16 T Nb_3Sn block dipole EuroCirCol

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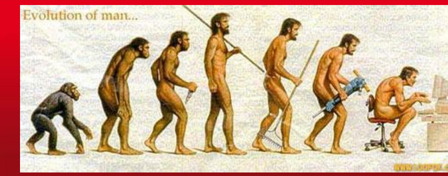
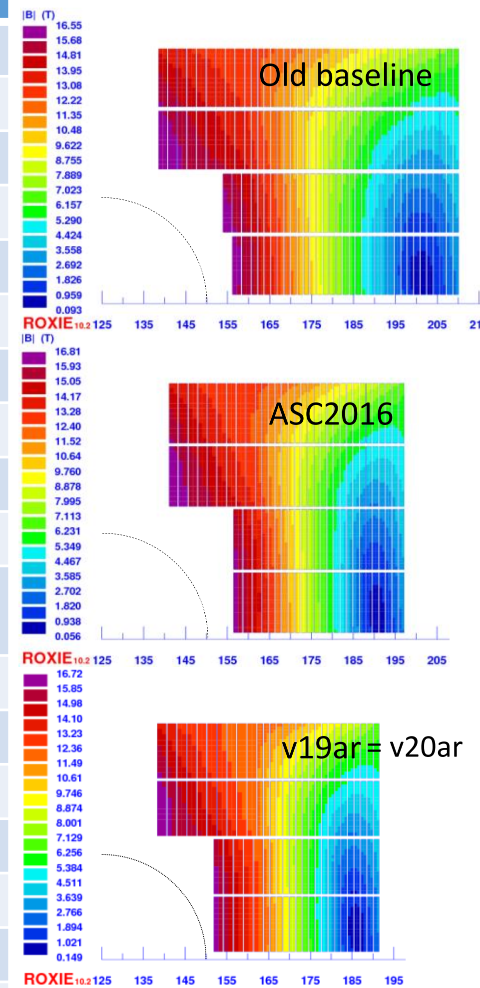
Acknowledgments: All WP5 members,

Helene Felice (CEA), Susana Izquierdo-Bermudez, Etienne Rochepault, Paolo Ferracin (CERN)

Design evolution



Quantity	old baseline	ASC2016	v20ar	Unit
strand diameter	1.1 – 0.7	1.1 – 0.7	1.155 – 0.705	mm
nb of strands	24 – 37	24 – 39	21 – 35	N/A
width	13.85	14.25	13.05	mm
average thickness	2.0 – 1.25	2.0 – 1.25	2.1 – 1.25	mm
Cu/nonCu	1.0 – 1.0	0.8 – 1.6	0.8– 2.3	N/A
I_{nom}	8470	10930	10990	A
B_{peak}	16.56	16.81	16.74	T
LL margin (1.9 K)	16.8	13.95	14.01	%
Inductance diff. (2 ap)	88.19	48.06	39.80	mH/m
Stored energy (2 ap)	3340	3016	2518	kJ/m
Nb of turns	153 = 2+3+9+9 +32+32+33+33	114 = 3+3+9+9 +22+22+23+23	104 = 5+5+10+10 +18+18+19+19	-
Fx & Fy (per ½-coil)	8817 & -3703	8473 & -3572	8042 & -3347	kN/m
Hotspot	310	348	349	K
Bore thickness	6.0	6.3	1.75	mm
Midplane shim	2.0	1.45	1.75	mm
LdxI (1 aperture)	373	263	218	HA/m
I/Ic HF-LF	-	-	0.47 – 0.61	-
Conductor area (2 ap)	**190**	**151.9**	**133.7**	cm^2
4578 x 14.3 x 8.7 weight	**10820**	**8652**	**7614**	tons

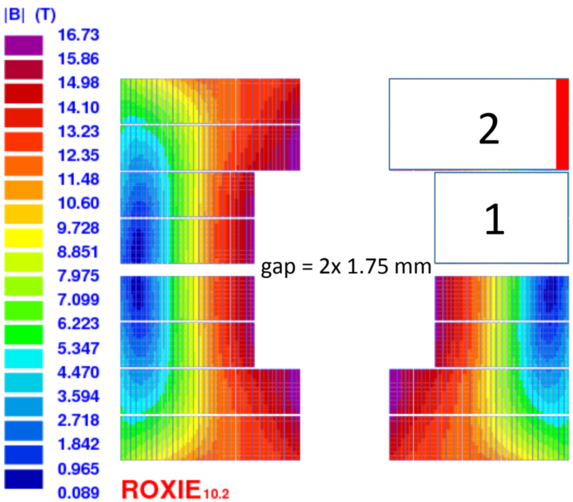


insulation = 0.15 mm

margin&cnc drop

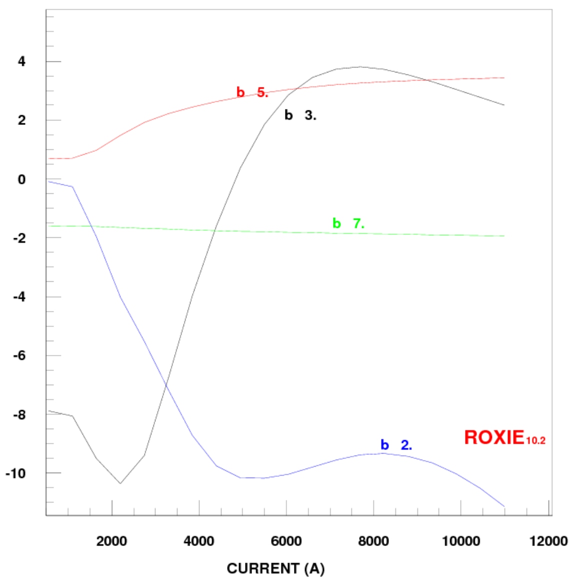
bore tip th. decrease

Version v20ar – Emag 1/2



Δy1 [mm]	Δy2 [mm]	B [T]	b3	b5
+ 0.0	+ 0.0	16.0	2	3
- 0.5	+ 0.0	16.05	21	8
- 0.5	- 0.5	16.12	16	7
- 1.0	- 0.5	16.17	34	11
- 1.0	- 1.0	16.23	29	11

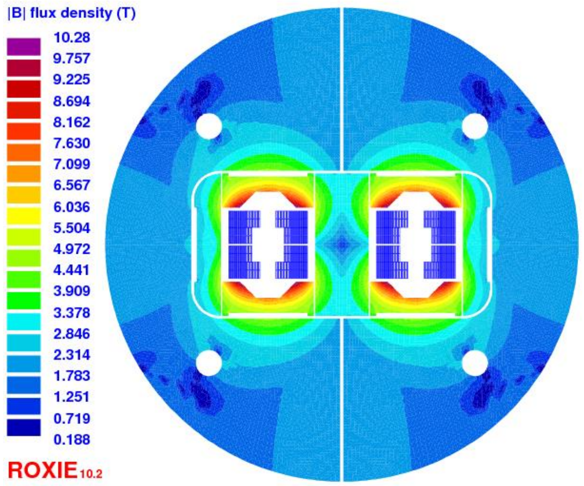
2 turns (in red) could potentially be saved
133.7 cm² -> 131.5 cm²
1.65 % or 125 tons

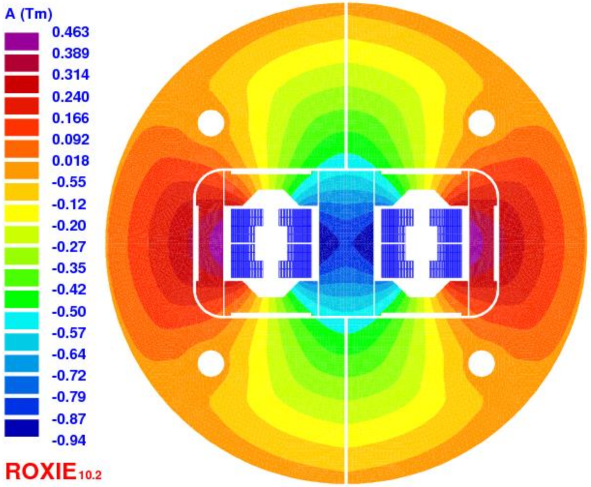


I have not managed to find a way to recover the harmonic content while keeping the field saving.


```
NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:    -11.13264  b 3:      2.50314
b 4:     -0.38669  b 5:      3.43328  b 6:     -0.01247
b 7:     -1.93500  b 8:     -0.00039  b 9:     -1.38595
```

Version v20ar – Emag 2/2





- Rod hole: size and positioning not yet defined (Axial loading).
- So far: 45 mm in diameter/223 mm and 63° wrt the aperture
- If closer to the ap. or bigger in diameter -> field drop to compensate…

Basic approach:

- ~Fz = 2518 kN/side
- Yield strength ss316LN: 930 MPa [MPA = N/mm²]
- 30 mm in diameter for 4 rods
- Margin: yield strength 450 MPa -> 42 mm

