Design of ERMC-RMM

FCC Week 2017
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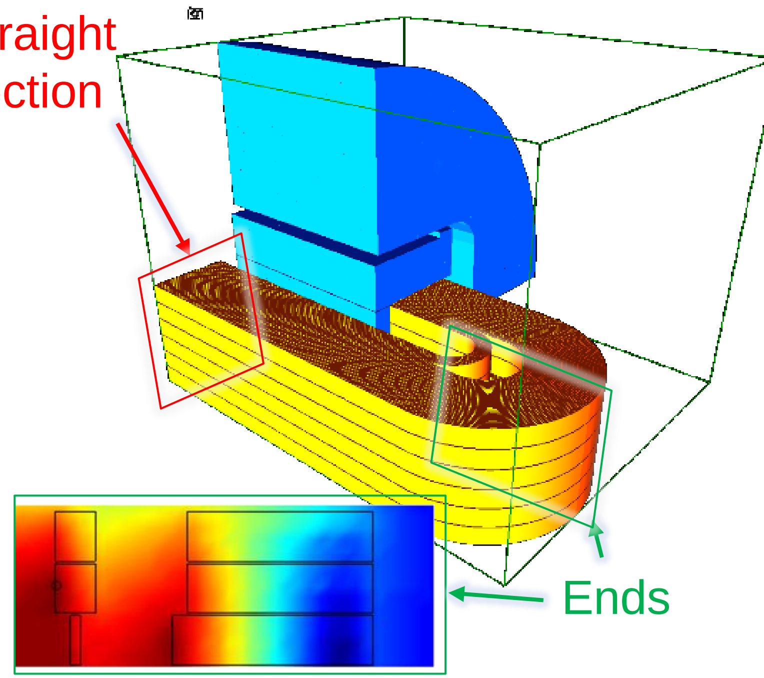
CERN-MSC-MDT

Outline

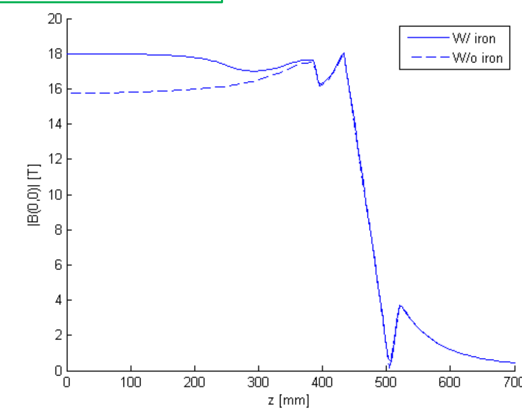
1. 1^{st} 3D magnetic optimization
2. Choice of iron lengths
3. Impact on the 3D mechanical design
4. 2^{nd} 3D magnetic optimization
5. Design of the axial support
6. 3D Mechanical analysis

1st 3D magnetic optimization

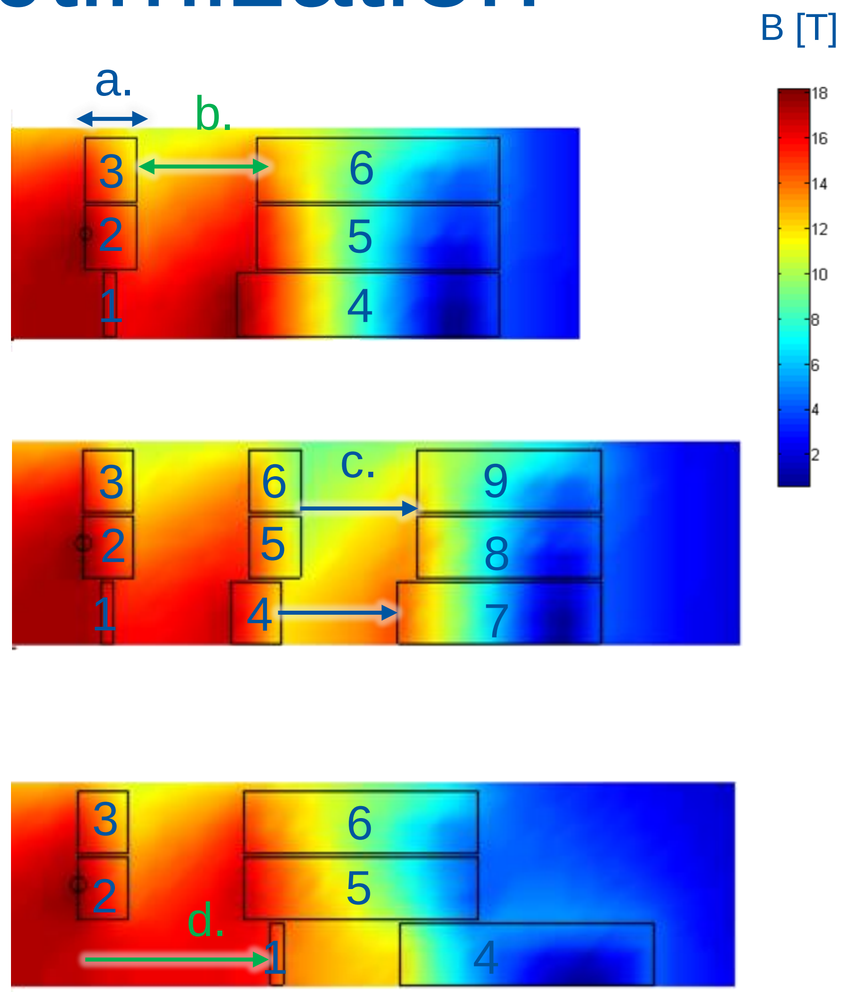
- **1st Objectives:**
  - Additional operational margin in the coil ends → **Peak field 1 T lower than in the straight section (ΔBpeak = 1 T)**
  - Minimize the conductor length



- **Process**:
  - Choice of iron lengths based on requirements
  - Parametric studies without iron
  - 1st order optimization without iron
  - 2nd order optimization with iron
  - Optimized for RMM, checked for ERMC



1st 3D magnetic optimization



Introducing spacers:

a. Varying # turns in inner blocks

b. Varying spacer length

→ ΔBpeak = 0.2T

c. Introducing a 2nd spacer

d. Shifting layers

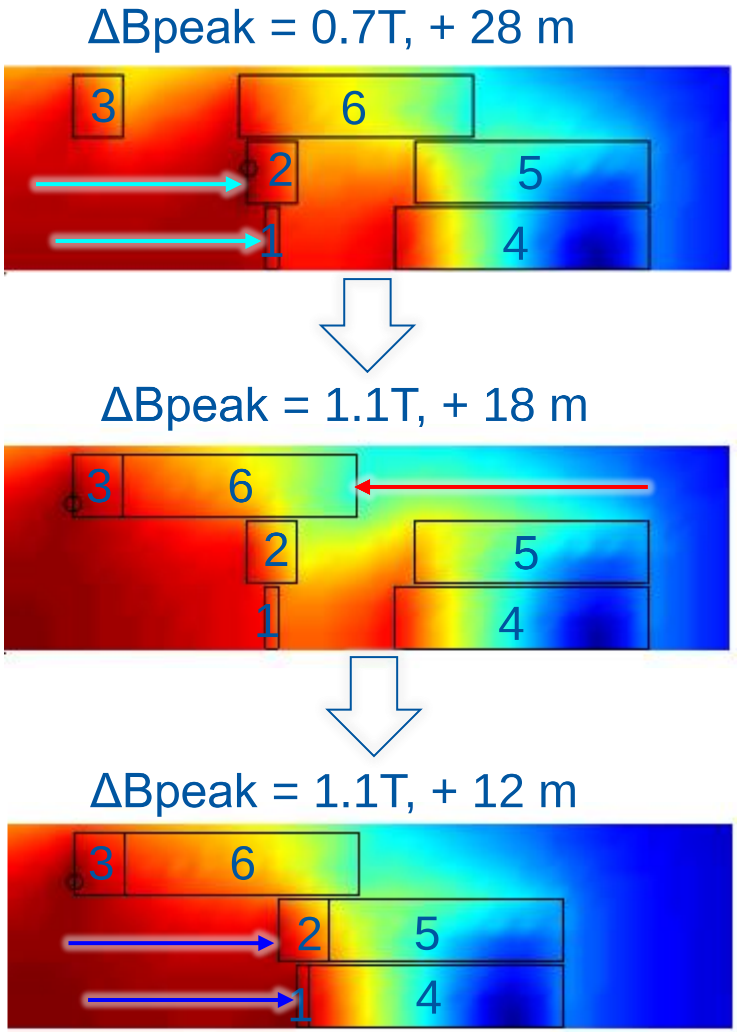
- Shifting 1+2 is the most efficient
- similar effect to adding an additional spacer
- Less risks during assembly and operation

1st 3D magnetic optimization

d. Shifting layers 1+2: decreases Bpeak, but increases the length

e. Moving block 6 in decreases Bpeak while decreasing the length

f. Moving blocks 1+2 out is more efficient than moving blocks 4+5

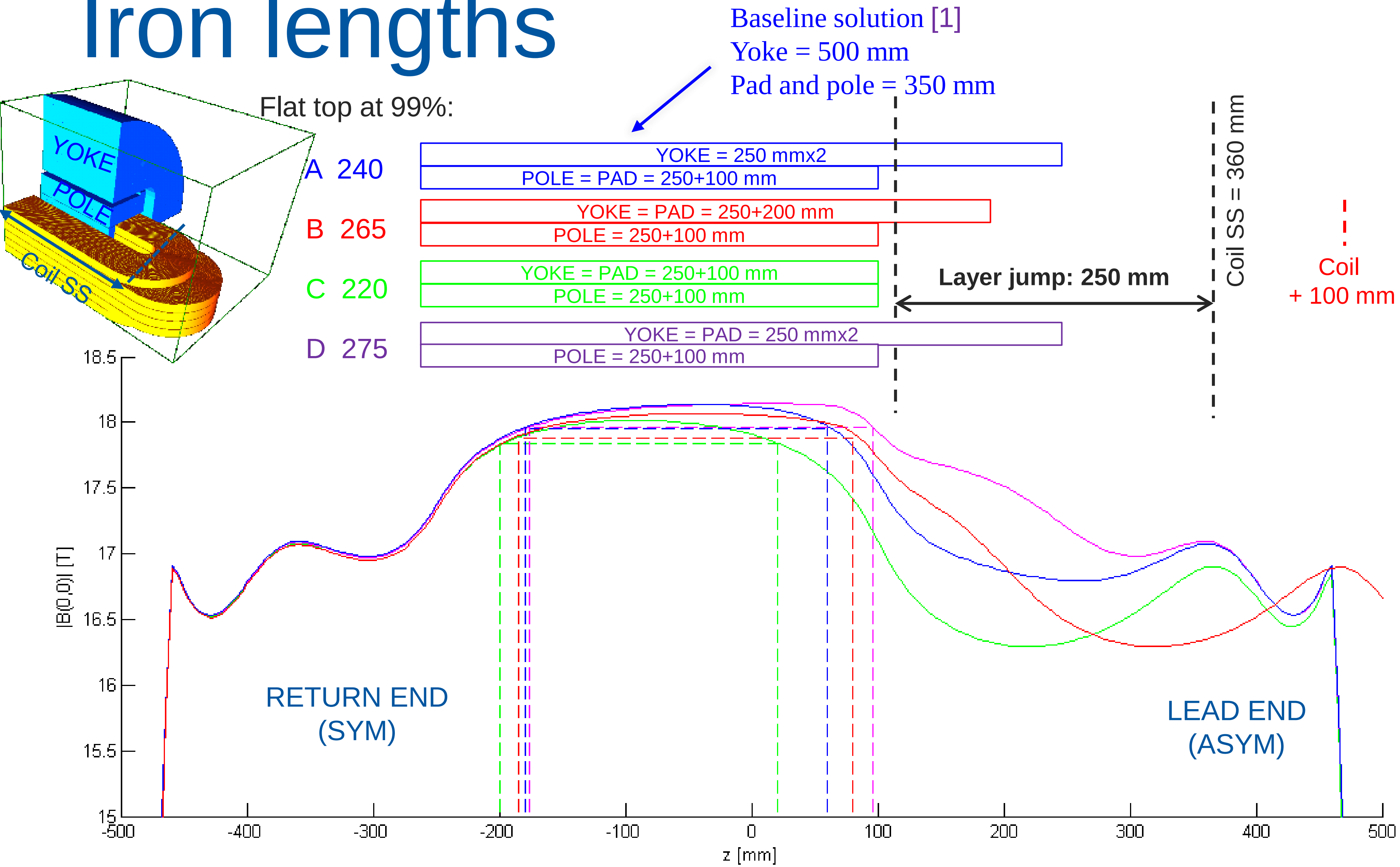


Optimized solution [1]

