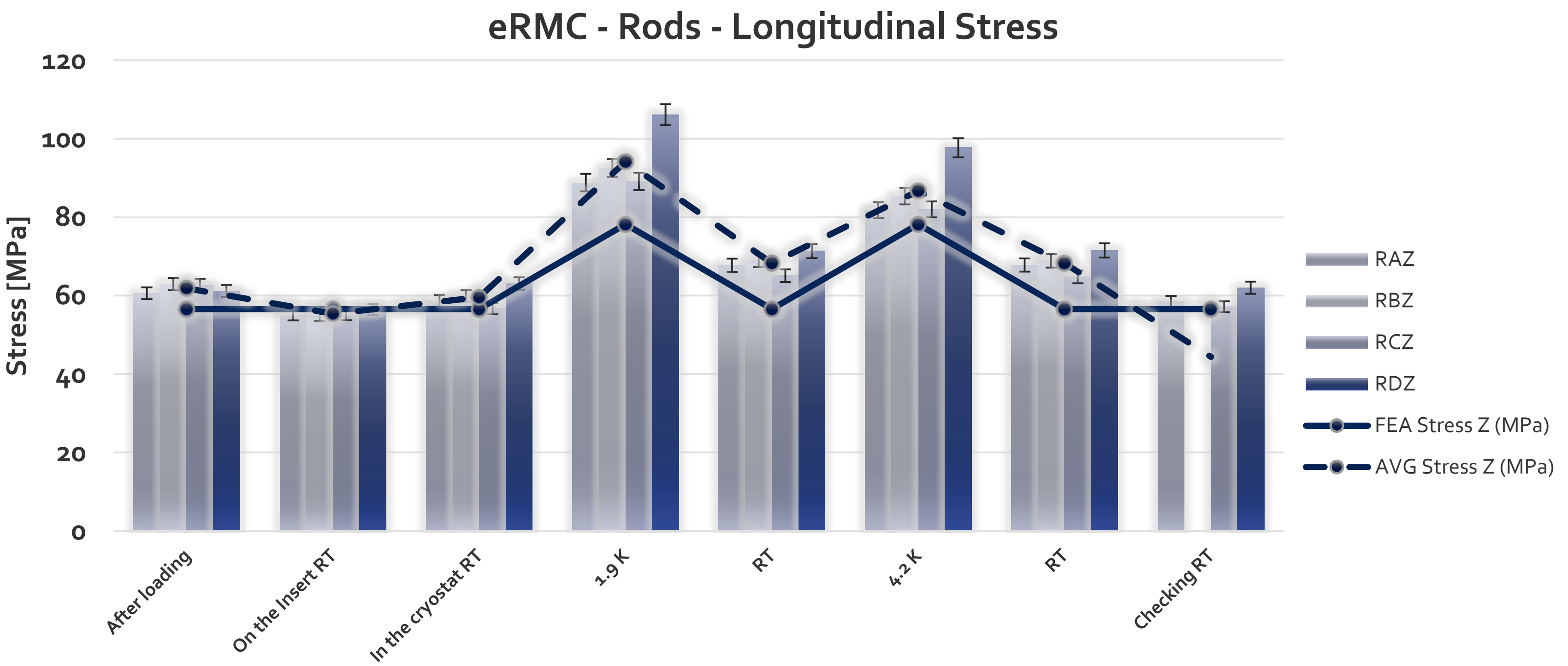




	Rod Pre-load F_z	Rod Cool-Down F_z	Energization	
	[% L. F.]*	[% L. F.]*	Max. Tension [MPa]	Max. Gap [μm]
16 T	14	76	64	106
18 T	11	56	90	135
16 T	32	100	56	94
18 T	24	75	80	133
16 T	72	139	46	76
18 T	53	104	77	110
16 T	97	167	40	62
18 T	72	125	72	99
16 T	135	208	30	44
18 T	100	155	66	85

eRMC – Feedback from experience

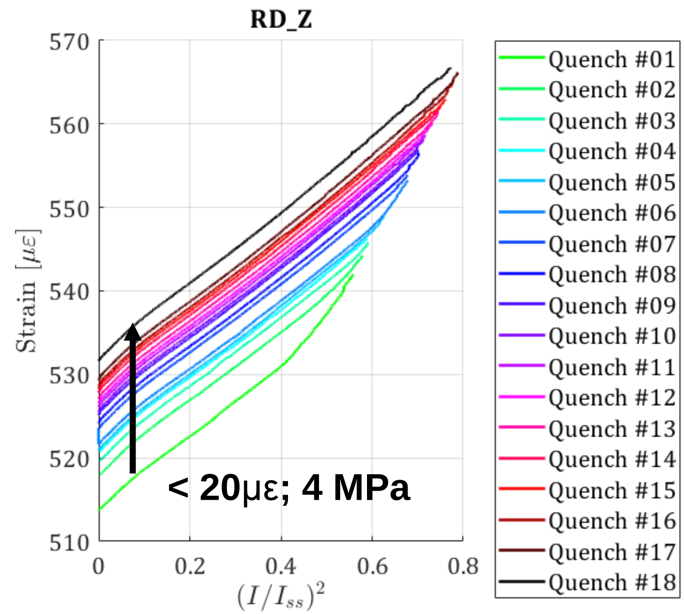
- eRMC1a was assembled with stainless steel rods.
- Target pre-load level: 60 MPa in the rods at RT (50 % F_{em} @ 16 T),80 MPa at 1.9 K (70 % F_{em} @ 16 T),
- As in all the rest of magnets loaded longitudinally with this concept, good fitting between measured and FEA (specially in the second thermal cycle)



Assembly report EDMS 2333771

eRMC – Feedback from experience

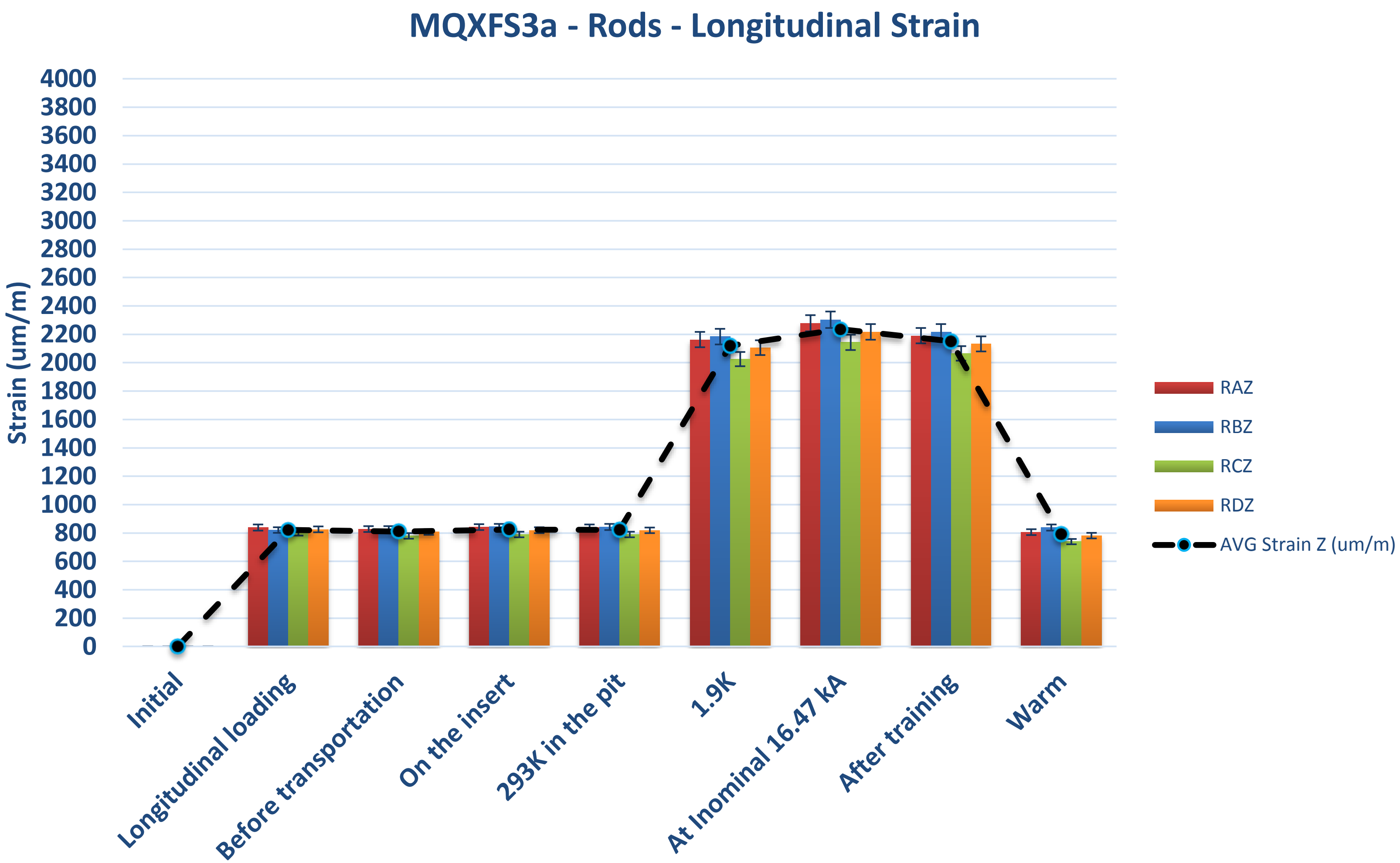
- The model (including friction) predicts 10 % of electromagnetic forces going to the rods, very consistent with measurements.
- Small ratcheting effect observed during training, also very common in all the magnets with this kind of structure, studied in the past [1].