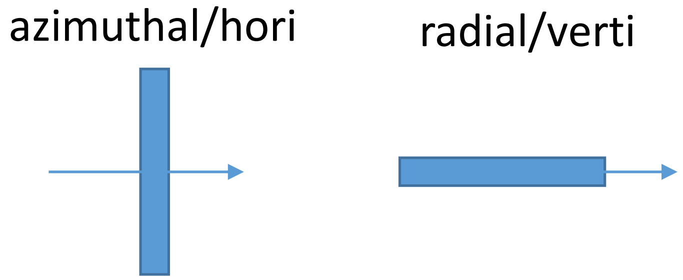
Mechanical parameters

- Young modulus modifications

[GPa]	New baseline 7oct16			Old baseline		
Temp	300 K	4.2 K	direction	300 K	4.2 K	direction
Nb_3Sn	25*	+10% 27.5	azimuthal/hori	44	44	azimuthal/hori
Nb_3Sn	+20% 30	33	radial/verti	52	52	radial/verti
Ti6Al4V	115	126.5	isotrope	130	130	isotrope

measured values

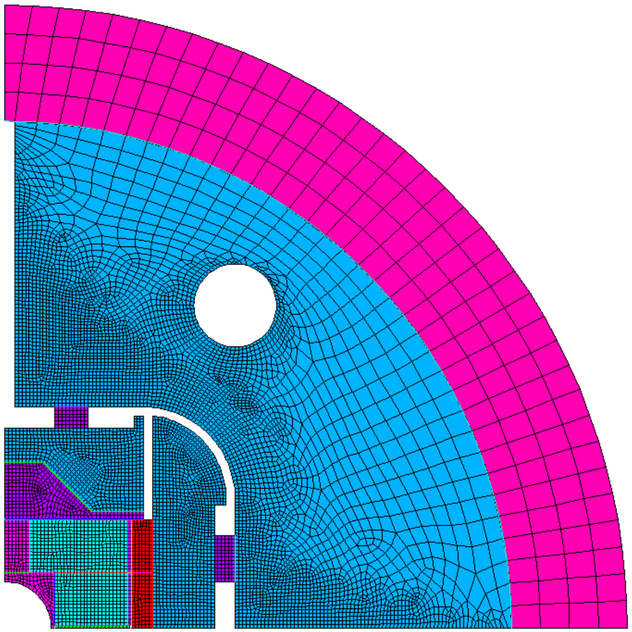
20 GPa instead of 25 GPa

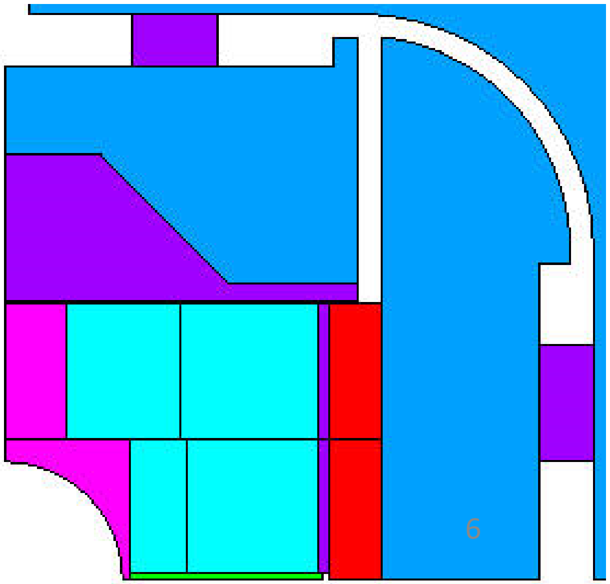


Structure overview

- 63 mm thick shell
- 750 µm ←
- 50 µm ↓
- 1.75 mm thick bore tip

- Contacts/symmetry:
  - sliding; 0.2 friction
  - glued: coils with pole vertically and with shoes
  - rail is a block for rigidity

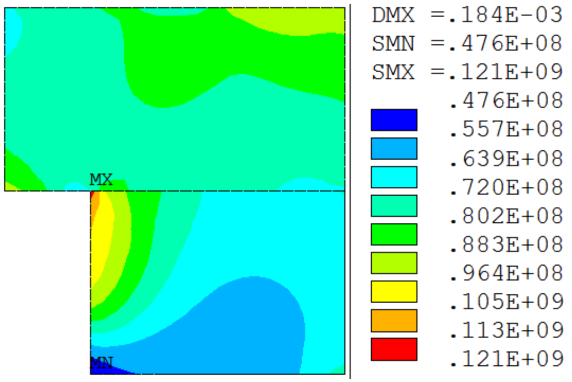




Coil stress distribution

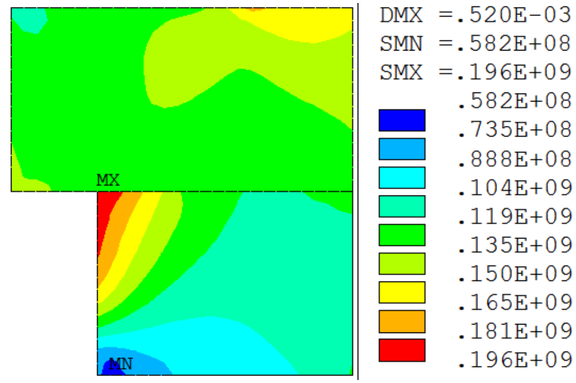
von Mises

Key



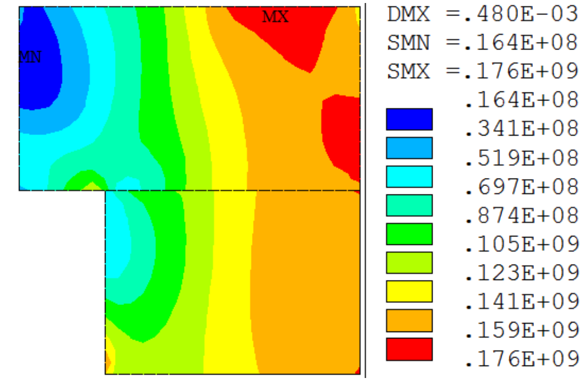
+121 MPa

Cold – 4.2 K



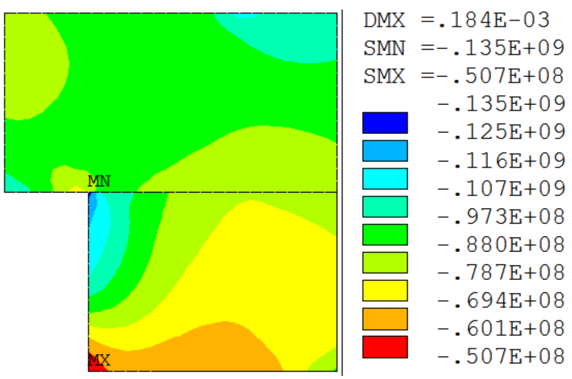
+196 MPa

16.8 T (105% nominal)

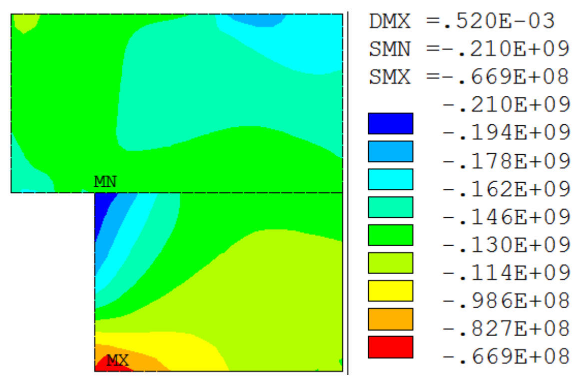


+176MPa

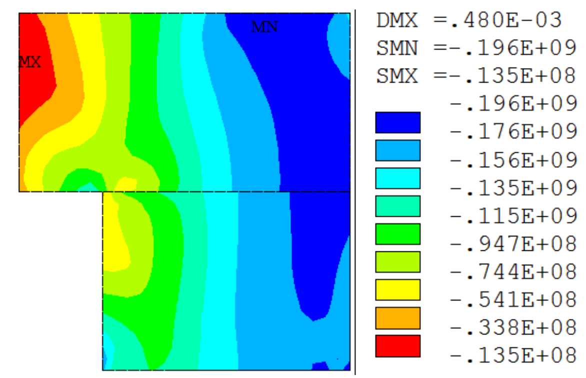
σII – compression max



-135 MPa



-210 MPa

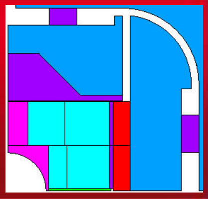


-196 MPa

- Where is the 200 MPa limit coming from?

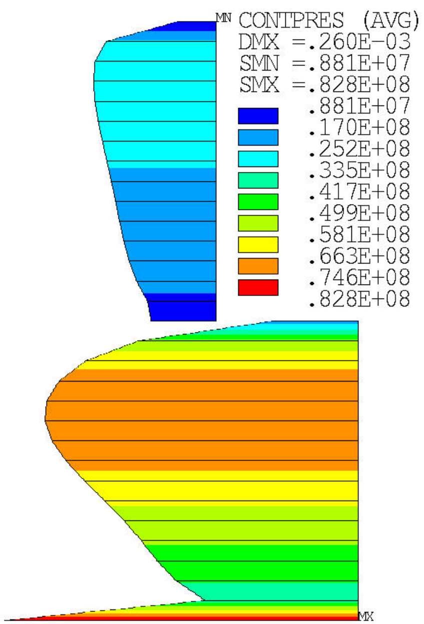
comparison measurements vs simulation with… von Mises

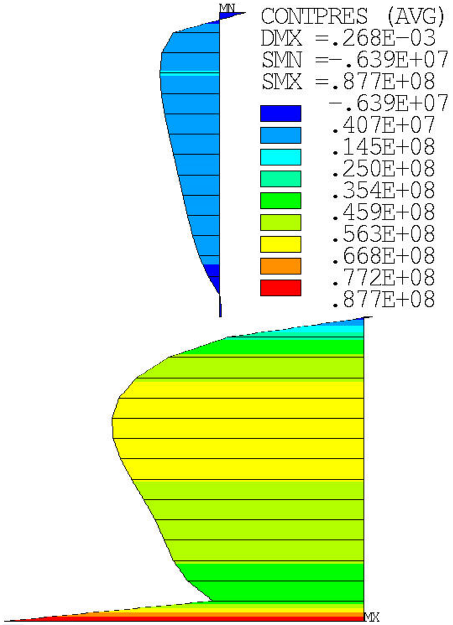
Coil peak stress [MPa]



