ERMC and RMM Design Update

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Annual EuroCirCol WP5 meeting

7th November 2016

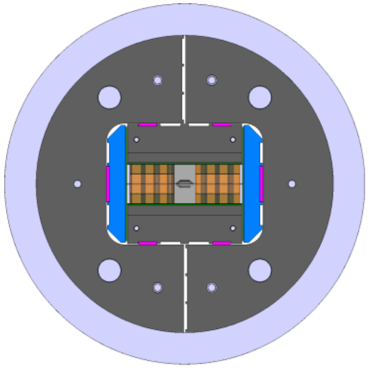
Motivation

ERMC

Enhanced Racetrack Model Coil

16 T midplane field

- Demonstrate field on the conductor
- Coil technology development

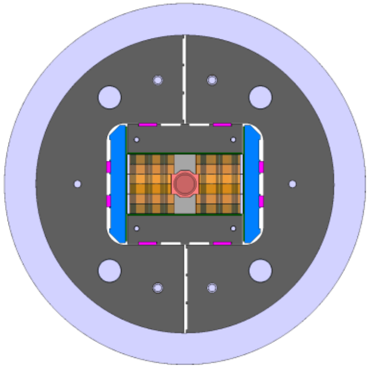


RMM

Racetrack Model Magnet

16 T in a 50 mm cavity

- Demonstrate field on the aperture
- Mechanics (including inner coil support)



Base for the development of the technology needed for the 16 T dipole program

Motivation

Stage 1 priorities:

1. Demonstrate the field
   - Design based on the "available" critical current density (~20% lower than FCC target at 18 T, 4.2 K)
   - As field quality is not an objective, profit from the use of an iron pole to decrease the ratio between the field in the aperture and in the coil to ~ 1
2. Study the mechanics

Non graded design

- Engineering design well advanced
- Plan to start winding beginning of 2017

Stage 2 priorities:

1. Coil size → Grading
   - Design based on the target FCC critical current density
   - High Field Nb_3Sn splice development needed
2. Field quality (b_n<10 units, including iron saturation)
   - Still, it will need to be accommodated within the same structure, changing only the collar pack assembly

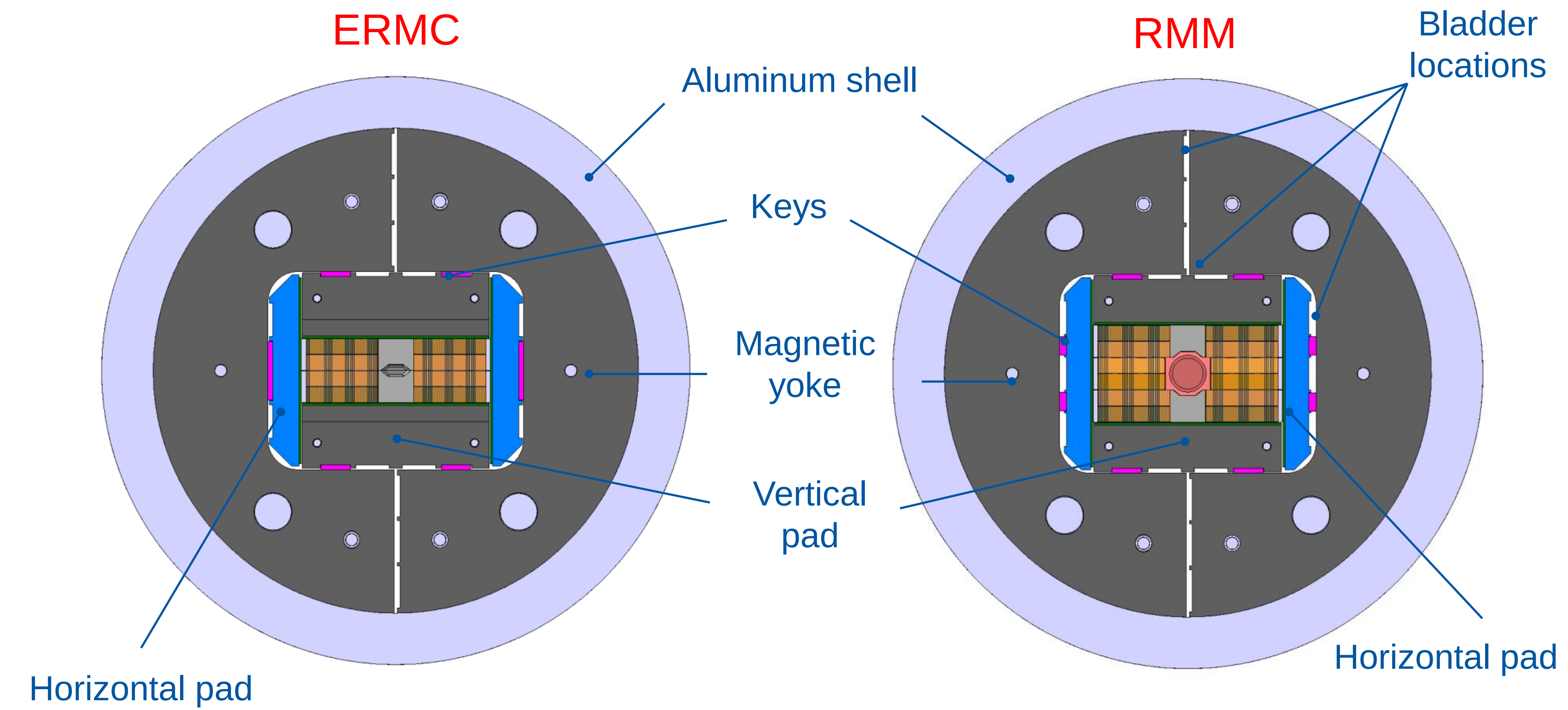
Graded design

- Conceptual design and parametric studies
- Final cross section will follow as much as possible EuroCirCol guidelines

Non-Graded Design

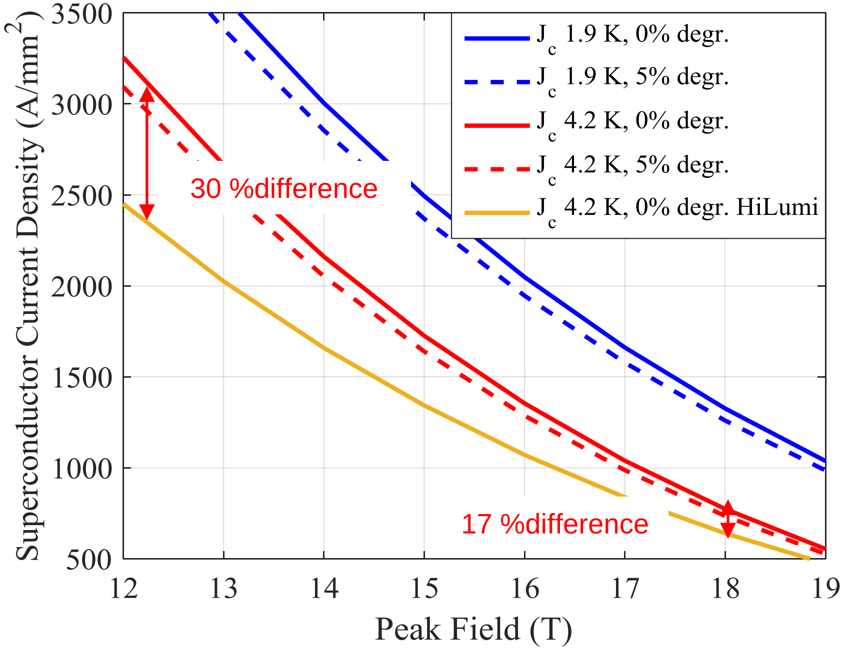
Overview of magnet design

Same structure for the two magnets. Only the horizontal pad is different to optimize the stress in the coil.



Conductor and cable parameters

- 40 strands, 1 mm diameter
- Cu/Sc: 1
- J_c at 4.2 K
  - 3250 A/mm^2 at 12 T
  - 1725 A/mm^2 at 15 T
  - 1215 A/mm^2 at 18 T
- Cabling degradation = 5 %
- Stainless steel core
  - 14 mm x 0.025 mm
- Assumed growth during HT[1]
  - 3 % in thickness
  - 1% in width



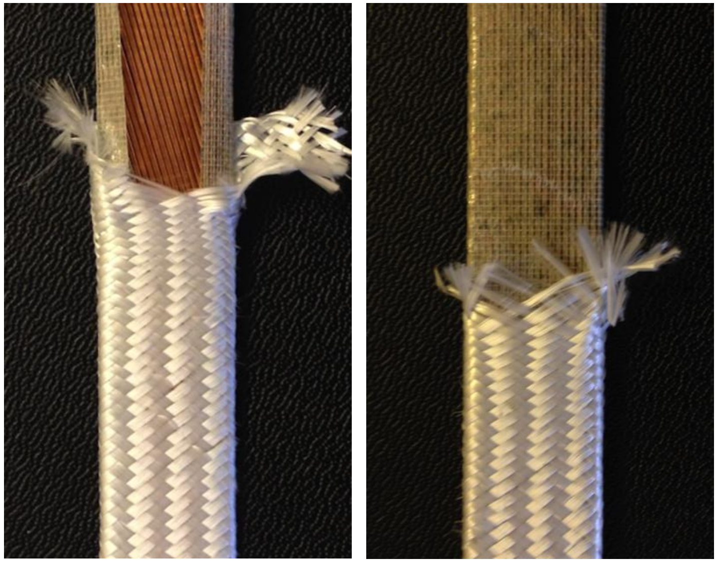
	Before Heat Treatment	After Heat Treatment
Cable bare width, mm	20.900	21.109
Cable bare thickness, mm	1.820	1.875

[1] E. Rochepault, et. al., Dimensional Changes of Nb3Sn Rutherford Cables During Heat Treatment, MT24

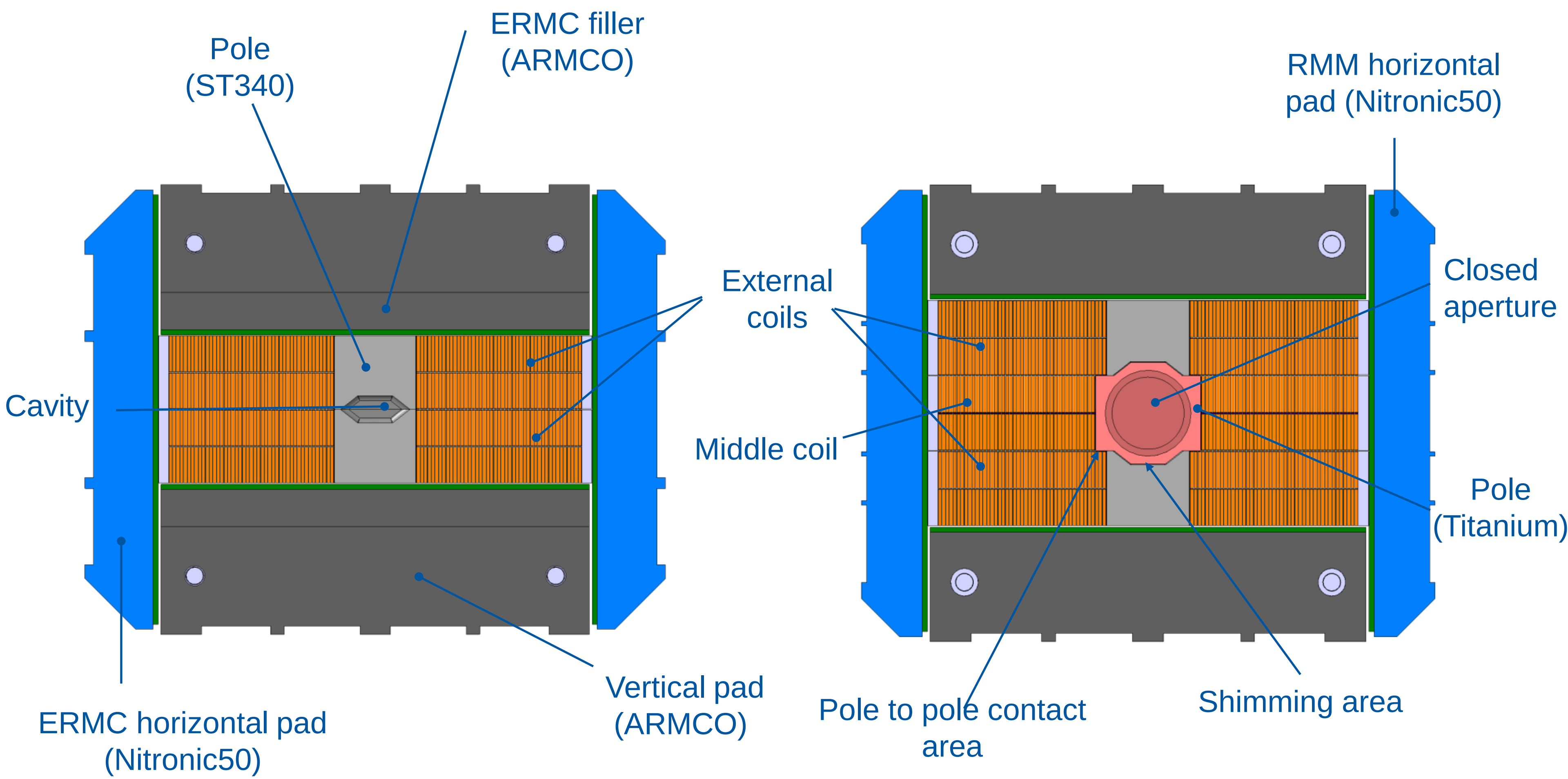
Cable insulation

- Insulation thickness per side = 0.150 mm
- Mica sheets (COGEBI FIROX®, 0.080 mm thick) with three different widths, to evaluate the maximum width that is technically feasible (33/35/38 mm)
- Tests in CGP scheduled on the bradding parameters for second half of November using FRESCA2 cable.

11 T cable



Coil Pack Design

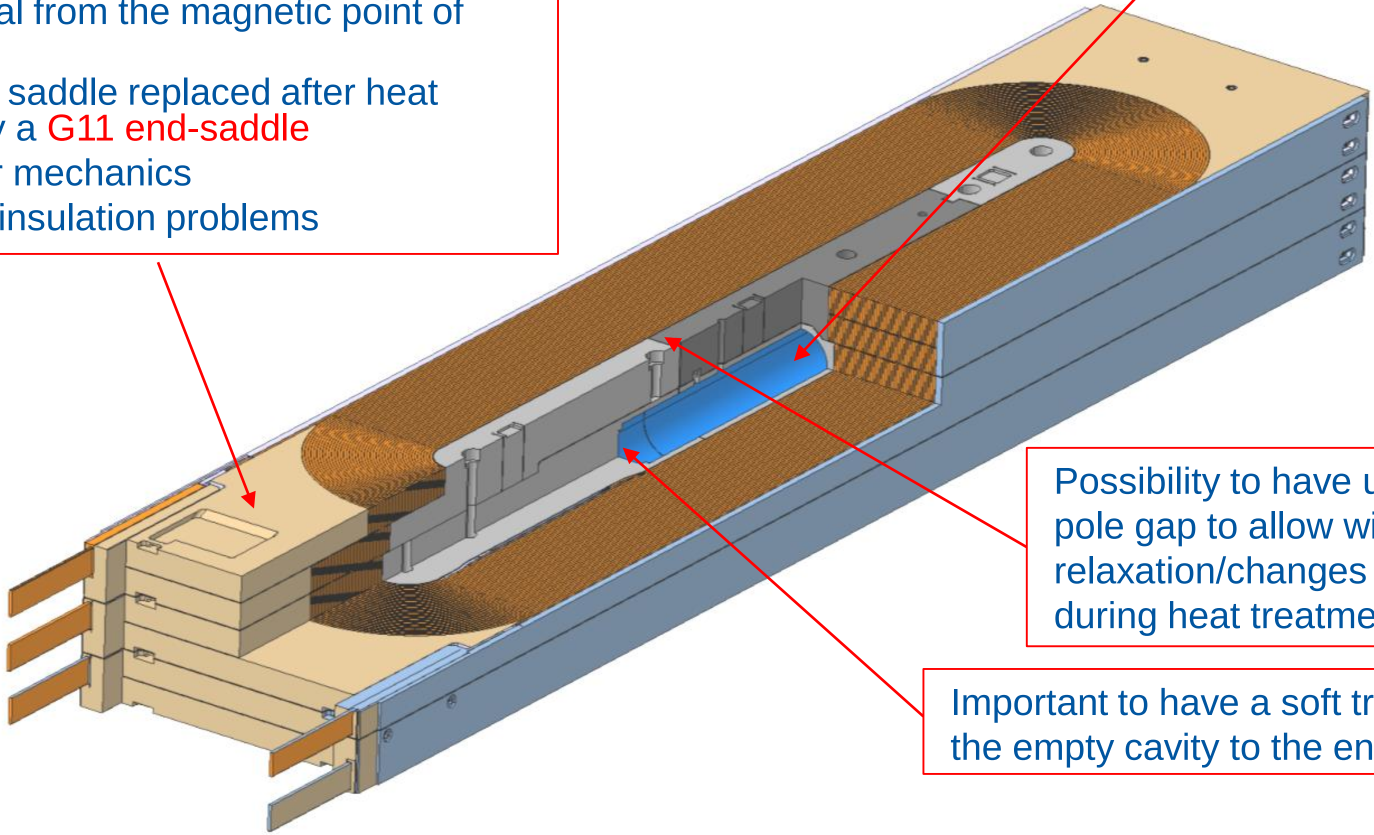


Coil Design

Integration of instrumentation to measure the field and stress is not a trivial problem

No end-spacers
- Optimal from the magnetic point of view

Metallic end saddle replaced after heat treatment by a G11 end-saddle
- OK for mechanics
- Avoid insulation problems



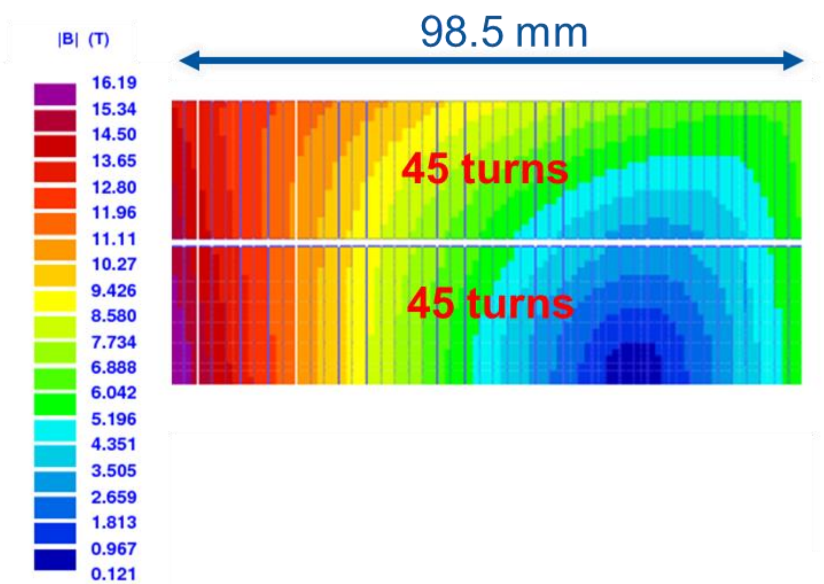
Possibility to have up to 3 mm of pole gap to allow winding relaxation/changes on the length during heat treatment.