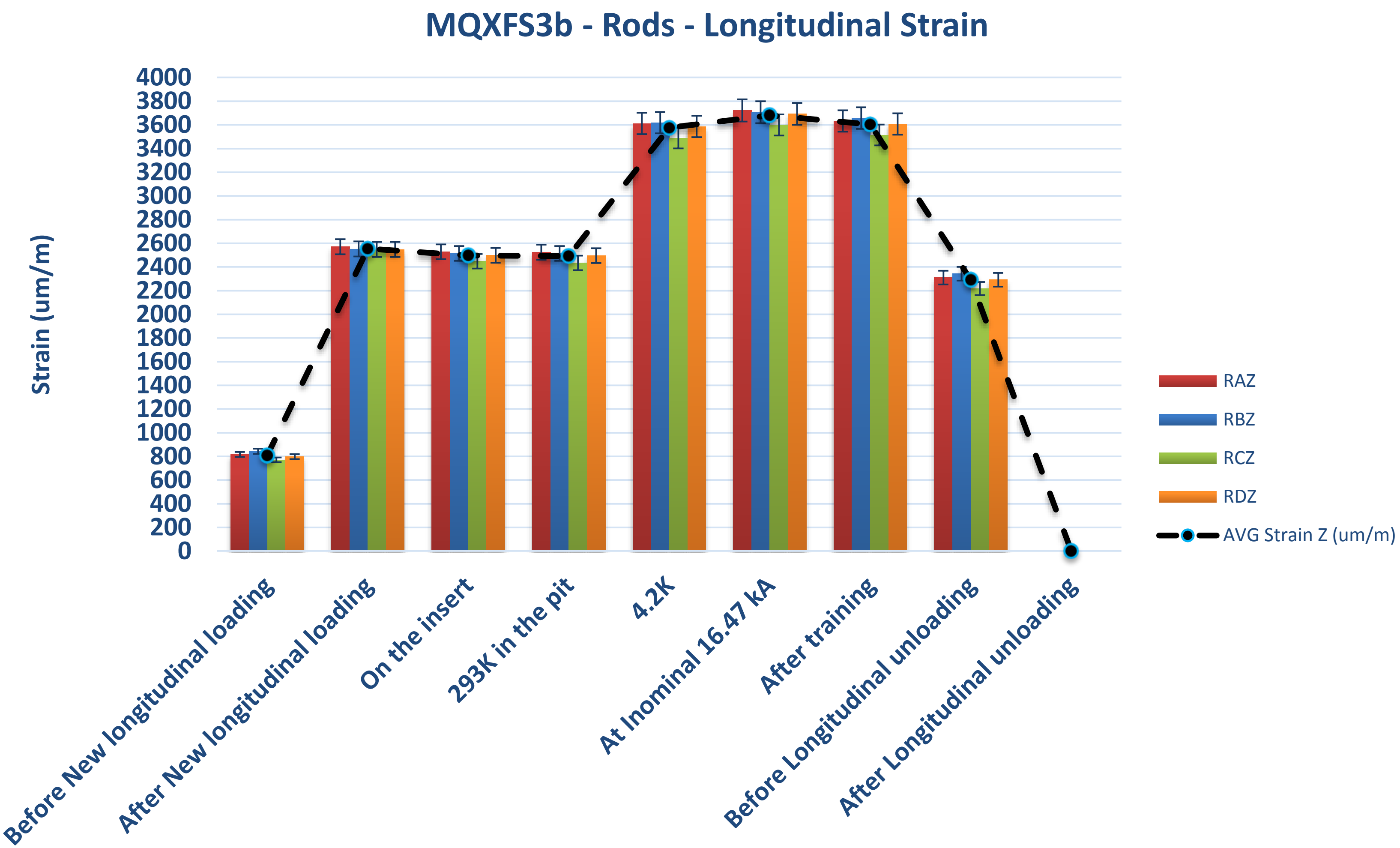


Delta in the rods during powering from 0 to 16 T

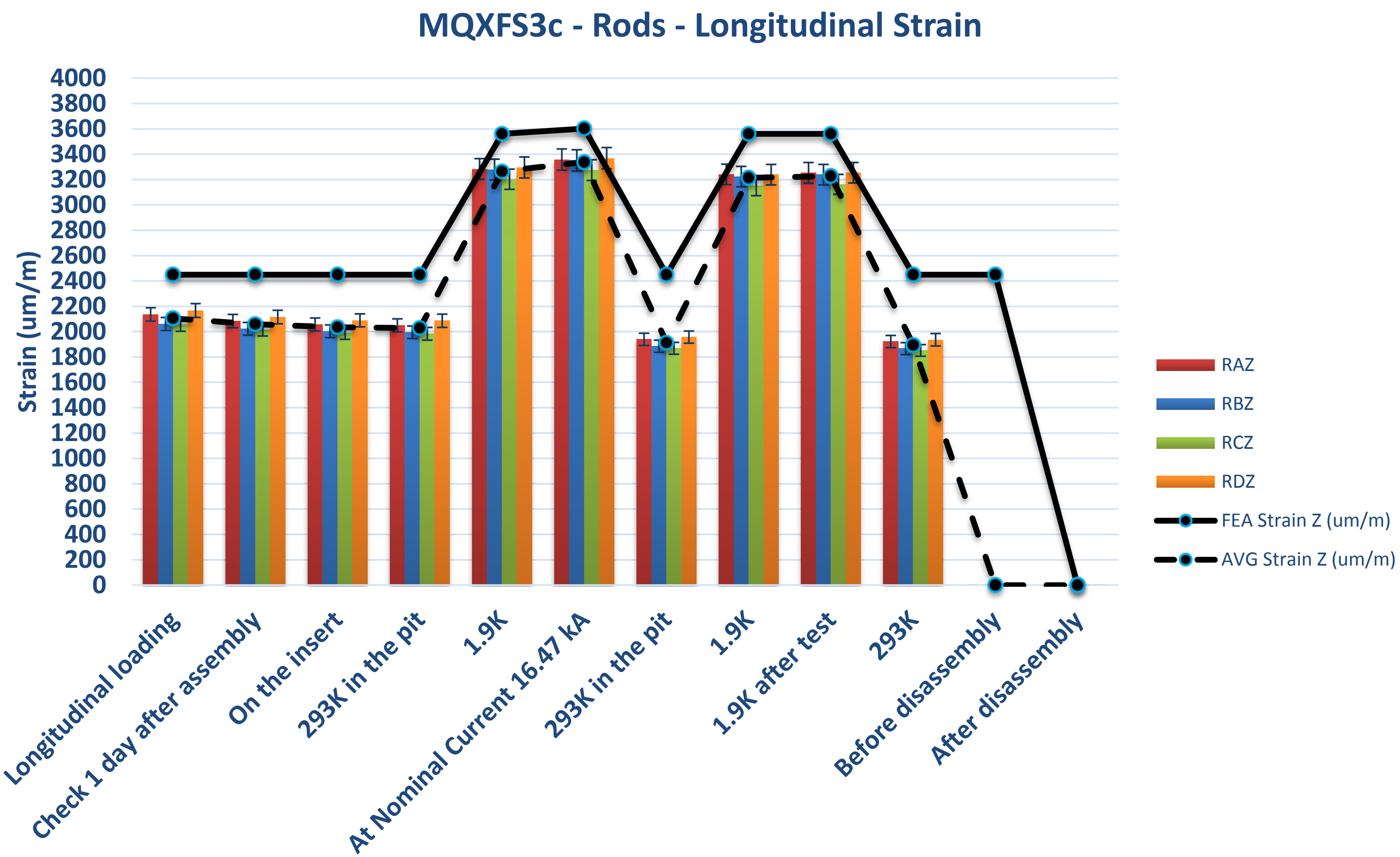
	Rod Strain [με]	Rod Stress [MPa]	Force [MN]	% of F_{em} at I_{nom}	Rod elongation [mm]
eRMC	35	6	0.02	10	0.12

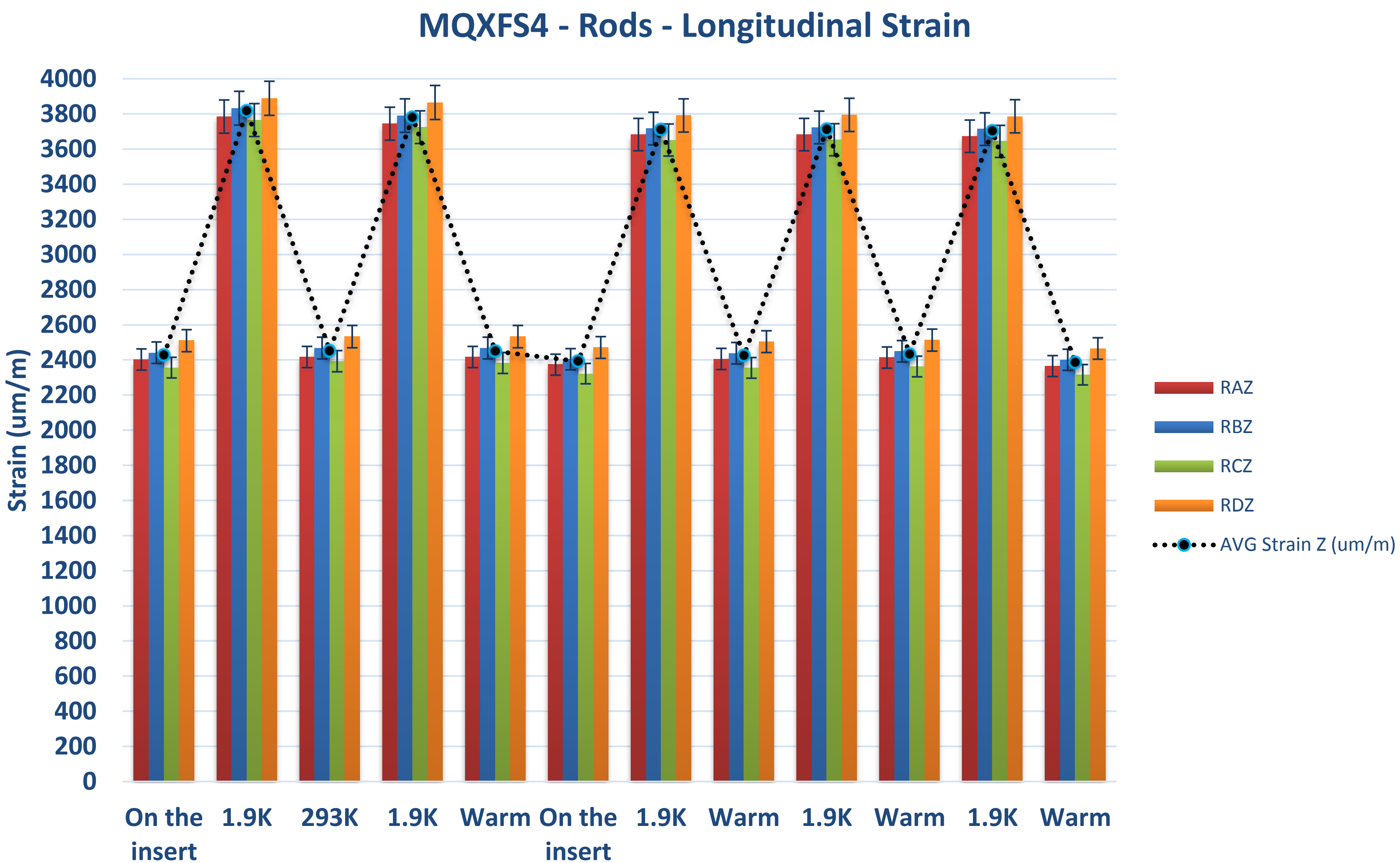
[1] P. Ferracin, S. Caspi, and A. F. Lietzke *"Towards Computing Ratcheting and Training in Superconducting Magnets"* *IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 17, NO. 2, JUNE 2007*


MQXFS3a - Rods - Longitudinal Strain
Strain (um/m)
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Initial
Longitudinal loading
Before transportation
On the insert
293K in the pit
1.9K
At Inominal 16.47 kA
After training
Warm
RAZ
RBZ
RCZ
RDZ
AVG Strain Z (um/m)



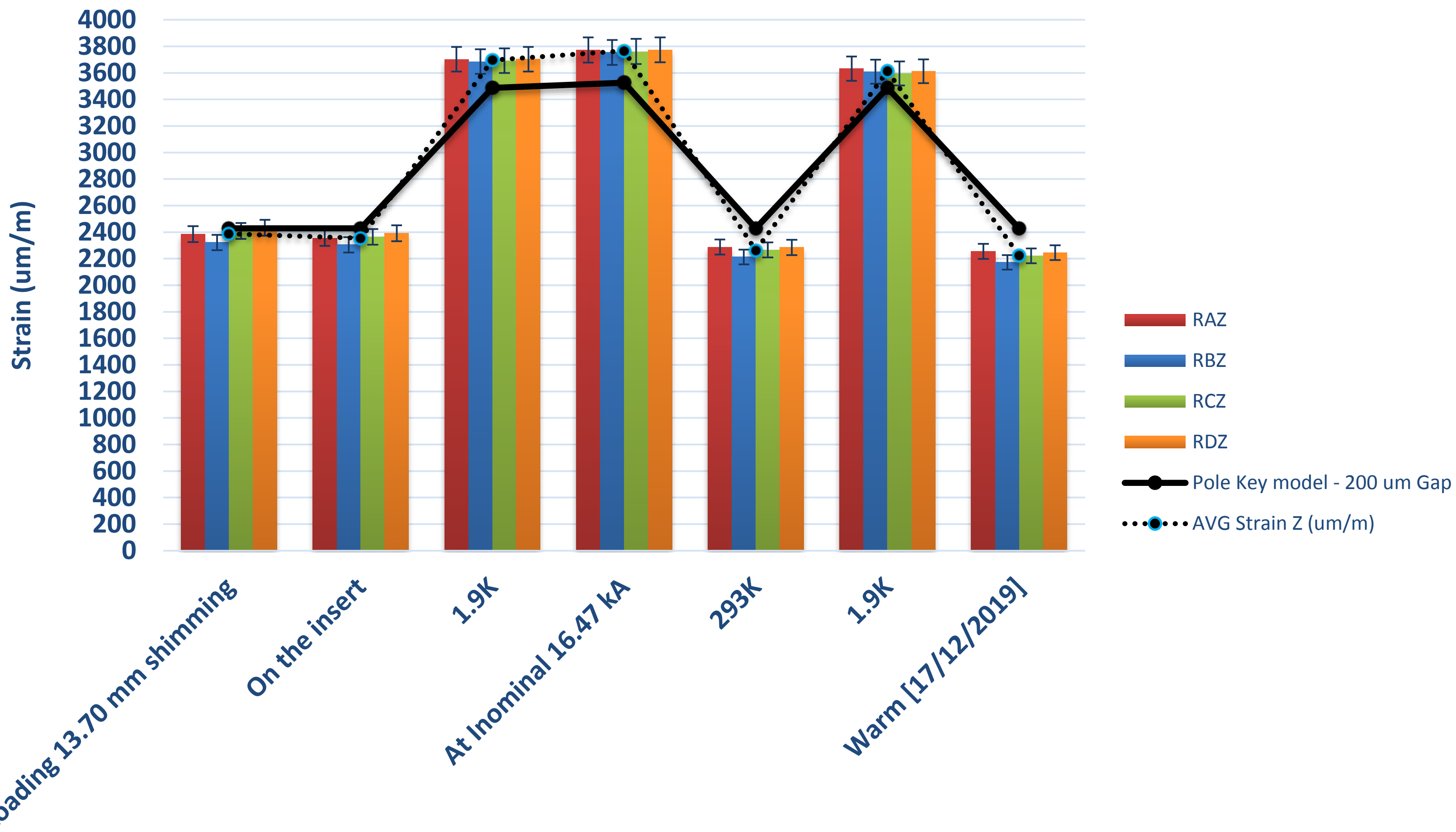
MQXFS3b - Rods - Longitudinal Strain
Strain (um/m)
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Before New longitudinal loading
After New longitudinal loading
On the insert
293K in the pit
4.2K
At Inominal 16.47 kA
After training
Before Longitudinal unloading
After Longitudinal unloading
RAZ
RBZ
RCZ
RDZ
AVG Strain Z (um/m)