MPa	Key	Cool-down	16.0 T	16.8 T
von Mises stress	121	196	175	177
σIII (close to σx)	135	210	196	196
contact traction			+8	-7

Opening with
50 MPa bladders
↓ 100 µm
← 850 µm
I cannot open vertically
if I push horizontally



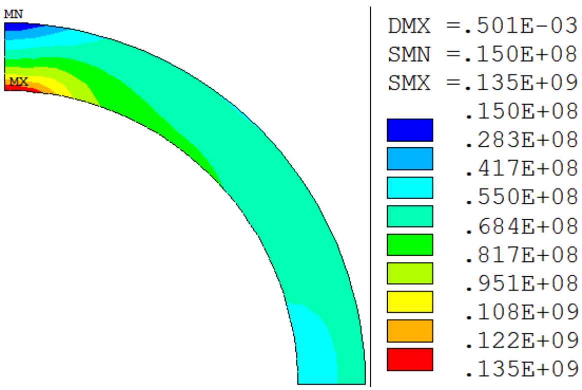


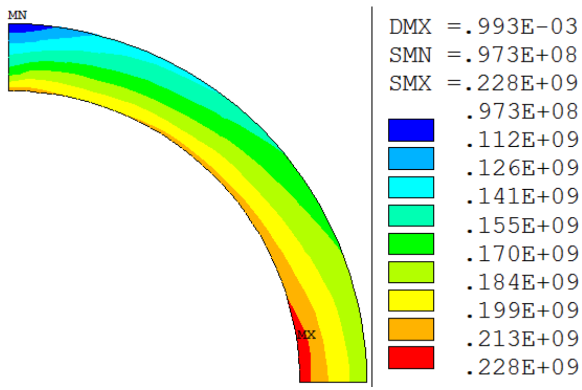
Aluminum shell

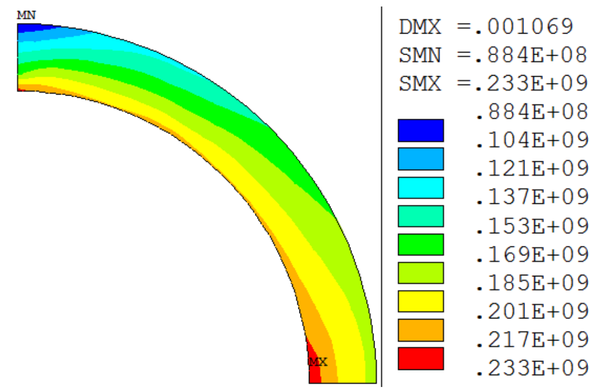
$R_{p0.2}$	RT	cold
AL 7075	480 MPa	690 MPa

Key | Cold – 4.2 K | 16.8 T (105% nominal)

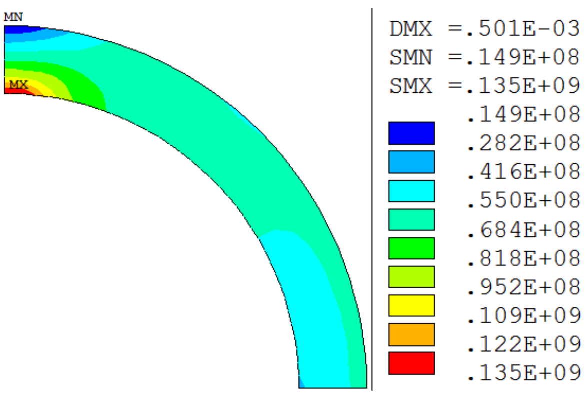
von Mises

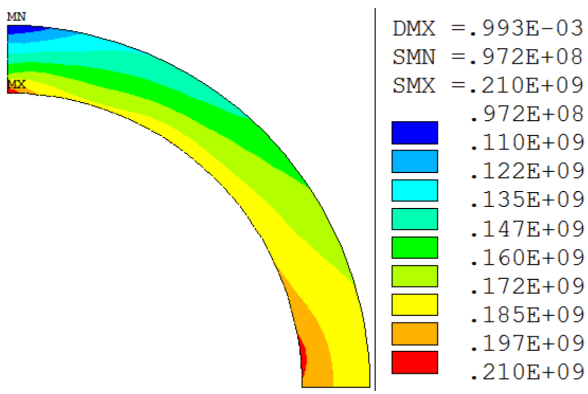


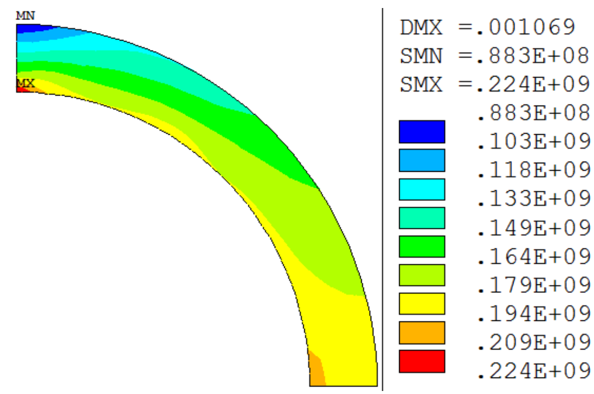




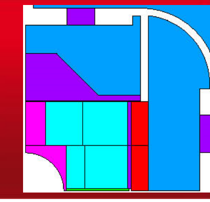
σI – tension max







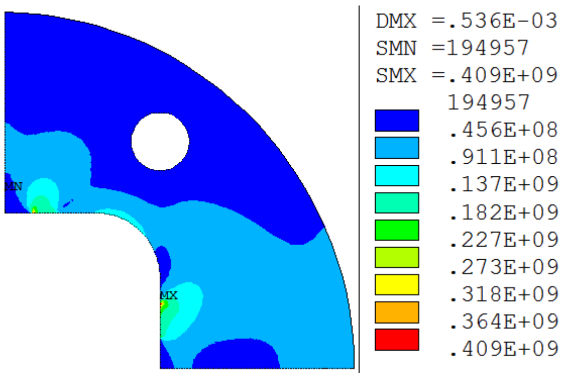
Iron yoke

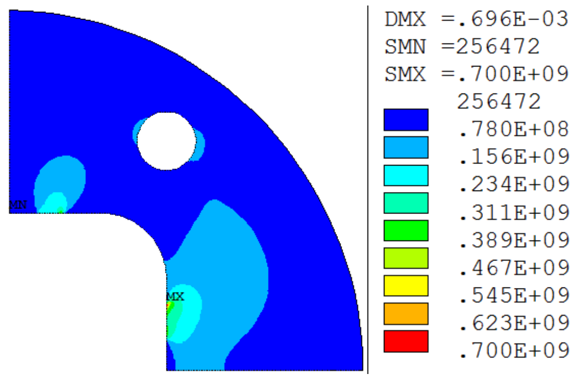


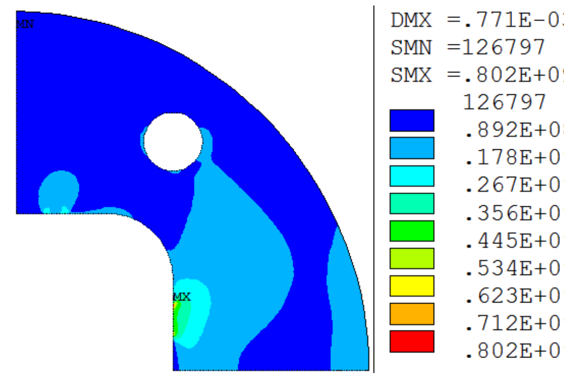
$R_{p0.2}$	RT	cold/tension
Magnetil	180 MPa	723 MPa/200 MPa

Key | Cold – 4.2 K | 16.8 T (105% nominal)