Important to have a soft transition form the empty cavity to the end region.

2D magnetic analysis

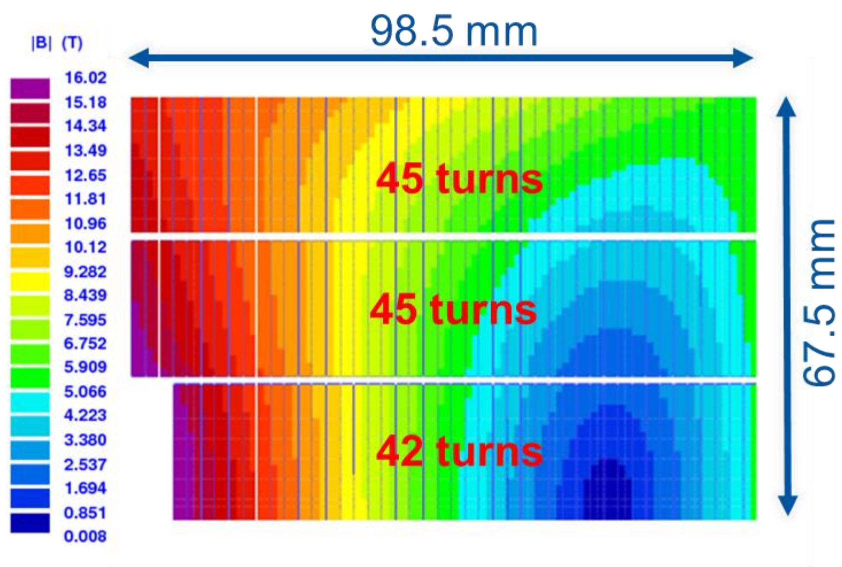
ERMC

- Two double-layers with 45 turns each wounded around a magnetic pole
- B_p/B_o = 1.097

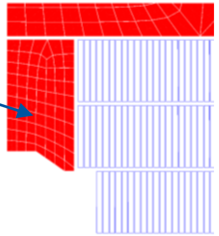


RMM (ERMC double layers +)

- Middle double layer with 42 turns each wound around a titanium closed cavity
- Coil aperture radius = 31 mm
- Closed aperture radius = 25 mm
- B_p/B_o = 1.097



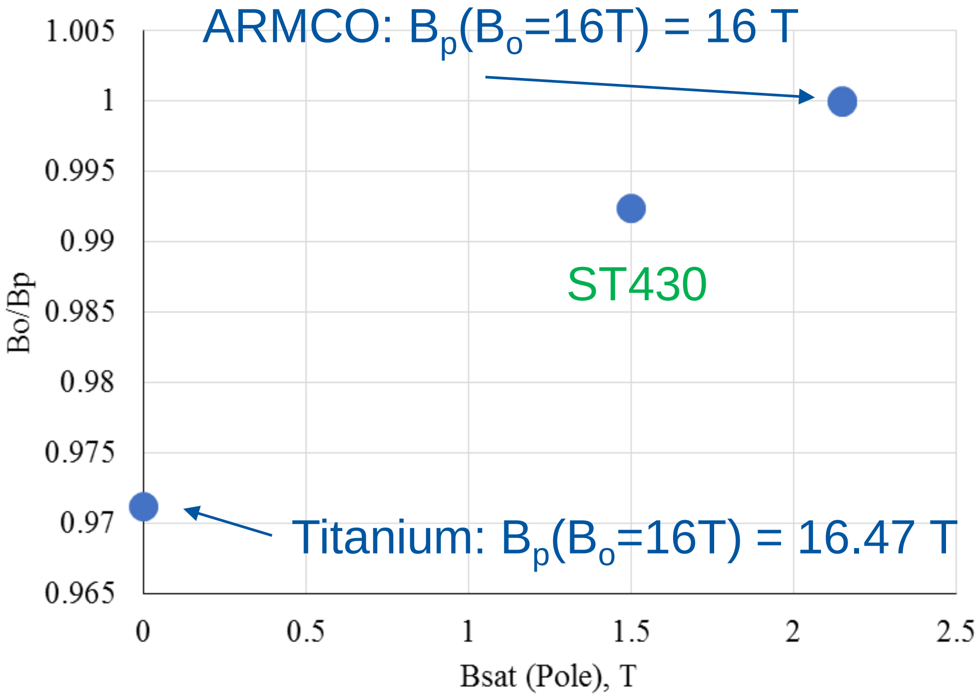
2D magnetic analysis



Central post on ARMCO vs. Titanium:

- Gain 3 % margin on the load line thanks to the use of an ARMCO pole
- To get similar gain through an increase of the coil size, the coil needs to be 20 % larger.
- Negative impact on field quality (100 units of b_3 due to saturation)
- Mechanically on the limit as the yield limit of ARMCO at Room Temperature is 180 Mpa.

Material of the central post	0.2 % YS RT (MPa)	Saturation (T)
430 Stainless Steel	310	1.47
Armco	180	2.15
AISIS 1010 Carbon Steel	220-350 (305)	2.05



Baseline solution: Stainless Steel 430

- 1 % less margin on the load line
- The yield limit at RT is 310 MPa

Load line and margin

Operation conditions:

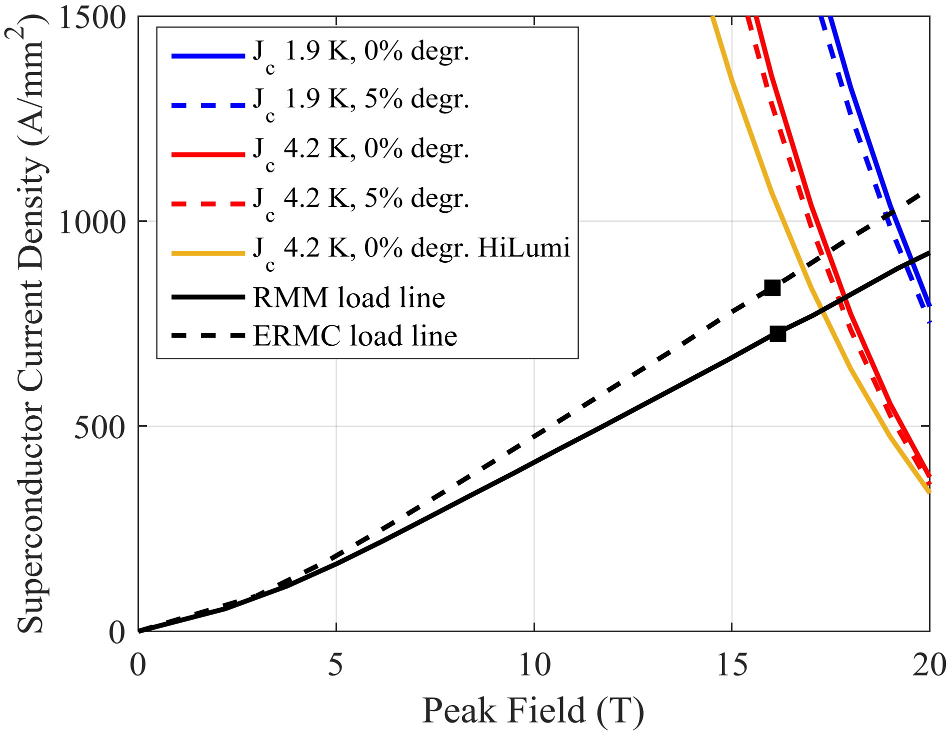
- I_{op} = 13.1 kA (ERMC);11.4 kA(RMM)
- B_{bore} = 15.7 T (ERMC);16.0 T (RMM)
- B_{peak} =16.0 T (ERMC);16.2 T (RMM)

Short sample conditions at 4.2 K:

- $I_{ss,4.2K}$ = 14.4 kA (ERMC);12.7 kA (RMM
- B_{peak} =17.3 T (ERMC); 17.7 T (RMM)

Short sample conditions at 1.9 K:

- $I_{ss,1.9K}$= 15.9 kA (ERMC);14.1 kA (RMM)
- B_{peak} =18.9 T (ERMC)/19.4 T (RMM)

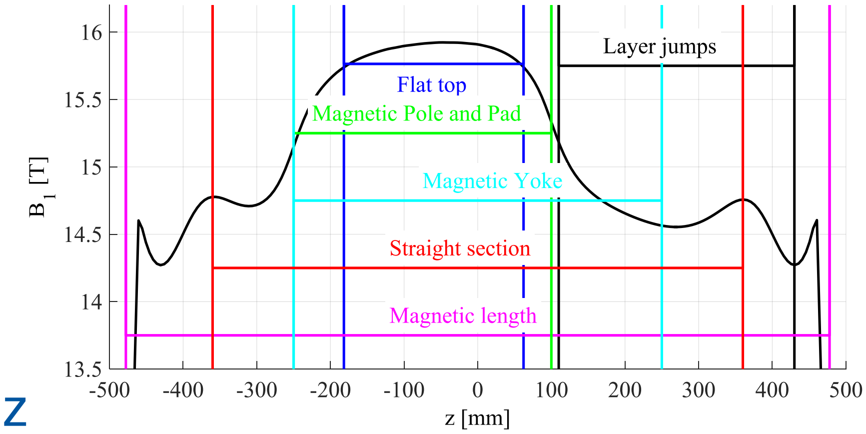


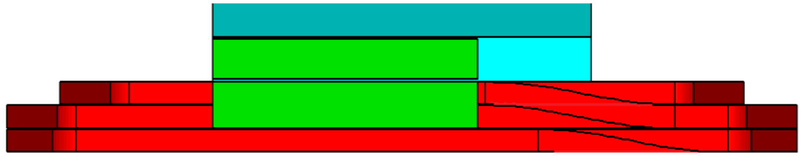
~ 20 % margin at 1.9 K; ~ 10 % margin at 4.2 K

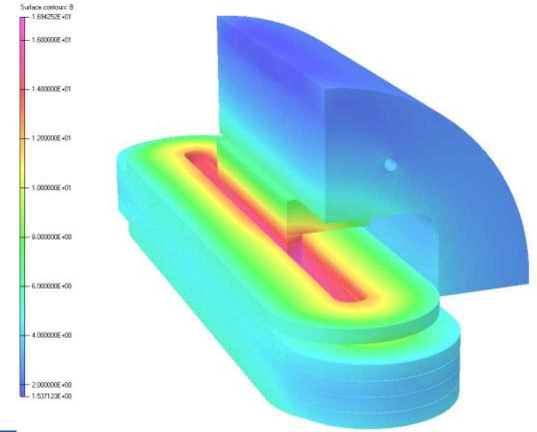
Etienne Rochepault

3D Magnetic Analysis

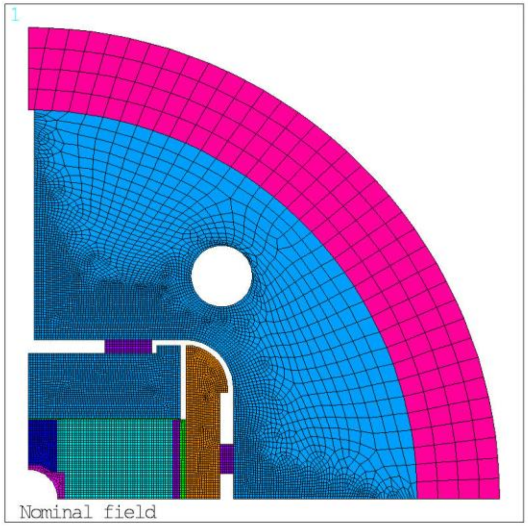
- Coil length ~ 1 m
  - 1105 mm (from conductor to conductor)
  - 1280 mm (including end-saddles)
- Magnetic length ~ 1 m
  - 897 mm (ERMC) and 956 mm (RMM)
- 1 % uniformity of B_y over 230 mm in z
- Peak field:
  - 1.1 T less in the coil ends than in the straight section
  - 0.7 T (RMM)/0.9 T (ERMC) less in the layer jump than in the straight section
- More details: https://indico.cern.ch/event/535593/contributions/2176444/attachments/1282649/1906308/160601_ERMC_3D_Design_v2.pdf



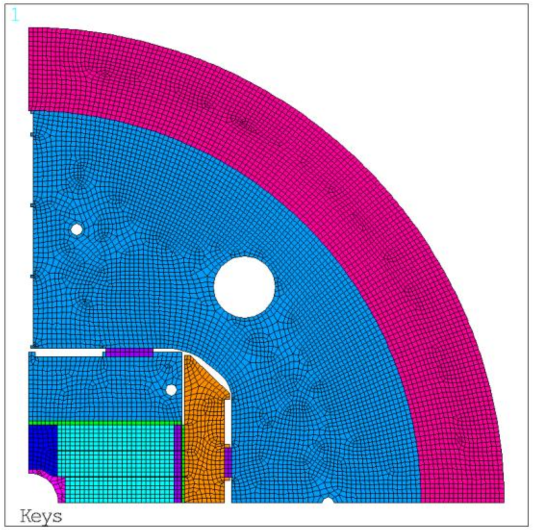




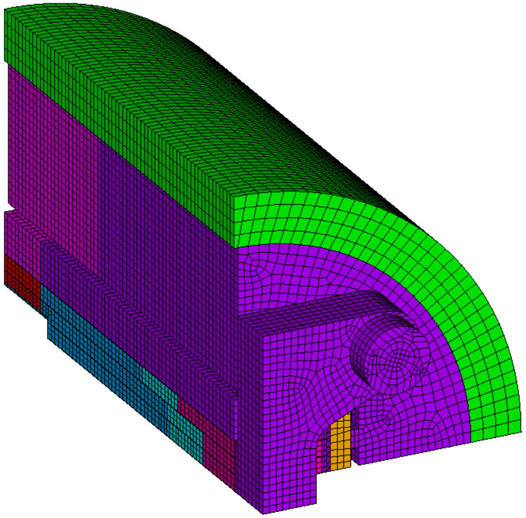
Overview of ANSYS models



S. Izquierdo



R. Ortwein



E. Rochepault

Unless otherwise specified:

- Coil pre-load to prevent separation/tension between pole turn and central post with e.m. forces at 18 T
- 0.2 friction between components
- Coil parts bonded (layer to layer and coil to pole)
- Coil E-modulus = 44GPa/52GPa (2D); 44 GPa (3D)

Mechanical design criteria

- Pole-coil contact in pole-turns midpoint

  $p_{cont} \geq 2$ MPa
- Max bladder pressure

  < 50 MPa
- Bladder should open the

  interf=interf$_{nom}$ + 100µm
- All components **$\sigma \leq R_{p\ 0.2}$**
- For iron at 4.3K (brittle)

