Summary on Longitudinal Loading of Nb_3Sn magnets at CERN

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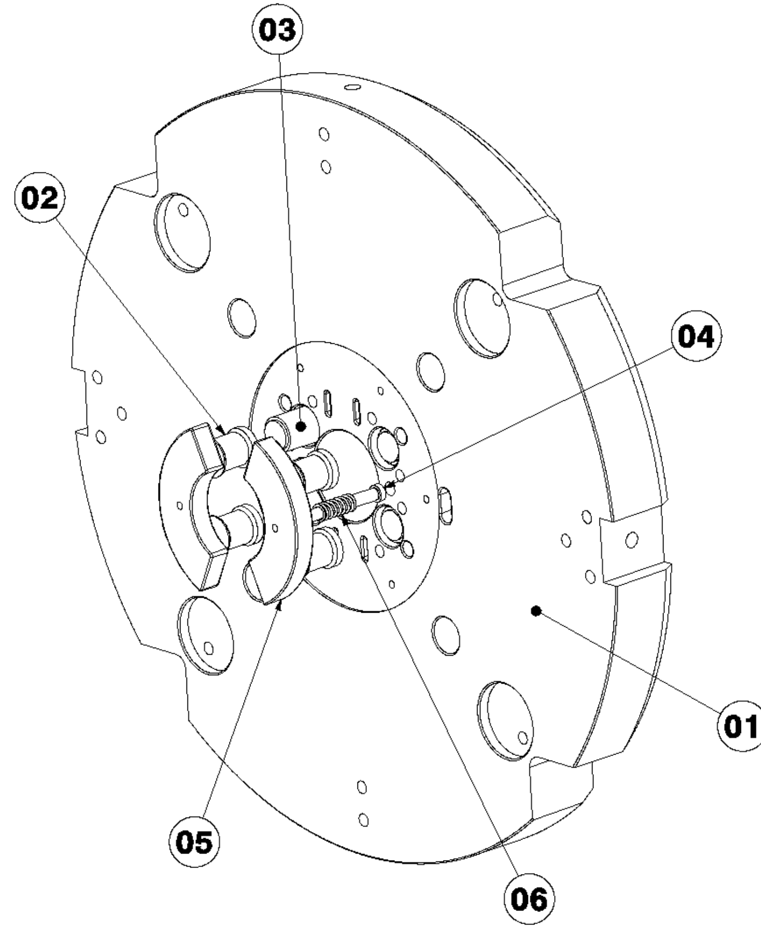
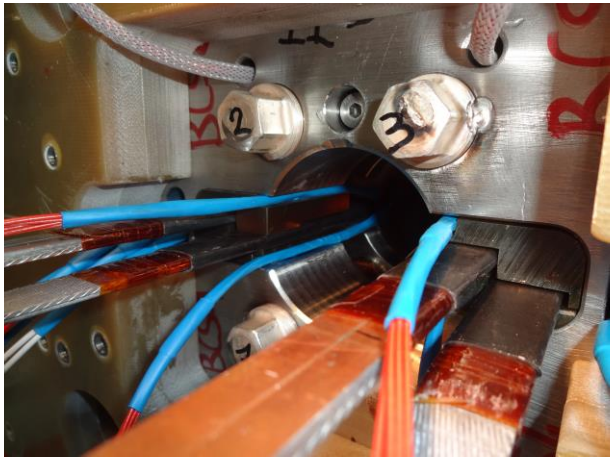
11 T - concept

- 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.