MQXFS3c - Rods - Longitudinal Strain
Strain (um/m)
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Longitudinal loading
Check 1 day after assembly
On the insert
293K in the pit
1.9K
At Nominal Current 16.47 kA
293K in the pit
1.9K
1.9K after test
293K
Before disassembly
After disassembly
RAZ
RBZ
RCZ
RDZ
FEA Strain Z (um/m)
AVG Strain Z (um/m)

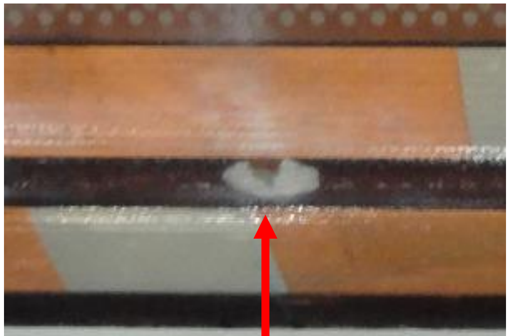


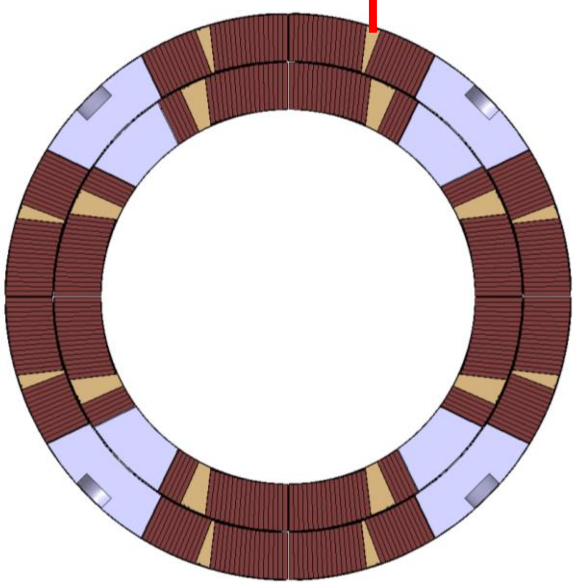
MQXFS4 - Rods - Longitudinal Strain
Strain (um/m)
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
On the insert
1.9K
293K
1.9K
Warm
On the insert
1.9K
Warm
1.9K
Warm
1.9K
Warm
RAZ
RBZ
RCZ
RDZ
AVG Strain Z (um/m)

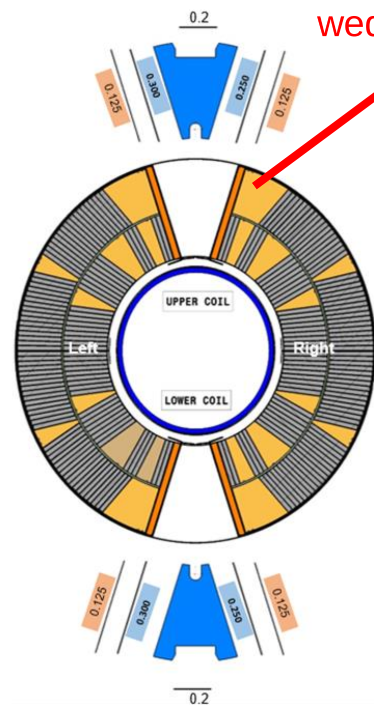
MQXFS6 - Rods - Longitudinal Strain



Conductor axial strain

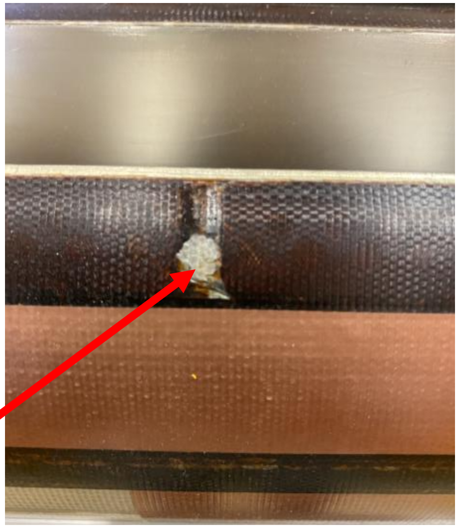






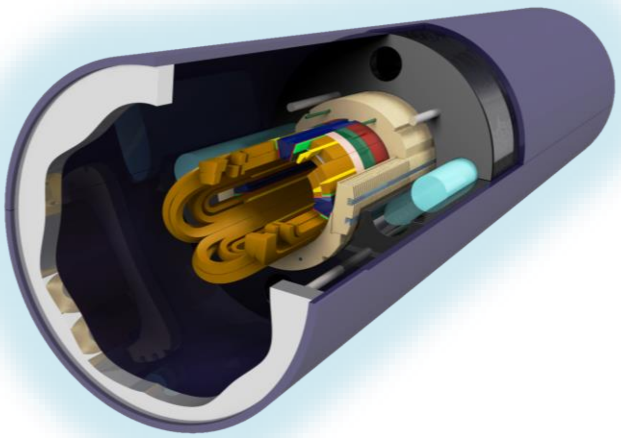
ODS copper wedge

Coil GE03 after cold test

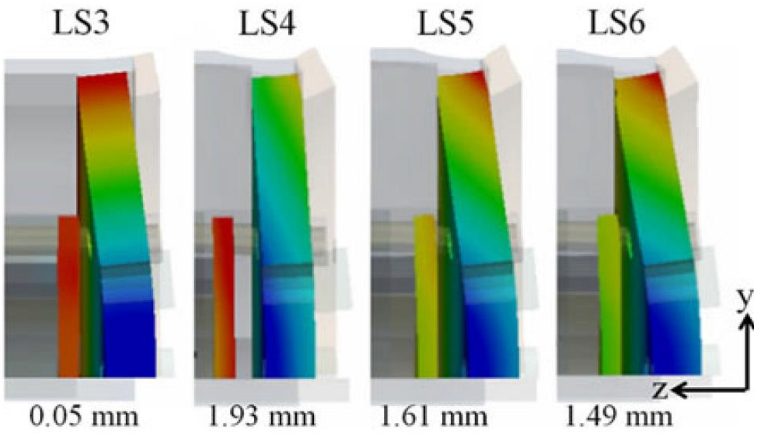


MKQXF (FEAC)

- FEAC performed a design study on MKQXF, a pole loading concept magnet, using MQXF coils.
- End design converged to a model with 4 bullets, a 50-mm-thick endplate, 4 rods of 30 mm diameter and pre-tension on the bullets that corresponds to an induced gap at the bullets – coil end plate interface of 0.5 mm.
- Computed coil elongation during powering, for the 7.2 m magnet is 0.32 mm, due to the bending of the end-plate.
  - Remark: Not so clear in [1] how the FEA model is scaled to the full length magnet: *"The E-modulus of the stainless steel rods that connect the two end plates of the magnet was scaled down to the length of 1.55 m, to accurately model the behaviour of the assembly over the total length of the magnet."*



Assembly 4.2 K 140 T/m 155 T/m

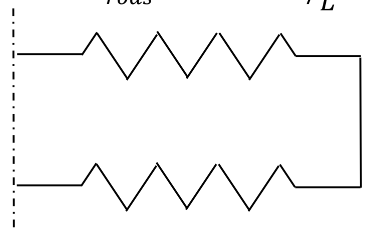


[1] Charilaos Kokkinos; Mikko Karppinen, High Gradient Nb3Sn Quadrupole Demonstrator MKQXF Engineering Design IEEE Transactions on Applied Superconductivity Year: 2018, Volume: 28, Issue: 3

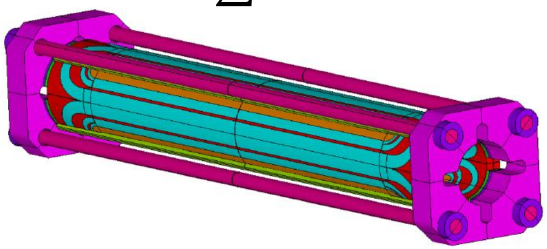
MQXF vs MKQXF

- According to FEA, similar coil elongation in the two configurations. Possible origin:
  - MKQXF larger bending of the end plate.
- Further analysis on MKQXF FEA model might provide further clarifications.

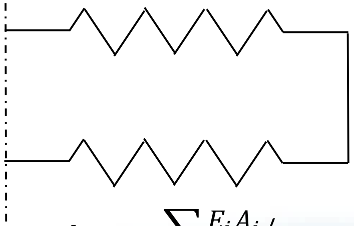
$$k_{rods} = {E_{rod} A_{rod}}/{L}$$



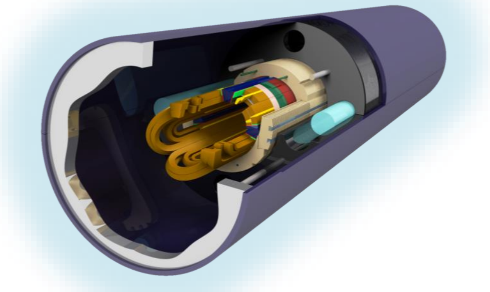
$$k_{coil} = \sum {E_i A_i}/{L}$$



$$k_{shell-yoke} \gg k_{rods}$$



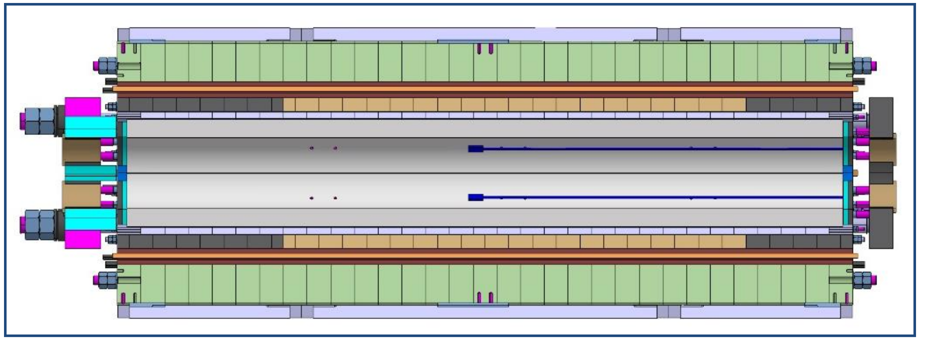
$$k_{coil} = \sum {E_i A_i}/{L}$$



	MQXF	MKQXF
End plate thickness, mm	75 (Nitronic 50)	50 (stainless steel)
Rods diameter, mm	36 (aluminium/stainless steel)	30 (stainless steel)
Coil elongation for the 7.2 m magnet, including friction	0.28 mm	0.32 mm