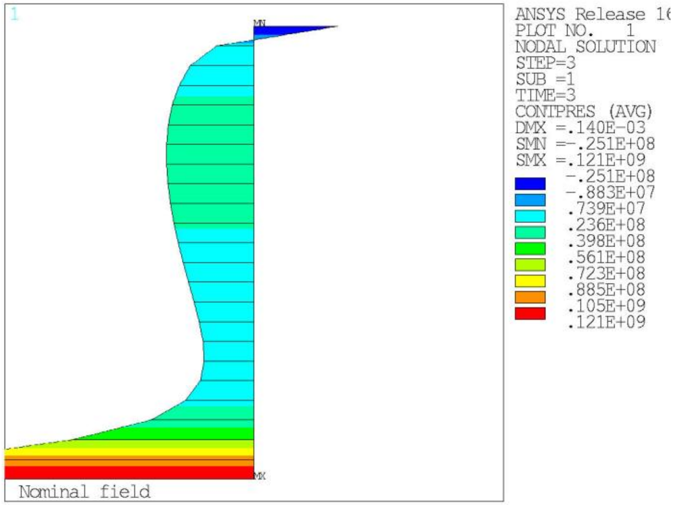
  $\sigma_I \leq$ ~200 MPa

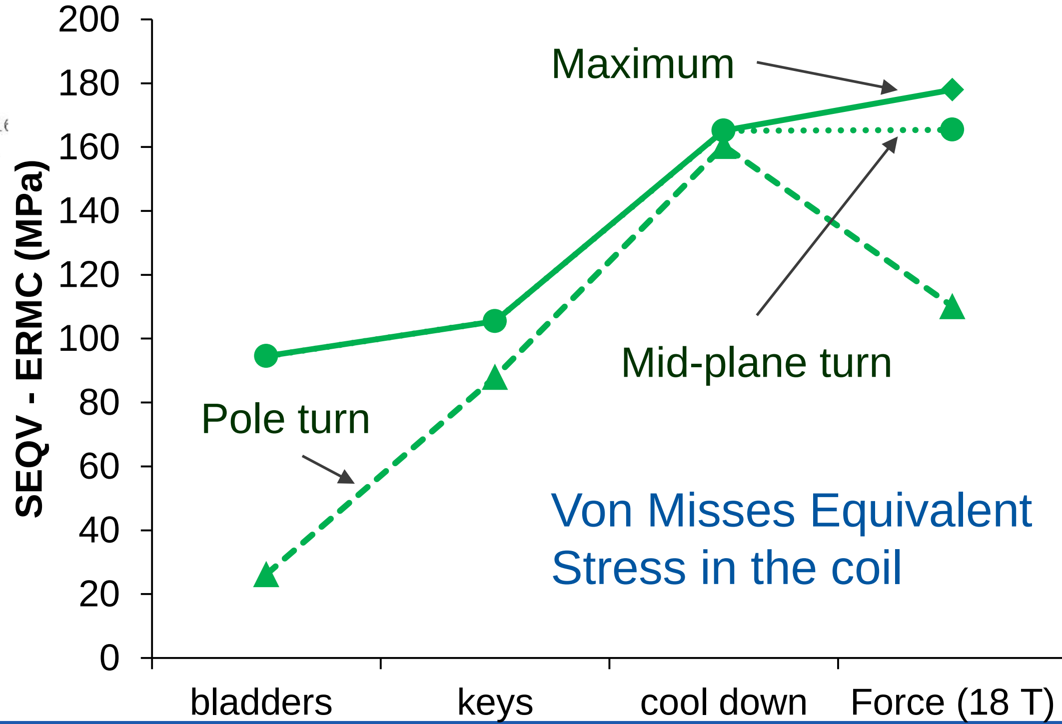
Material	$R_{p\ 0.2}$ [MPa]	
	293 K	*4.3 K*
Al 7075	*480*	*690*
SS 316 LN	*286*	*930*
NITRONIC 40	*353*	*1240*
MAGNETIL	*180*	*723*
Ti 6Al 4V	*827*	*1654*

Coil stress (ERMC)

TARGET:

- To have a pressure on the pole > 2 MPa at 18 T central field
- All structural components below the yield limit with sufficient margin

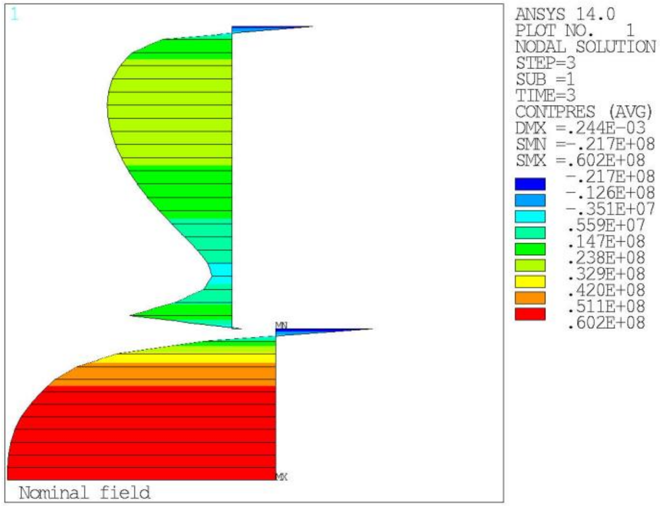


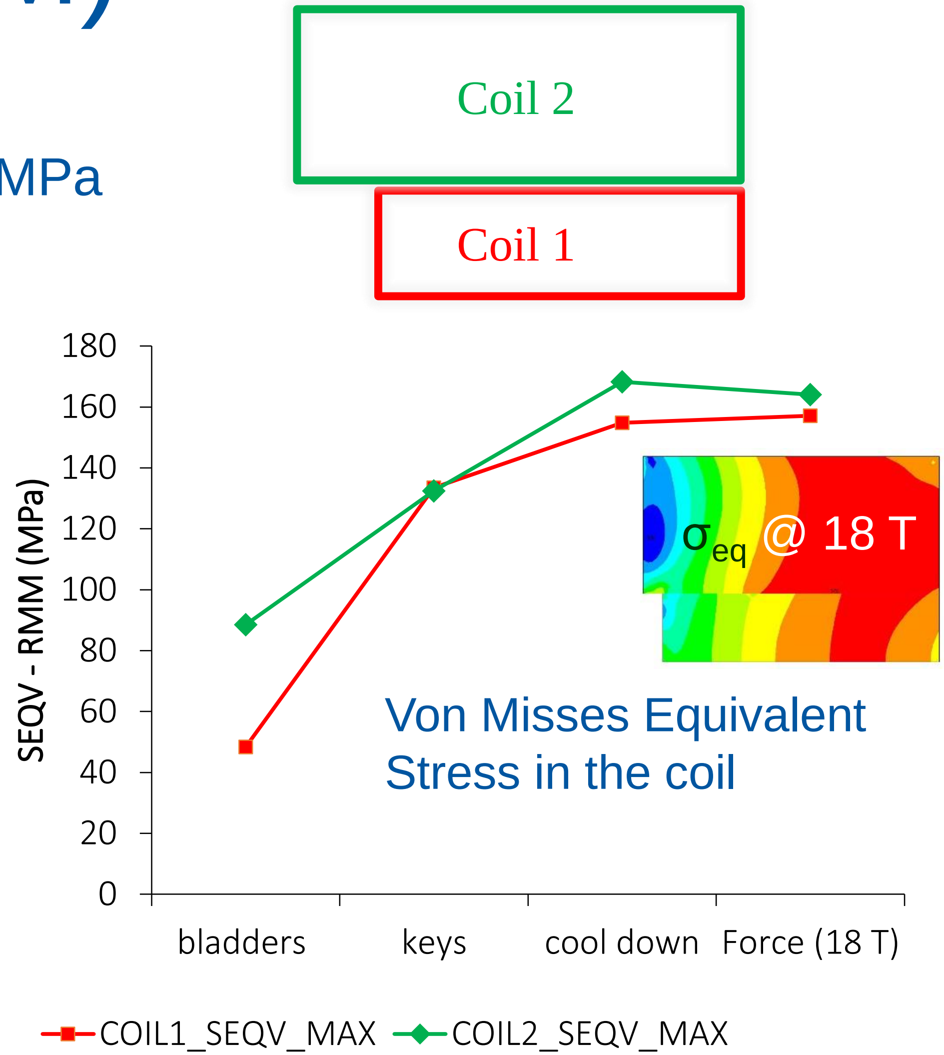


Coil stress (RMM)

TARGET:

- To have a pressure on the pole > 2 MPa at 18 T central field
- All structural components below the yield limit with sufficient margin

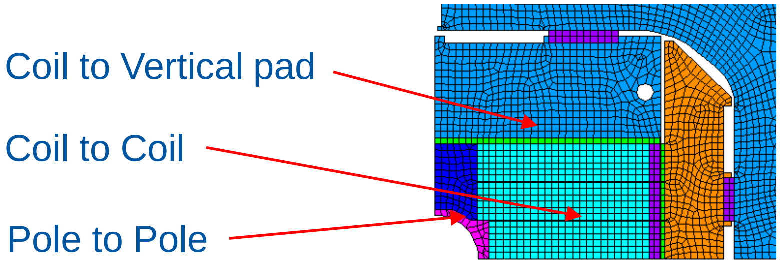


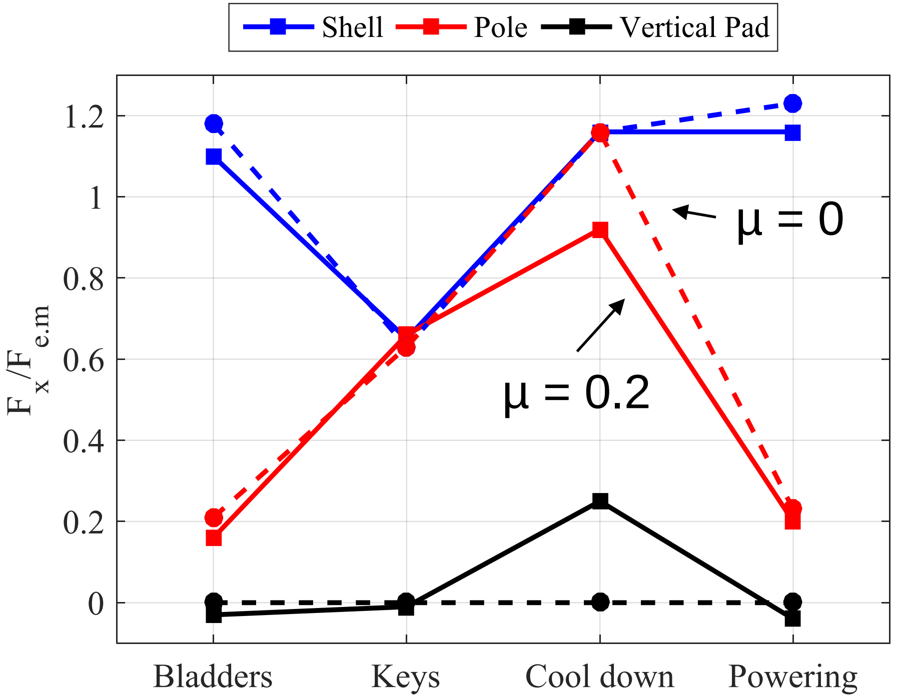


Sensitivity analysis: Friction

Key surfaces:

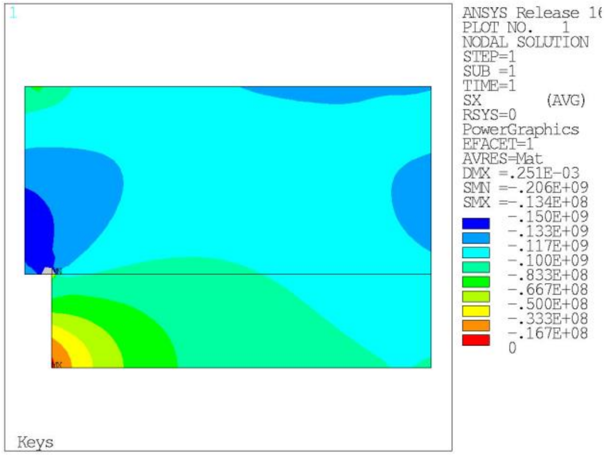
- Coil to vertical pad.
  - The vertical pad intercepts 20 % of the force during cool down for μ = 0.2.
  - For μ >>, problems to transfer the force to the coil.
- Coil to coil.
  - If the two coils are glued, at warm the external coils are overloaded in the high field region and the intermediate coil unloads during powering.
  - For very low friction, at warm the external coils are overloaded in the low field region and the intermediate coil unloads during powering.
- Pole to pole.
  - In general, it is beneficial to have similar μ among coils and among poles

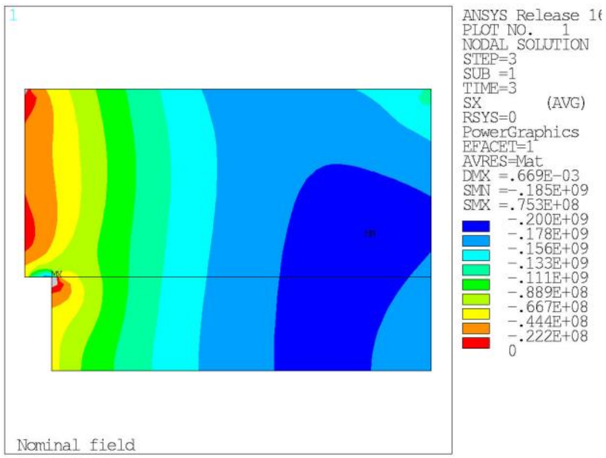




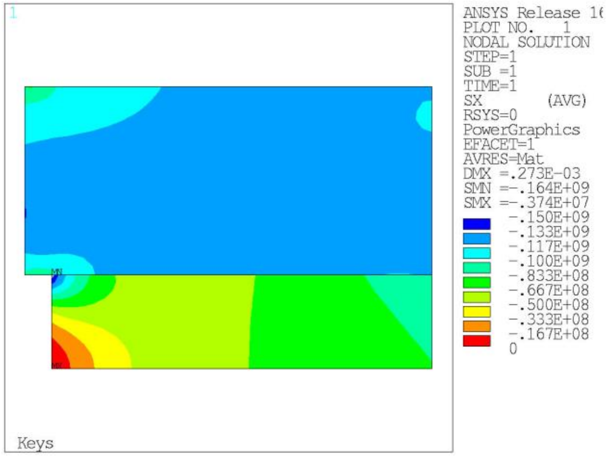
Sensitivity analysis: Friction

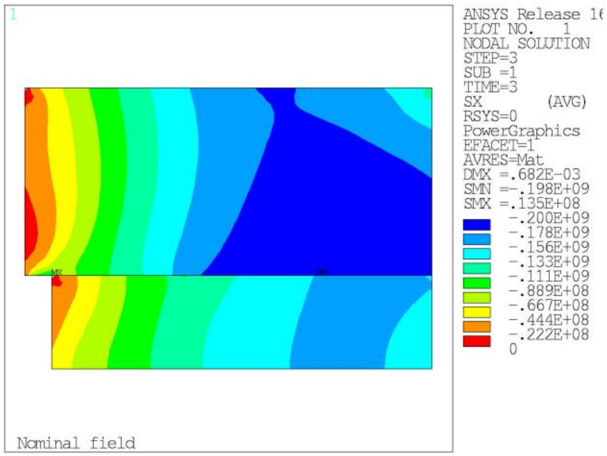
All glued





μ = 0.2 among coils





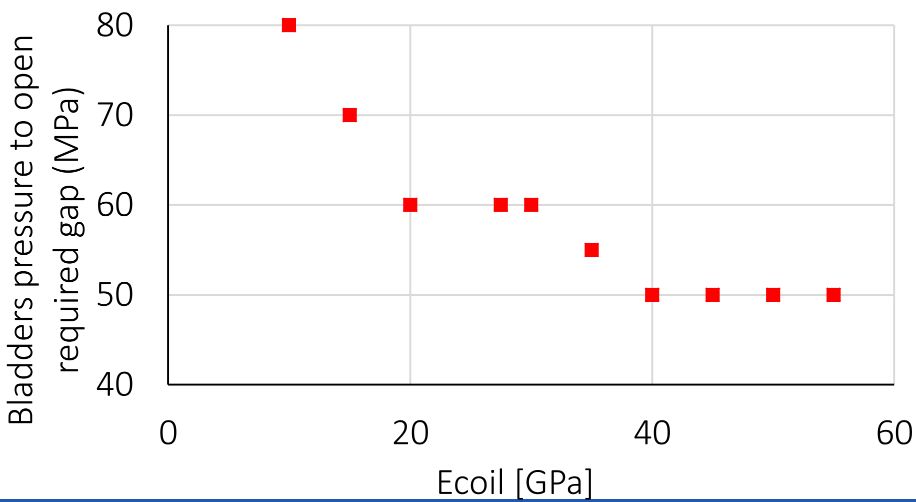
Sensitivity analysis: coil E-modulus

E_x/E_y = 44/52 GPa → E_x/E_y = 25/30 GPa
- Δ(coil peak stress at RT) = 20 MPa
- Δ(bladders pressure) =10 MPa

E_x/E_y (RT and 1.9 K)= 25/30 GPa → E_x/E_y (RT) = 25/30 GPa; E_x/E_y (1.9K)= 27.5/33 GPa
- Δ(coil peak stress) = 5 MPa (RT); 10 MPa (1.9 K)

E_x/E_y (RT and 1.9 K)= 25/30 GPa → E_x = E_y (RT and 1.9 K)= 27.5 GPa
- Δ(coil peak stress) < 5 MPa (RT and 1.9 K);

- The main impact of having a coil much softer than what we assumed in the original design:
  - Larger interference needed at warm → increase of the required bladder pressure and coil peak stress at warm



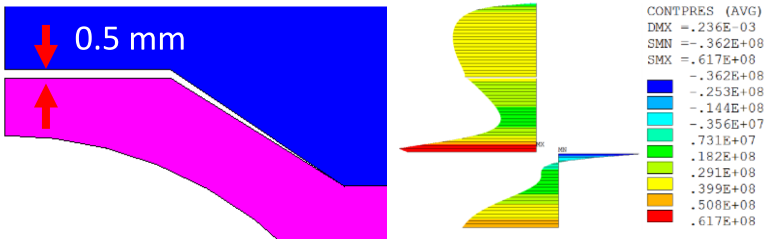
Rafal Ortwein

Assembly tolerances

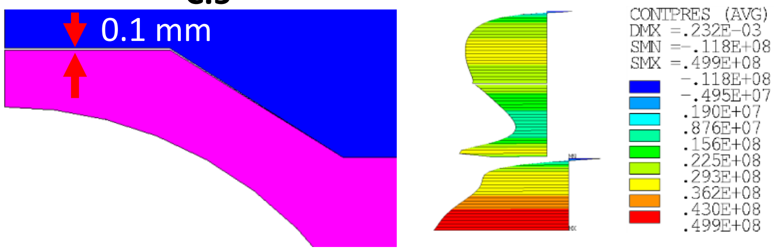
- In order to pre-load the lower coil, contact in the top surface of the poles after cool down is desirable.