Bullet gauges

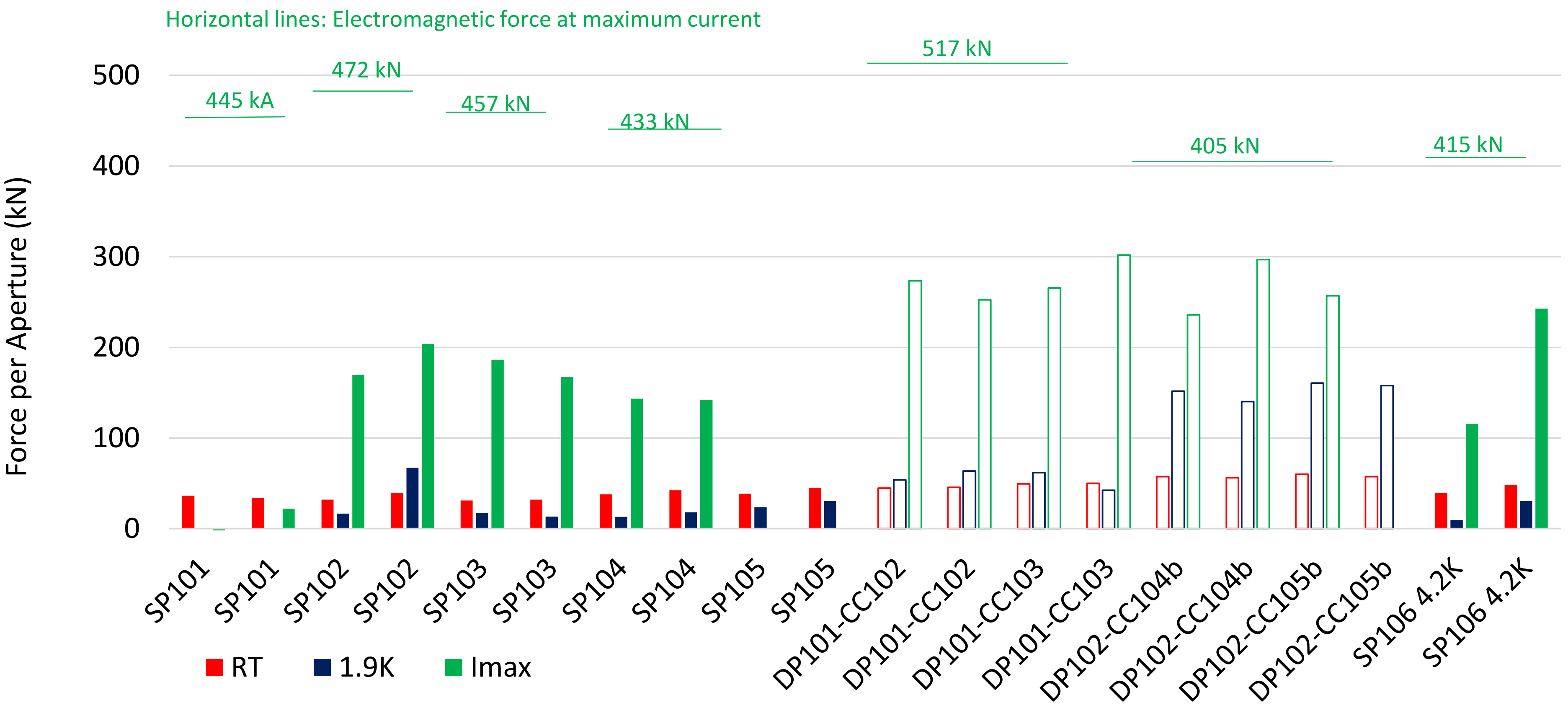




11 T – longitudinal pre-load

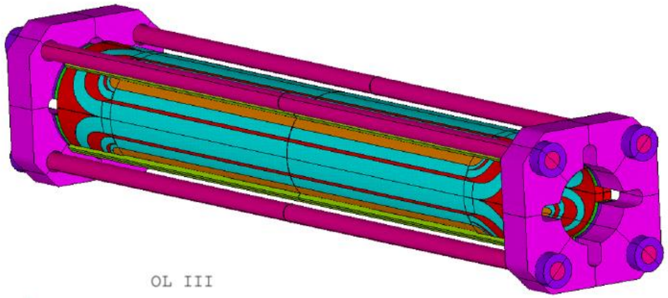
Overall behavior:

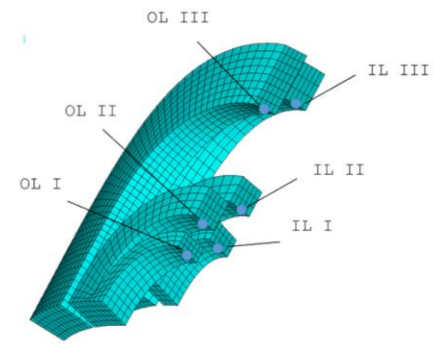
- Pre-load at room temperature at 30-60 kN/aperture (5-10 % of the electromagnetic forces)
- During cool down, around 50 % of the force is lost (except in DP102, where the force seen by the bullets increases by a factor 3).
- During powering, around 30 % of the load is transferred to the bullet gauges.



MQXF - Concept

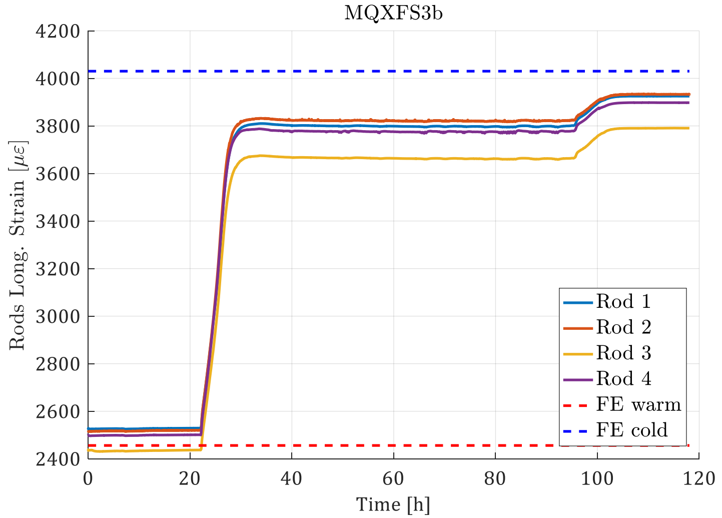
- Direct connection between the motion of the rod and the one of the coil ends
  - Coil elongation measured by the strain gauges on the rods.
- Goal: keep the pole turn under compression during powering.
- Short models (1.2 m):
  - Aluminum rods, 36 mm diameter
  - Nitronic 50 end plate, 75 mm thick
- Long magnets (7.2 m):
  - Stainless steel rods, 36 mm diamter
  - Nitronic 50 end plate, 75 mm thick