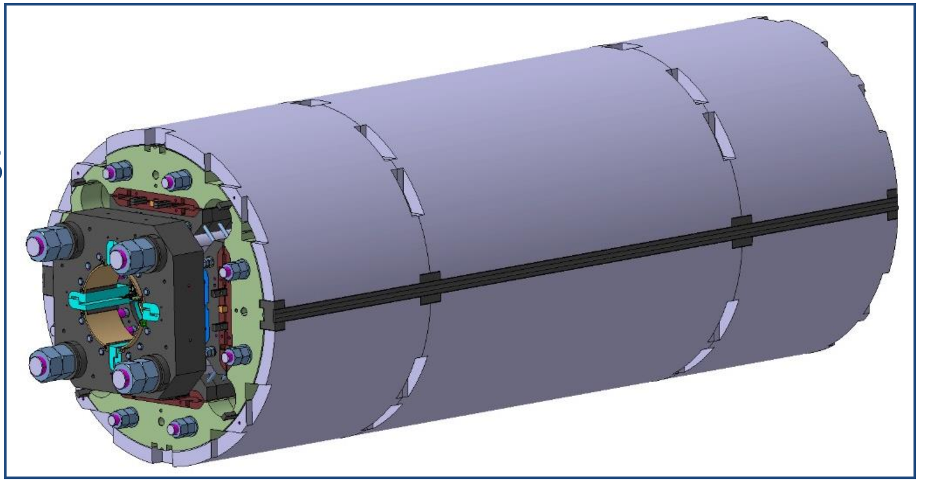
MQXFSD1

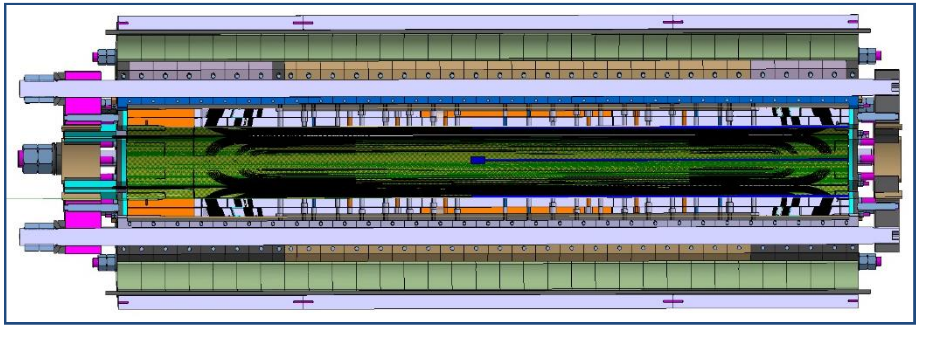
- Instrumentation
  - 4 CERN + 4 LARP strain gauge stations (ϑ and z) in shell
  - 4 CERN + 12 LARP strain gauges stations (ϑ and z) in dummy coils
  - 4 strain gauges z on rods
  - Total: **52 gauges**
- 1 loading at LBNL
- 1 cool-down at LBNL
  - No thermal cycles



MQXFS1 (or AT1)

- Structure 1 used for first short model
  - ½ + 1 + ½ shell segments
  - Thick laminations
  - LE axial pre-load

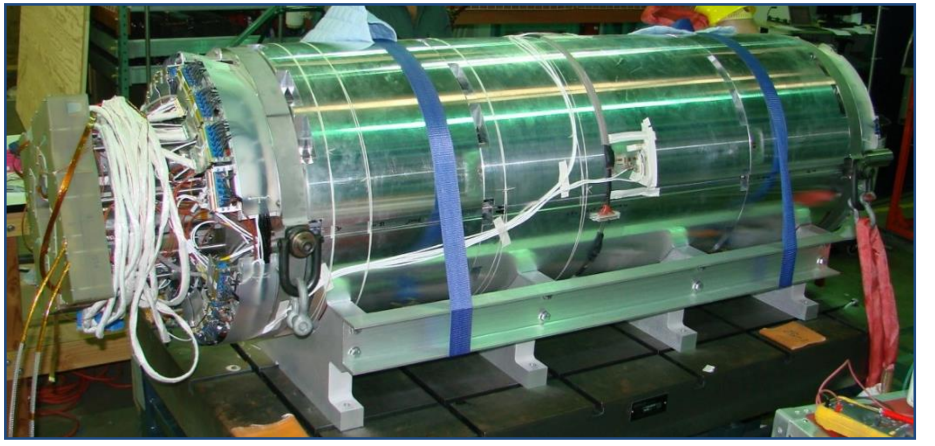


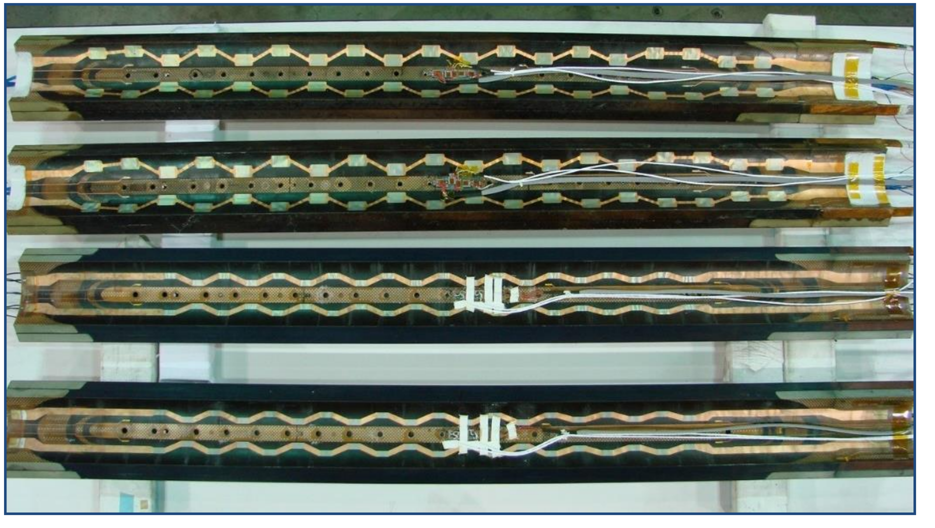


- Assembled/loaded in summer 15, cooldown in winter
- Coil 3, 5, 103, 104

MQXFS1 (or AT1)

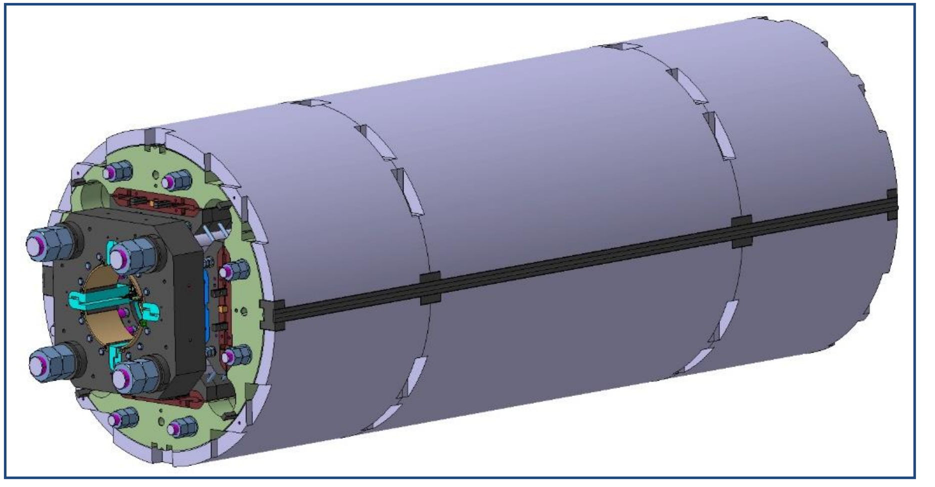
- Instrumentation
  - 4 CERN + 4 LARP strain gauge stations (ϑ and ***z***) in shell
  - 4 CERN + 4 LARP strain gauges stations (ϑ and ***z***) in dummy coils
  - 4 strain gauges ***z*** on rods
  - Total: **36 gauges**
- 1 loading at LBNL
- 1 cool-down + warm-up at FNAL
- Next cool-down soon at FNAL

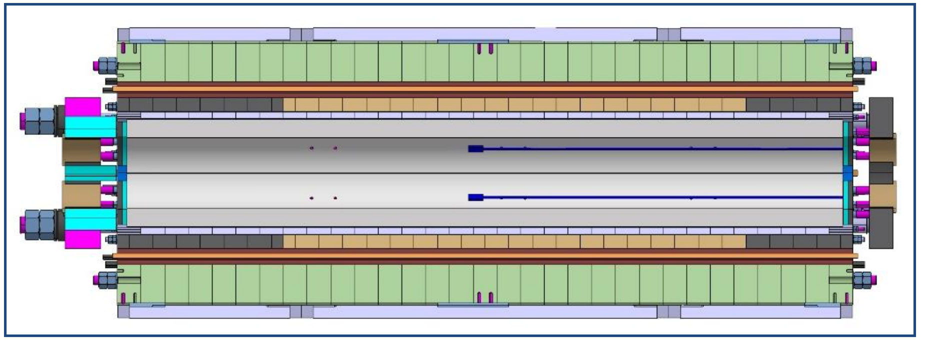




MQXFS Support Structure # 2

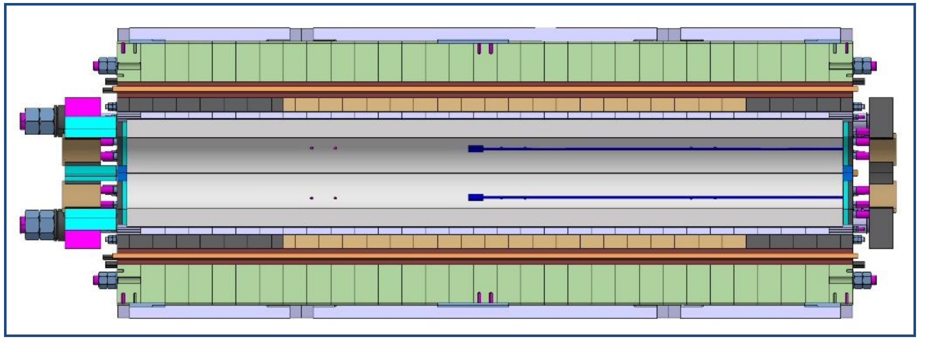
- ½ + 1 + ½ shell segments
  - Fabricated with final lengths and new smaller cut-outs
- All other components from structure 0
- LE axial pre-load
- To be qualified in first half 2016 with dummy coils
  - **MQXFSD2**





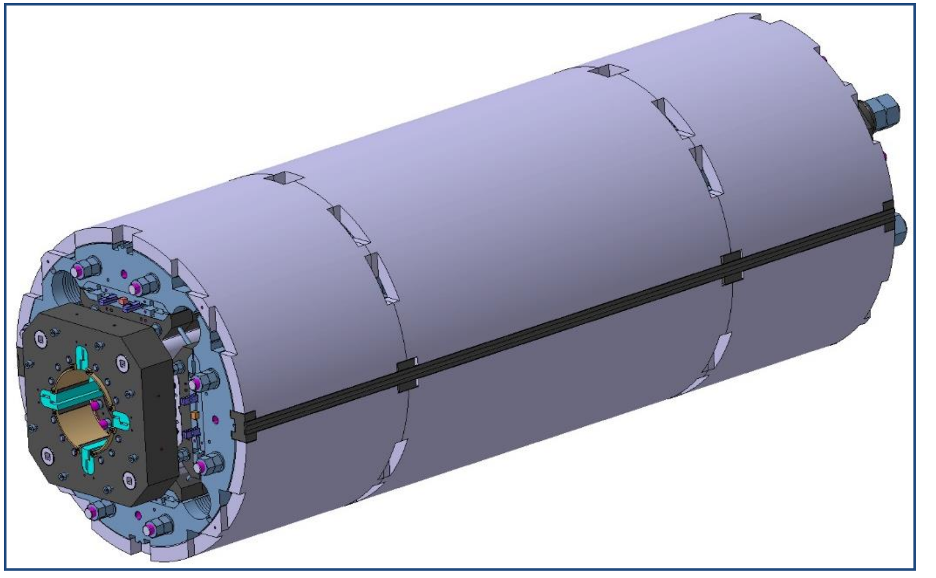
MQXFSD2

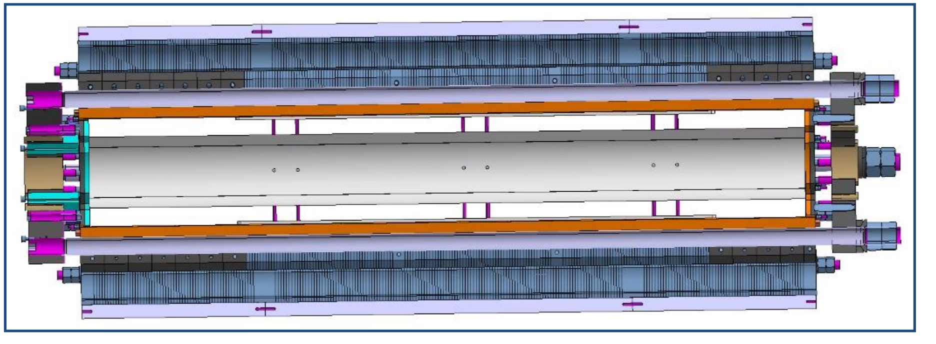
- Instrumentation
  - 4 CERN strain gauge stations (ϑ and z) in shell
  - 12 CERN strain gauges stations (ϑ and z) in dummy coils
  - 4 strain gauges z on rods
  - Total: **36 gauges**
- 1 loading + cool-down performed at CERN
- To be done (Feb. 16)
  - Thermal cycle, II loading, II cool-down and thermal cycle at CERN