- Plan:
  - Shim the interface pole to pole based on final coil measurements to have a gap during assembly= 0.2± 0.1 mm

C.1



C.5



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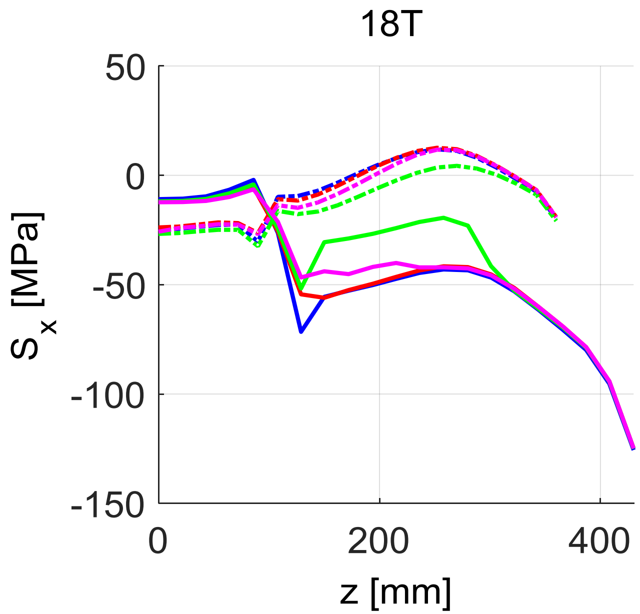
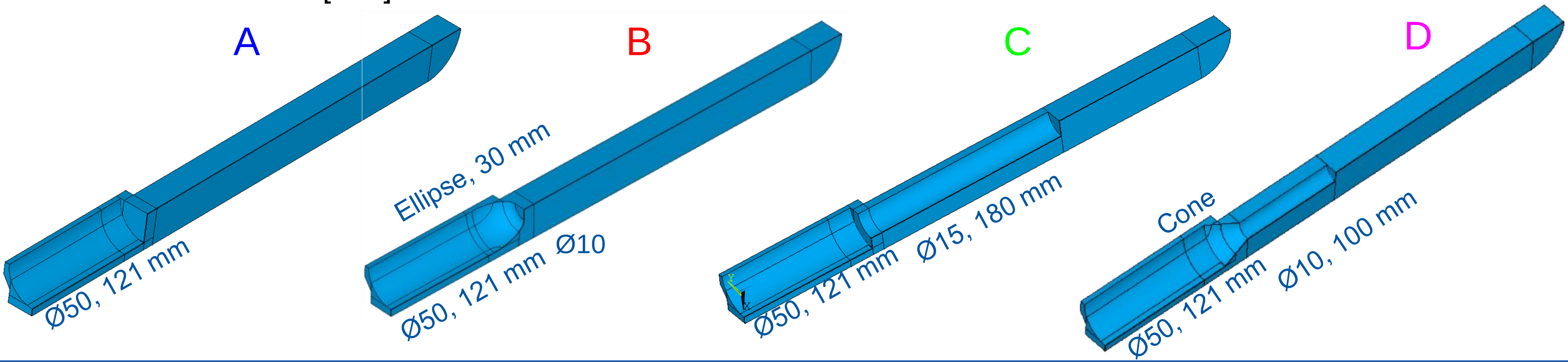
Central post transition



- The transition between the “filled” and “empty” part of the cavity in the central segment is critical.
- Important to make it as smooth as possible (more critical on the magnet lead end as we have the layer jump)



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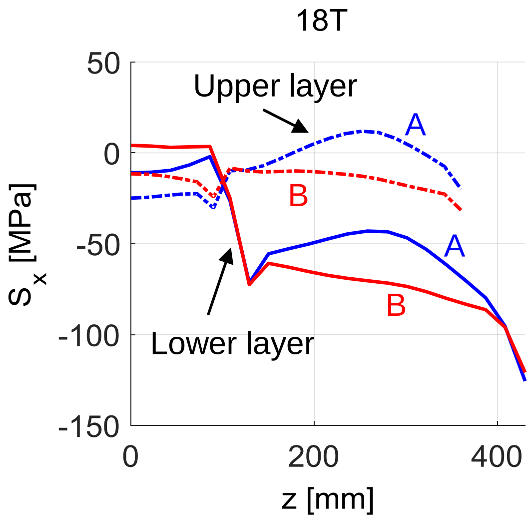
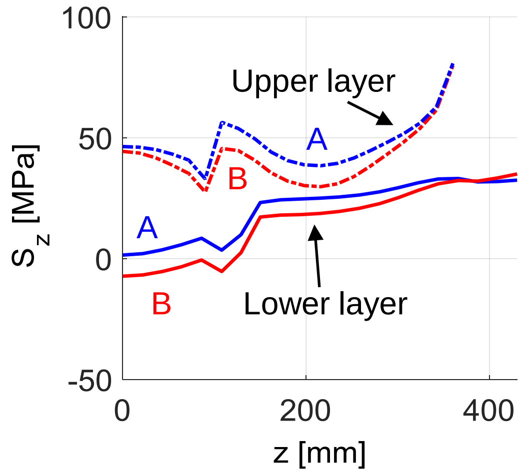
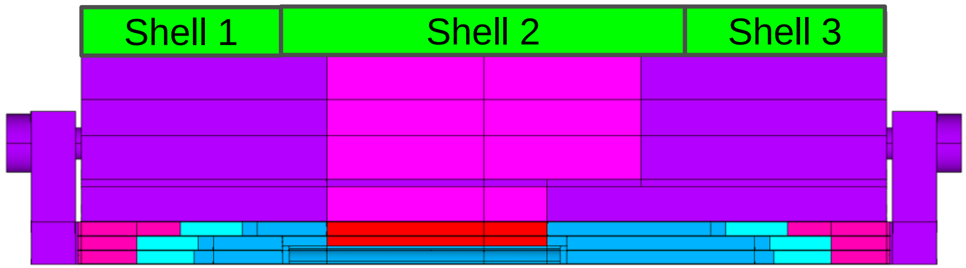
Aluminium shell segmentation



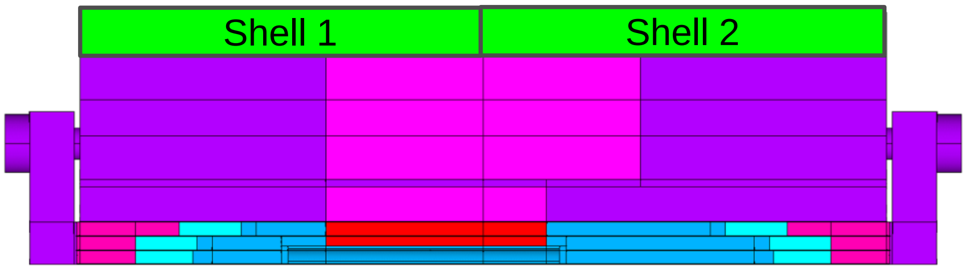


- Max. shell length that can be "easily" manufactured = 800 mm
- Different configurations studied:
  - A: Spit of the shell in the extremities



- B: Central split of the shell

Best solution for stress uniformity in the coil.

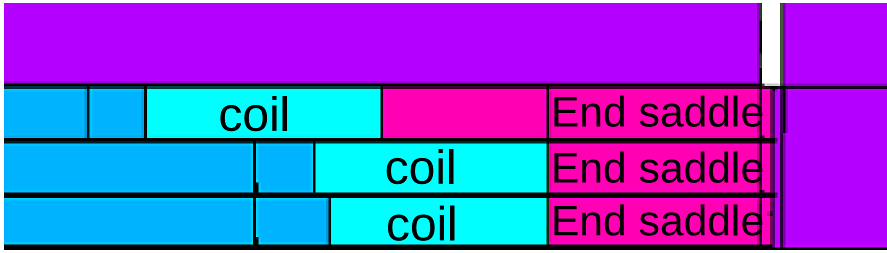


Etienne Rochepault

Longitudinal loading

- For the moment mainly questions.
- Two possible approaches:
  - Design to provide a longitudinal force equal to the Lorentz longitudinal forces
    - Aluminium rods
    - End plate thickness > 150 mm
  - Design to provide a “rigid” wall against Lorentz forces but not preload.
- The material of the end spacers also plays a important role

With G10 spacers, we are able to provide more load, but larger imbalance between coils during powering because of the differences on end saddle coils between top and bottom layers.



Quench protection

- Stored energy at I_{nom} =1.5 MJ/m (ERMC)/ 2.1 MJ/m (RMM)
- Differential inductance at I_{nom} = 16.6 mH/m (ERMC)/ 31.1 mH/m (RMM)
- Protection with only dump:
  - Limiting the terminal voltage to 1 kV → T_{max} ~ 300 K
- Protection with quench heaters (+dump, if desired)
  - Very low current density overall → large time margin ~ 170 ms
  - Protection would be OK even if reducing the copper to superconductor from 1 to 0.6

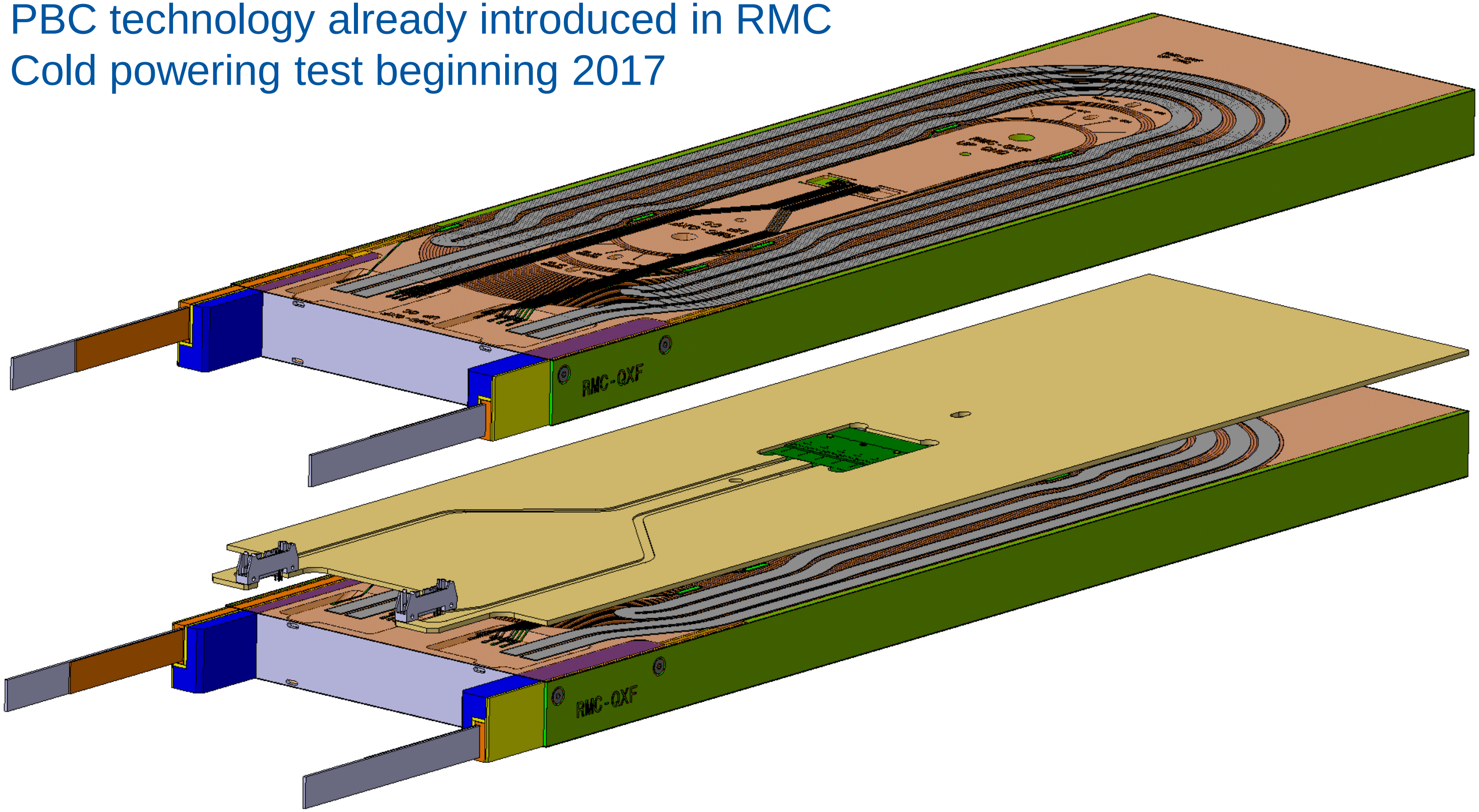
Parameter	Unit	Cu/SC 1	Cu/SC 0.8	Cu/SC 0.6
Nominal bore field B_{nom}	T	16	16	16
Nominal current I_{nom}	kA	11.4	12.8	14.6
Insulated cable energy density at I_{nom}	MJ/m^3	86	91	97
Insulated cable current density at I_{nom}	A/mm^2	245	276	314
Time margin at I_{nom}	ms	168	110	65
Number of turns per quadrant	--	132	111	93

Instrumentation

- Field measurements
  - ERMC: hall probes + PCB coils
  - RMM:
    - Option A: hall probes only
    - Option B: hall probes + PCB coils
- Strain measurements
  - Strain gauges
    - 3 gauges/coil in ERMC
    - 2 gauges/coil in RMM
    - Gauges in the shell
  - Fibre optics
    - Details not addressed yet
- Quench localization
  - Voltage taps, to monitor pole turn and external turns
  - Quench antenna

Field measurements: RMC

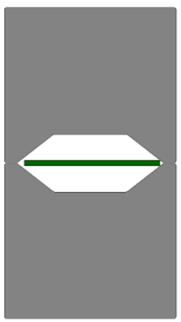
- PBC technology already introduced in RMC
- Cold powering test beginning 2017

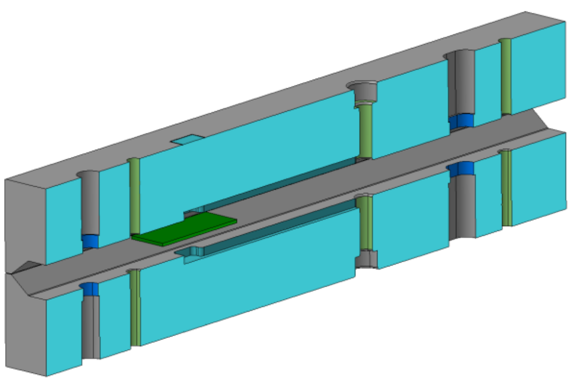


Magnetic Measurements: Carlo Petrone

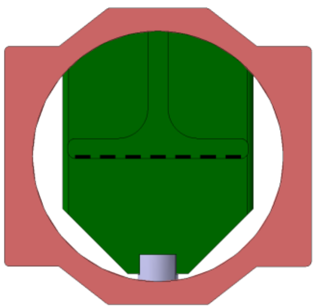
Field measurements ERMC/RMM

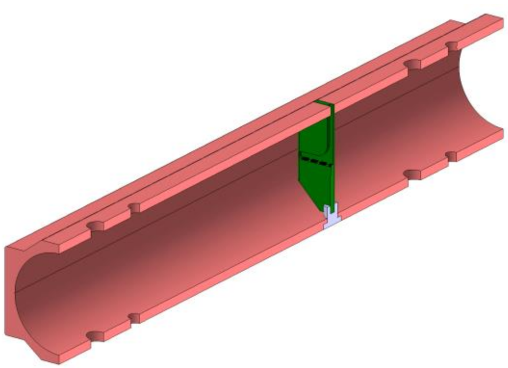
ERMC:
hall probes + PCB coils



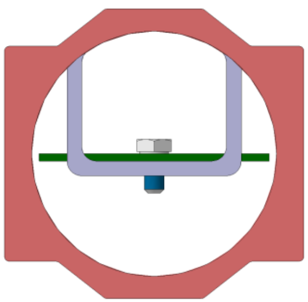


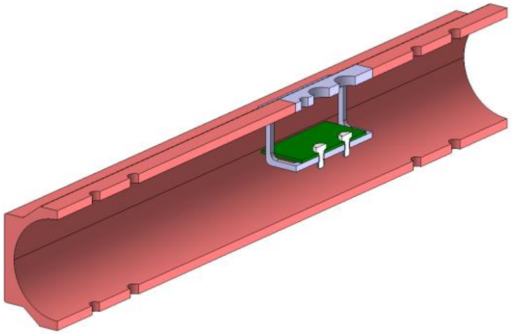
RMM Option A:
hall probes only





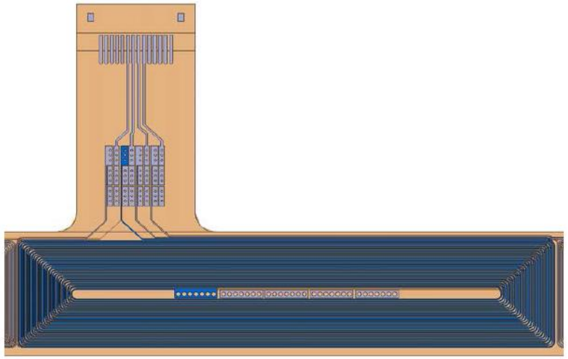
RMM Option B:
hall probes + PCB coils
(significant impact on pole rigidity)

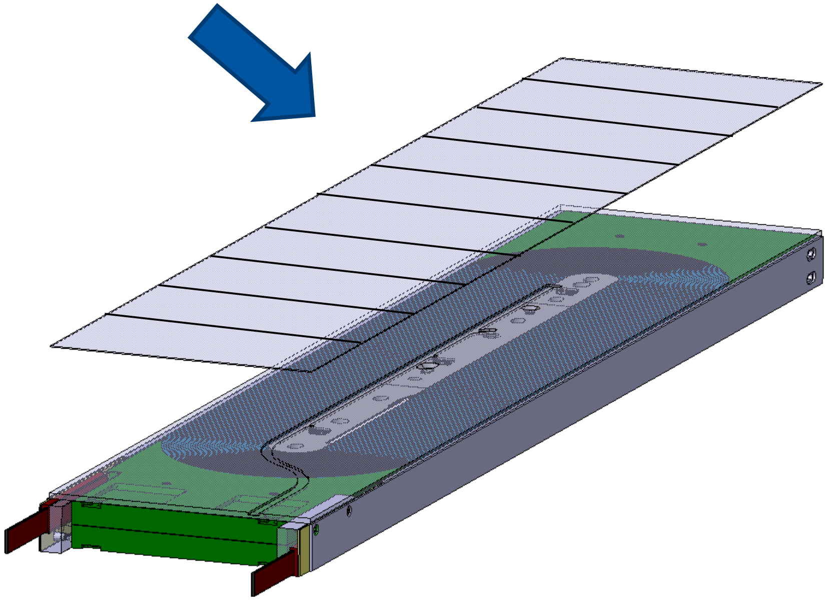




Quench antenna

Flexi-PCB are being developed for quench detection in Feather 2.