- **No end-spacer → simpler manufacturing**
- **Shifted layer → minimum peak field**

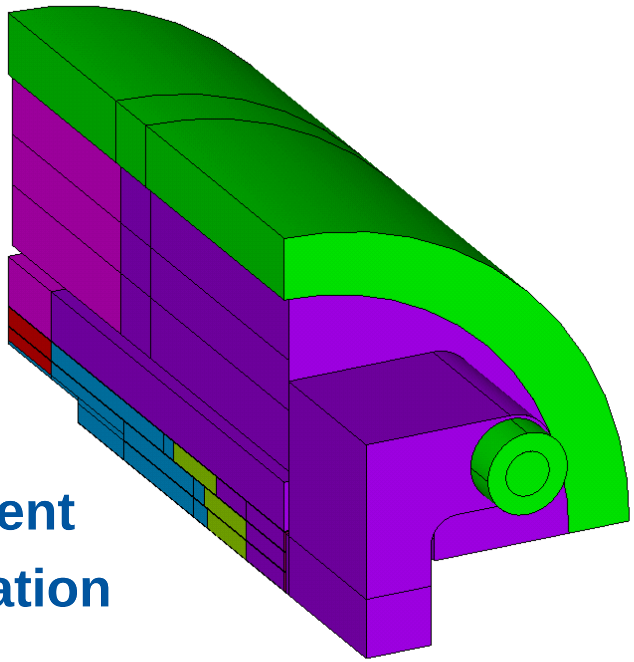
[1] S. Izquierdo Bermudez et al., “Design of ERMC and RMM, the Base of the Nb_3Sn 16 T Magnet Development at CERN”, ASC2016

Iron lengths



Axial mechanical support

- Structure designed for RMM, up to 18 T ultimate field
  → up to 3 MN of axial Lorentz forces
- Tie rods + endplate
  - used in R&D magnets at CERN/MDT
  - Can apply large pre-load force if needed
  - Allow tuning the pre-stress



Goals:

- Limit the conductor motion during powering

→ **Minimum pole-to-coil tension and detachment**

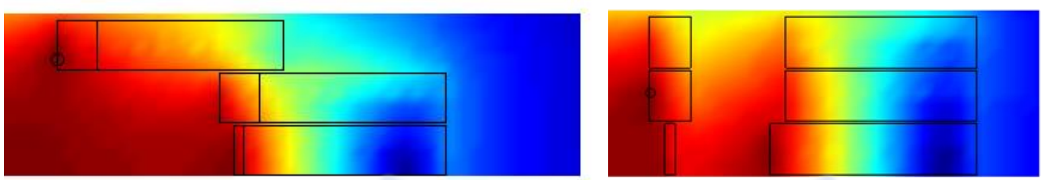
- **Coil stress < 150/200 MPa at Pre-load/Operation**
- Structural components below yield stress

Impact on 3D mechanical design

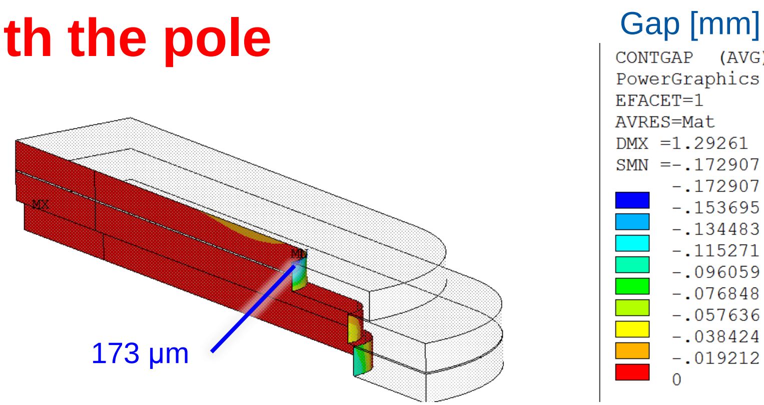
- Shifted layer optimum from the magnetic point of view
- Drawback: un-balanced forces in layer 3

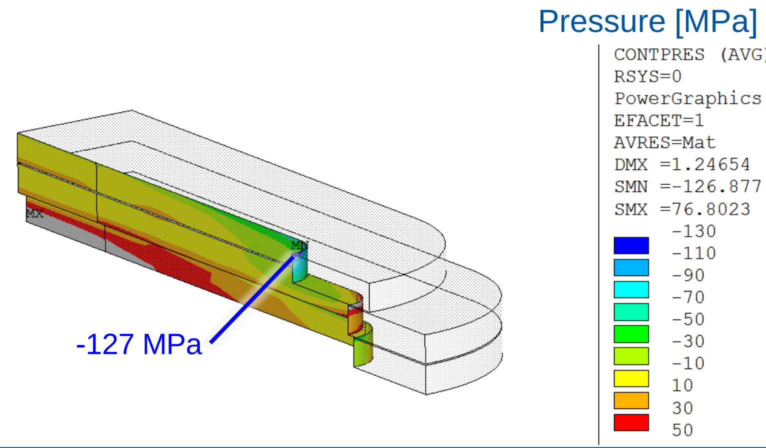
→ **Non-manageable tension and gap with the pole**

→ **No force management found**



Fz [kN], 18 T	Shifted	40 mm spacers
Layer 1	158	15+218 = 233
Layer 2	168	55+184 = 239
Layer 3	**362**	47+161 = 208
Total	688	679





2nd magnetic design optimization

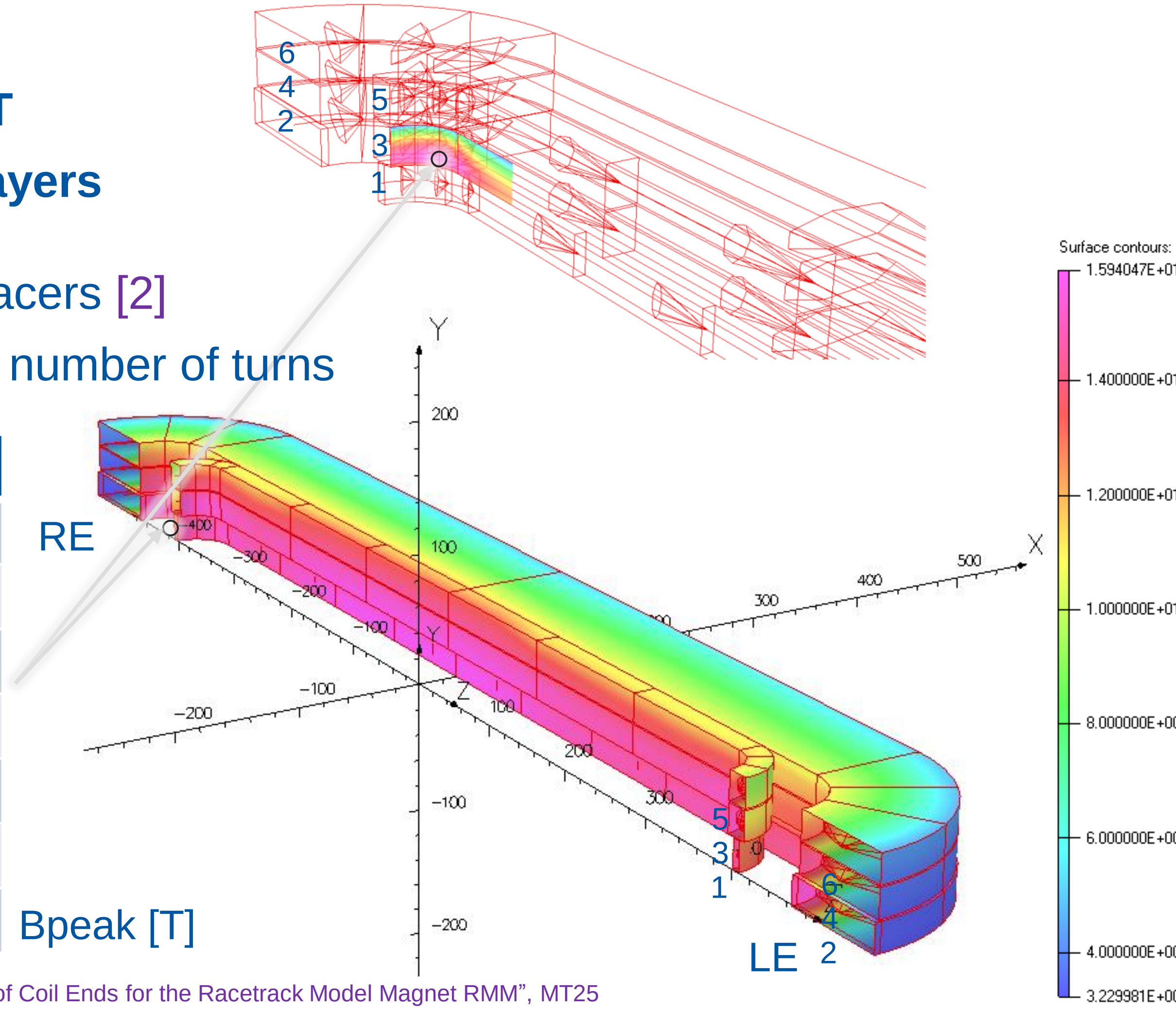
Objectives adapted:

- **Relaxing ΔBpeak to 0.5 T**
- **Balanced forces in the layers**

2nd optimization run using spacers [2]

→ Varying spacer length and number of turns

Bore field	15.9	18.1
Center	**16.0**	**18.3**
Coil end 1	15.3	17.7
Coil end 2	**15.5**	**18.0**
Coil end 3	**15.5**	**18.0**
Coil end 4	14.5	16.8
Coil end 5	14.4	16.7
Coil end 6	13.2	15.4

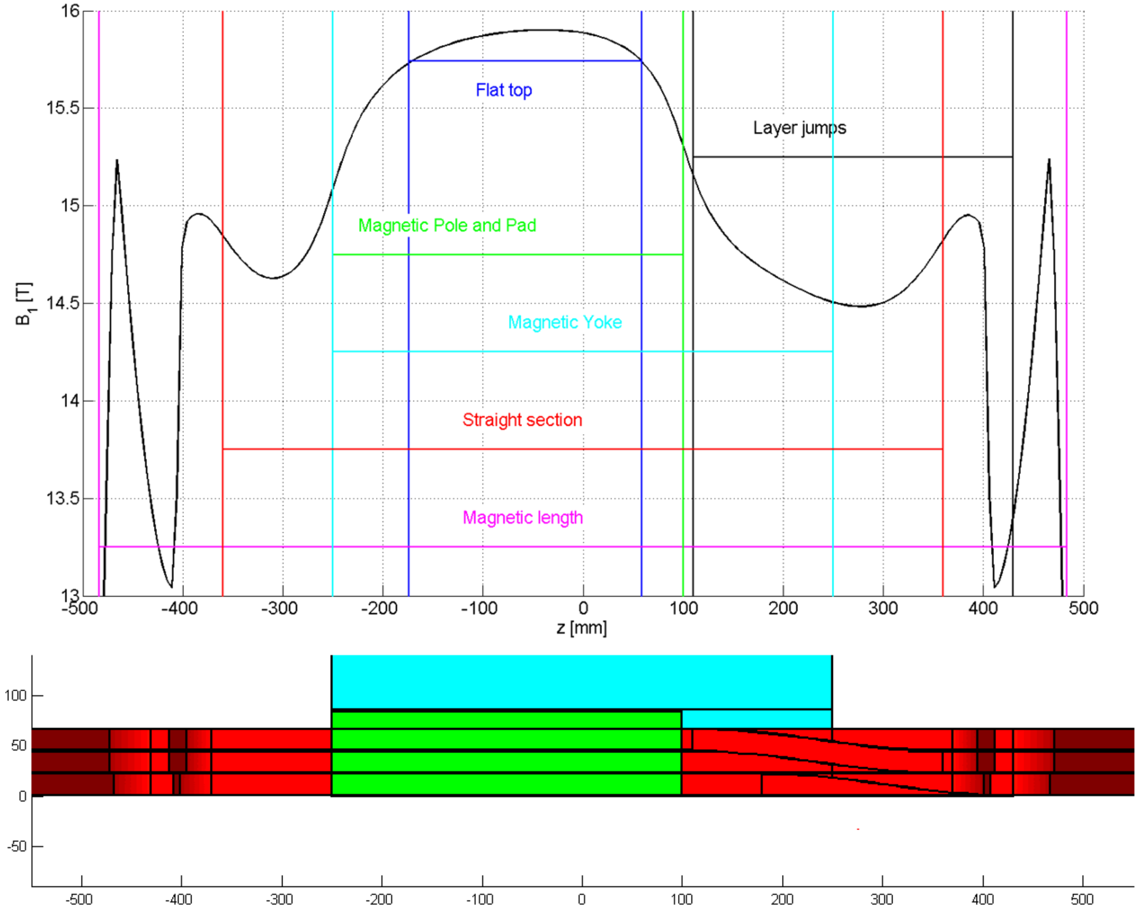


[2] E. Rochepault et al., "3D Magnetic and Mechanical Design of Coil Ends for the Racetrack Model Magnet RMM", MT25