MQXFS Support Structure 3 and 4

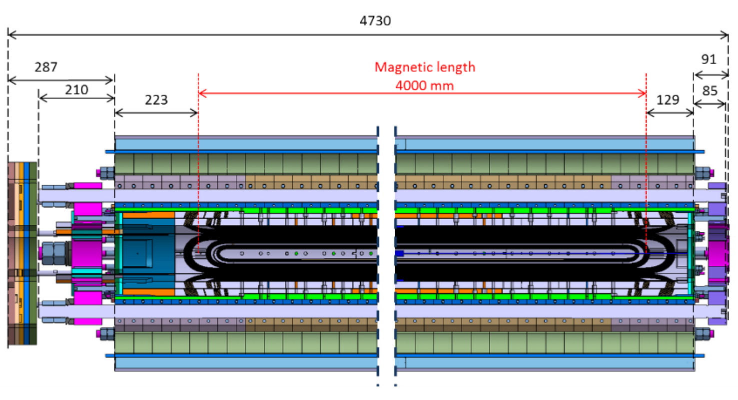
- ½ + 1 + ½ shell segments
- Thin lamination for pad and yoke
- RE axial pre-load
- 2 sets of components delivered at CERN
  - Except 1 set of shells and 1 set of collars
- To be qualified at CERN in first half Mar./Apr. 2016 with dummy coils
  - **MQXFSD3**

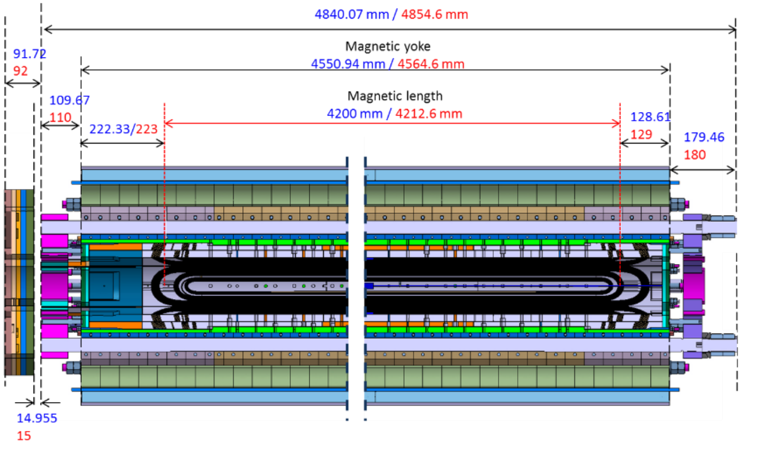




From structure 1-2 to structure 3-4

- Nuts and pre-loading system moved from LE to RE
  - Reduced lengths of the leads → field quality
  - Easier pre-loading operation
  - Increased distance between Q1 magnets





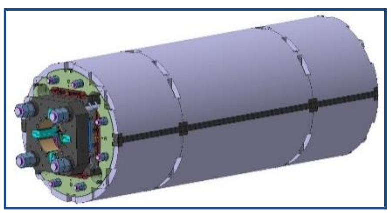
Short model support structures overview

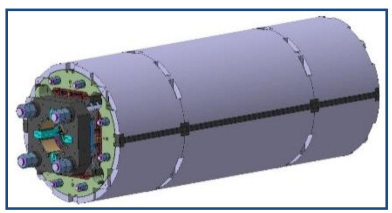
- **Structure 1**
- Used in
  - MQXFSD1
  - MQXFS1

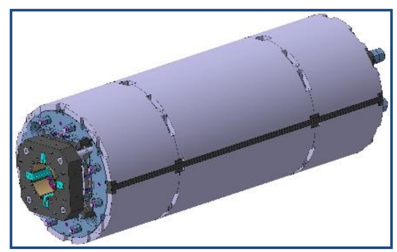
- **Structure 2**
- Used in
  - MQXFSD0
  - MQXFSD2
  - MQXFS2

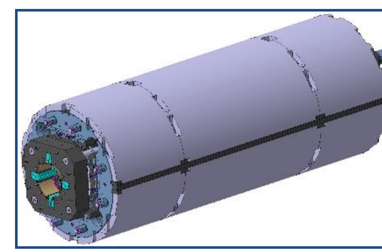
- **Structure 3**
- Not assembled
- To be used in
  - MQXFSD3
  - MQXFS3
  - MQXFS5

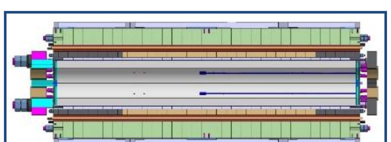
- **Structure 4**
- Not assembled
  - Missing shell and collars
- To be used
  - MQXFSD4(?)
  - MQXFS4

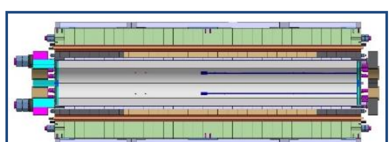


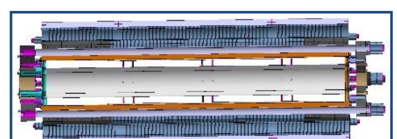


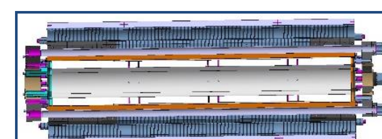






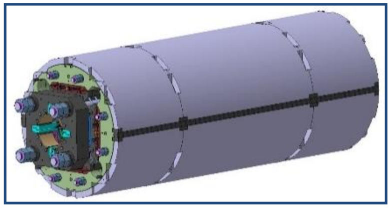


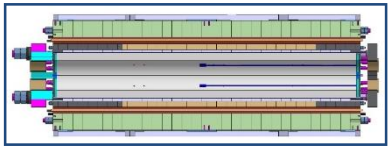




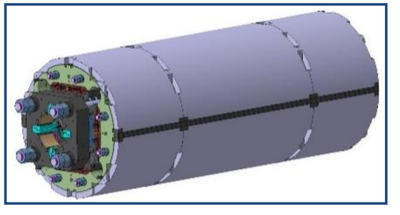
Short model support structures overview

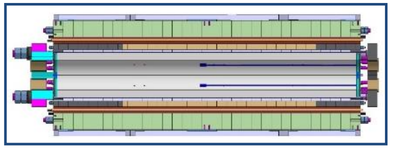
- **Structure 1**
- Used in
  - MQXFS1/1b/1c/1d/1e



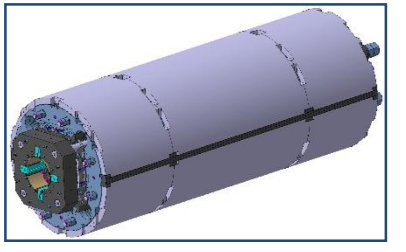


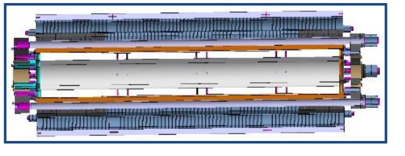
- **Structure 2**
- Used in
  - MQXFS3c
  - MQXFS6/6b/6c

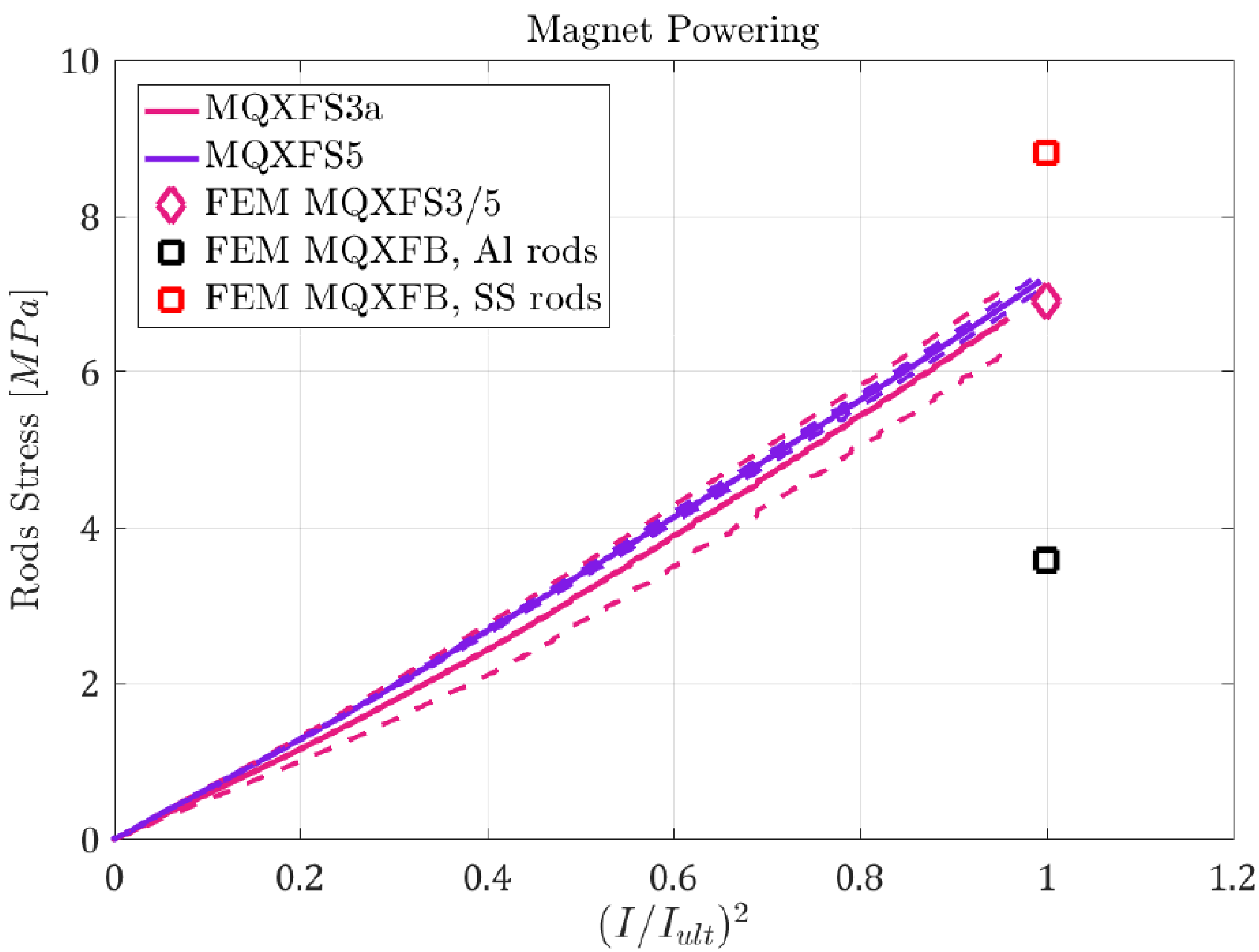




- **Structure 3**
- Used in
  - MQXFS3/3b
  - MQXFS5
  - MQXFS4/4b/4c






Magnet Powering
MQXFS3a
MQXFS5
FEM MQXFS3/5
FEM MQXFB, Al rods
FEM MQXFB, SS rods
Rods Stress [MPa]
$(I/I_{ult})^2$
0
2
4
6
8
10
0
0.2
0.4
0.6
0.8
1
1.2