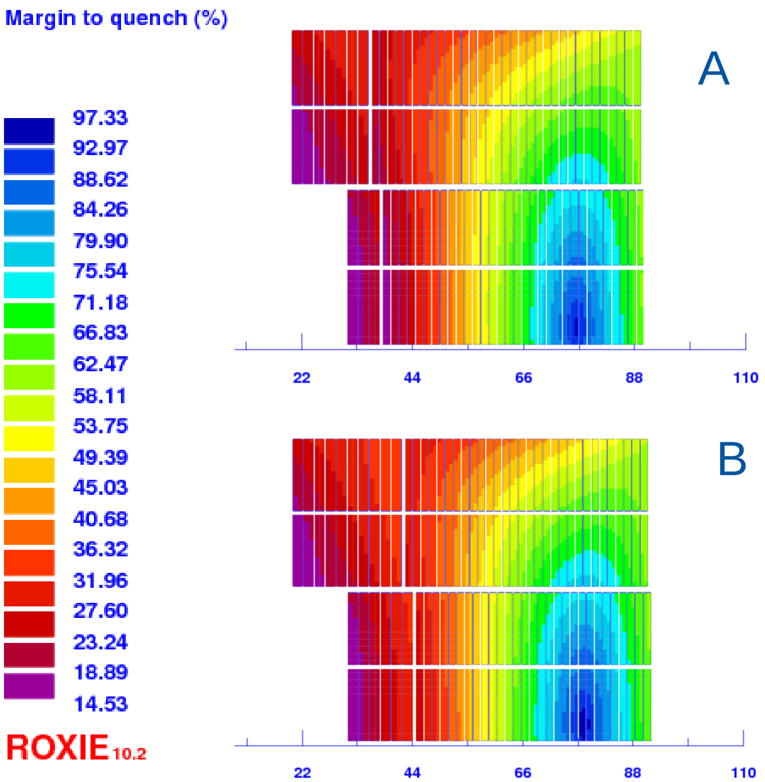
Plan: use the same technology of quench localization in ERMC and RMM placing the coils in the outer surfaces of the coil pack.

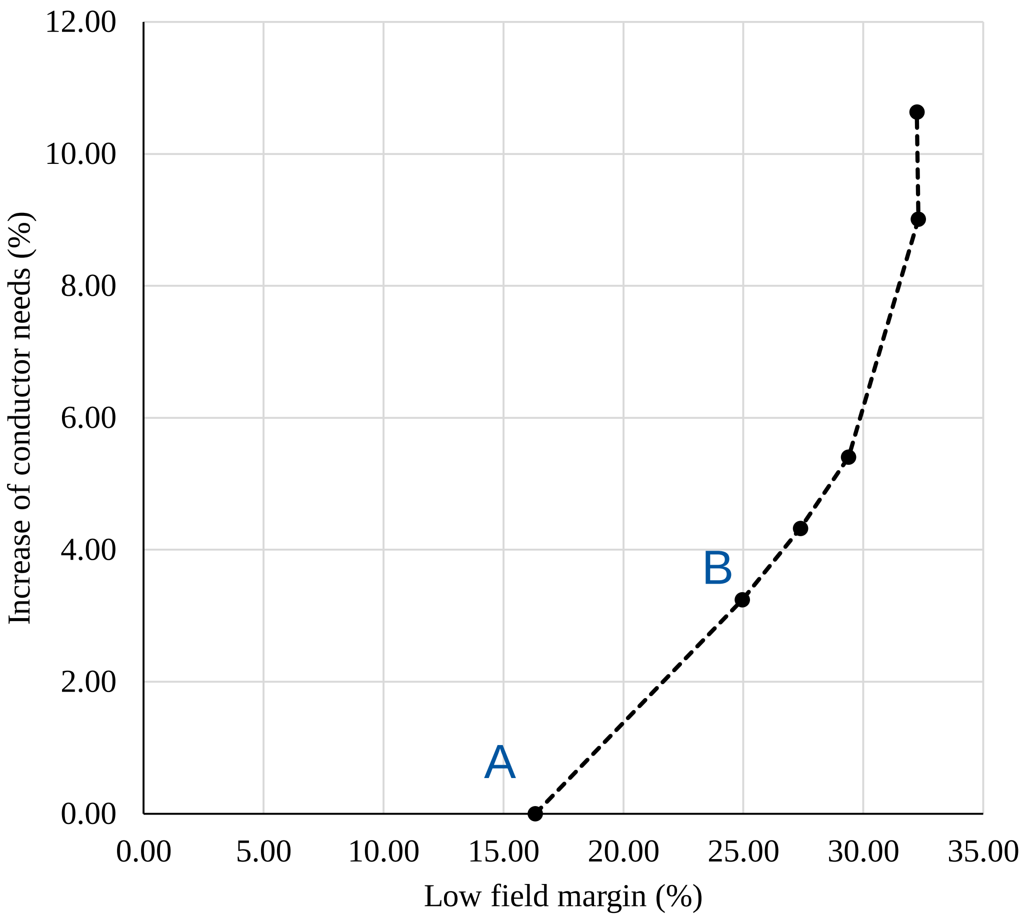
Graded Design

Graded Design

- Final decision on the coil cross section geometry to be built not finalized yet.
  - Follow directions from EuroCirCol
- Nevertheless, lot of analysis done to address some important questions:
  - How important is to define the grading ratio?
  - What is the cost of the low field margin?
  - What is the cost of the inner support and mid-plane shim?
  - What is the role of the thermal gradients in the coil during quench?
  - How are we going to do the high field splice?

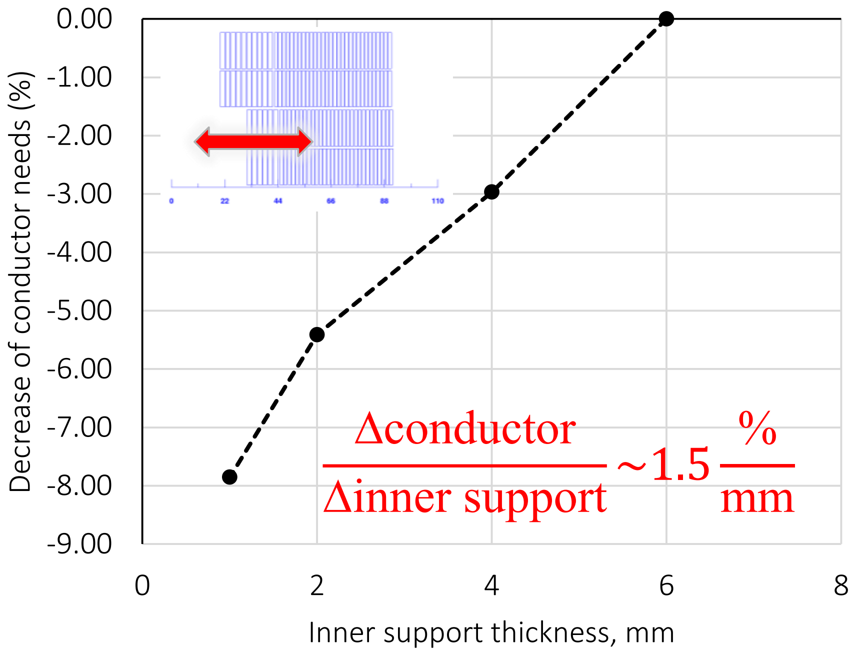
The “cost” of the low field margin

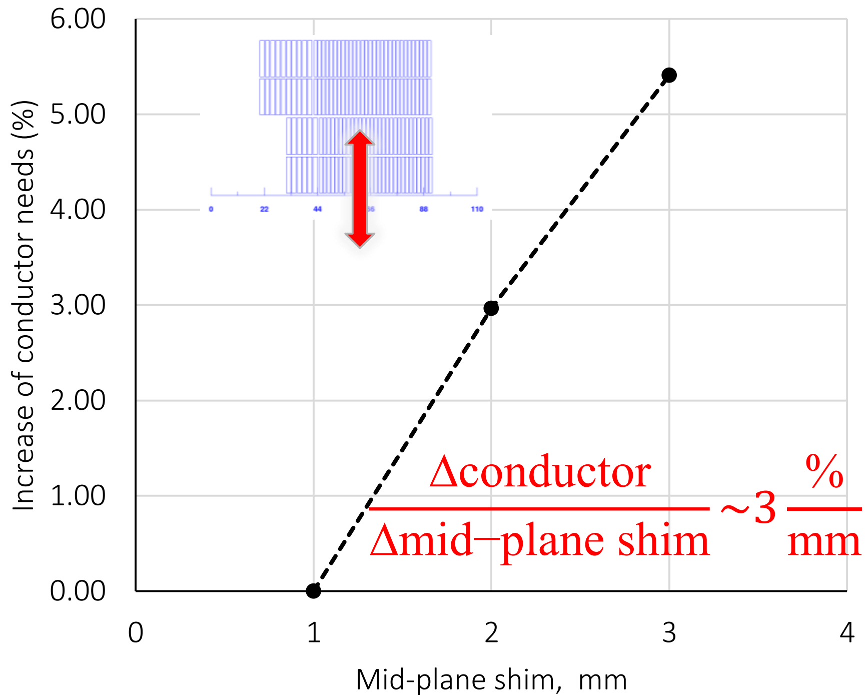




Inner support and mid-plane shim

- 1 mm of mid-plane shim is equivalent to 2 mm of inner support wall thickness in terms of increase of conductor needs.
- Preliminary mechanical analysis show no significant impact on the pole tip displacement for decrease of inner support from 6 mm to 2 mm (see C. Lorin) .

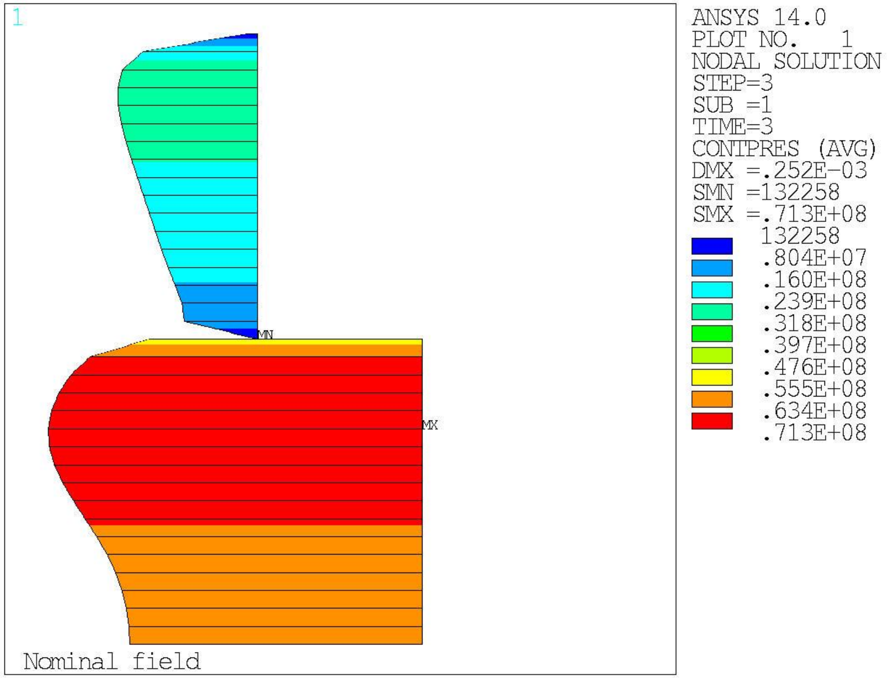


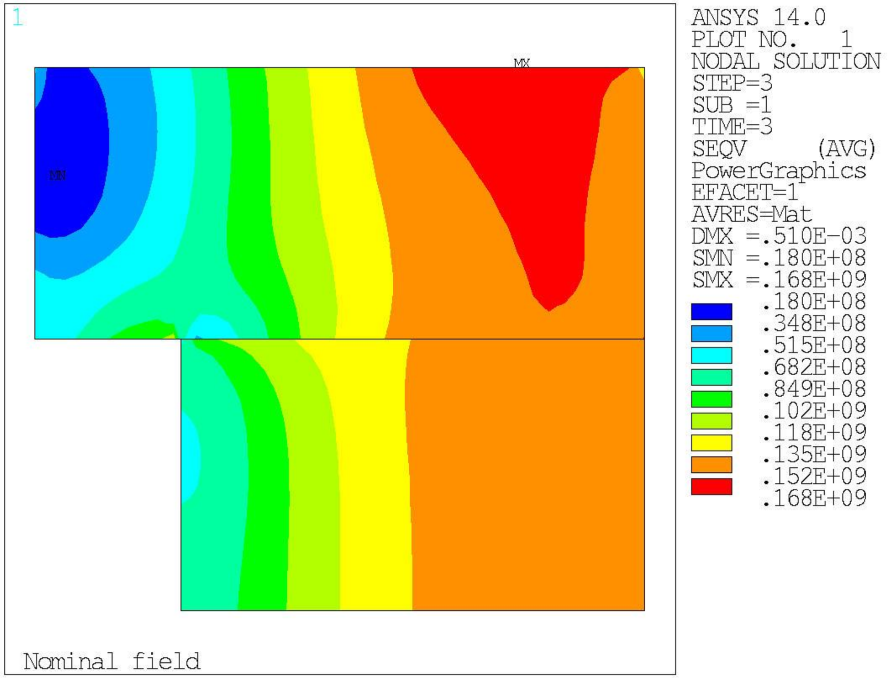


Coil stress

TARGET:

- To have a pressure on the pole > 2 MPa at 16 T central field



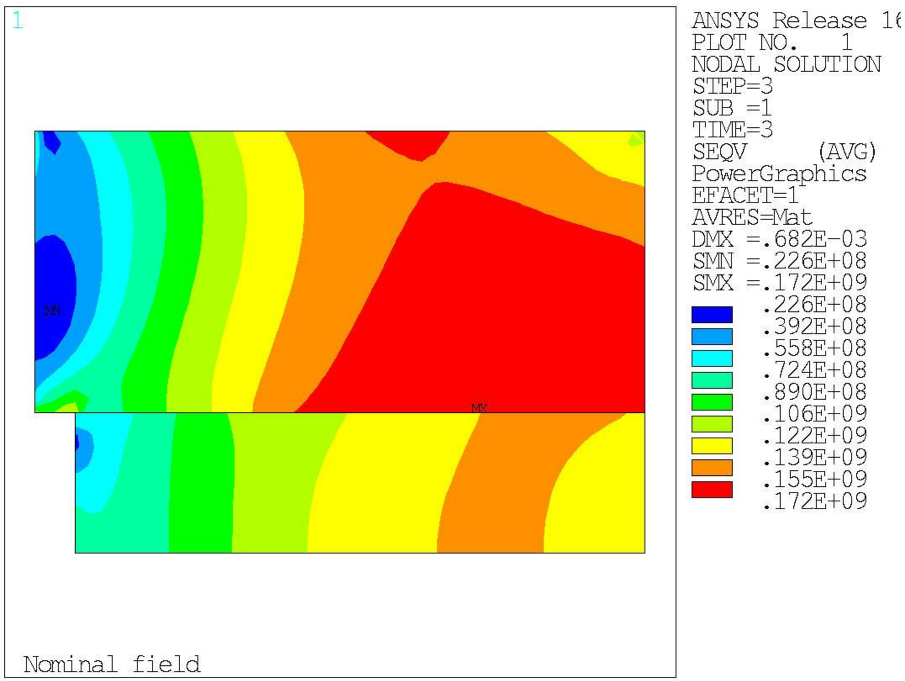


Seq_{max}(assembly) = 120 MPa

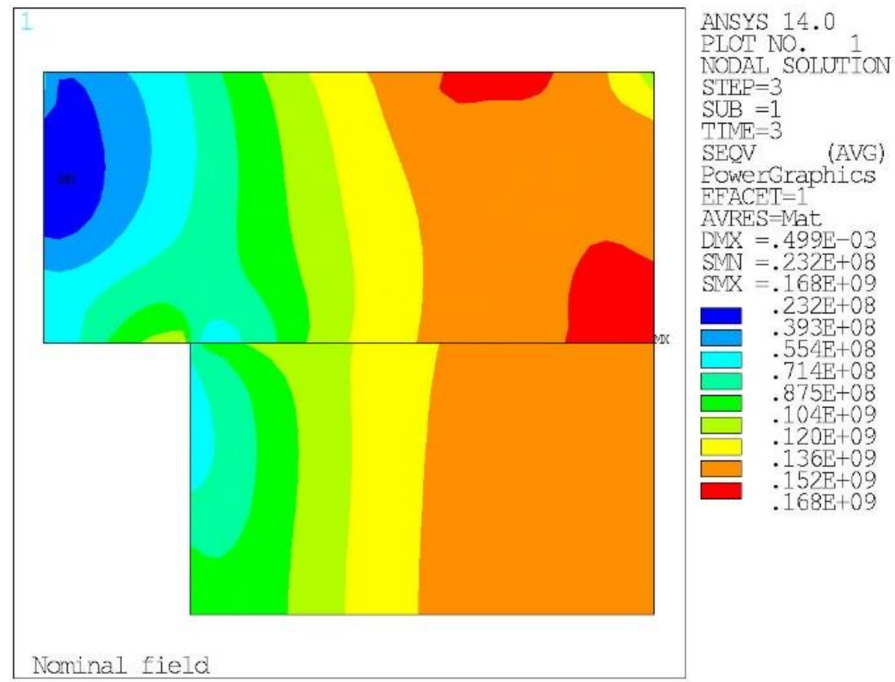
Seq_{max} (cool down) = 200 MPa

Coil stress: Graded vs. Non graded

Similar level of stress in the graded design at 16 T than in the non-graded at 18 T