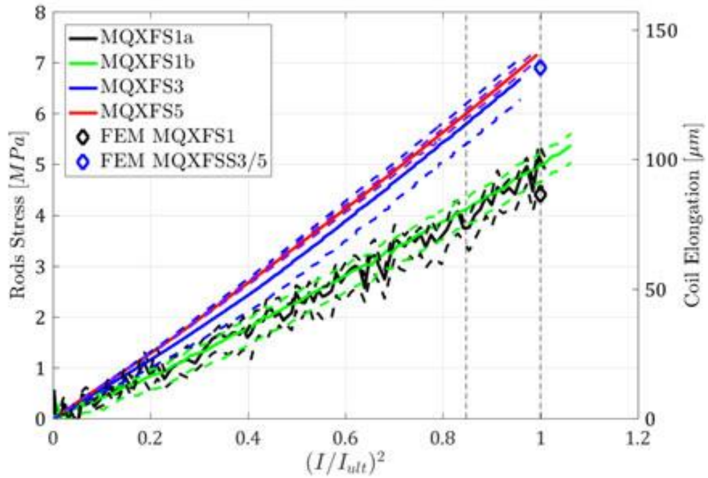




MQXF – Longitudinal Pre-load

- Electromagnetic forces = 1.2 MN at nominal
- Applied longitudinal pre-stress
  - MQXFS1a/b & MQXFS3a : $800\ \mu\varepsilon$ at R.T., $0.6\ MN$ at cold
  - MQXFS1c, MQXFS3b/c, MQXFS4 and MQXFS5: $2500\ \mu\varepsilon$ at R.T., $1.12\ MN$ at cold
- The model predicts reasonably good the effect of cool down
- Different slope between MQXFS1 and MQXFS3/5. To fit the measurements, 0.16 friction coefficient in MQXFS1, 0.13 for MQXFS3/5. Coil to collar shim might be the source of the difference:
  - MQXFS1 is G10,
  - MQXFS3/5 several layers of Kapton
- 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.

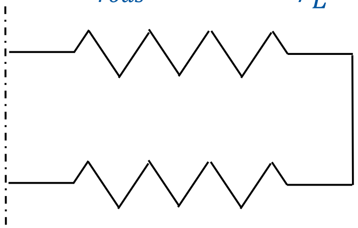




G. Vallone, et. al., Mechanical analysis of the short model magnets for the Nb_3Sn low-beta quadrupole MQXF, *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, 2016.

MQXF – From short to long

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

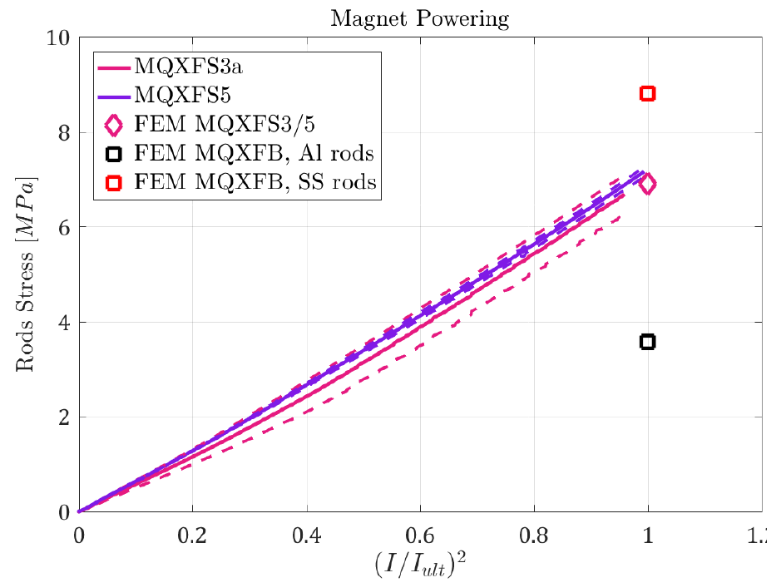


$k_{coil} = \sum {E_i A_i}/{L}$

- 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 %)

TABLE I
MAIN PARAMETERS GOVERNING THE LONGITUDINAL MOTIONS

Parameter	Unit	MQXFS	MQXFB
e.m. Force, Nominal Current	MN	1.2	1.2
Coil Stiffness	MN/mm	1.10	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



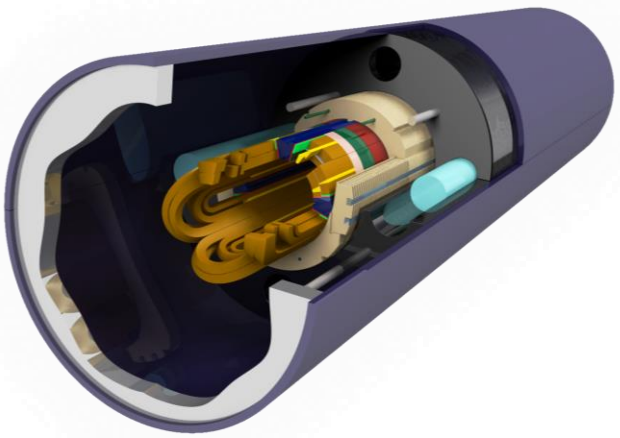
G. Vallone, et. al., Mechanical Design Analysis of MQXFB, the 7.2 m long-β quadrupole for the High-Luminosity LHC Upgrade, *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, 2016.