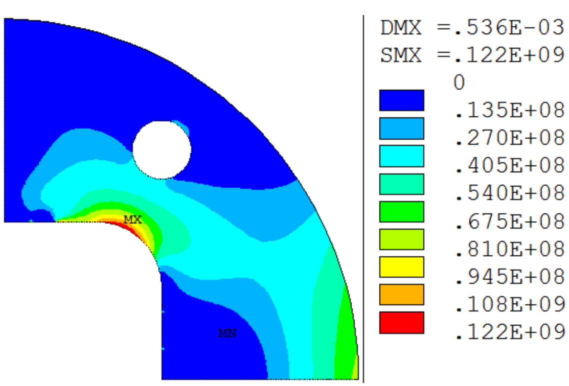
von Mises

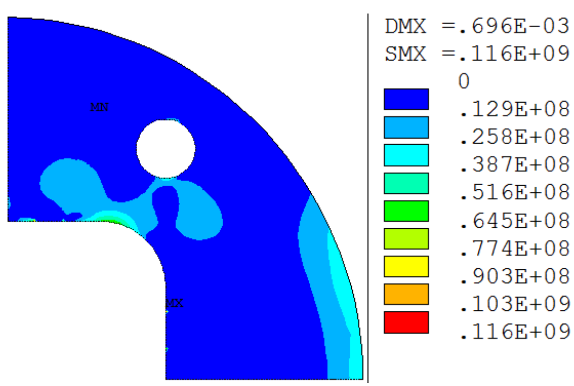


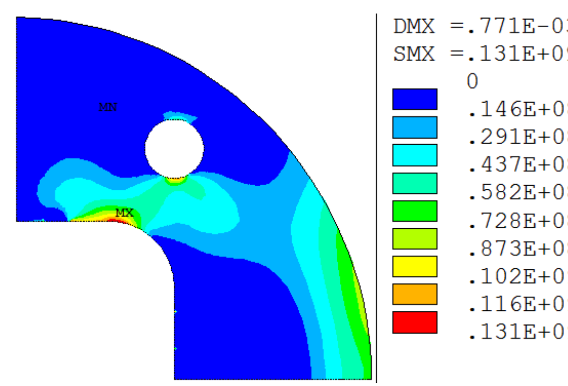


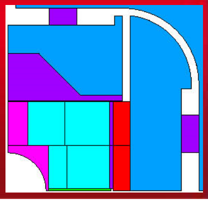


σI – tension max







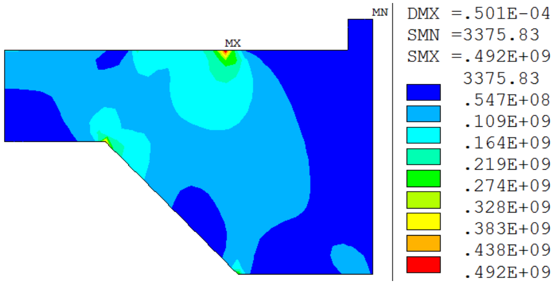


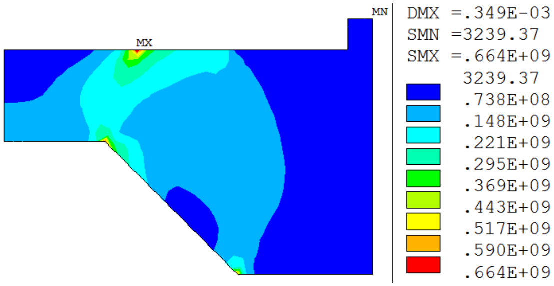
Iron pad1

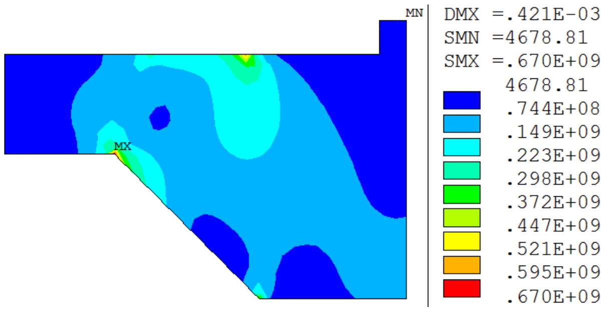
$R_{p0.2}$	RT	cold/tension
Magnetil	180 MPa	723 MPa/200 MPa

	Key	Cold – 4.2 K	16.8 T (105% nominal)

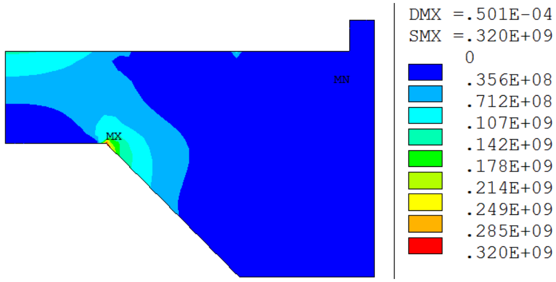
von Mises

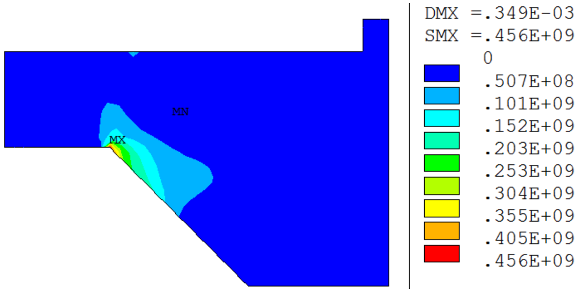


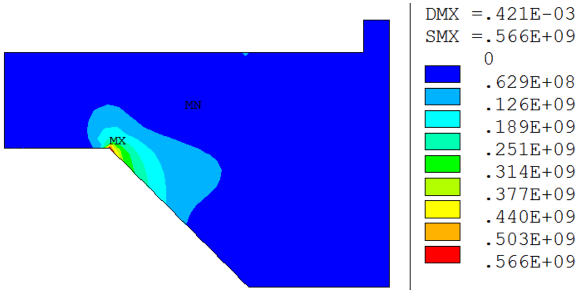


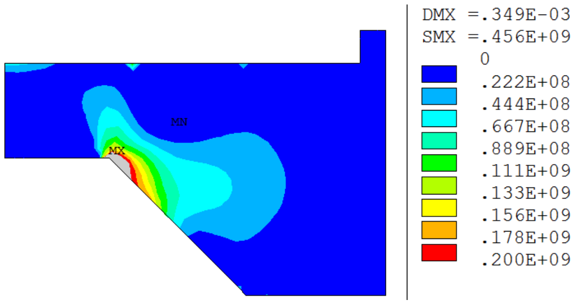


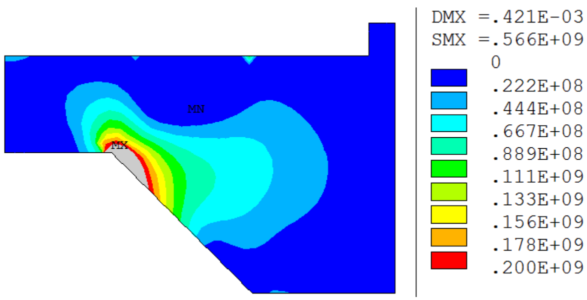
σl – tension max



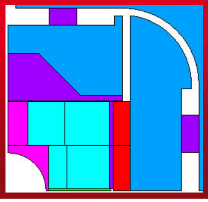








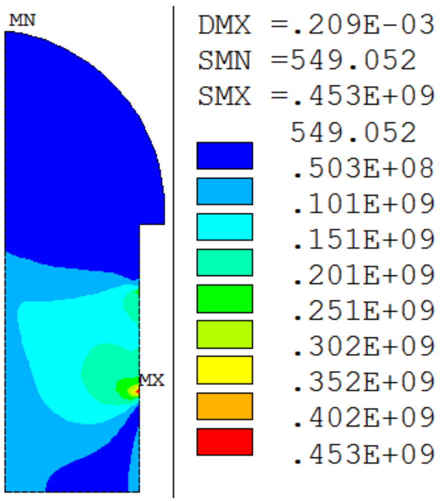
Iron pad2

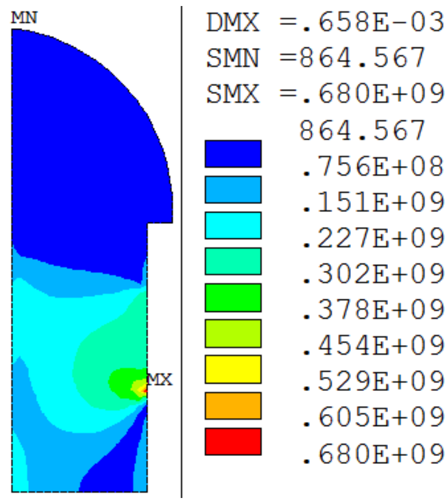


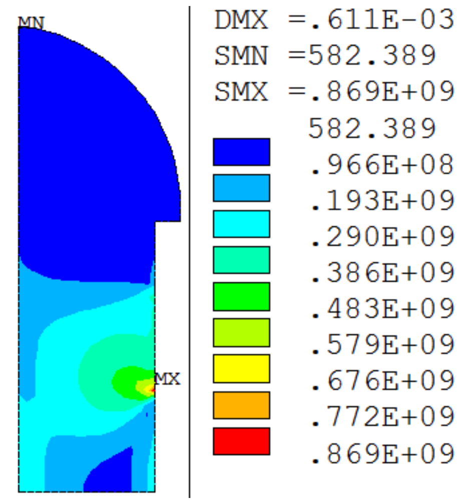
$R_{p0.2}$	RT	cold/tension
Magnetil	180 MPa	723 MPa/200 MPa

	Key	Cold – 4.2 K	16.8 T (105% nominal)