Non graded design: Stress at 18 T
Max. 172 MPa

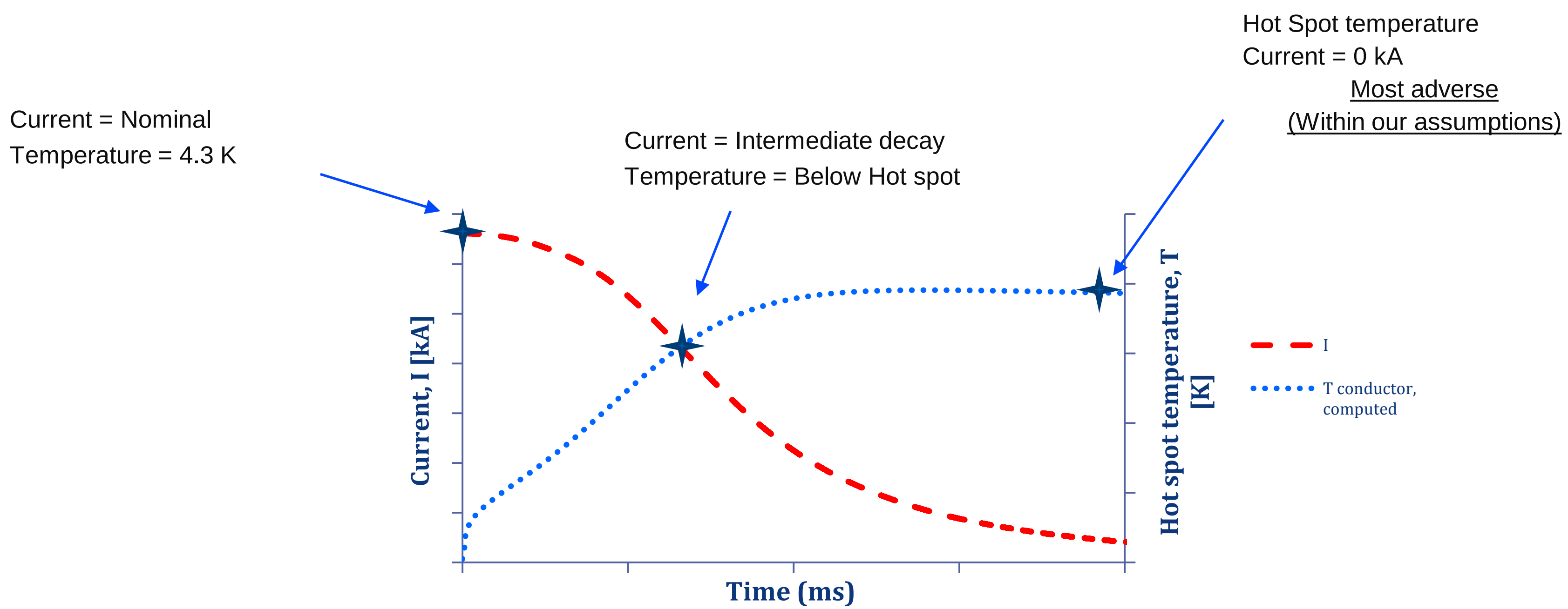


Graded design: Stress at 16 T
Max. 168 MPa

What about quench?

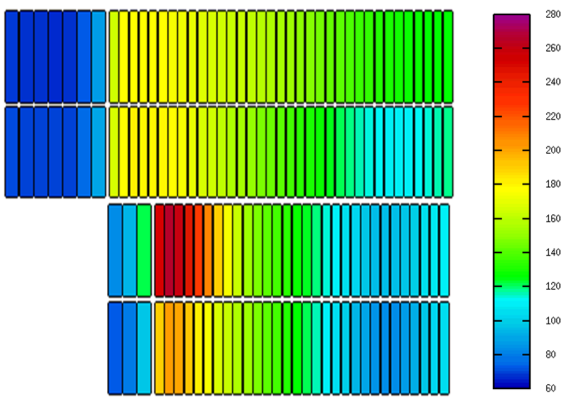
- Due to the very different operation conditions in the low field and high field region, large temperature gradients are expected in the coil.

		HF	LF
Overall current density	A/mm^2	270	420
MIITS available	MA^{2}s	32.60	13.26
MIITS consumed	MA^{2}s	9.93	9.9
Average temperature	K	64	155
Time left to quench	ms	289	43

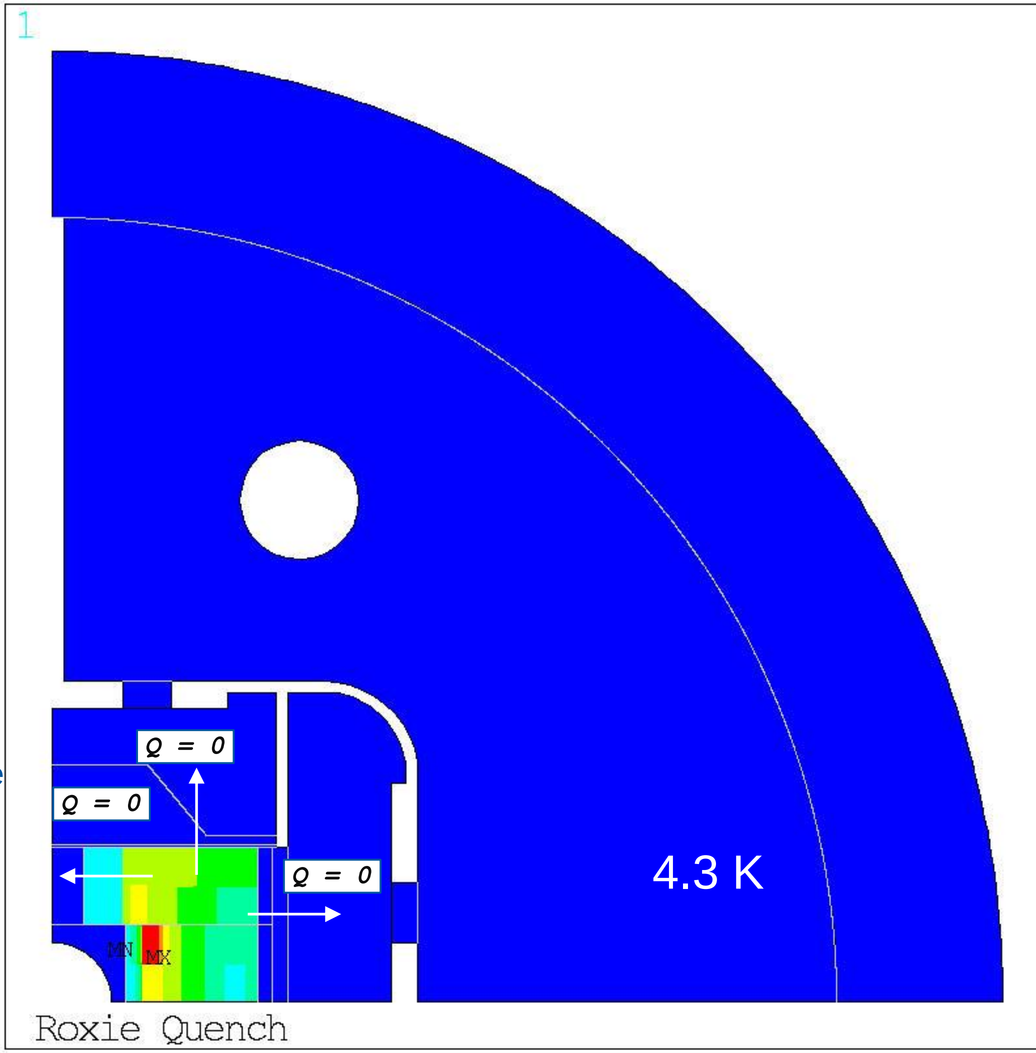


Stress due to thermal gradients

- Temperature computed using ROXIE and exported to ANSYS.
- Every turn in ANSYS is modelled with a different temperature.
- No heat transfer from the coil to the structure.
- Coil properties:
  - Constant isotropic E-modulus (25 GPa)
  - PRxy = 0.3
  - Thermal expansion is a function of the temperature

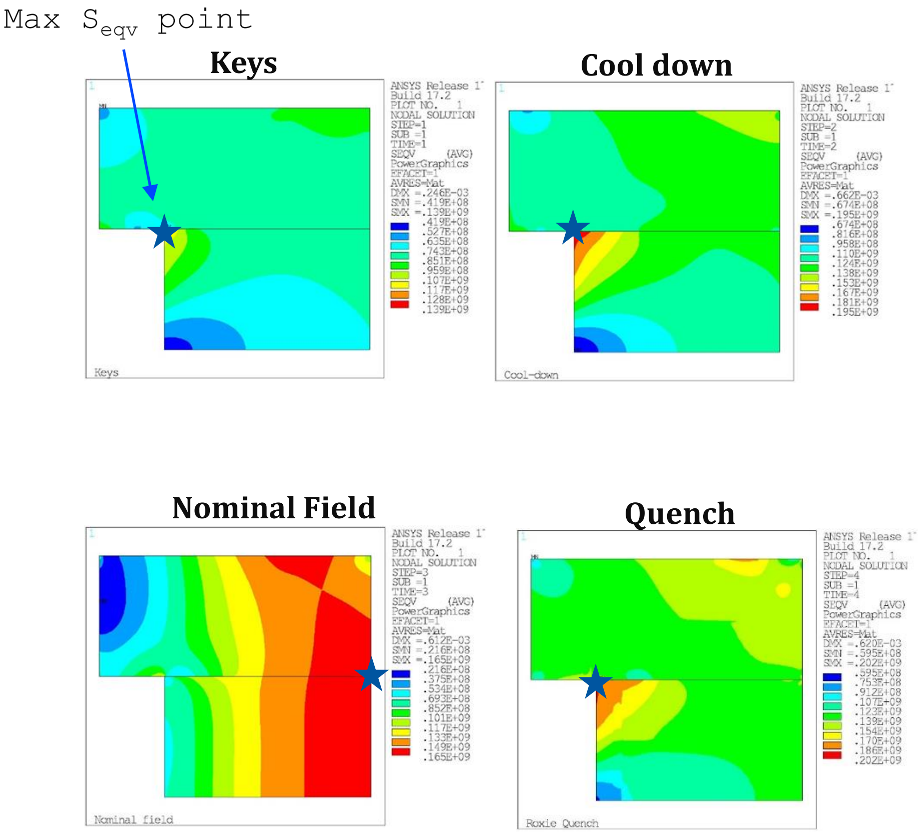


ROXIE Temperature imported in ANSYS

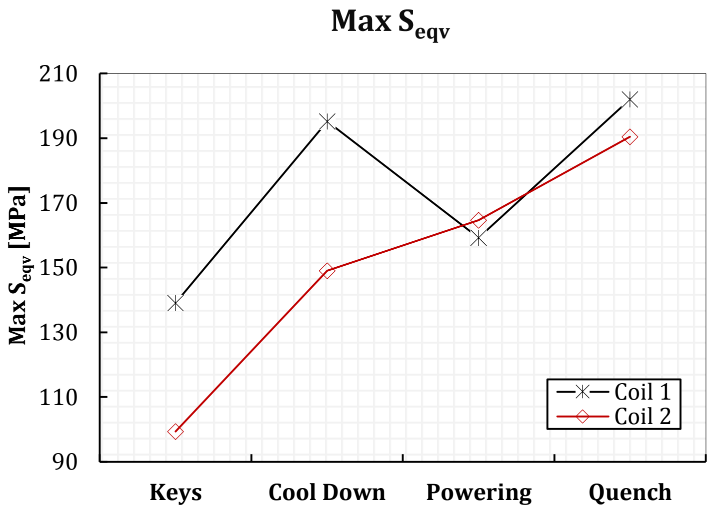


J. Ferradas Troitino

Stress due to thermal gradients

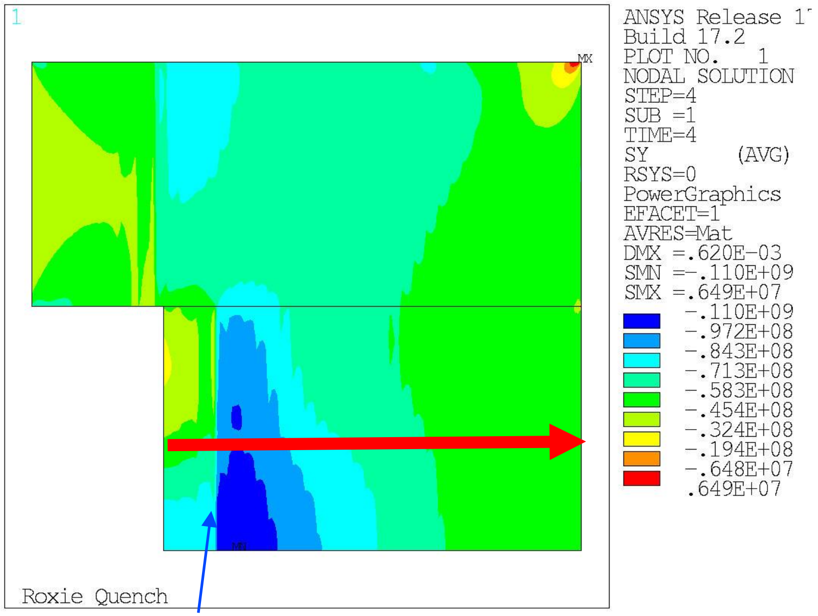


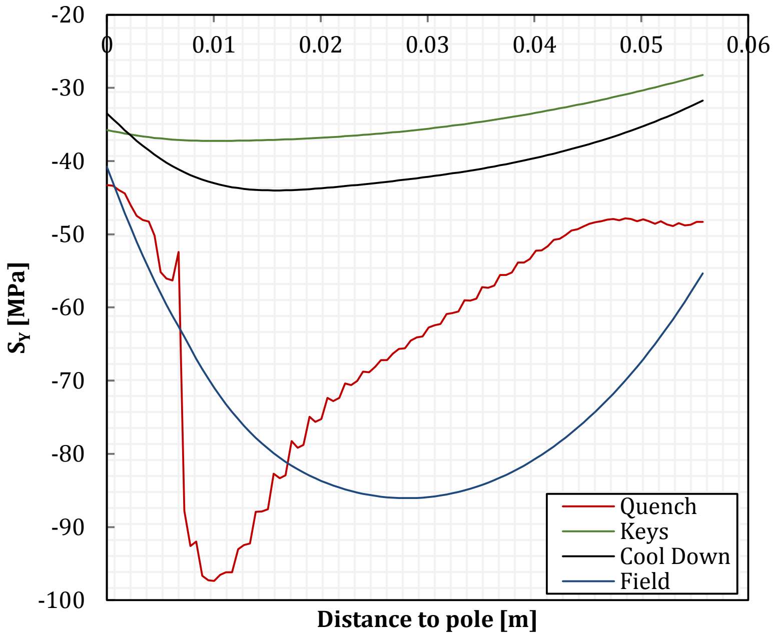
- The amplitude and profile of S_{eqv} and S_x is similar to the value after cool down.



Stress due to thermal gradients

- $\Delta S_y \sim 50$ MPa in the low field – high field interface



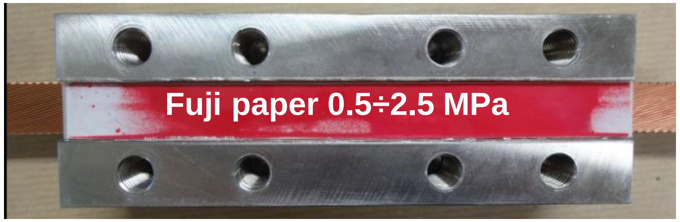


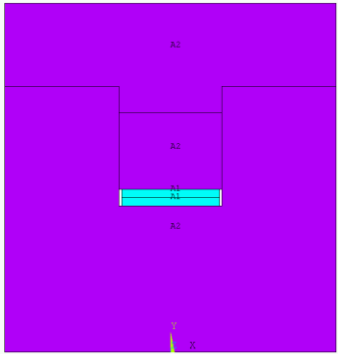
Stress interface

Details will be addressed by Jose in the Next EurocCirCol Meeting.