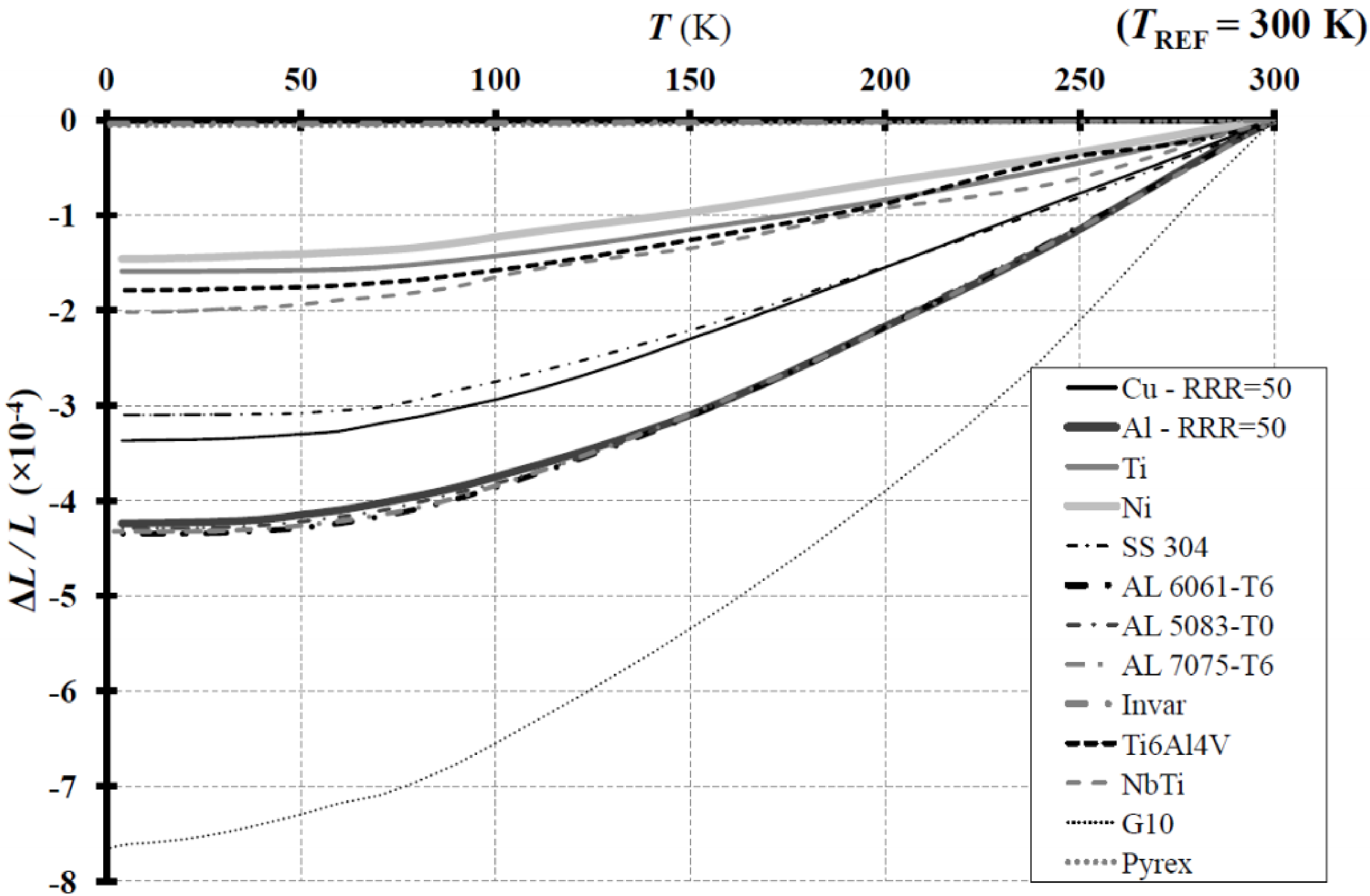
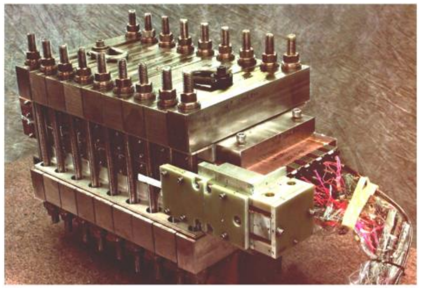


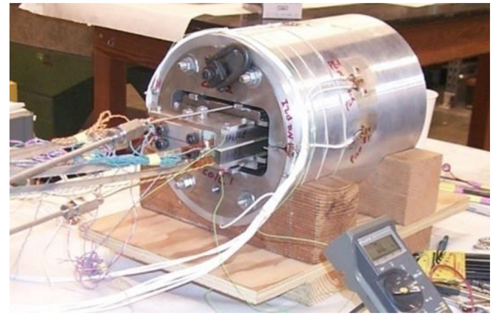
Fig. 8: $\Delta L / L = \int_{T_{REF}=1\,K}^{T} \alpha(T)\mathrm{d}T$ as a function of the temperature for different solid materials

The road to shell structures at LBNL



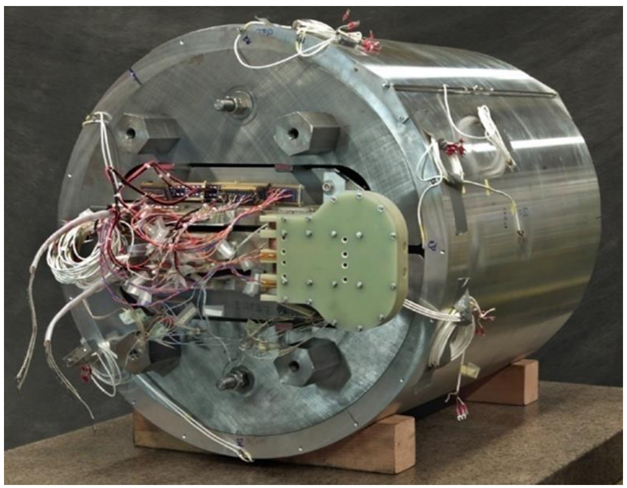
RD2 - 6 Tesla

RT1 - 12 Tesla

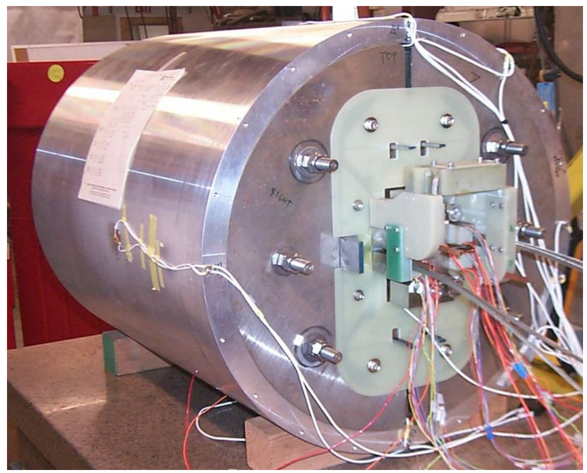


SM-01 - 12 Tesla

•SQ01 short quad



RD3-b - 14.5 Tesla



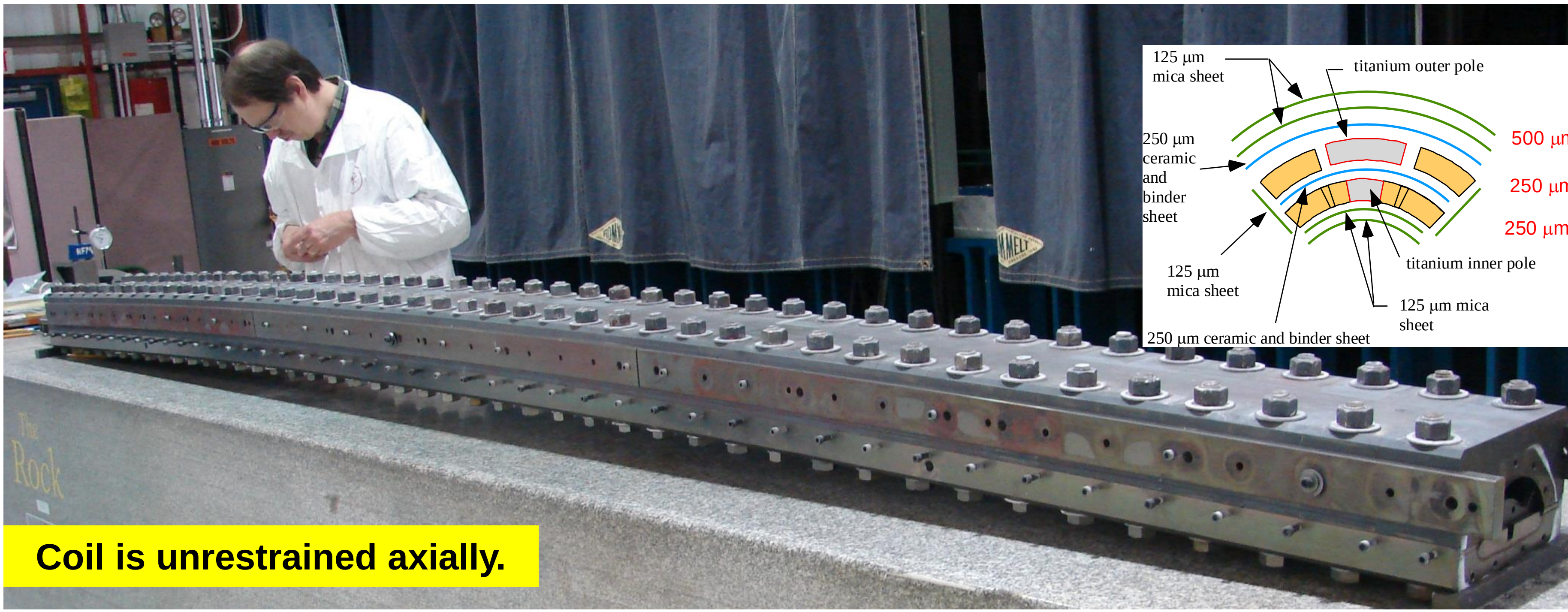
HD1 - 16 Tesla

•TQS, quad

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

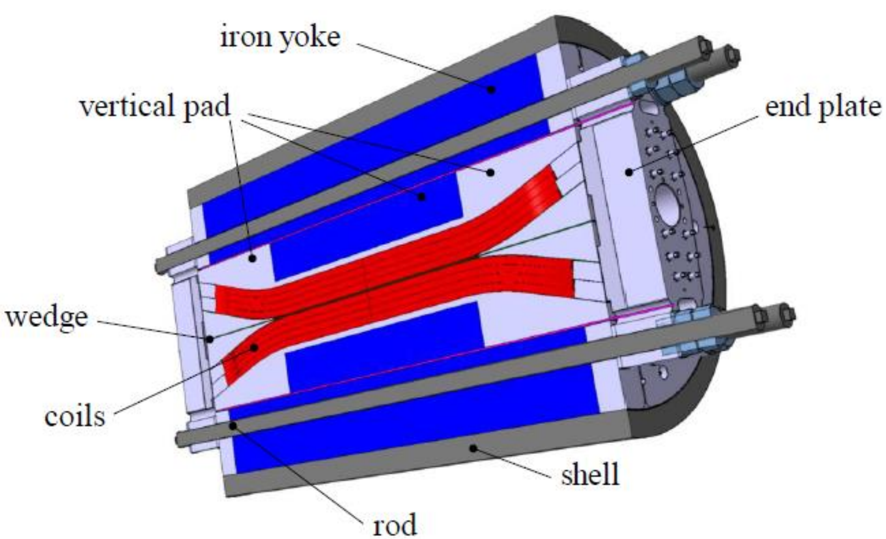
LQ – 3.7 m long quad for LARP

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



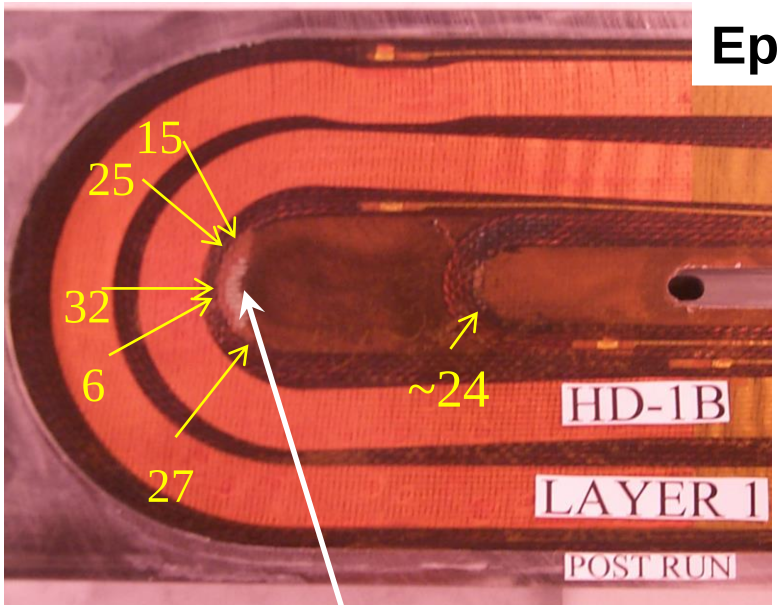
Coil is unrestrained axially.