MKQXF (FEAC)

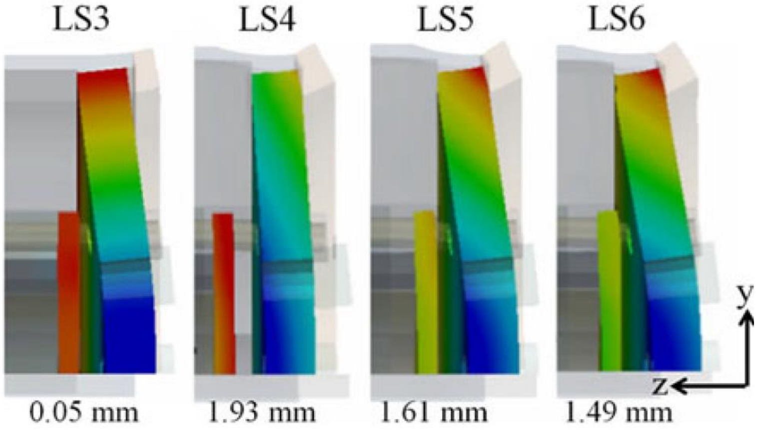
- FEAC performed a design study on MKQXF, a pole loading concept magnet, using MQXF coils.

- 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."*



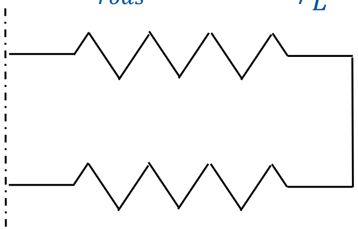
Assembly 4.2 K 140 T/m 155 T/m



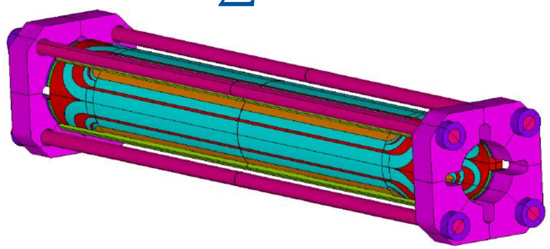
MQXF vs MKQXF

- 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.