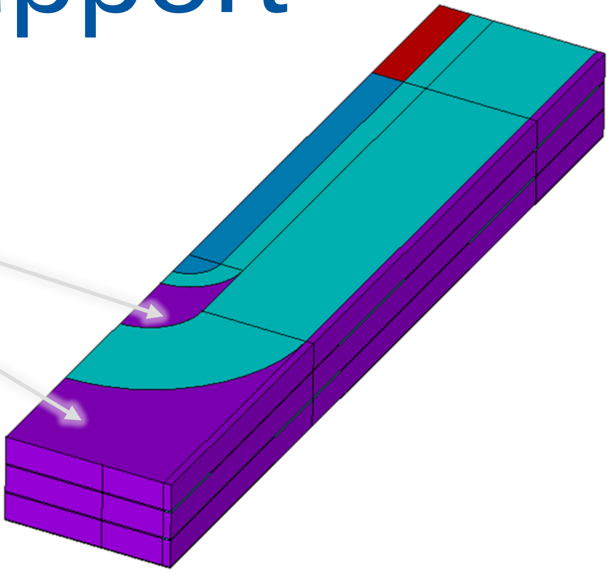
Magnet lengths

Parameter	Unit	ERMC	RMM
Straight section	mm	740	740
Coil unit length	m	184	185
Magnet unit length	m	384	567
Length of magnetic pole and pad	mm	350	350
Length of magnetic yoke	mm	500	500
Flat top length (at 99 %)	mm	230	233
Magnetic length	mm	908	967

Central field

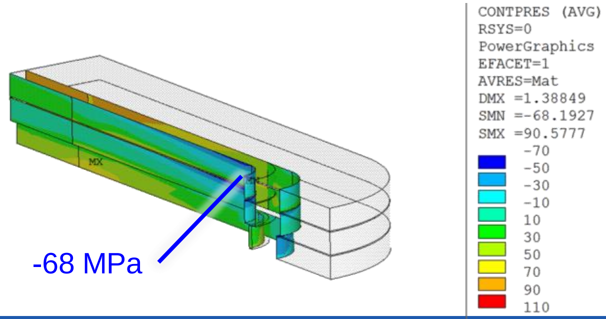


Design of the axial support

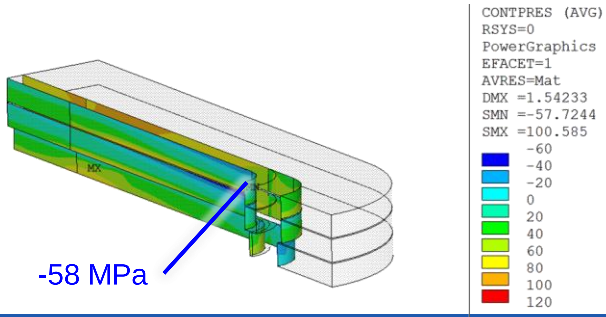


- End-shoe and spacer material
  - G11 [1]:
    - Mechanically softer
    - no need for electrical insulation
  - **Stainless steel → preferred solution** [2]:
    - **Mechanically stiffer**
    - **maintains better the pre-load**
- **Impact of contacts:**
  - **20% of pre-load force reaches the pole tip**
  - **Remainder goes in friction and bonded contacts**

Coil bonded, 0.2 friction elsewhere



Coil bonded, 0 friction elsewhere



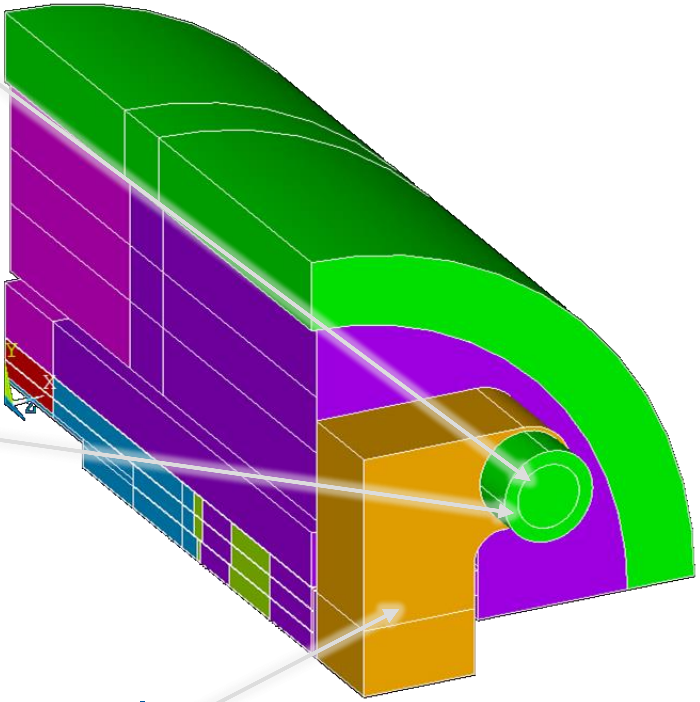
40 mm spacers

100% E.M. Fz pre-load + 50% Cool-Down

Design of the axial support

- Rod material: Al Vs. Stainless steel
  - Higher yield stress
  - Higher thermal contraction
  - → **higher pre-stress due to cool-down**
  - **Enough margin for both options**

- Increasing rod diameter:
  - Higher force during pre-load
  - → **less bending of the end-plate**
  - **Higher pre-stress due to cool-down**

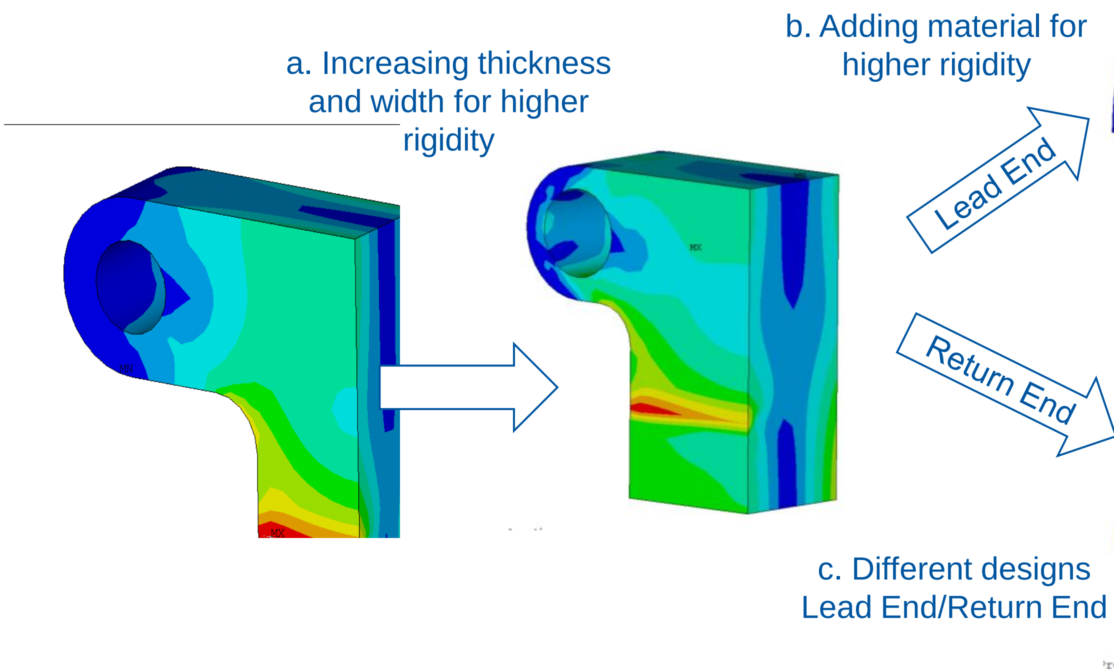


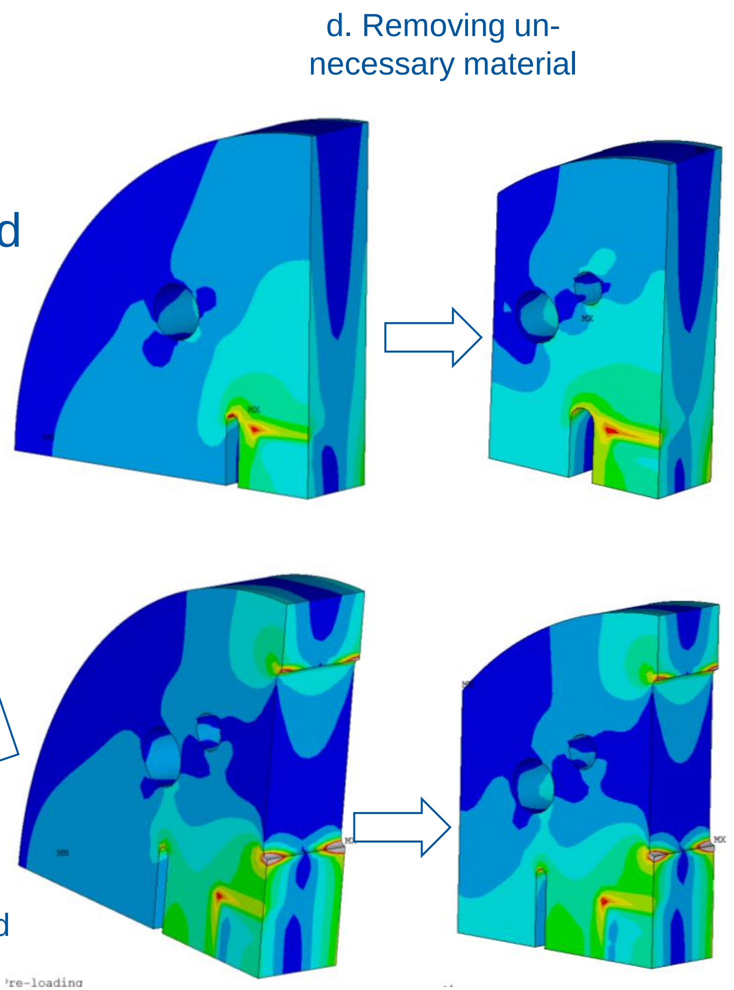
- End-plate material: Nitronic 40 Vs. Stainless steel
  - **Higher yield stress**
  - **Enough margin to consider both options**

Design of the axial support

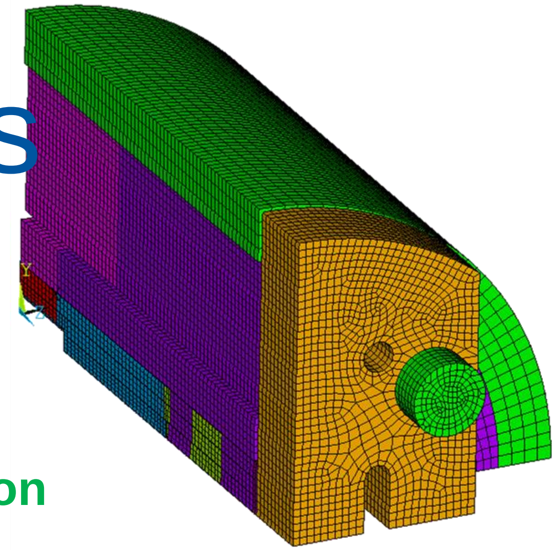
Goals:

- 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 applying the pre-stress on the Return End