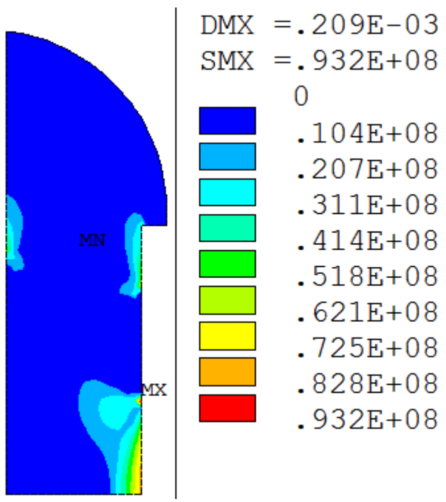
von Mises

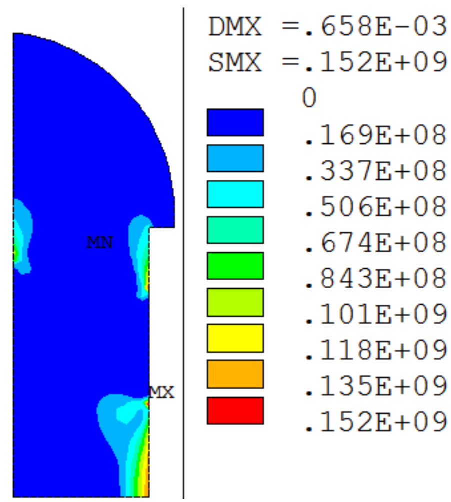


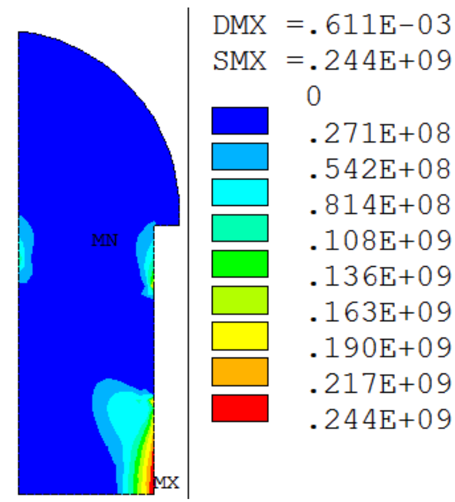




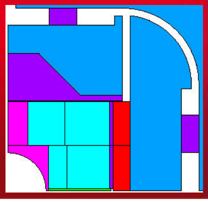
σI – tension max







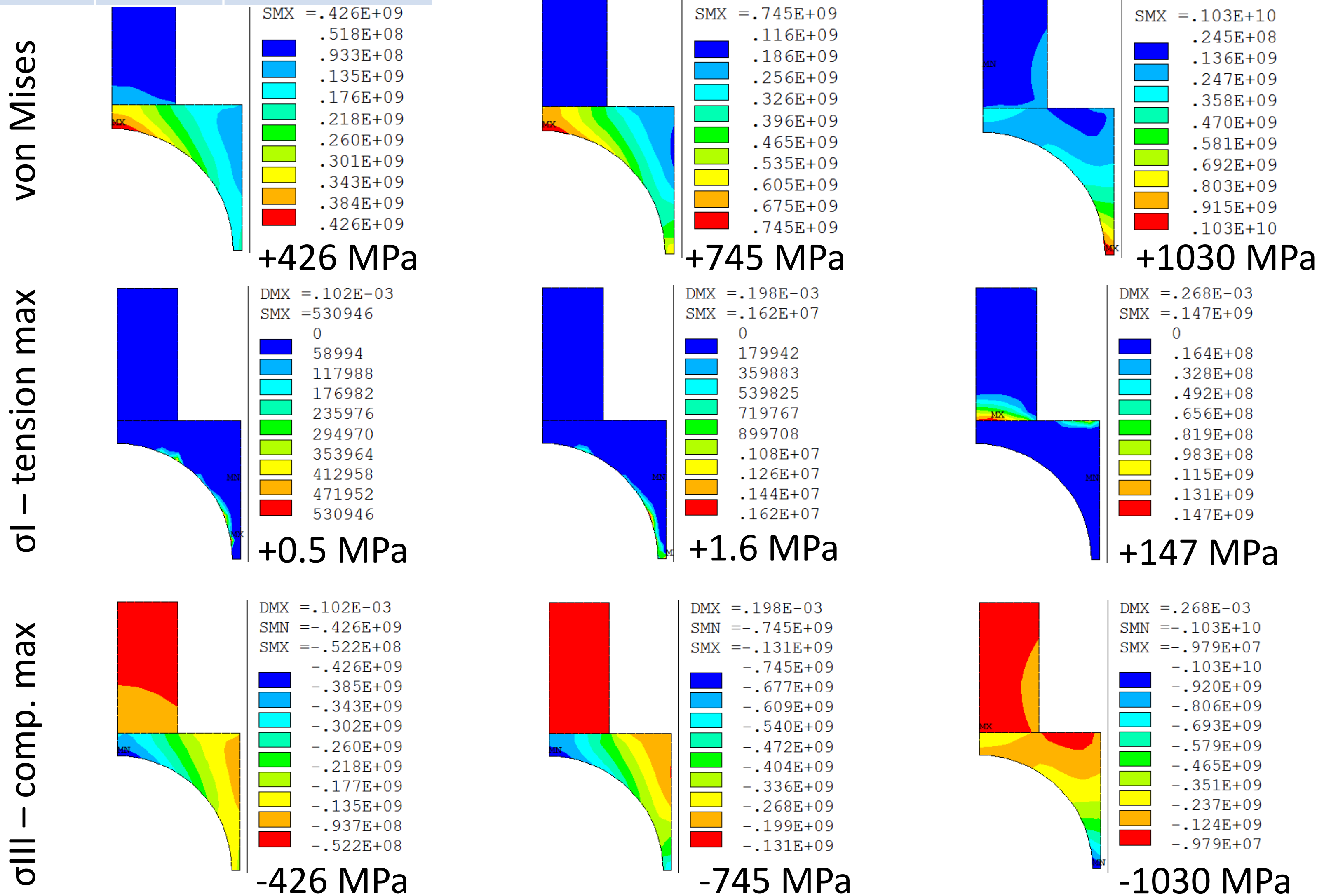
Titanium pole



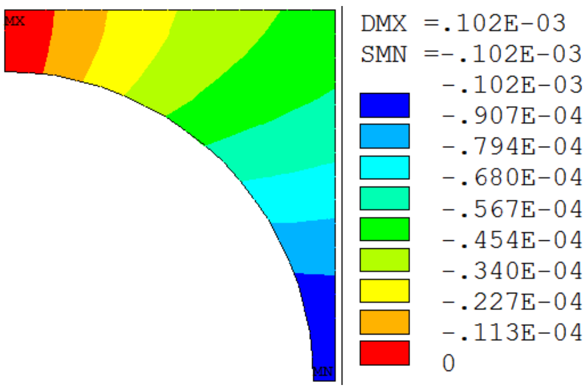
$R_{p0.2}$	RT	cold/tension
Ti-6Al-4V	827 MPa	1624 MPa

Cold – 4.2 K

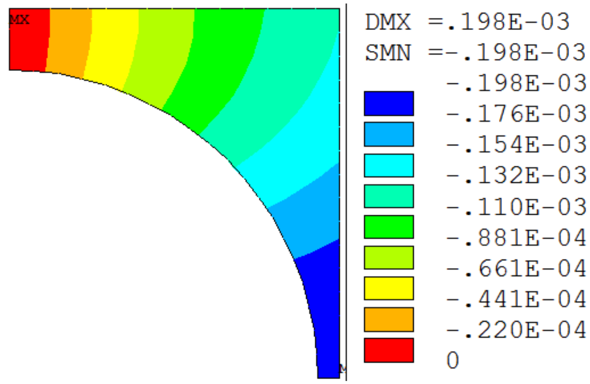
16.8 T (105% nominal)



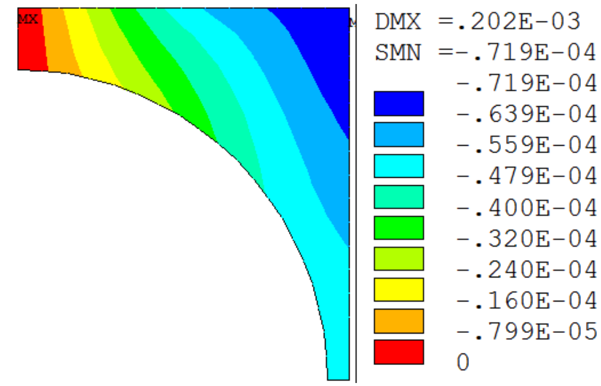
Bore tip displacement



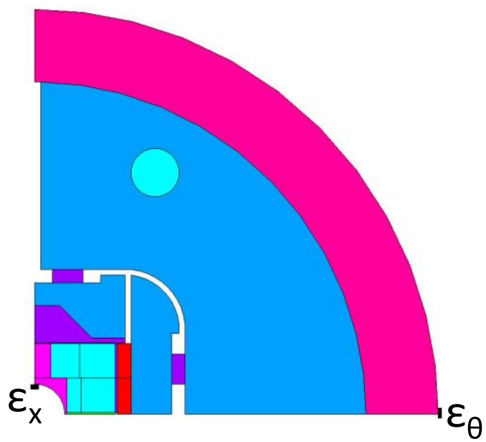
-100 µm
100 µm <-



-200 µm
100 µm <-



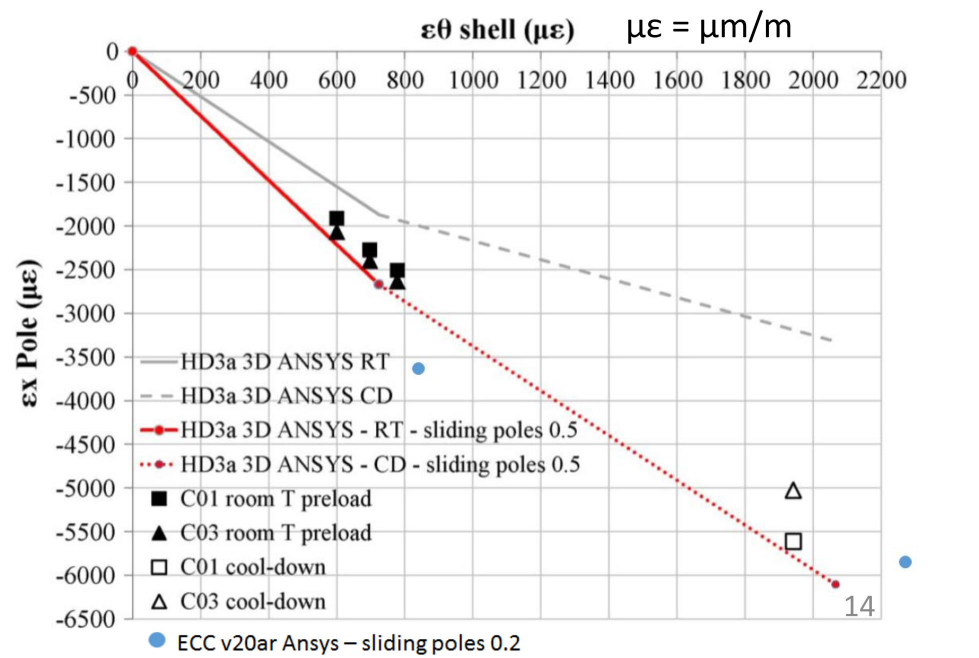
-50 µm
150 µm ->



Challenges in the Support Structure Design and Assembly of HD3, a Nb_3Sn Block-Type Dipole Magnet