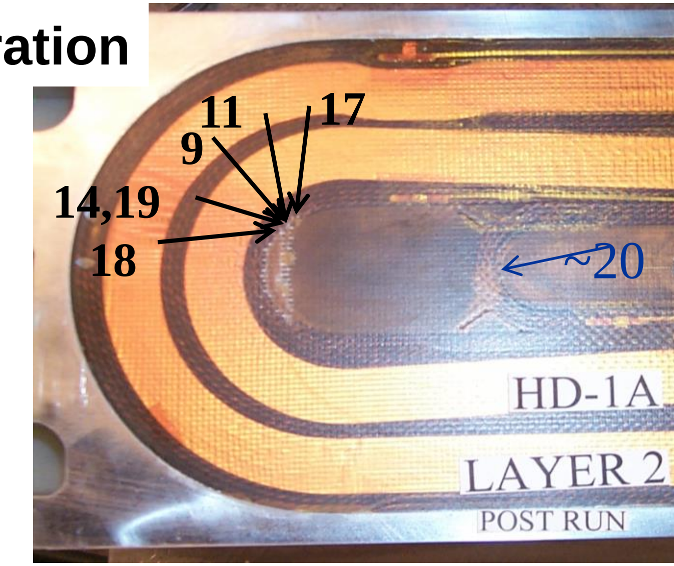
"Development and coil fabrication for the LARP 3.7-m Long Nb3Sn Quadrupole" 19 August 2008

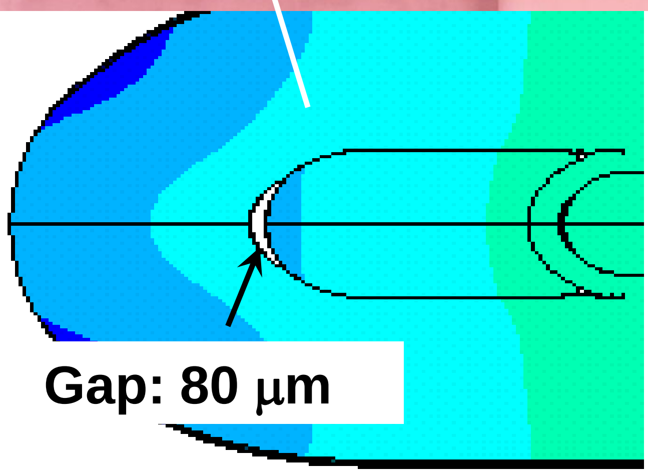

iron yoke
vertical pad
end plate
wedge
coils
shell
rod

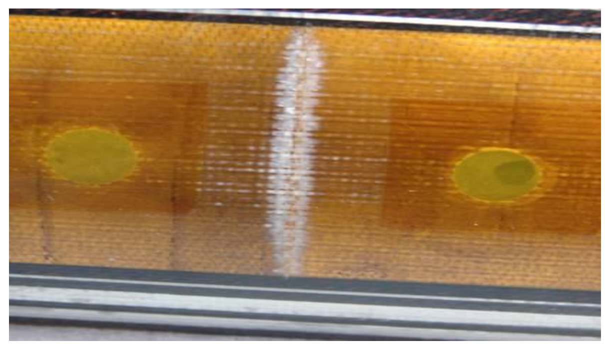
Axial displacements and quench location (HD1, TQ)