3D Mechanical analysis

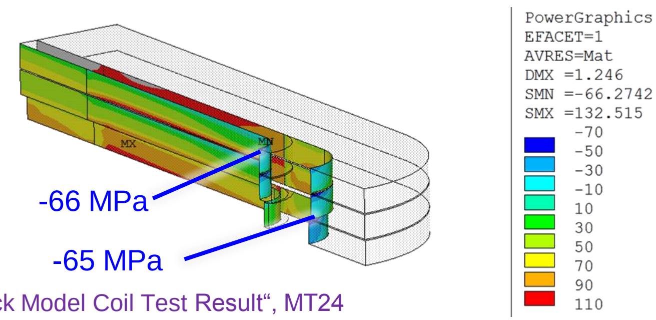


- Structure re-optimized using 2nd magnetic design [2]
- Coil ends can accept some motion e.g. RMC [3]: 16 T peak field, 95% SS, 25 MPa tension, 25 μm gap
- **Axial pre-load can be tuned to reduce coil end motion**

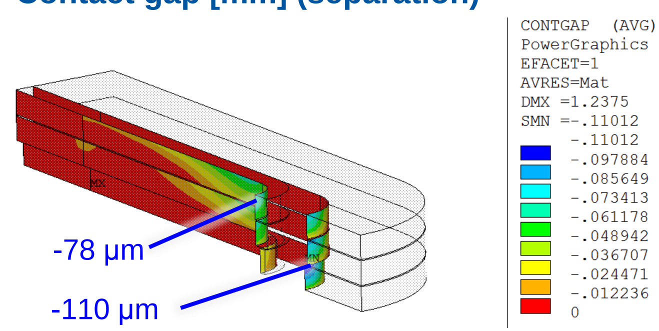
Rod Pre-load Fz		Rod Cool-Down Fz		16 T Operation			18 T operation		
[% 16 T Fz]	[% 18 T Fz]	[% 16 T Fz]	[% 18 T Fz]	[% Fz]	Tension [MPa]	Gap [μm]	[% Fz]	Tension [MPa]	Gap [μm]
14	11	76	56	78	64	106	59	90	150
27	20	**100**	75	**103**	56	94	77	80	133
72	53	139	**104**	143	46	76	**107**	66	110
102	76	169	126	173	25	42	129	45	75
135	**100**	208	155	209	-4	0	156	8	13

Pre-load = 53% of 18 T Fz
After Cool-Down = 104%

Contact pressure [MPa] (bonded)



Contact gap [mm] (separation)



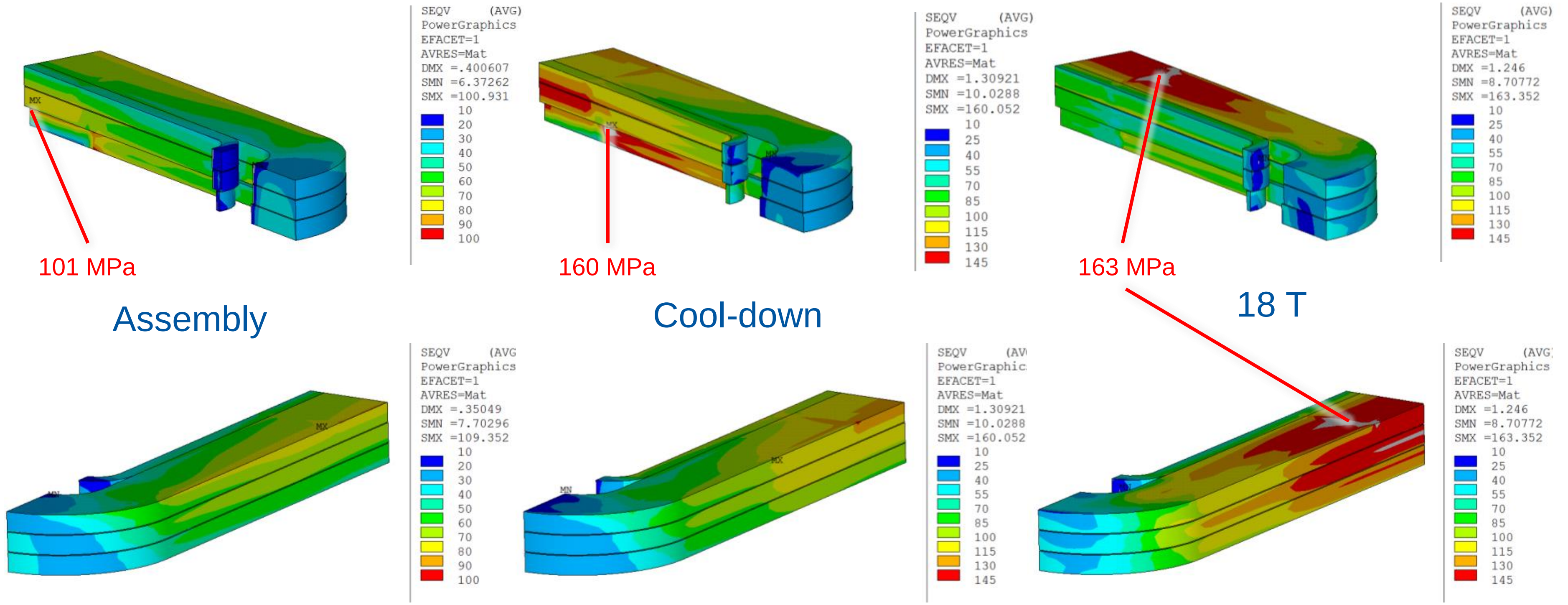
[3] J.C. Perez et al., “16 T Nb3Sn Racetrack Model Coil Test Result“, MT24

3D Mechanical analysis

Von Mises Stress [MPa]:

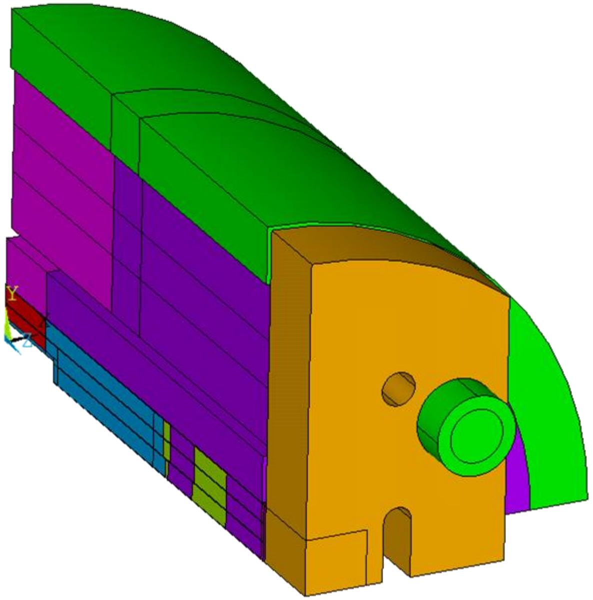
→ **Peak stress in the straight section**

→ **<150 at Pre-load, <200 Cool-Down/Operation**



Equivalent (Von Mises) Stress [MPa]

Summary: Baseline design



- 2D: representative of a block-coil FCC design
  - 50 mm bore, 16 T
  - 10/19% margin at 4.2/1.9 K
  - 3 double-layer pancakes
  - Bladder & Keys pre-load

- 3D: racetracks for simplicity of fabrication
  - Aligned coil-ends with 1 spacer/layer
  - 0.5 T lower Bpeak in the ends → **magnetic margin**
  - Ends optimized to limit the coil motion → **«mechanical» margin**

- Room for R&D
  - **Different materials considered for axial support**
  - **Possibility to tune the pre-load**

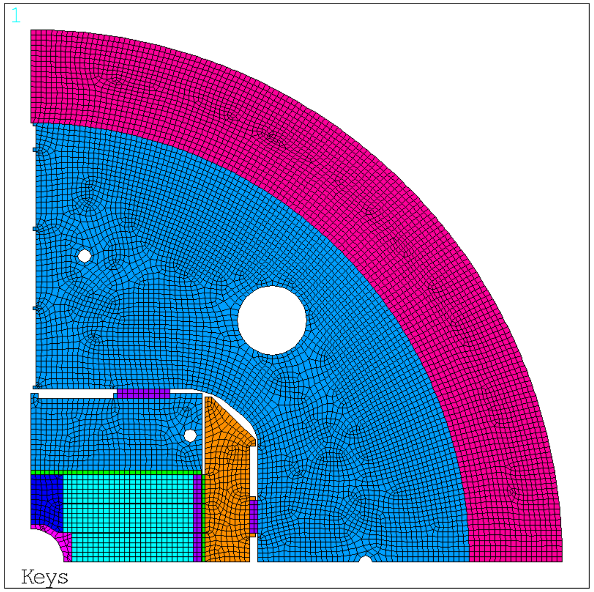
Thank you for your attention!

Backup slides

2d Mechanical design

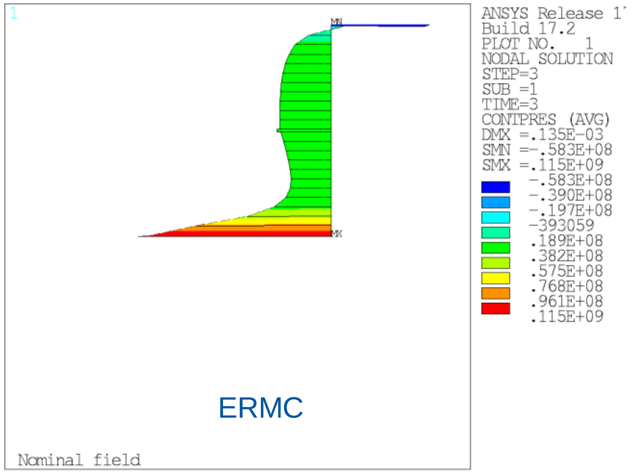
Goals:

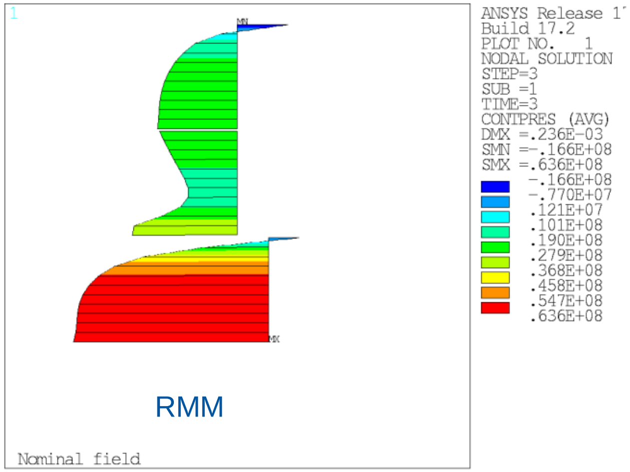
- Limit the conductor motion during powering → Minimum pole-to-coil tension and detachment
- Coil stress < 200 MPa at all steps
- Use the same structure for ERMC and RMM
- Structural components below yield stress
- Structure must withstand 18 T ultimate field



Bladder&Keys Shell-based support structure

Pole-Coil contact pressure [Pa]