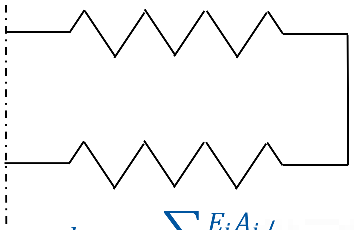
$k_{rods} = {E_{rod} A_{rod}}/{L}$



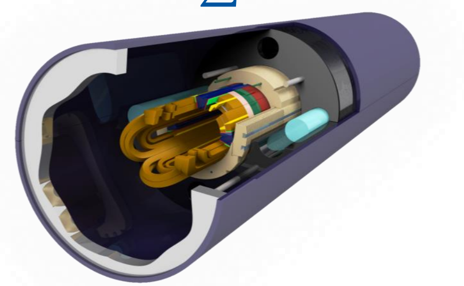
$k_{coil} = \sum {E_i A_i}/{L}$



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



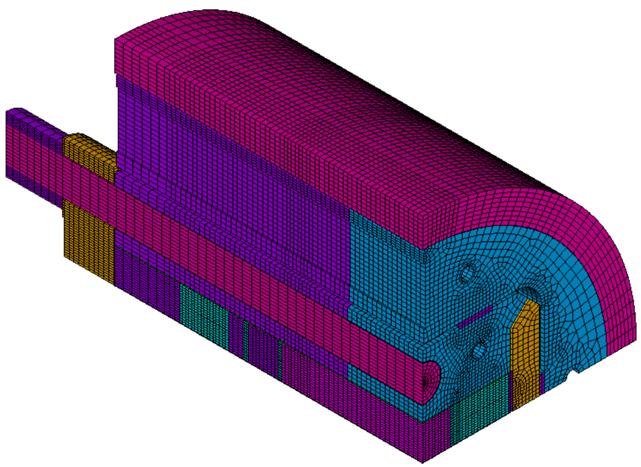
$k_{coil} = \sum {E_i A_i}/{L}$

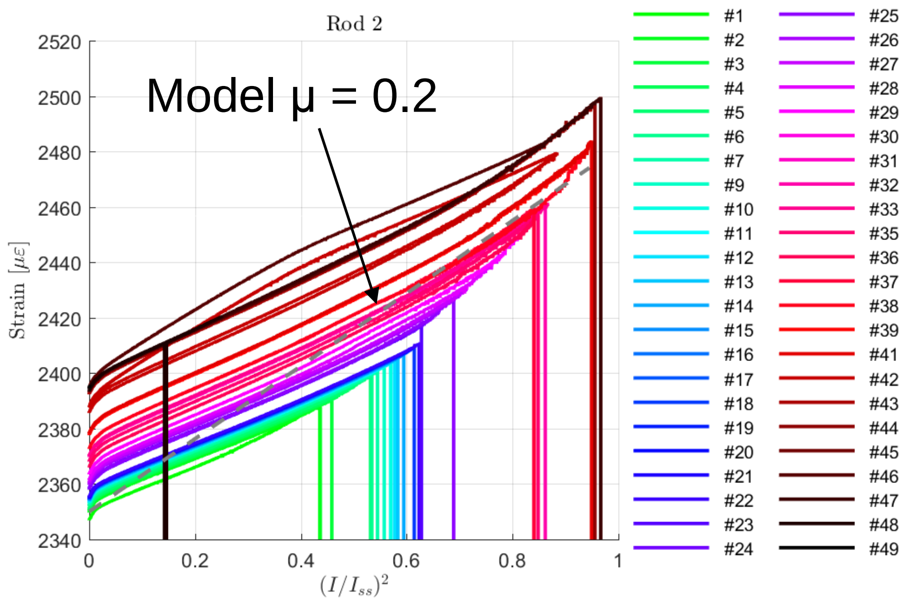


	MQXF	MKQXF
End plate thickness, mm	75 (Nitronic 50)	50 (stainless steel)
Rods diameter, mm	36 (aluminium/stainless steel)	30 (stainless steel)
Coil elongation for the 7.2 m magnet, including friction	0.28 mm	0.32 mm

RMC

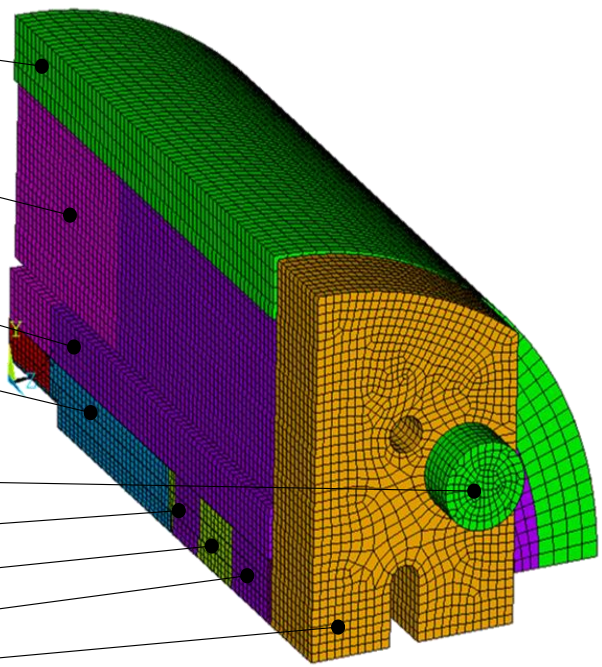
- Axial loading concept as MQXF
    - Longitudinal rods diameter = 48 mm (Aluminum)
    - End plate thickness = 70 mm (Nitronic 50)
- Axial pre-load in magnets tested: ~ 30 % of the electromagnetic forces at room temperature, 60 % after cool down → around 45 MPa of tension in the end pole turn at maximum current.
- Initial measured slope in the rods smaller than in the model → could be match using slightly larger friction coefficient.