H. Felice, F. Borgnolutti, S. Caspi, D. W. Cheng, D. R. Dietderich, P. Ferracin, A. Godeke, A. R. Hafalia, J. M. Joseph, J. Lizarazo, M. Marchevsky, S. Prestemon, G. Sabbi, and X. R. Wang

µε = µm/m



Block magnet comparison

	Bore	Pole tip	displacement [µm]		Δdisp [µm]	Strain [µm/m]		Δε [µm/m]	Δε/Δdisp	Material properties	
Magnet	field [T]	thickness [mm]	cold	powering	pow-cold	cold	powering	pow-cold	[µε/µm]	Nb3Sn	Ti-6Al-4V
ECC block v20ar	16.8	1.75	-198	-49	149	-5887	-1580	4307	29	ECC (E~25;30;27.5;33 GPa)	116 GPa / 126.5 GPa
ECC block v19ar	16.8	1.75	-169	-57	112	-5231	-1598	3633	32	LARP (E~44 GPa,52 GPa)	130 GPa / 130 GPa
ECC block v18ar	16.8	1.9	-162	-50	112	-4558	-1019	3539	32	LARP (E~44 GPa,52 GPa)	130 GPa / 130 GPa
ECC block v17ar	16.8	2	-167	-55	112	-4436	-955	3481	31	LARP (E~44 GPa,52 GPa)	130 GPa / 130 GPa
ECC block v16ar	16.8	6.3	-179	-72	107	-4878	-1272	3606	34	LARP (E~44 GPa,52 GPa)	130 GPa / 130 GPa
Fresca2	13	5	-304	-140	164	-5048	-2480	2568	16	LBNL (E~44 GPa,44 GPa)	100 GPa / 120 GPa
Fresca2	13	6.5	-306	-142	164	-5051	-2481	2570	16	LBNL (E~44 GPa,44 GPa)	100 GPa / 120 GPa
Fresca2	13	8	-307	-141	166	-5058	-2472	2586	16	LBNL (E~44 GPa,44 GPa)	100 GPa / 120 GPa
Fresca2	15	8	-409	-190	219	-7187	-3778	3409	16	LBNL (E~44 GPa,44 GPa)	100 GPa / 120 GPa
Fresca2	13	16	-232	-101	132	-3931	-1042	2889	22	LBNL (E~44 GPa,44 GPa)	100 GPa / 120 GPa
RMM_graded_v21_d	16	1	-174	-56	118	-4617	-1071	3546	30	LBNL (E~44 GPa,44 GPa)	110 GPa / 120 GPa
RMM_graded_v21_c	16	2	-173	-55	118	-4666	-1056	3610	31	LBNL (E~44 GPa,44 GPa)	110 GPa / 120 GPa
RMM_graded_v21_b	16	4	-171	-55	116	-4757	-1115	3643	32	LBNL (E~44 GPa,44 GPa)	110 GPa / 120 GPa
RMM_graded_v21_a	16	6	-168	-58	111	-4832	-1245	3587	32	LBNL (E~44 GPa,44 GPa)	110 GPa / 120 GPa
HD3	14	1.65	-134	-51	83	-3690	-667	3023	36	LARP (E~44 GPa,52 GPa)	110 GPa / 120 GPa

ECC displacement and strain **impacted** by material properties not by bore tip thickness

RMM_graded and **ECC** similar behavior with similar properties

Fresca2 biggest displacement – **HD3** smallest displacement…

HD3: Helene Felice (CEA)
RMM_graded: Susana Izquierdo-Bermudez (CERN)
Fresca2: Etienne Rochepault, Paolo Ferracin (CERN)

HD2 training

Recent Test Results of the High Field Nb_3Sn Dipole Magnet HD2

P. Ferracin, B. Bingham, S. Caspi, D. W. Cheng, D. R. Dietderich, H. Felice, A. R. Hafalia, C. R. Hannaford, J. Joseph, A. F. Lietzke, J. Lizarazo, G. Sabbi, X. Wang

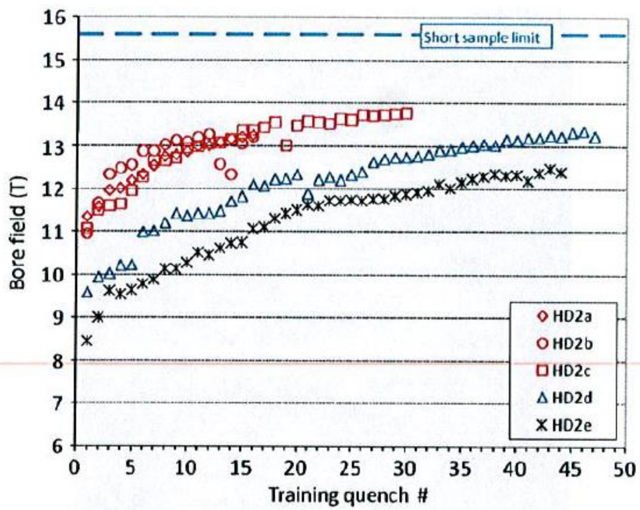


Fig. 5. Bore field (T) as a function of training quenches. The short sample limit of 15.6 T bore field corresponds to a coil peak field of 16.5 T.

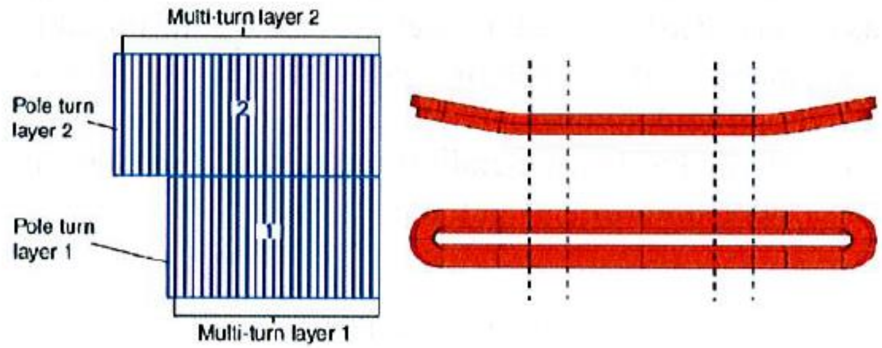


Fig. 7. Left: cross-section of coil layer 1 and layer 2 in the straight section. Right: side and top view of the coil. All the recorded training quenches occurred in the layer 1 pole turn, in the last 100 mm of the straight section, before the hard-way bend (areas comprised between dashed lines).

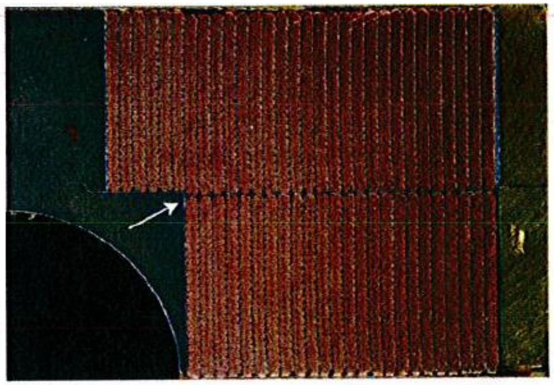


Fig. 10. Cross-section cuts of HD2 coil #1 in the center of straight section (top) and close to the beginning of the hard-way (bottom).

retested as under different pre-load conditions. The removal of the bore tube determined an increase of the coil clear aperture from 36 mm to 43 mm. The magnet reached a maximum bore field of 13.4 T after 46 quenches: no correlation was found between pre-load levels and quench performance. Consistently with previous tests, the quenches were located on the pole turn of layer 1, at the end of the straight section. No quenches were detected in the central part of the straight section or in the ends (after the hard-way bend). The voltage tap signals identified a

bore tip thickness HD2: 0.85 mm

Conclusion

- Margin 14% instead of 18% and cnc 0.8 instead of 1.0

-> 20% conductor saving

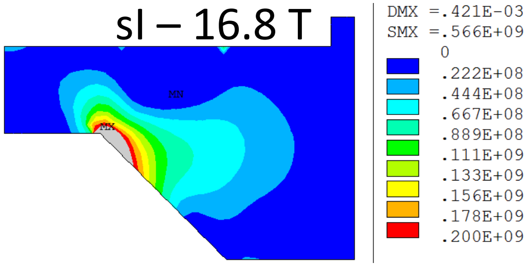
- Bore tip thickness 1.75 mm instead of 6.3 mm

-> 12% conductor saving

- Potential additional saving (2 turns):

- 2D mechanics looks good but one of the pad:

sl – 16.8 T



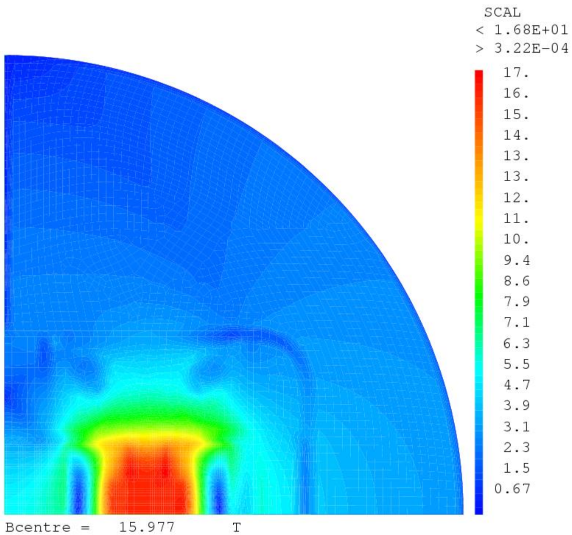
- No show-stopper for a thin bore tip
  - Fresca2 tests will provide new interesting data
- Geometrical conductor dimension variations? Jc?
- Splices dimensions?