Splice

- Mechanical characterization of Nb_3Sn-Nb_3Sn splices started.
  - First step: study the bonding of the cables during reaction for different pressure level and procedures.



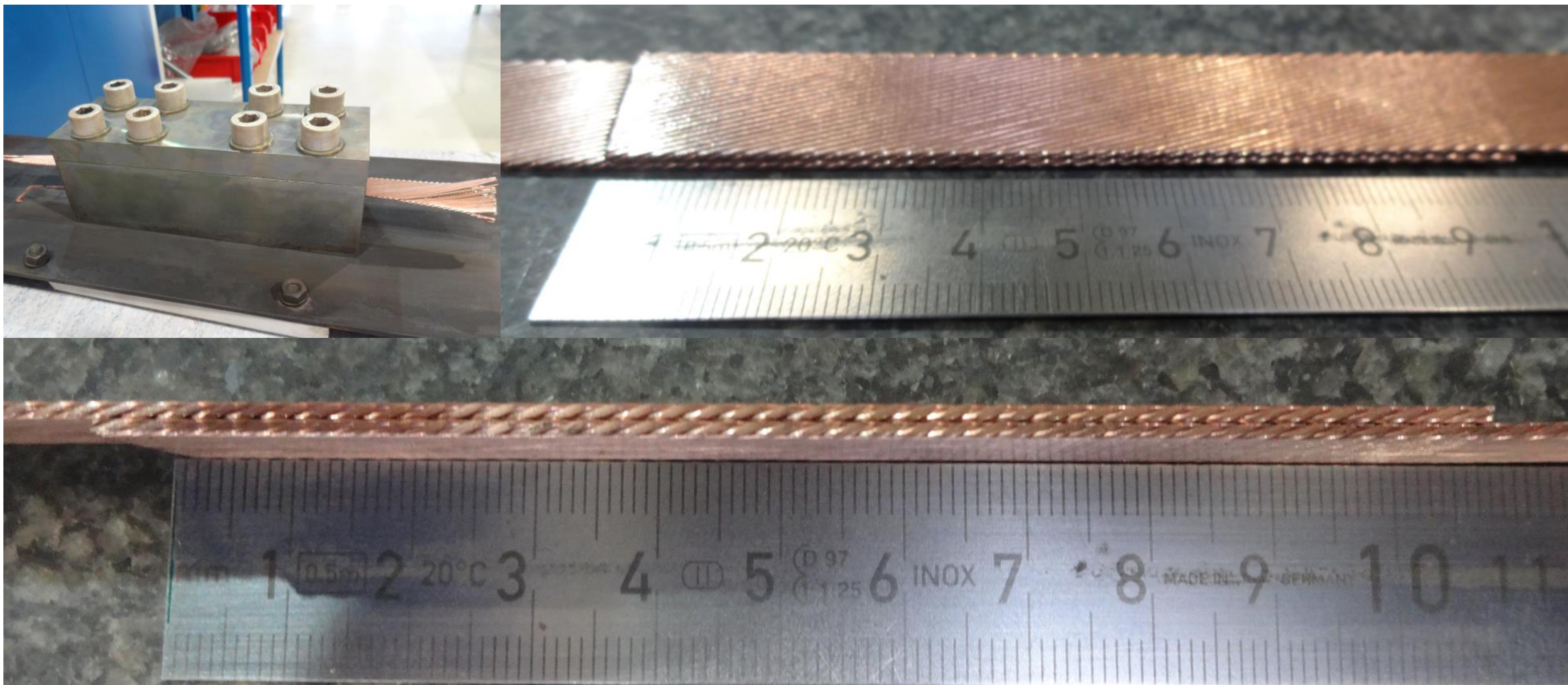


- Cables cleaned using acetone.
- Stress level during assembly = 2.5 MPa
- Cavity size: 15.5 x 2.5 mm (dimensions of the conductor before heat treatment)
- During reaction, due to the difference on thermal contraction between mould and cable:
  - Very small (or none) compression when neglecting the change of dimensions of the conductor during heat treatment
  - Large compression (~ 200 MPa) when assuming that the cable thickness increase by 3 %

$$\alpha_{Cu} = 16.6 \cdot 10^{-6} K^{-1}$$
$$\alpha_{Bronce} = 18 \cdot 10^{-6} K^{-1}$$
$$\alpha_{SS304} = 17.7 \cdot 10^{-6} K^{-1}$$

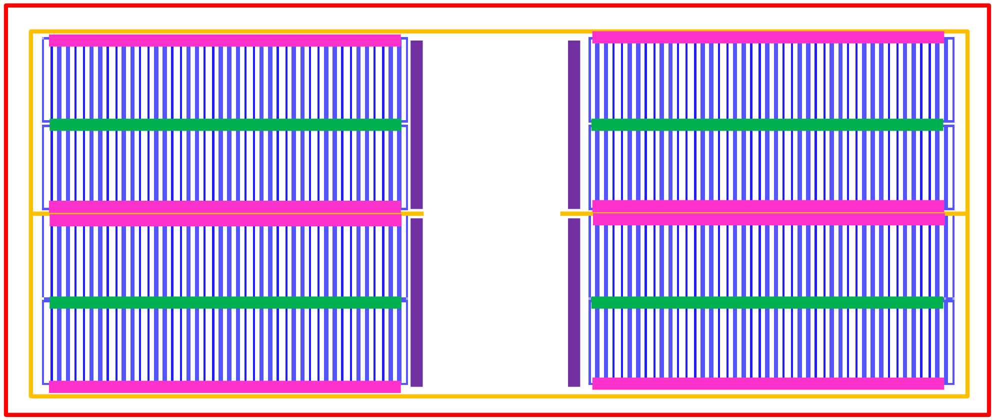
Splice

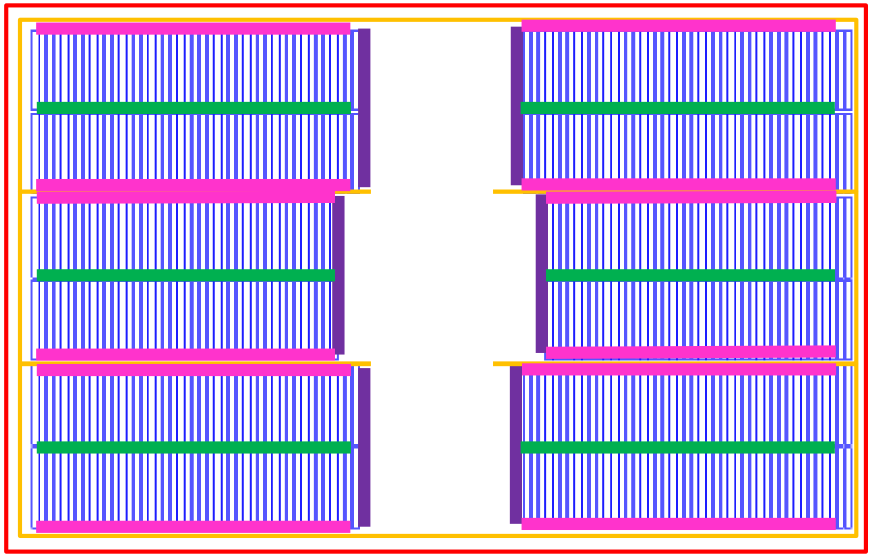
The cables are bonded after the heat treatment…how good is this bonding?



Electrical insulation

- 0.4 mm S2 glass between coil and pole
- 0.1 mm trace + 0.2 mm of S2 glass in the outer coil surfaces
- 0.5 mm S2 glass for the layer to layer insulation
- 0.125 mm of Kapton around the coils
- 0.125 mm of Kapton around coil assembly





Electrical insulation

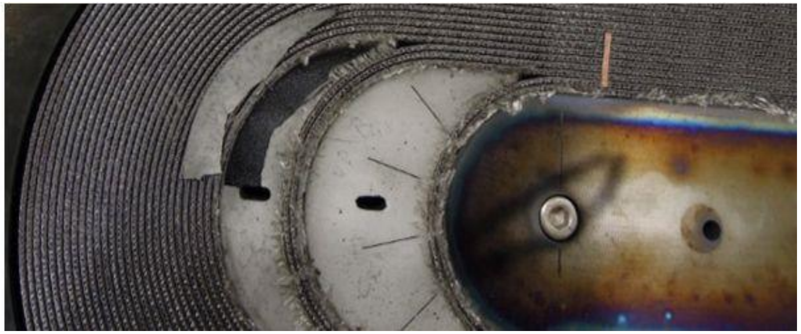
Weakest point for all coils produced in 927

↓

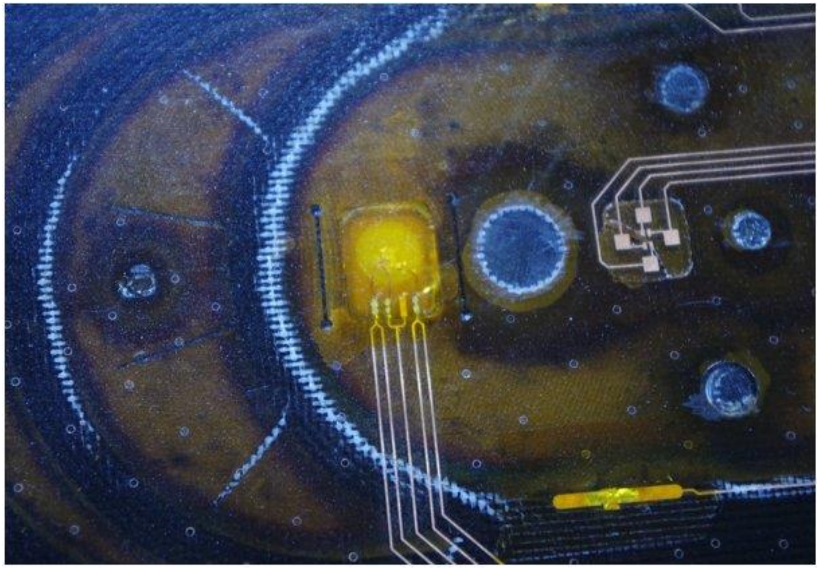
Coil to pole insulation

- Traditional approach to cope with the coil to pole insulation issue:
  - Ceramic plasma coating of end parts (problems of delamination)
  - Additional layers of S2-glass between pole and coil,
- “Innovative solutions” to be tried?
  - Do we really want to be glued in the pole/coil interface?
  - What about adding Mica?

RMC coil after reaction



SMC11T#1_c_101 after tests



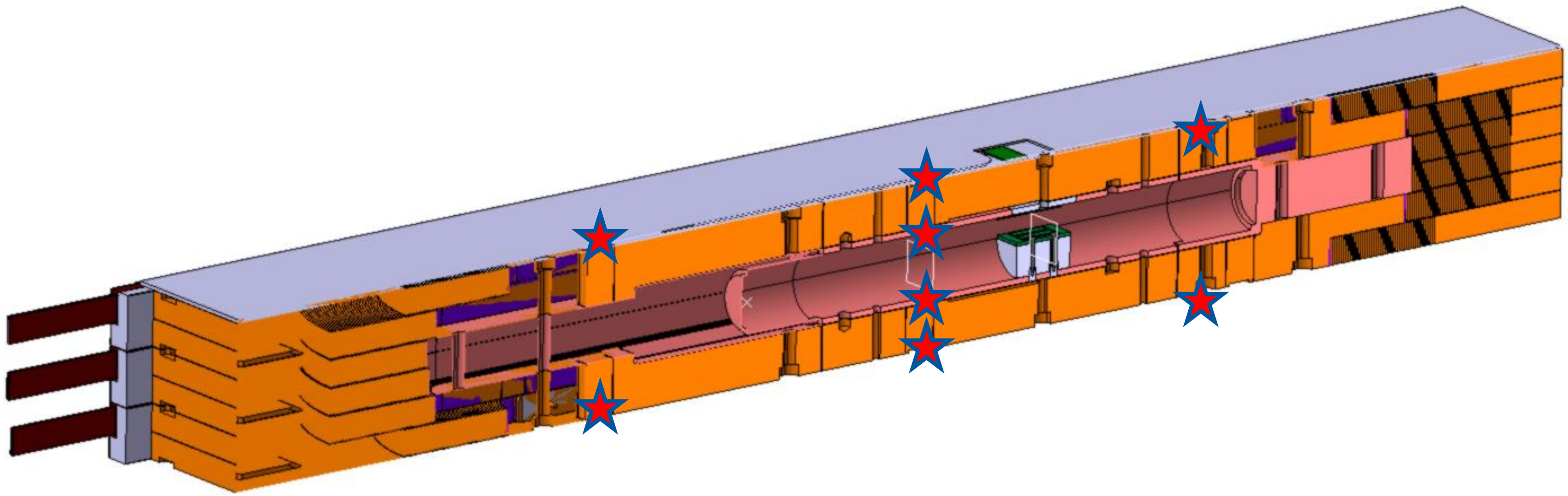
Summary

- Detailed engineering design for the non-graded magnet finalized.
  - Aim: Start winding beginning of 2017.
- Studies on graded design on-going, final decision on cross section will be taken considering EuroCirCol guidelines.
- Parallel on-going activity:
  - Cable insulation tests to define the mica width and braiding parameters.
  - Field measurements using hall probes and PCB coils.
  - Splice mechanical characterization.
- To be addressed in the future:
  - Splice electrical characterization
  - Mechanical characterization of coil properties on-going within 11 T and MQXF projects for stacks of cables and coils → extend to flat coils including coil end characterization?
  - Robustness of electrical insulation from coil to central post.
  - Quench localization methods further than voltage taps.
  - Mechanical measurements further than strain gauges.

Additional slides

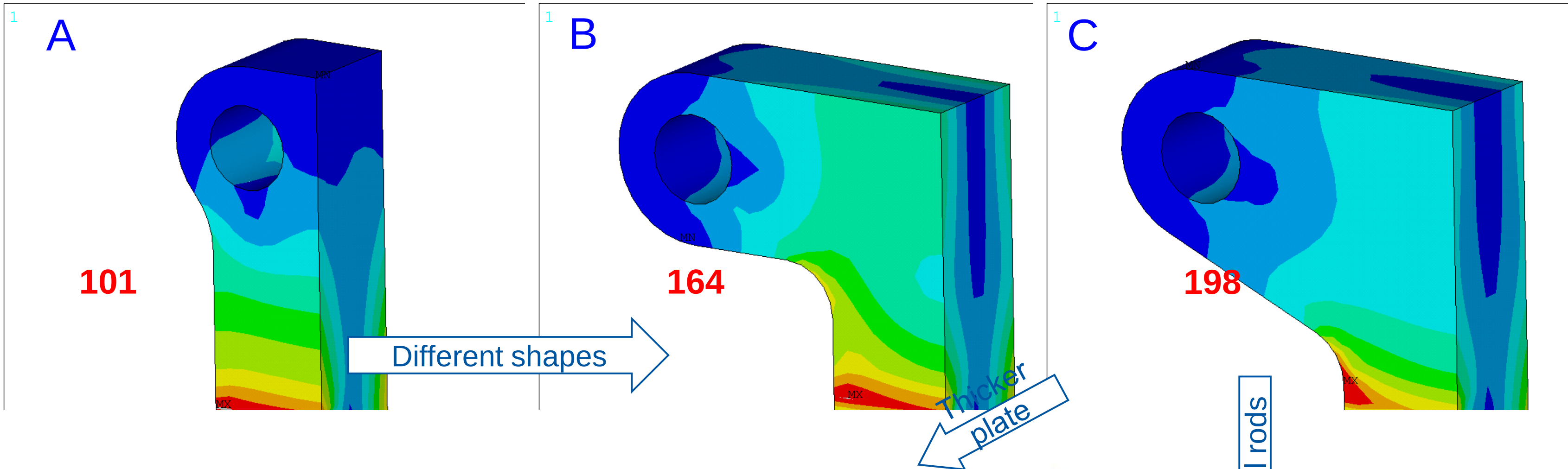
Strain measurements

- From “RMC type” installation to “MQXF type” installation → twisted wires routed through the top G10 plate instead of embedded in the trace.
- 3 strain gauges per coil in ERMC + 1 compensator
- 2 strain gauges per coil in RMM (top/bottom) + 1 compensator
- The gauges are 8.5 mm x 5.5 mm, with an active length of 3 mm x 3.2 mm (http://www.hbm.cz/Prospekty/Tenzometry/SG_C/cat_sg_c_e.pdf 1-LC11-3/120)



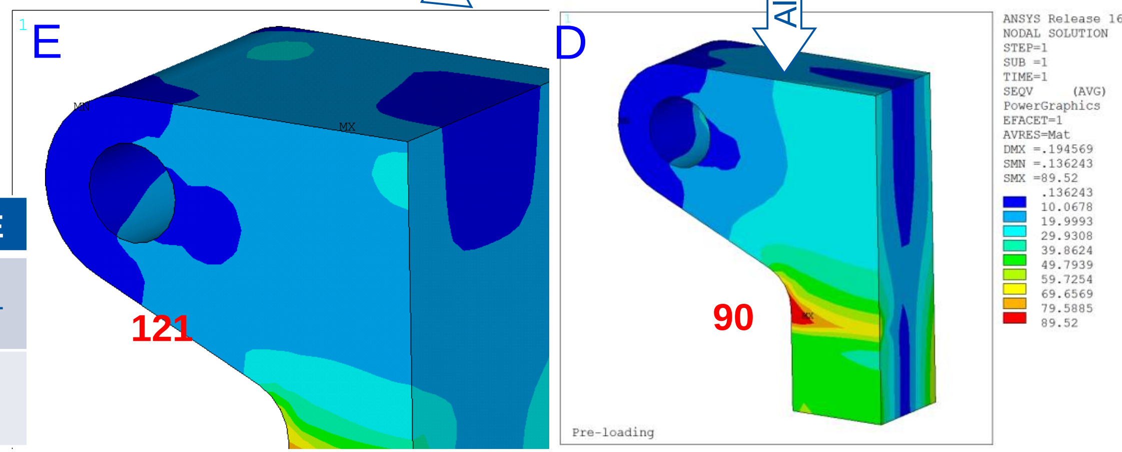
Longitudinal loading

0.3 mm rod-plate interf.