RMC QXF		Targeted	Achieved
Rod strain RT	μstr	1600	1359
Axial pre-load (RT+CD)	% EM	30+30	24+28

RMM: Longitudinal stiffness

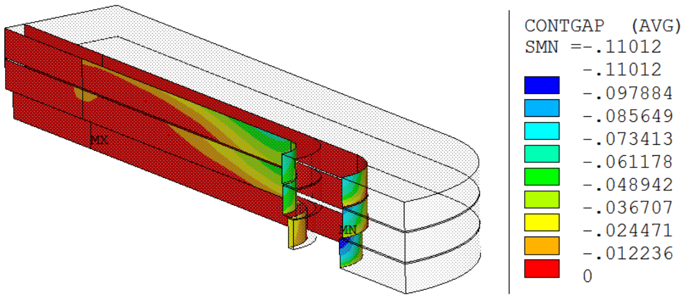


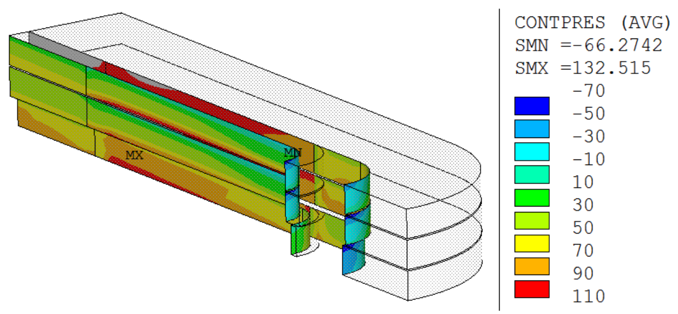
	11 T	MQXFS – Al rods	RMM- Al rods	RMM- SS rods
e.m. force per aperture at nominal field [MN]	0.44	1.2	2.4	
Coil length [mm]	1.6	1.1	0.97	
Magnet length [mm]	2	1.55	1.5	
Rod diameter [mm]	n.a.	36	64	
End-plate thickness [mm]	43	75	100	
Coil Stiffness [MN/mm]	1.40	1.10	4.06	4.06
Rod Stiffness [MN/mm]	n.a.	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-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)





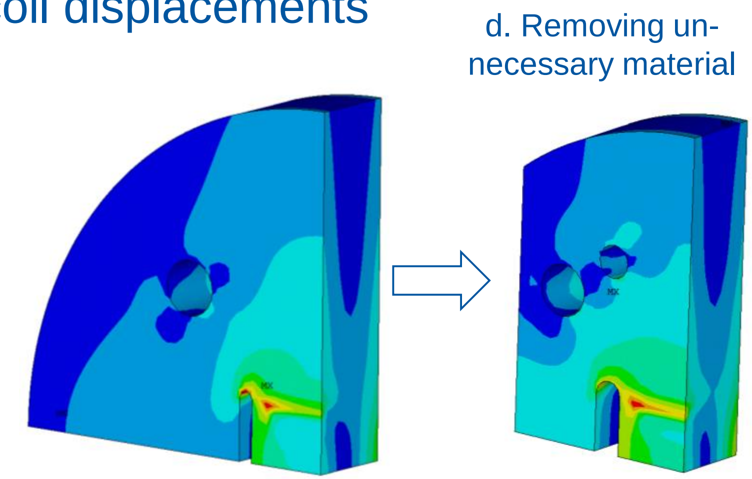
	Rod Pre-load Fz	Rod Cool-Down Fz	Energization	
	[% L. F.]*	[% L. F.]*	Max. Tension [MPa]	Max. Gap [μm]
16 T	14	76	64	106
18 T	11	56	90	135
16 T	32	100	56	94
18 T	24	75	80	133
16 T	72	139	46	76
18 T	53	104	77	110
16 T	97	167	40	62
18 T	72	125	72	99
16 T	135	208	30	44
18 T	100	155	66	85