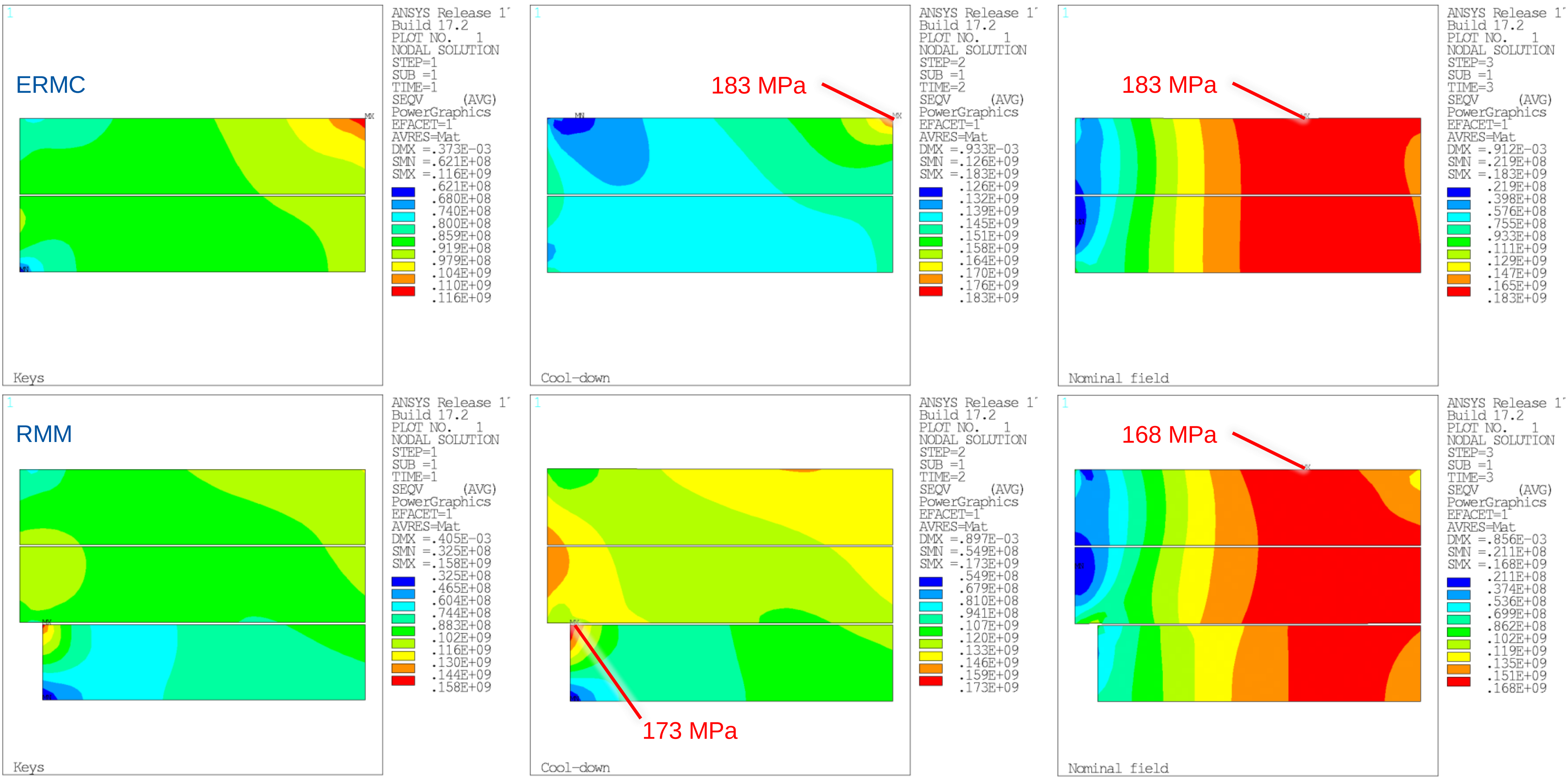
→ Marginal tension
→ Overall positive contact pressure

[R. Ortwein]

2d Mechanical design

Von Mises stress [Pa]
27.5/33 GPa modulus at cold

Assembly | Cool-down | Powering



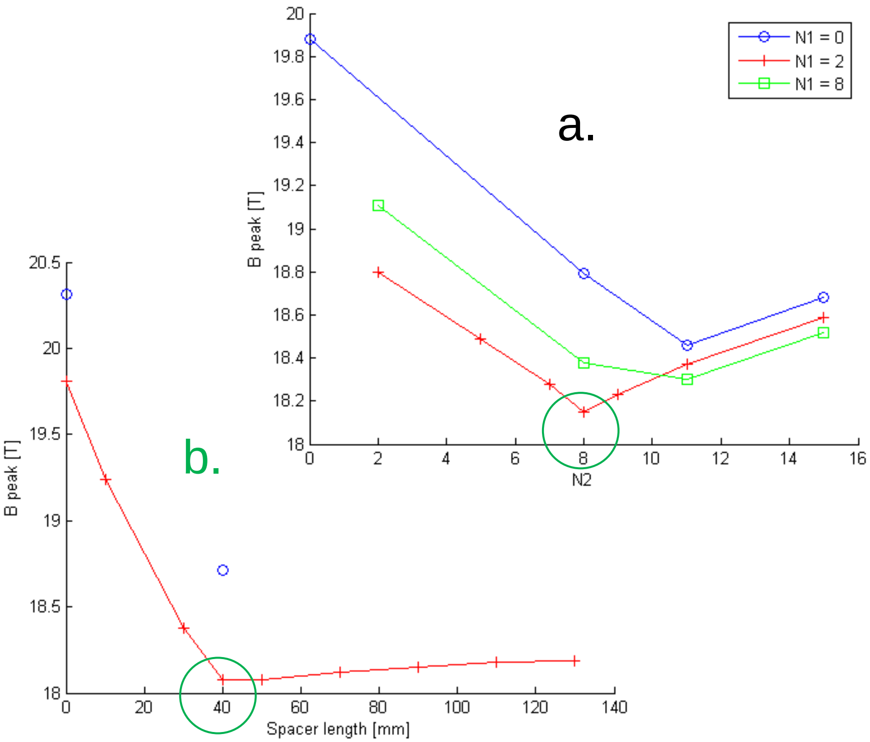
[R. Ortwein]

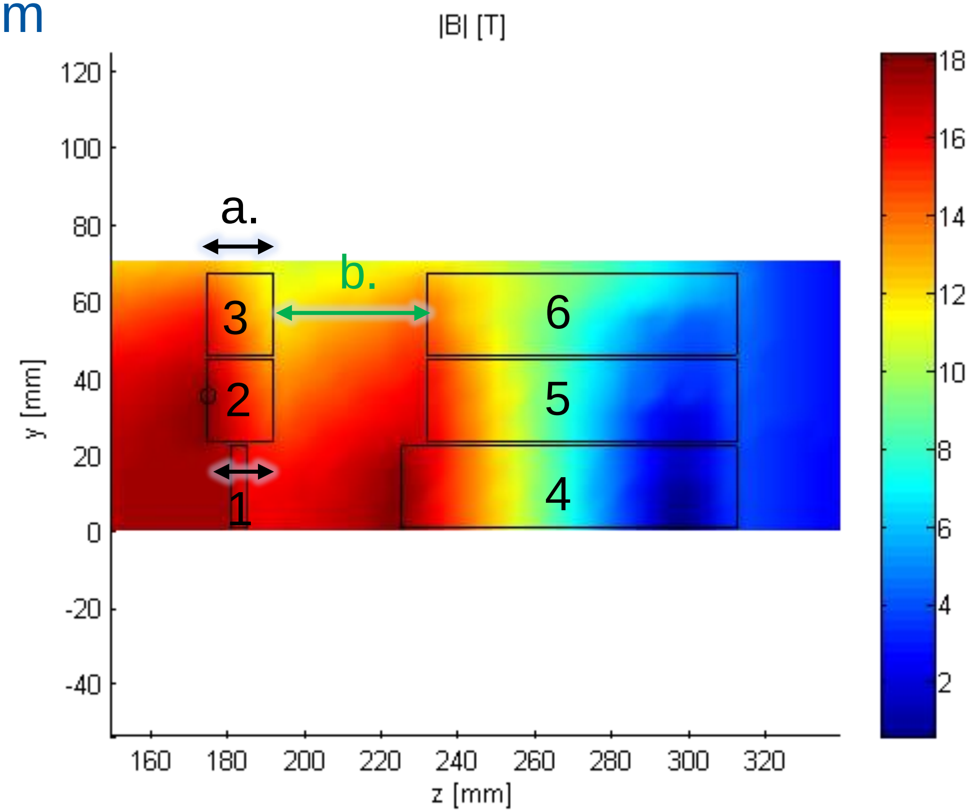
1st 3D magnetic optimization

Introducing spacers:

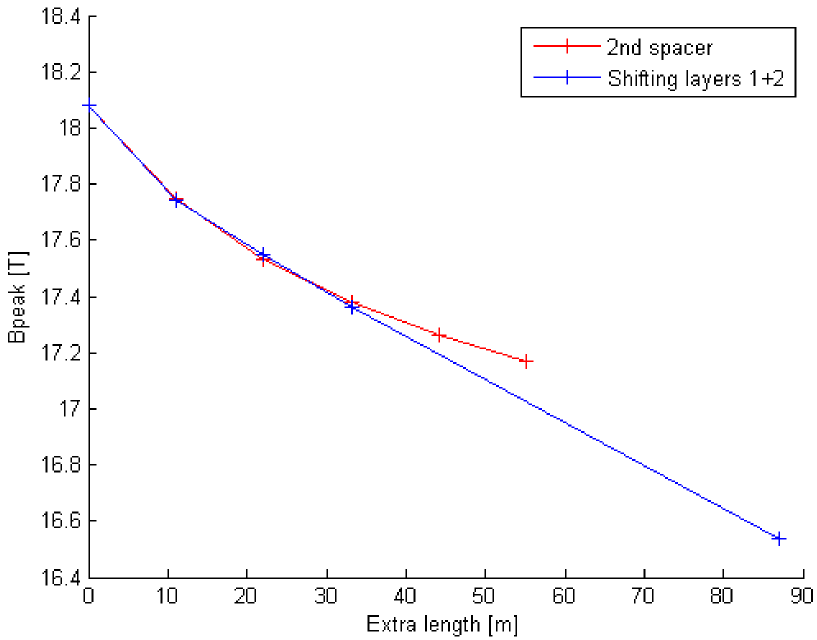
a. Varying # turns in inner blocks → N1 = 2, N2 = N3 = 8

b. Varying spacer length → 40 mm

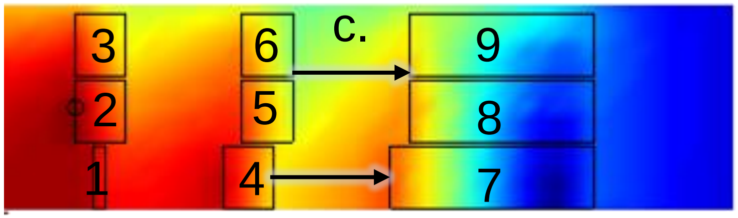




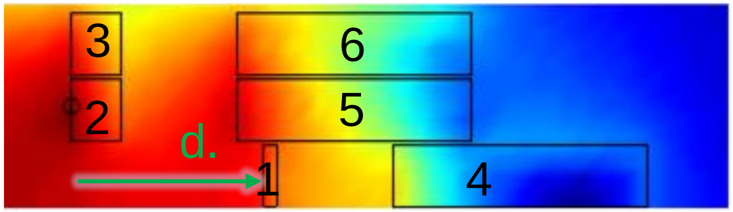
1st 3D magnetic optimization



c. Introducing a 2nd spacer



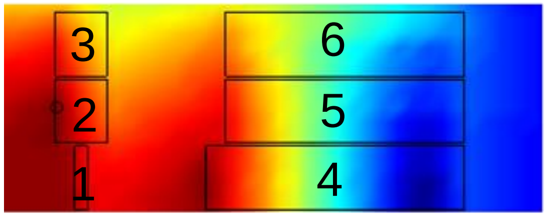
d. Shifting layers



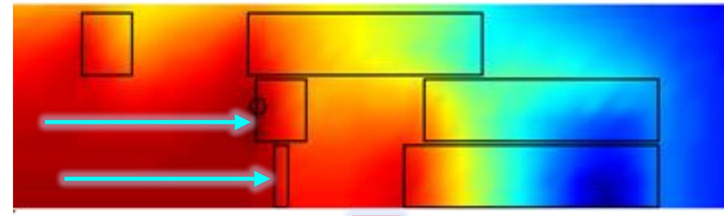
→ Shifting layers:

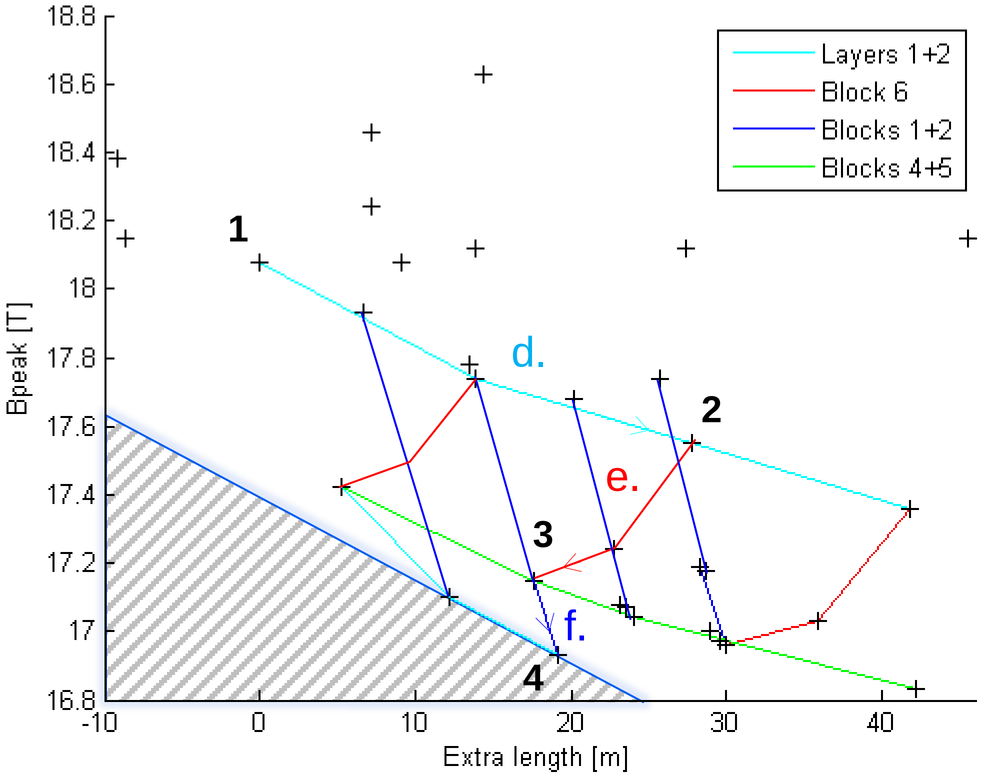
- Shifting 1+2 is the most efficient
- similar effect to adding an additional spacer
- Less risks during assembly and operation