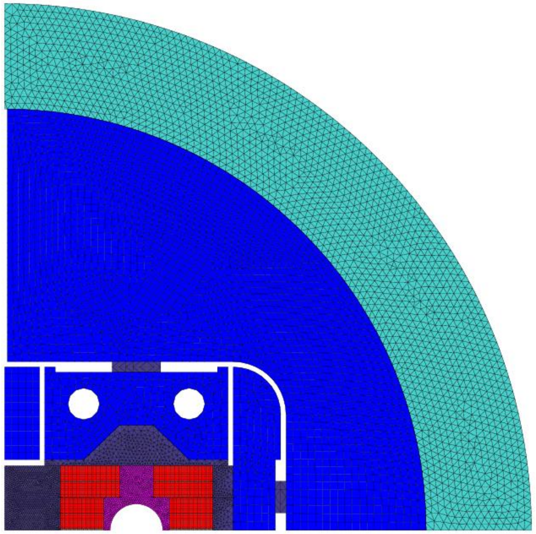
Extra slides:

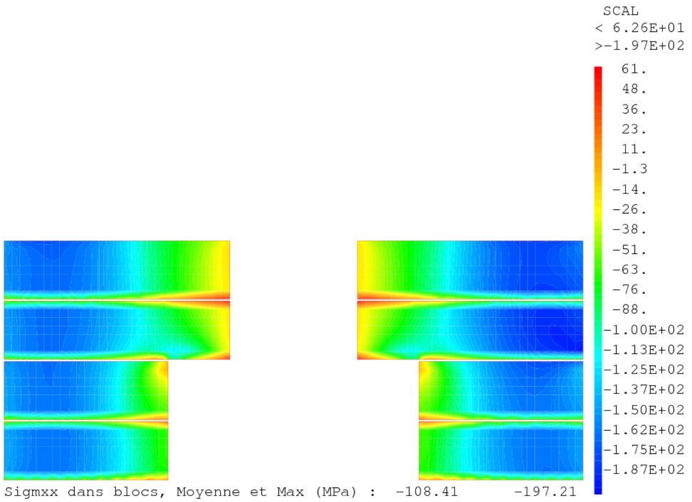
-double aperture	(1 slide)
-3D ends	(3 slides)
-1 double-pancake design	(4 slides)
-critical Nb_3Sn surface	(1 slide)
-stress distribution (quench)	(8 slides)

Double aperture

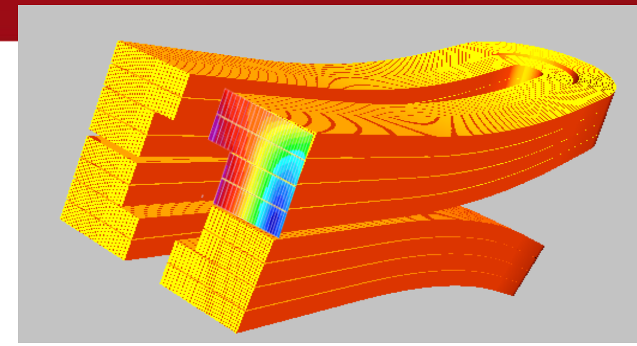
- On going work (M. Segreti – cast3m)
- Magnetic and mechanical ready. Not matched with v20ar so far.

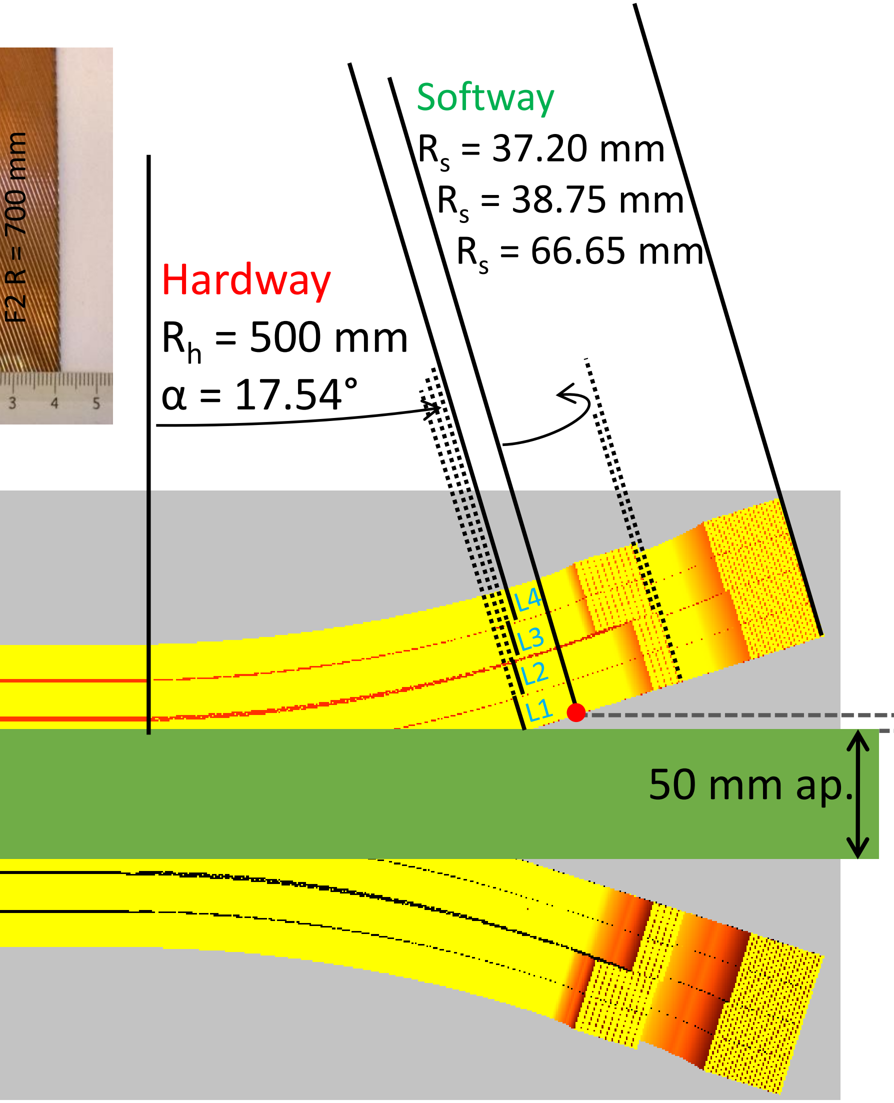






3D ends – Return end



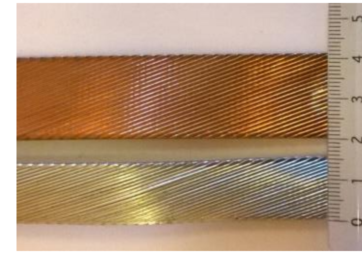


Straight section HF (LF)
L4 = 2.48 (+25) mm
L3 = 6.65 (+25) mm
L2 = 10.83 (+25) mm
L1 = 15.00 (+25) mm
-> +25 mm needs to be properly set depending on splice configuration.

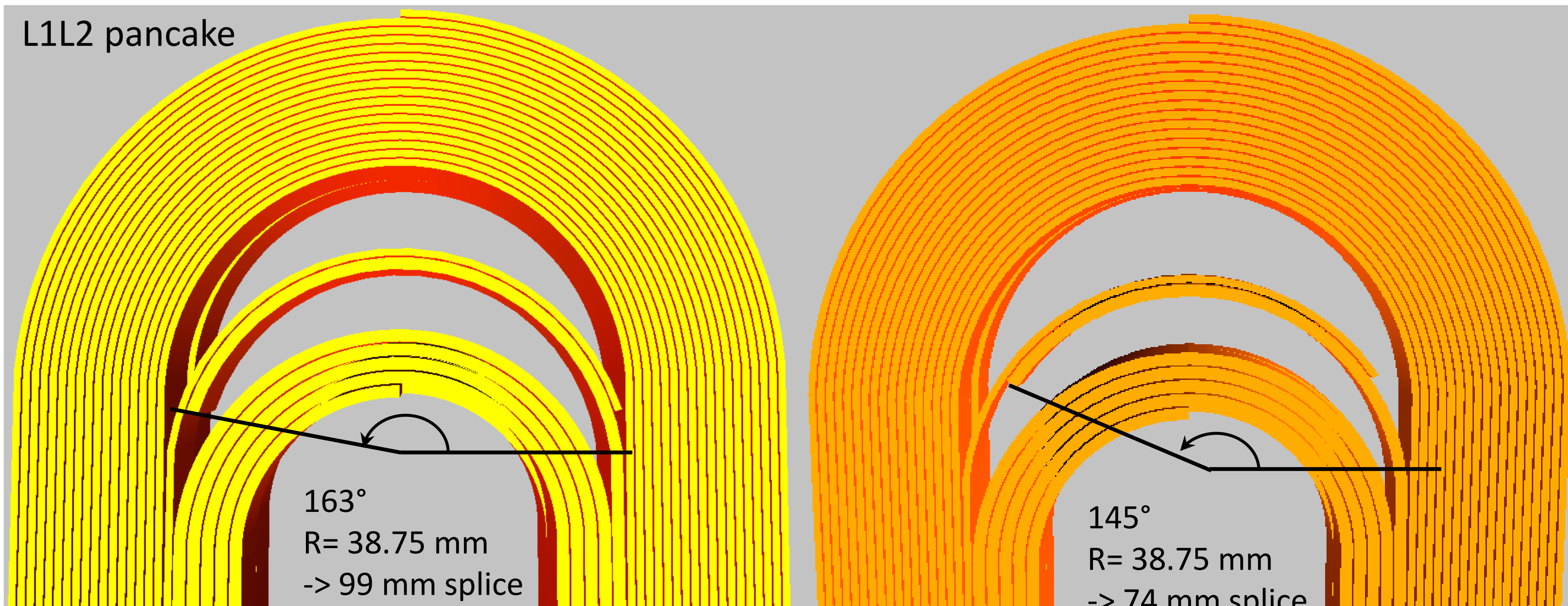
ap. + 4.52 mm
-> +4.52 mm needs to be properly set depending on end mechanical support.