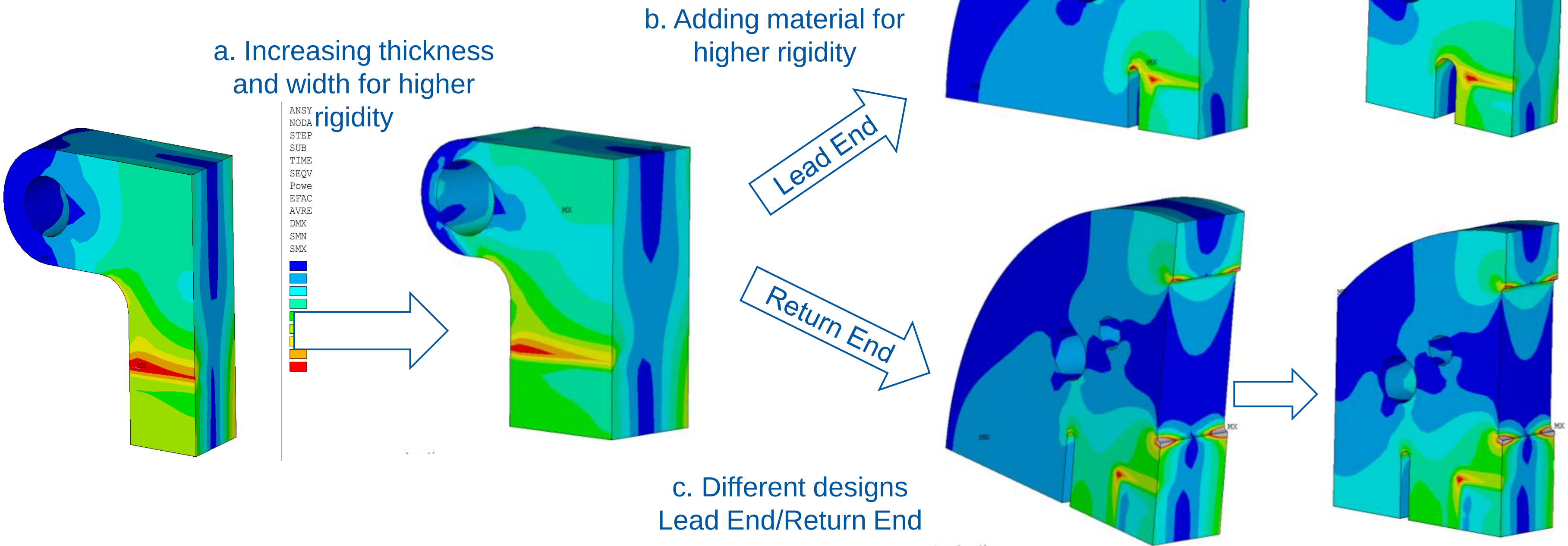
E. Rochepault, 3D Magnetic and Mechanical Design of Coil Ends for the Racetrack Model Magnet RMM, IEEE Appl. Supercond.

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





Final remarks

- In order to keep the pole turn under compression in RMM, excessive longitudinal force is needed during assembly → expect to have ~ 40 MPa of tension ~ 0.05 - 0.1 mm of gap on the pole tip.
- 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).