Epoxy discoloration







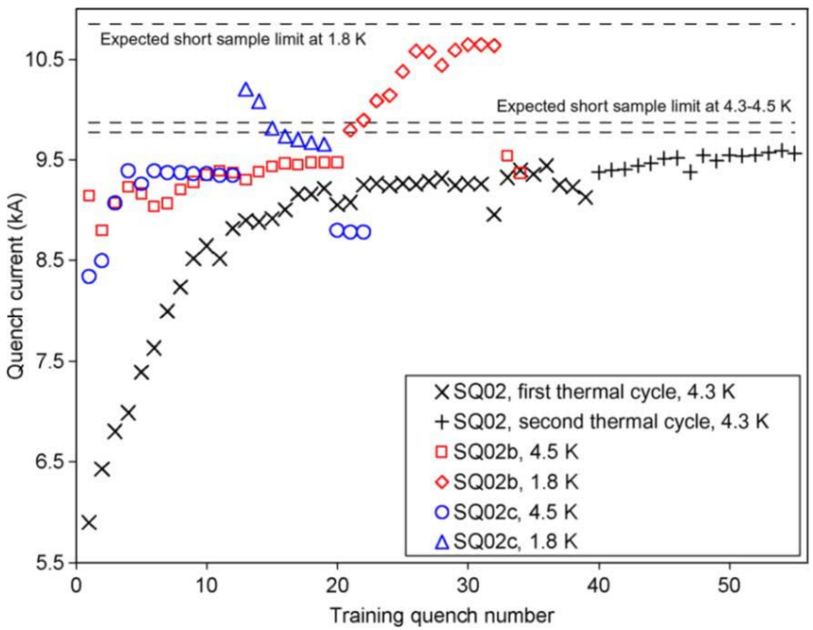


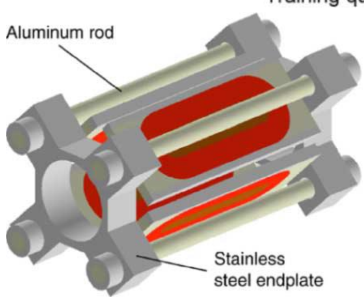
Coil 7

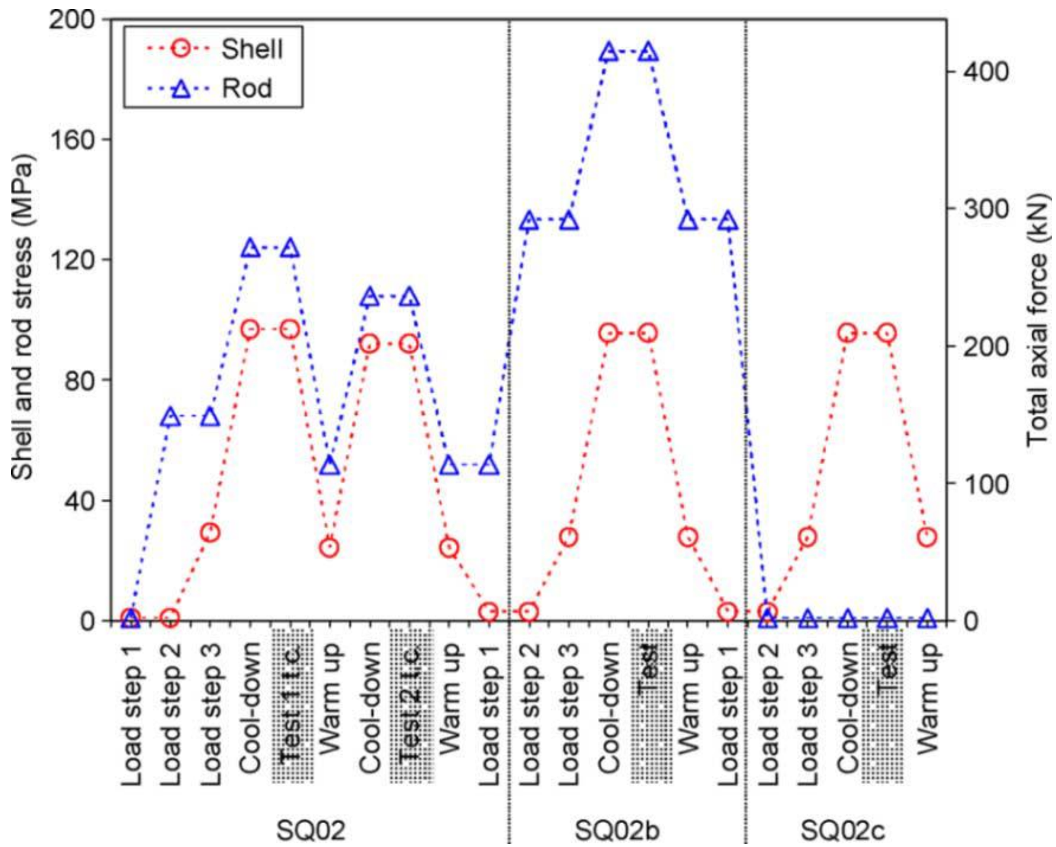
Broken fibers

SQ02 axial support system

Fz @ Iss = 0.37 MN/end



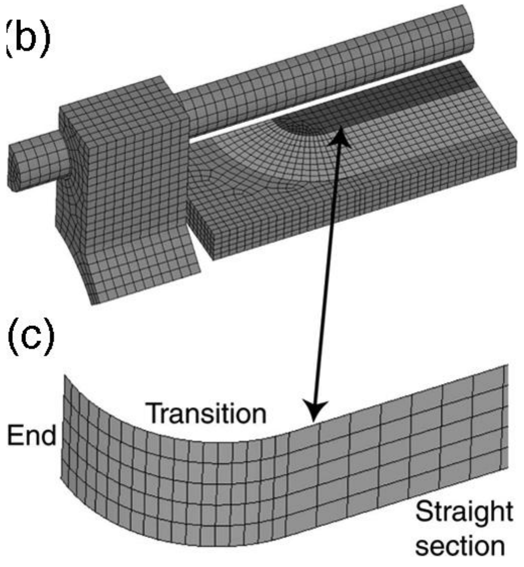




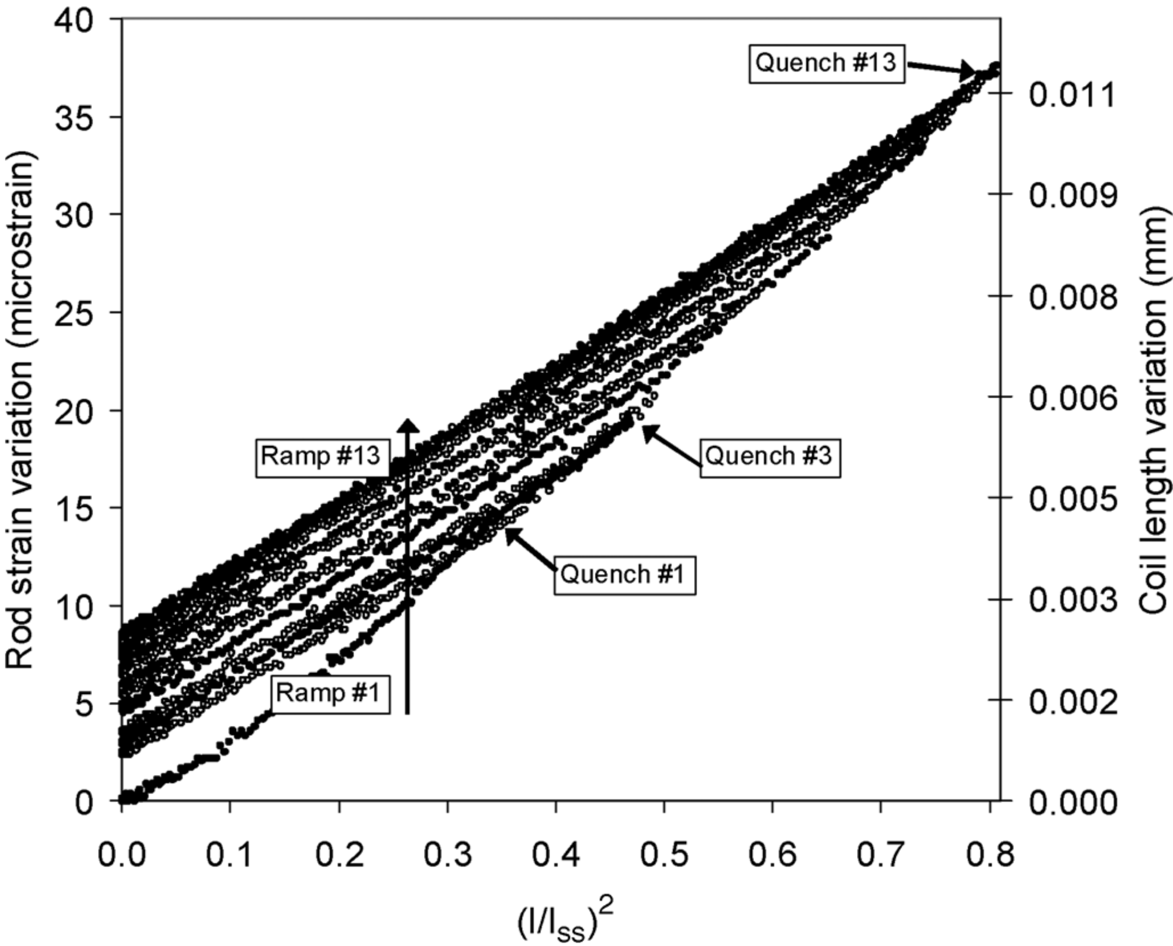
P. Ferracin et al "*Effect of Axial Loading on Quench Performance in Nb3Sn Magnets*"
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 18, NO. 2, JUNE 2008

SQ02 - Ratcheting Model

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



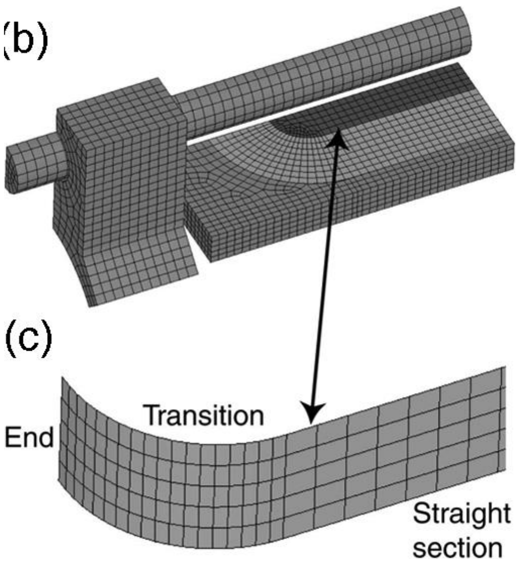
SQ02 geometry with contact region between coil and island



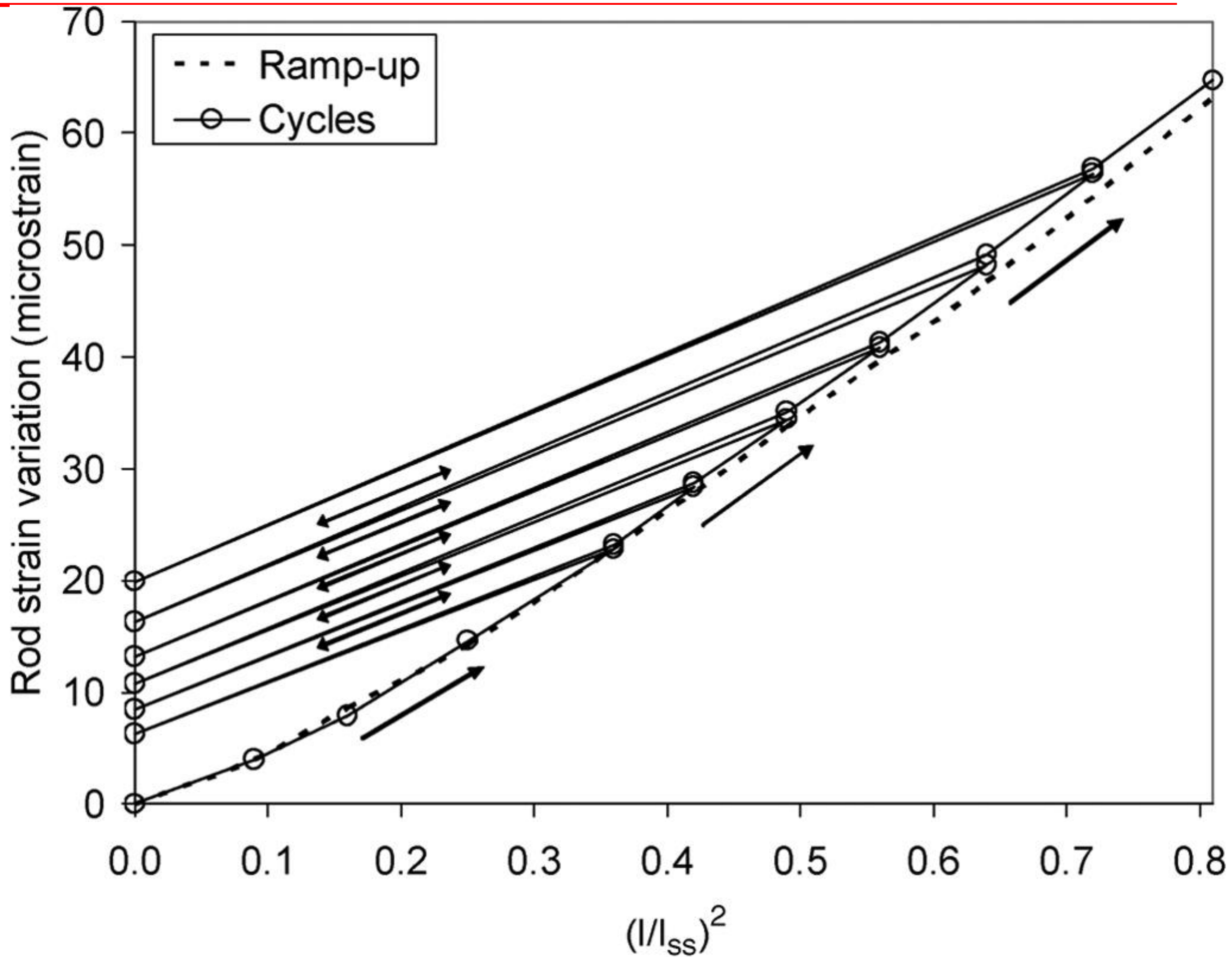
Measured rod strain as a function of the Lorentz force.

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

Ratcheting Model

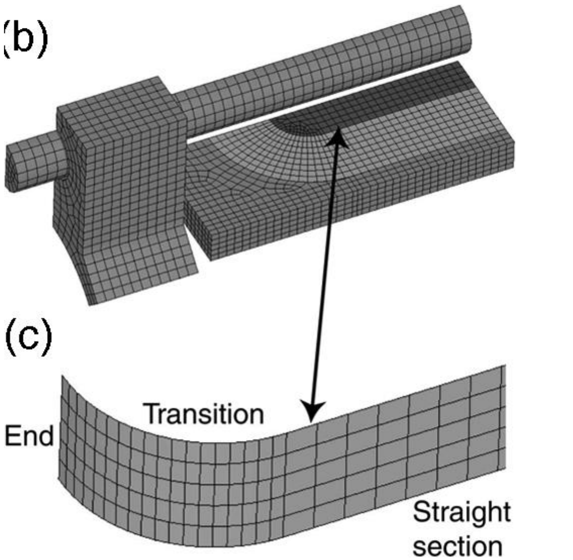


SQ02 geometry with contact region between coil and island

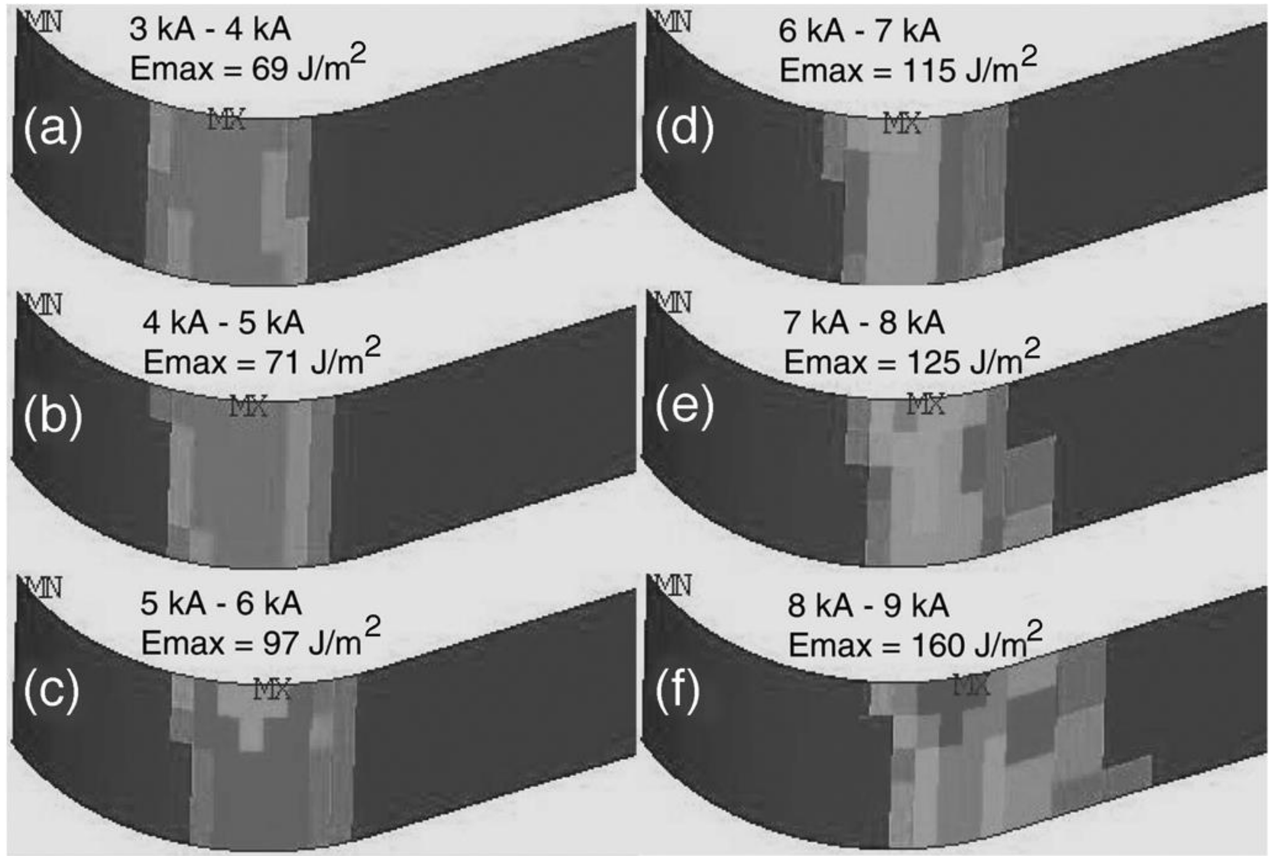


Computed variation of rod strain as a function of the Lorentz force.

Ratcheting Model



SQ02 geometry with contact region between coil and island



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

Coil Estimates

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

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

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

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

Plane-Strain Epsilon_z=0 (fixed-axial)

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

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

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

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

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

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