1st 3D magnetic optimization

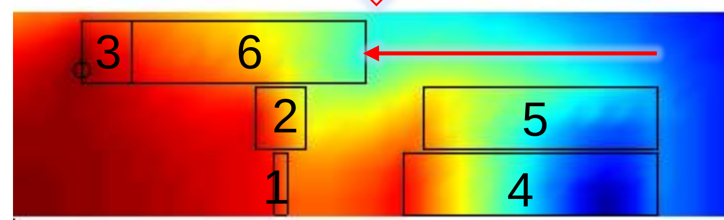
1


d. Shifting layers 1+2 decreases Bpeak, but increases the length

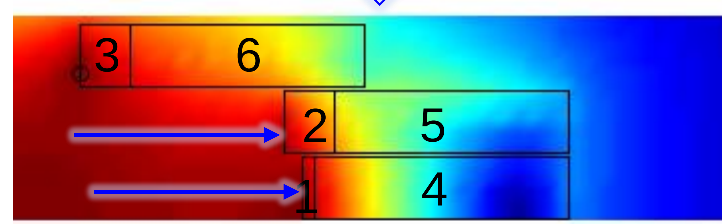
2




e. Moving block 6 in decreases Bpeak while decreasing the length

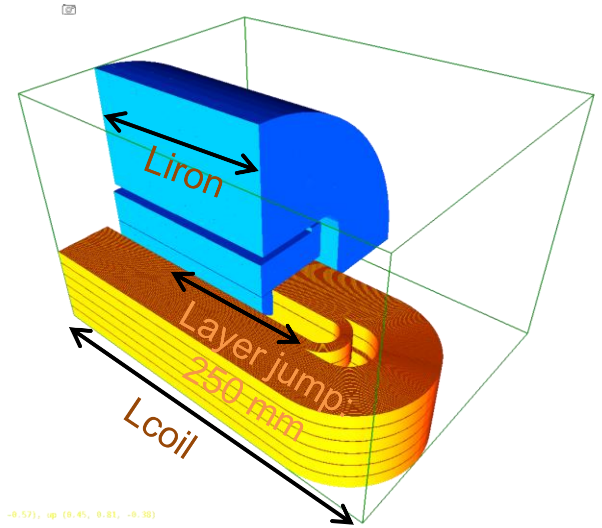
3


f. Moving blocks 1+2 out is more efficient than moving blocks 4+5

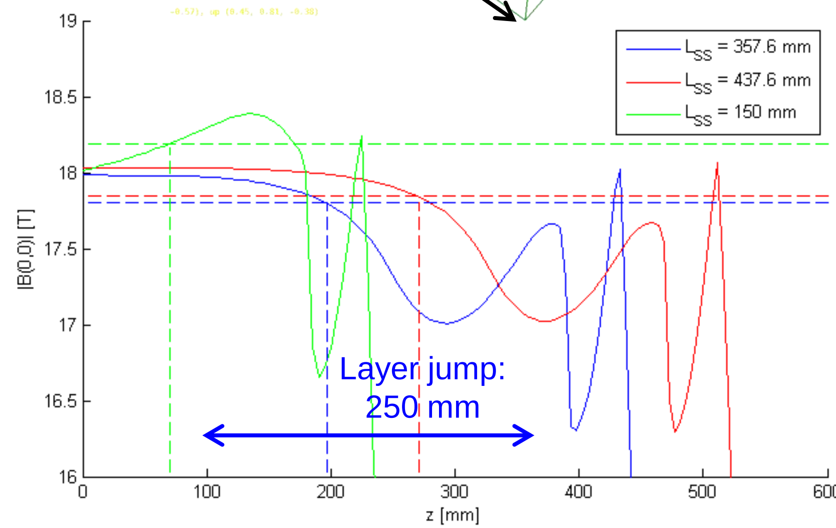
4


Trade-off with the magnet length

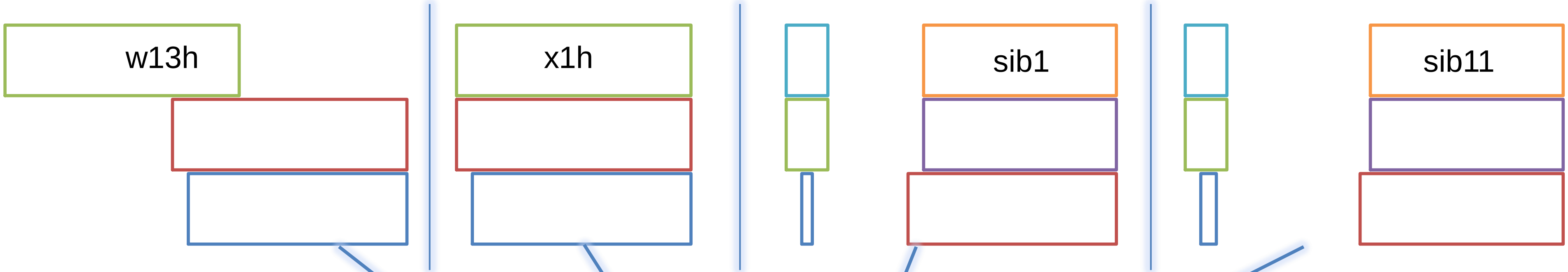
- Central iron parts → +2T central field
- Magnetic requirements:
  - "Flat top" > 200 mm
  → iron at least 300 mm
  - Lower peak field in ends and layer jump
  → Coil ends outside iron
- Limit in cable length: 600 m
  → Limit in coil length



L_{SS}-L_{iron} [mm]	L_{Coil} [mm]	Flat top [mm]	L_{Cond} [m]	Bpeak SS-ends [T]
0	624	140	318	-0.4
135	990	320	495	-0.1
215	**1040**	**394**	**538**	**0.1**
215	1200	542	622	0.1



Peak field in the ends

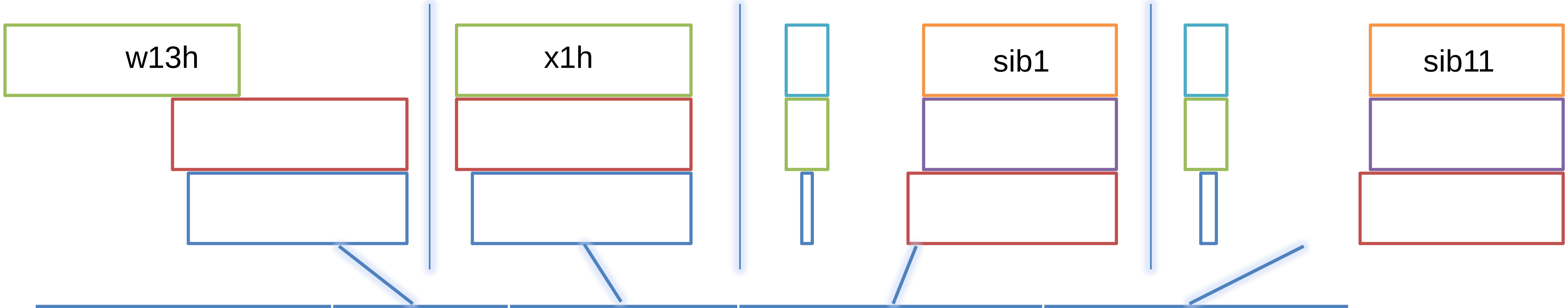


Bpeak [T], 16 T	Shifted	Aligned, no spacer	40 mm spacers		60 mm spacers	
Block in layer	1/1	1/1	1/2	2/2	1/2	2/2
Layer 1	14.8	**17.3**	15.5	15.8	15.3	15.4
Layer 2	14.4	17.2	**15.8**	14.5	**15.5**	14.5
Layer 3	**14.9**	15.9	14.7	13.3	14.4	13.3
Center	**16.0**	**16.0**	**16.0**		**16.0**	

→ Shifted case optimized for peak field (1T difference)

→ 60 mm spacers is a compromise between magnetics (still 0.5T difference) and mechanics (balanced forces)

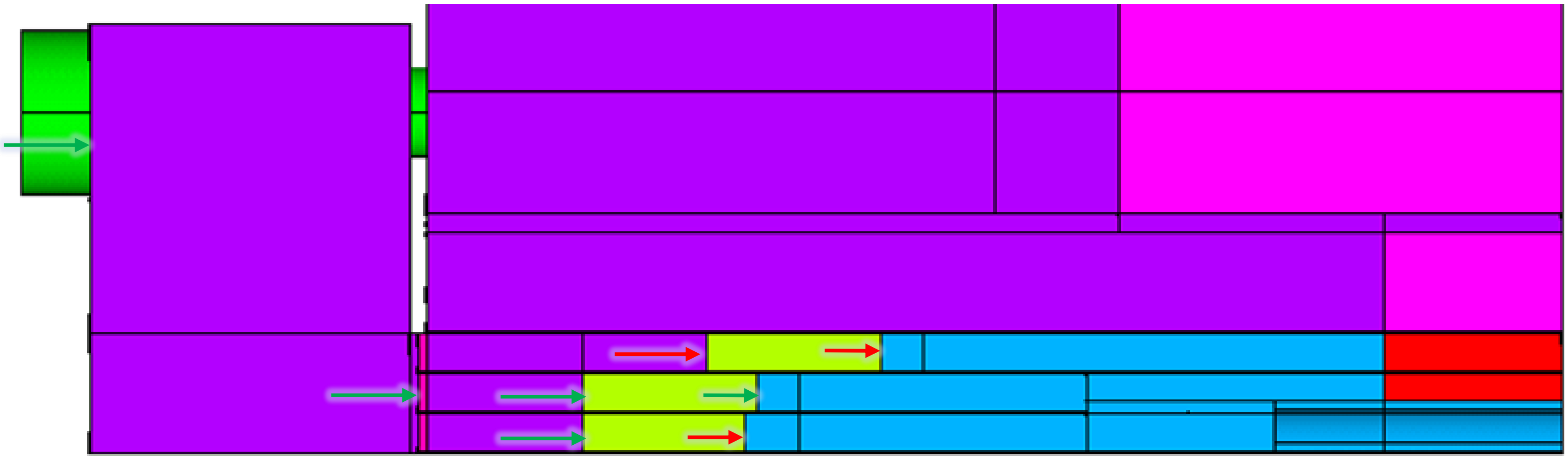
Lorentz forces in the ends



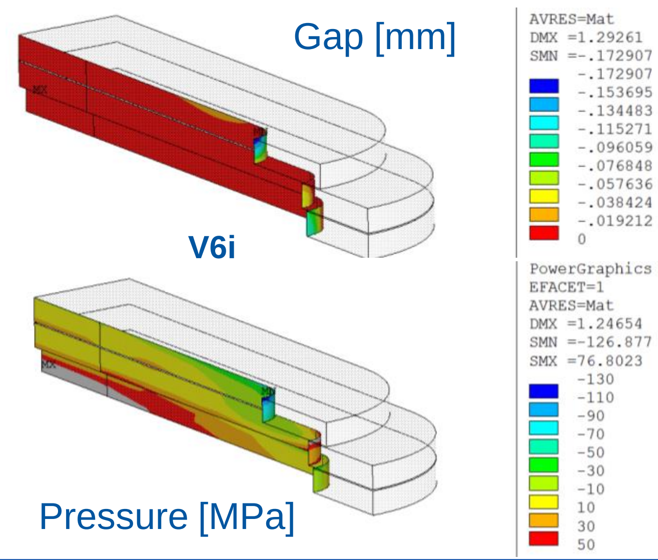
Fz [kN], 18 T	Shifted	Aligned, no spacer	40 mm spacers		60 mm spacers	
Block in layer	1/1	1/1	1/2	2/2	1/2	2/2
Layer 1	158	234	14.9	218	22.1	212
Layer 2	168	239	55.2	184	53.5	185
Layer 3	**362**	206	46.6	161	45.5	162
Total	688	679	679		680	