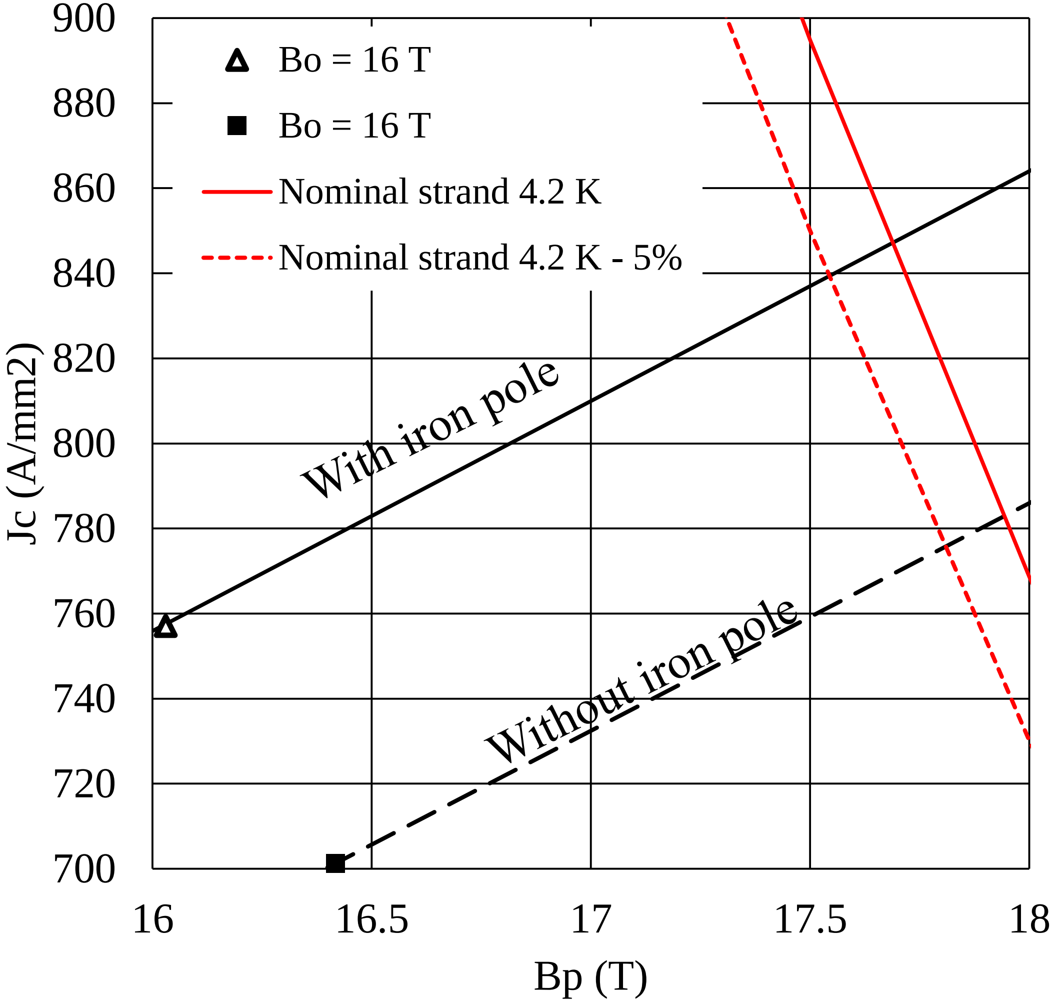
- Lorentz Force Fz @ 18 T = **3.0 MN**
- Force in the rods [MN], after Pre-load + Cool-Down:

	A	B	C	D	E	D+E
0.3 mm interf.	0.18	0.34	0.36	0.53	0.78	0.94
At yield limit	0.50	0.63	0.59	0.87	1.9	**2.5**

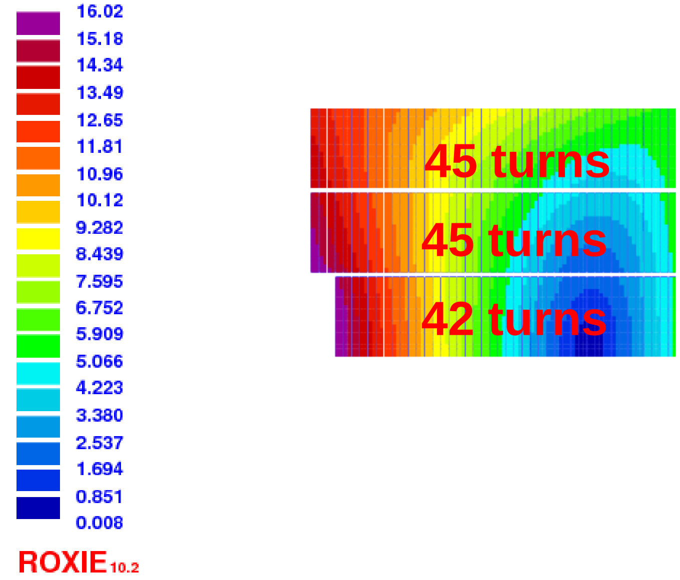


→ Optimum for "H" shape + thick plate + Aluminum rods

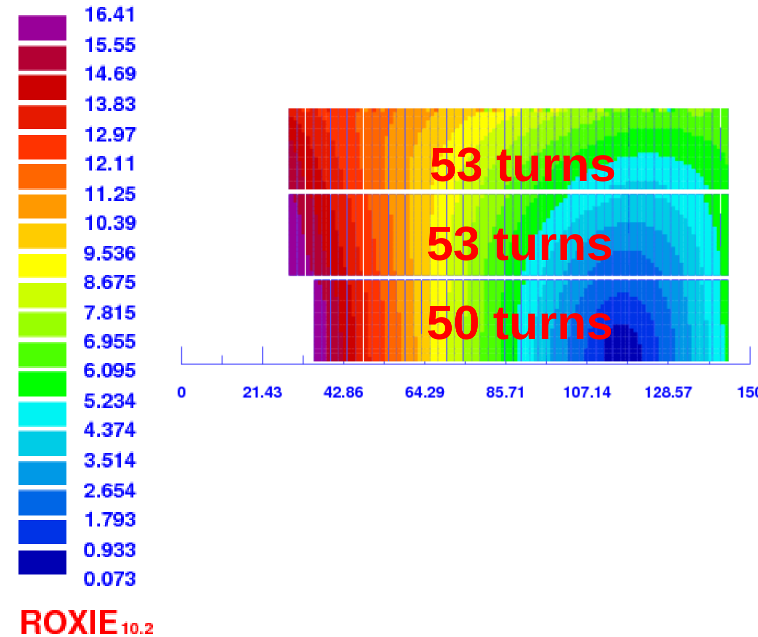
Iron Pole



900
880
860
840
820
800
780
760
740
720
700
Jc (A/mm2)
16
16.5
17
17.5
18
Bp (T)
Bo = 16 T
Bo = 16 T
Nominal strand 4.2 K
Nominal strand 4.2 K - 5%
With iron pole
Without iron pole



16.02
15.18
14.34
13.49
12.65
11.81
10.96
10.12
9.282
8.439
7.595
6.752
5.909
5.066
4.223
3.380
2.537
1.694
0.851
0.008
ROXIE10.2
45 turns
45 turns
42 turns



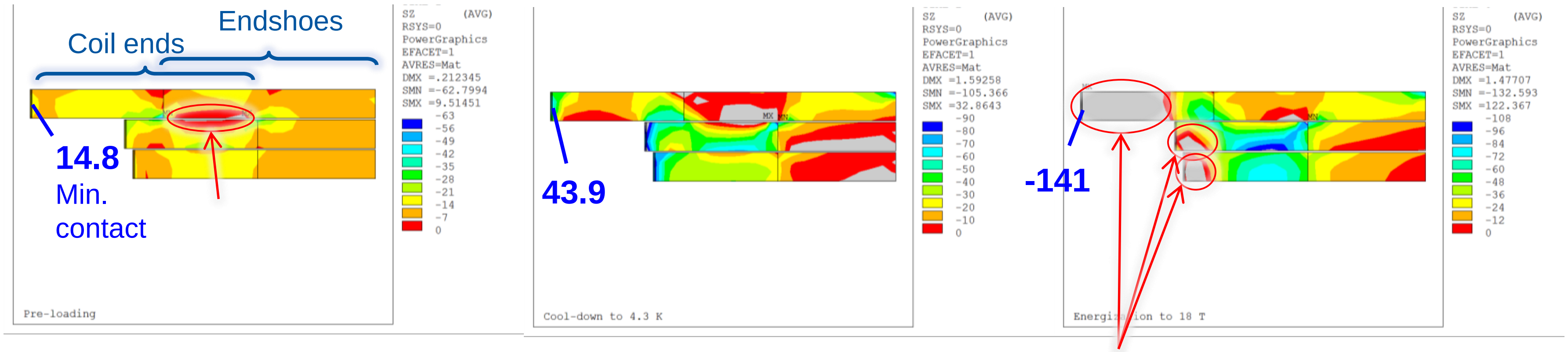
16.41
15.55
14.69
13.83
12.97
12.11
11.25
10.39
9.536
8.675
7.815
6.955
6.095
5.234
4.374
3.514
2.654
1.793
0.933
0.073
ROXIE10.2
53 turns
53 turns
50 turns
0
21.43
42.86
64.29
85.71
107.14
128.57
150

Material properties in ANSYS

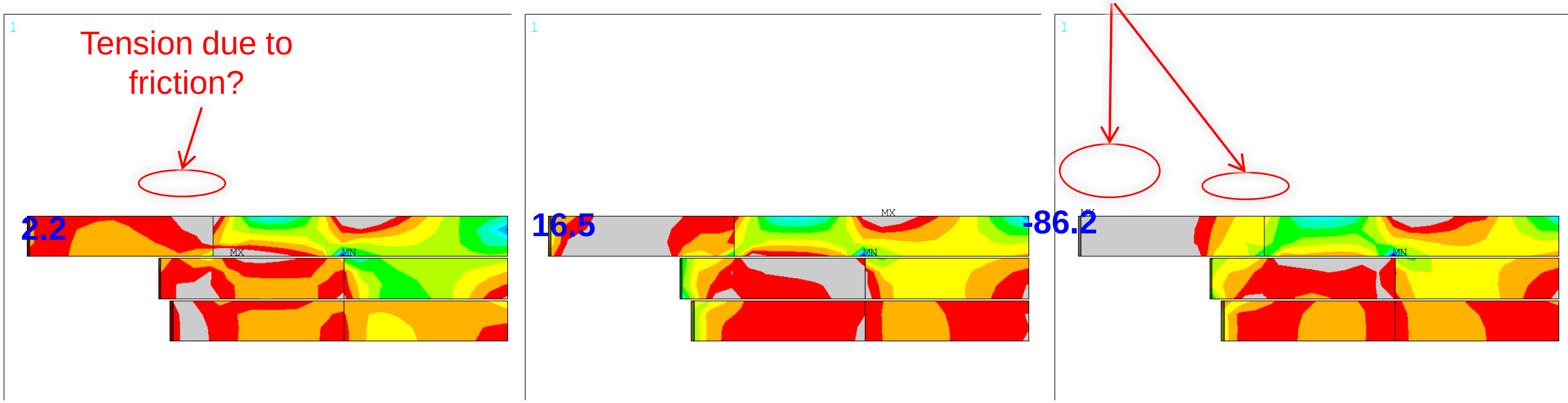
Material	E [GPa]		pr	$(L_{4.3K}-L_{293K})/L_{293K}$
	293 K	4.3 K	293 K/4.3K	293 K -> 4.3K
Coil	EX = 44 EY = 52 GXY = 21	EX = 44 EY = 52 GXY = 21	0.3	X = 3.36e-3 Y = 3.08e-3
Stainless steel	193	210	0.28	2.84e-3
Aluminum Bronze	110	120	0.3	3.12e-3
Iron	213	224	0.28	1.97e-3
Aluminum	70	79	0.34	4.2e-3
G10	30	30	0.3	7.06e-3
Titanium	110	120	0.3	1.8e-3
Nitronic 40	210	225	0.28	2.6e-3
ST430	200	210	0.28	1.74e-3

Longitudinal loading

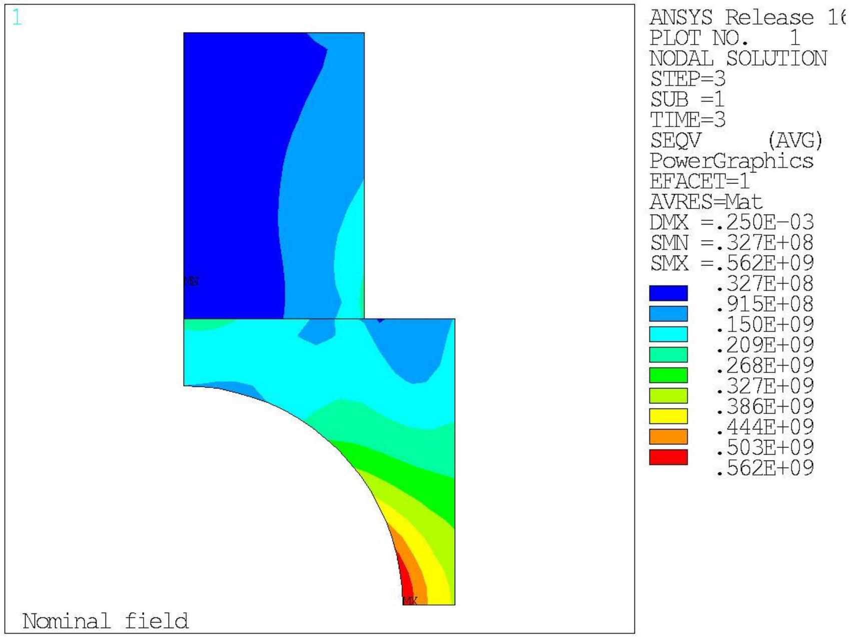
A: G11 endshoes, bonded

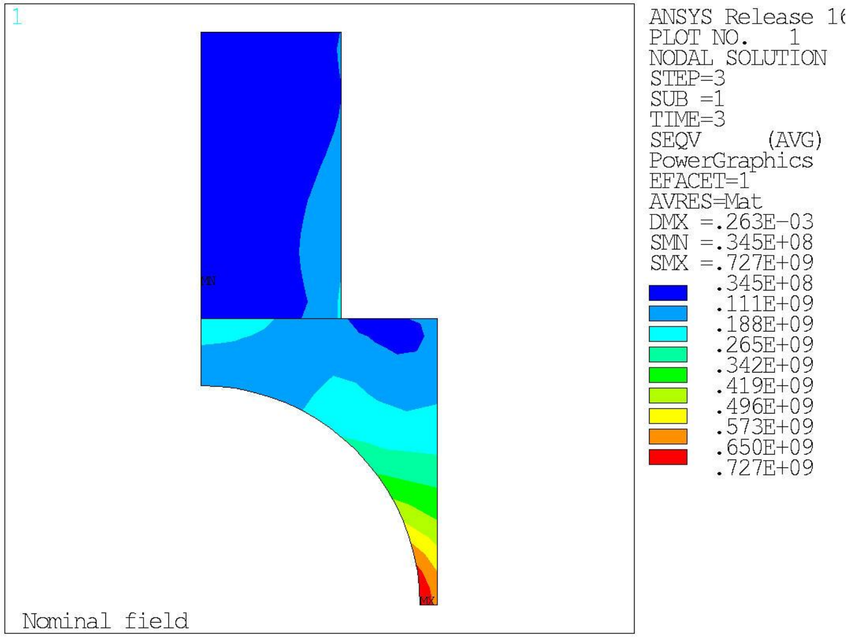


B: **SS** endshoes, bonded



	Set 1 (Old)	Set 2	Set 3 (EuroCirCol)	Set 4
Ex, warm	44	25	25	27.5
Ey, warm	52	30	30	27.5
Gxu, warm	21	12	12	
vxy, warm	0.3	0.3	0.3	0.3
Ex, cold	44	25	27.5	27.5
Ey, cold	52	30	33	27.5
Gxu, cold	21	12	13.2	
vxy, cold	0.3	0.3	0.3	0.3
Bladders pressure, Mpa	50	60	60	60
Horizontal interference, mm	1.12	1.32	1.27	1.3
Coil Max. σ_{VM} keys, Mpa	130	153	147	145
Coil Max. σ_{VM} cool down, Mpa	175	175	166	162
Coil Max. σ_{VM} powering, Mpa	167	163	163	164
Av. cont. pres. at pow. C1 (lower), Mpa	23.1	24	23.7	24.4
Av. cont. pres. at pow. C2 (upper), Mpa	10	10.3	10.3	10.4


1
ANSYS Release 16
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =1
TIME=3
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.250E-03
SMN =.327E+08
SMX =.562E+09
.327E+08
.915E+08
.150E+09
.209E+09
.268E+09
.327E+09
.386E+09
.444E+09
.503E+09
.562E+09
Nominal field


1
ANSYS Release 16
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =1
TIME=3
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.263E-03
SMN =.345E+08
SMX =.727E+09
.345E+08
.111E+09
.188E+09
.265E+09
.342E+09
.419E+09
.496E+09
.573E+09
.650E+09
.727E+09
Nominal field

6 mm **2 mm**