→ Total force equivalent in all designs
→ Shifted case unbalanced

3D Mechanical design



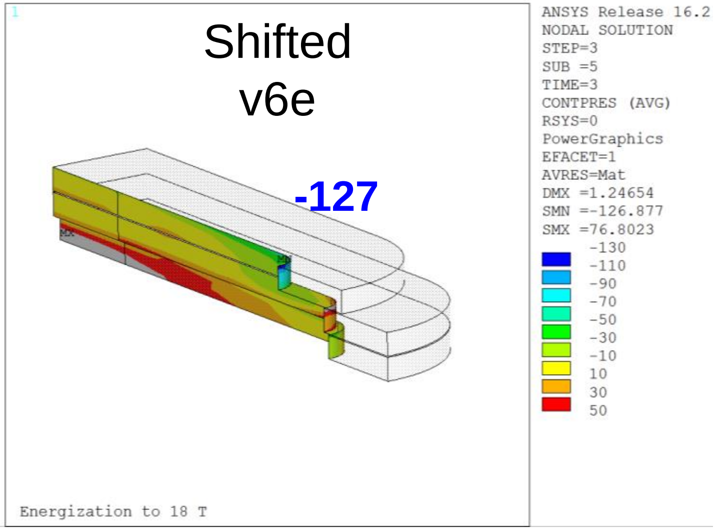
Layer	Endshoe 4.2 K	Coil,end 4.2 K	Pole 4.2 K	EM forces 18 T		Contact 18 T	Gap 18 T
	kN	kN	kN	kN	%	MPa	µm
1	196	70	43	158	27	-40	130
2	230	39	51	168	30	7	57
3	340	133	32	362	9	-127	173
Total	767	242	126	688	22		

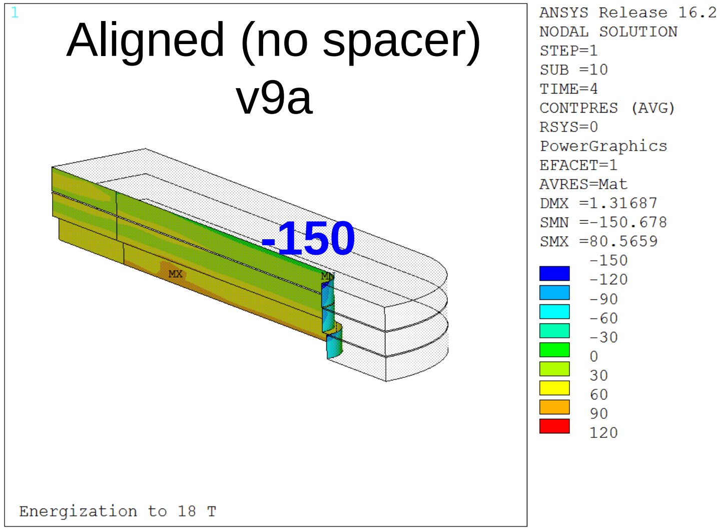


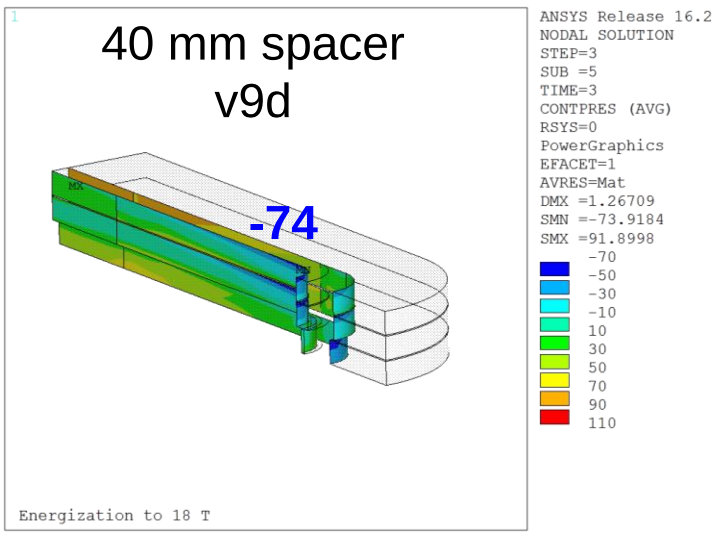
Goals: limit the conductor motion during powering

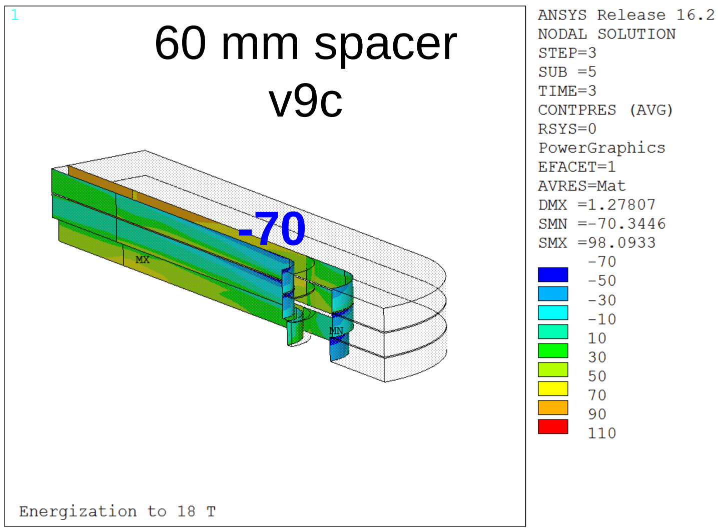
- Minimum pole to coil tension
- Minimum pole to coil detachment

Inner contacts



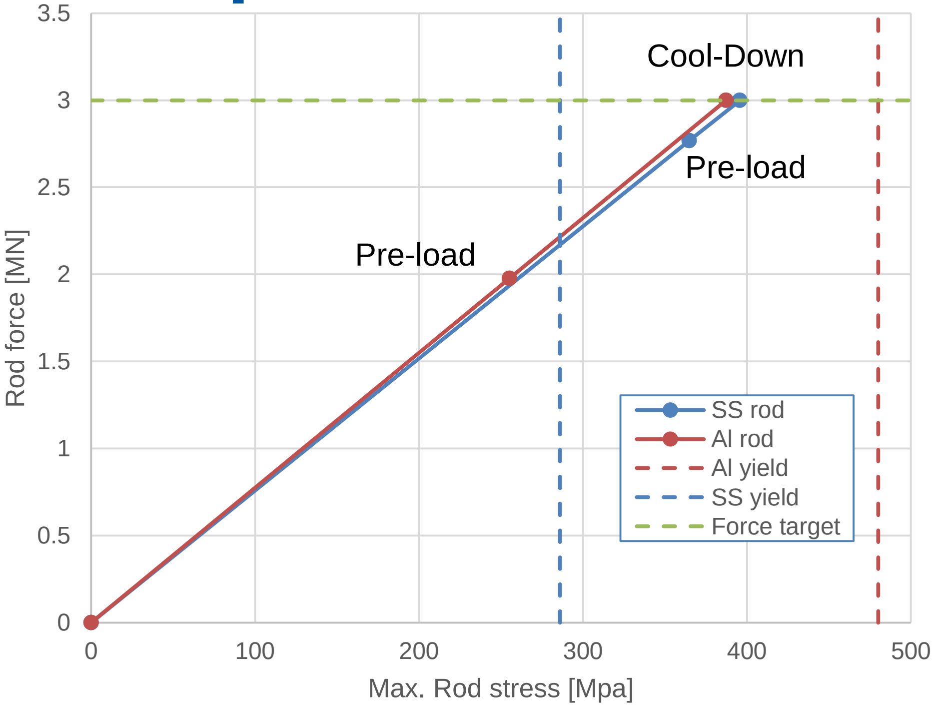


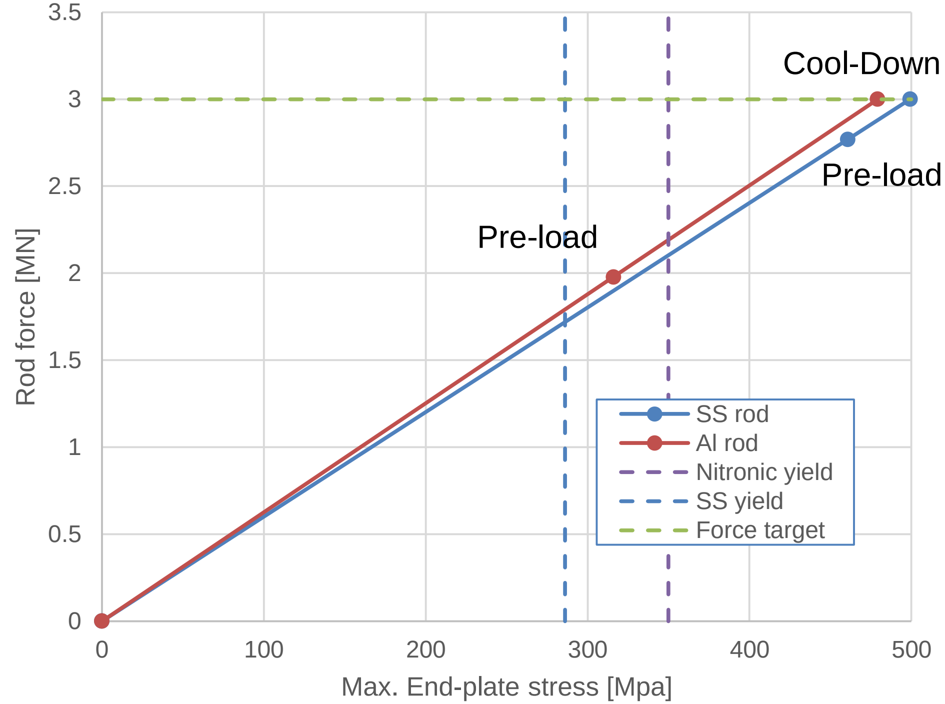




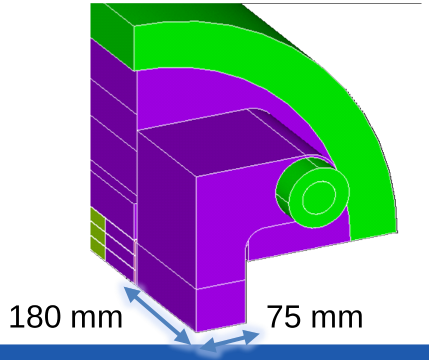
→ With spacers: Lower tension in the inner contacts

Impact of rod material (shifted)

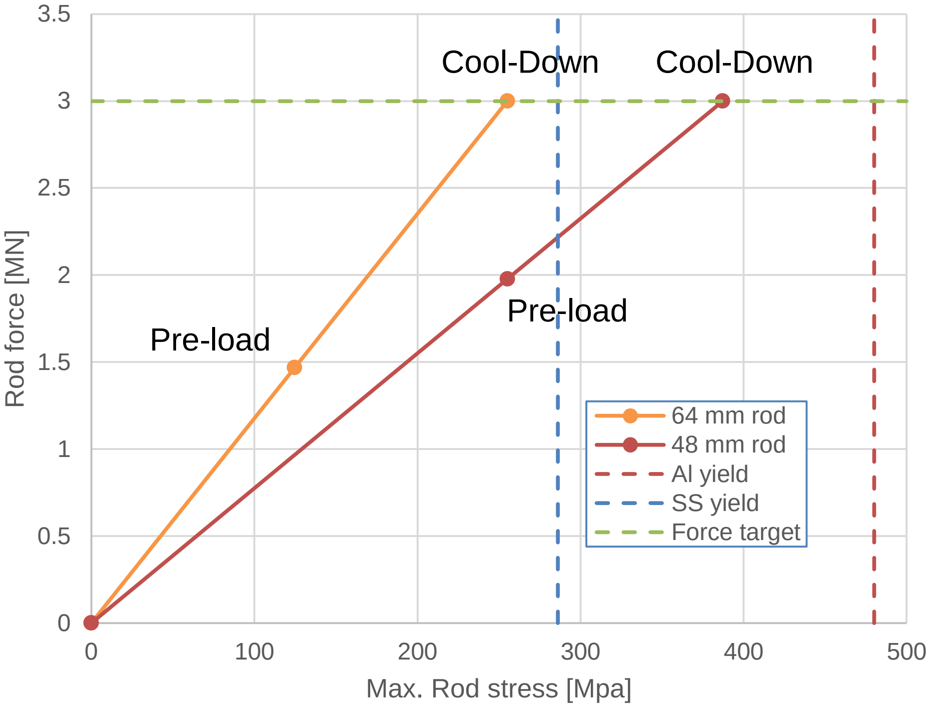


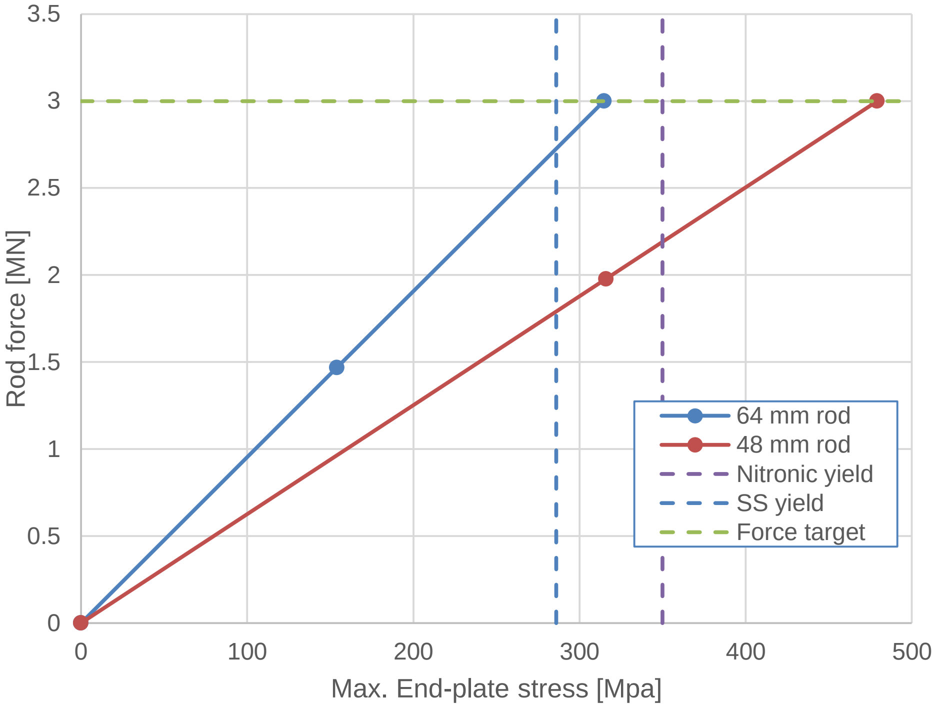


- Stainless steel rod:
  - **Limited by yield stress at room temperature**
  - **Low pre-stress due to cool-down**
  - **Increases bending (and peak stress) in the end-plate**
- Al rod:
  - **Higher yield stress**
  - **High pre-stress due to cool-down**



Impact of rod diameter (60 mm spacers)



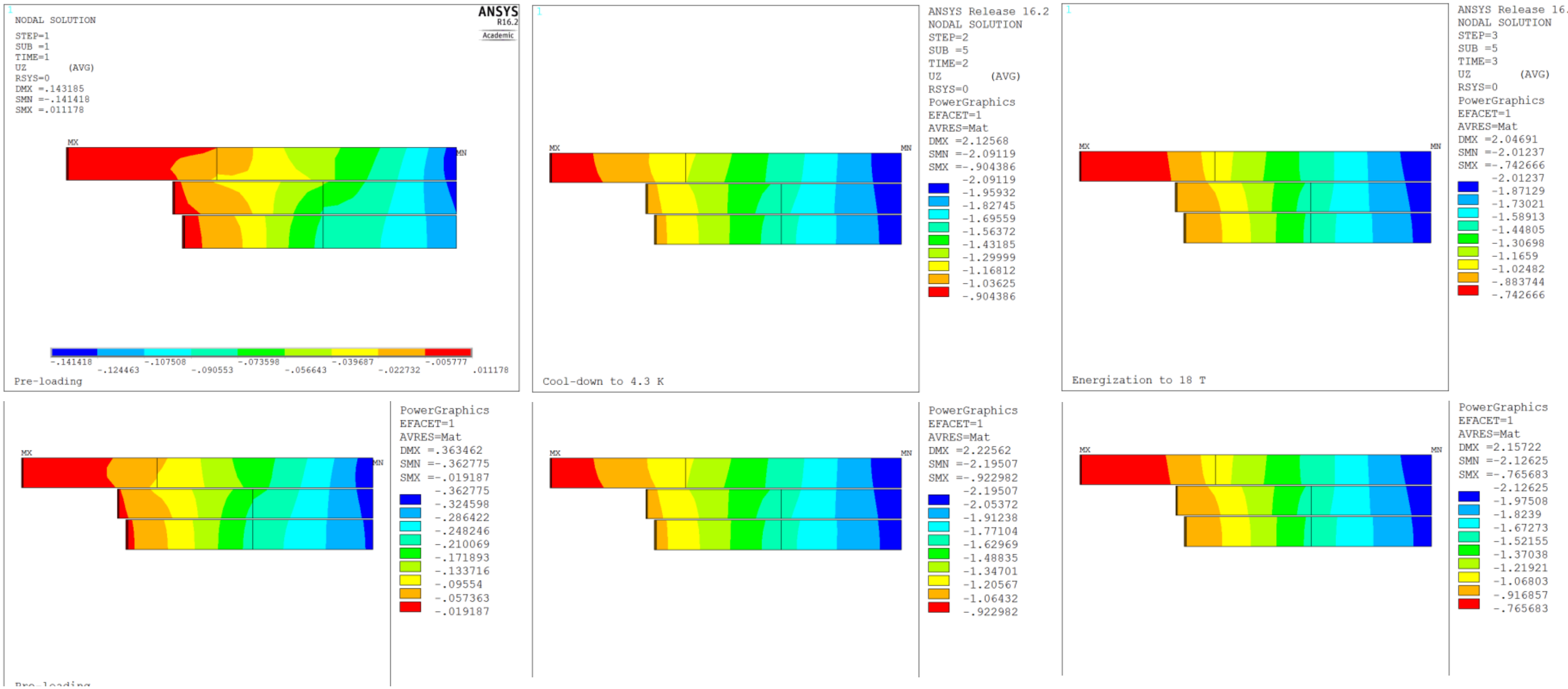


- 64 mm diameter:
  - **Higher force during pre-load → less bending of the end-plate**
  - **Higher pre-stress due to cool-down**
  - **Stainless steel rod can also be used without yielding**
  - **Stainless steel end-plate can also be used without yielding**

Impact of stainless steel rod (shifted)

V6e
Al rod

V6o
SS rod

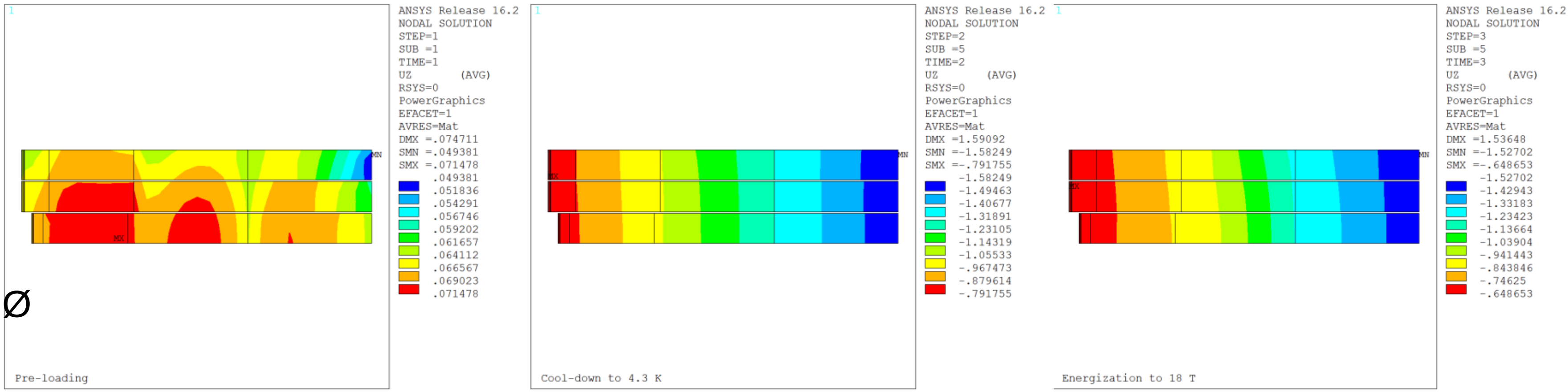


	Total force [MN]	Cool-Down [µm]		18 T [µm]		Difference [µm]	
		in	out	in	out	in	out
Al	2.9	-904	-2091	-743	-2012	+161	+79
SS	3.2	-922	-2195	-766	-2126	+156	+69

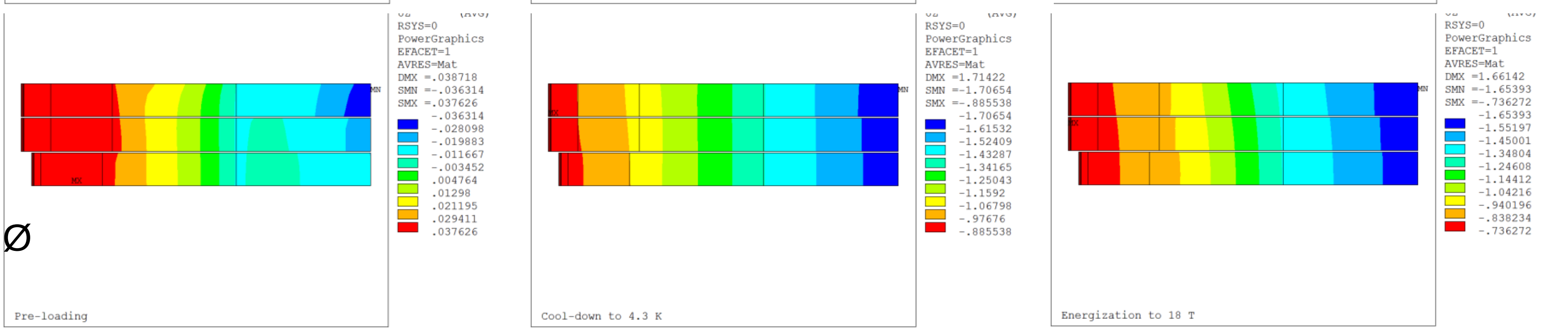
→ **Minor impact**

Impact of a bigger rod (60 mm spacers)

v9c
Al rods
48 mm Ø



V9e
Al rods
64 mm Ø

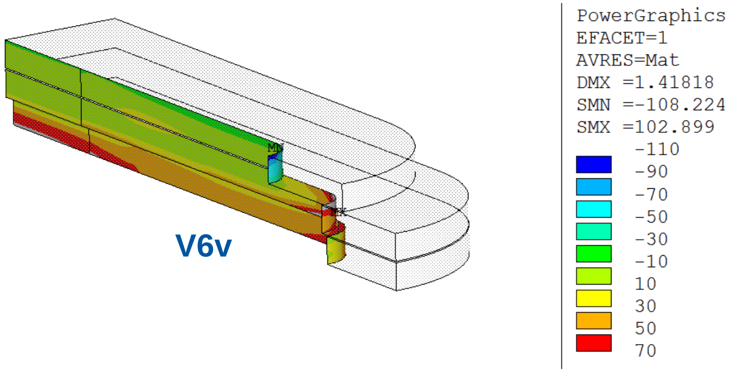


	Total force [MN]	Cool-Down [µm]		18 T [µm]		Difference [µm]	
		in	out	in	out	in	out
48 mm	3.2	-792	-1582	-649	-1527	+143	+55
64 mm	4.5	-886	-1707	-736	-1654	+150	+53

→ **Minor impact**

Alternative 1: «force management»

Layer	Endshoe 4.2 K	Coil,end 4.2 K	Pole 4.2 K	EM forces 18 T		Contact 18 T	Gap 18 T
	kN	kN	kN	kN	%	MPa	µm
V6i – nominal case							
1	196	70	43	158	27	-40	130
2	230	39	51	168	30	7	57
3	340	133	32	362	9	-127	173
Total	767	242	126	688	22		
V6v – sliding endshoe3*, pushing on layer 3 only							
1	89	139	78	158	49	-10	
2	86	147	79	168	47	30	
3	336	212	47	362	13	-108	
Total	511	498	204	688	36		



- 180 mm thick plate
- Max. pre-load load (limited by yielding in the plate)
- Stainless-steel end shoes
- Pre-load applied only on layer 3
- Endshoe 3 allowed to slide on layer 2

→ **No major improvement**