volume = 228 cm^3/half coil
length = 254 mm (*2 + ss -> oven length)
height = 89.8 mm (fits in coil pack ☺)

3D ends – Room for splices

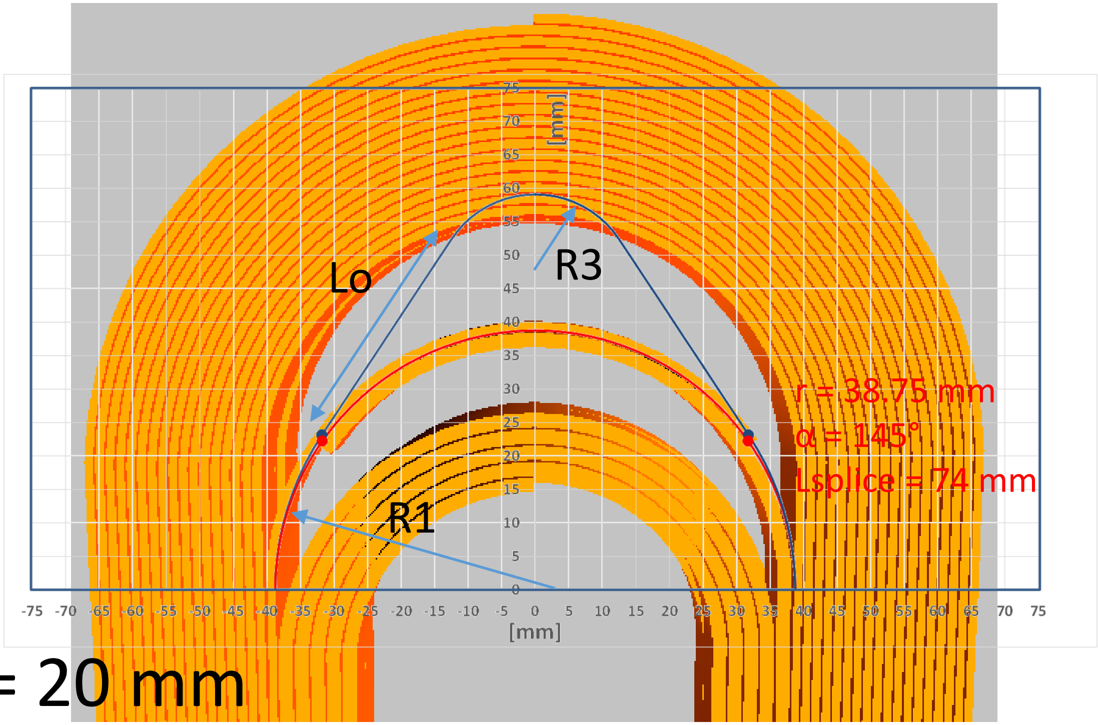


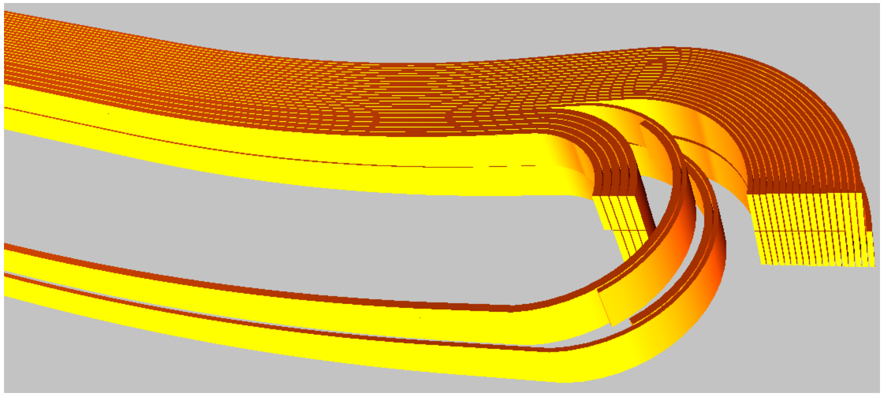
Tp HF cable ~ 98 mm
Tp LF cable ~ 97 mm
99 mm arc splice length -> 163°arc angle



3D ends – Room for splices

- Splice length
  - R1 = 42 mm
  - R3 = 15 mm
  - Lo = 35 mm
- Lsplice = 100 mm
- Extra end length = 20 mm



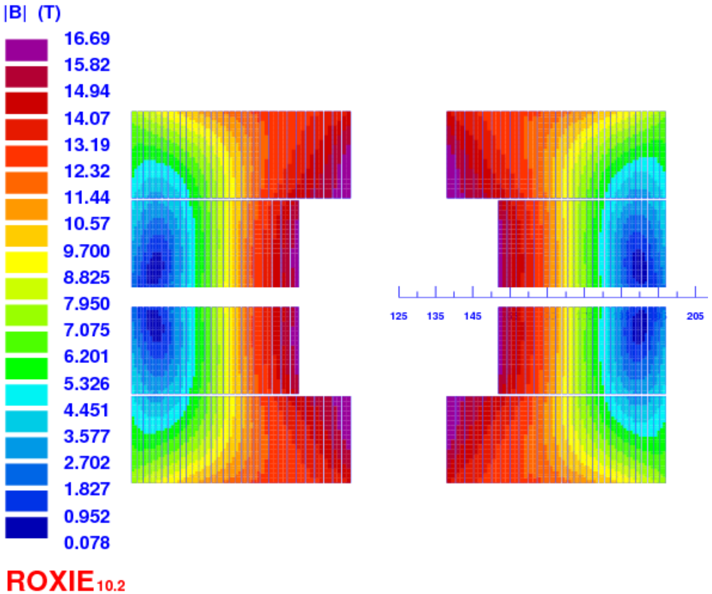


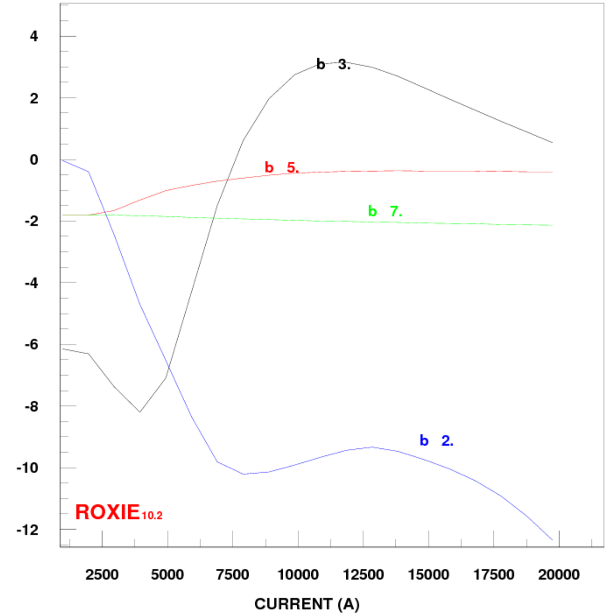
Different splices (double pancake)
Do we need room in-between the two coils?

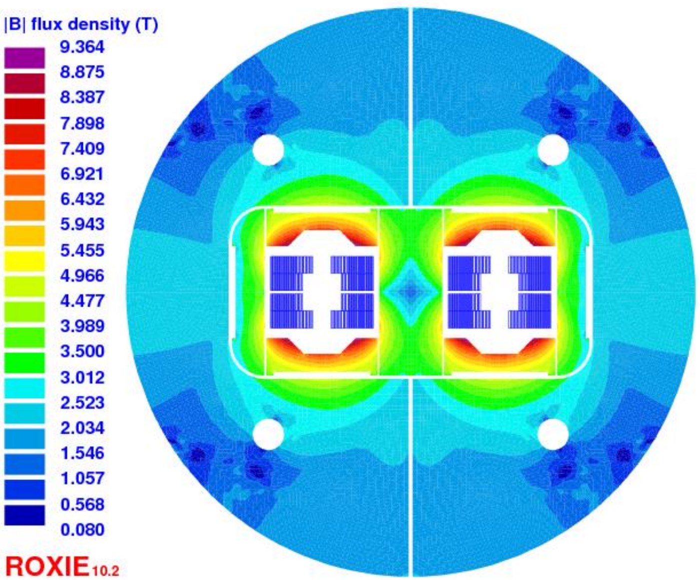
Single double pancake design

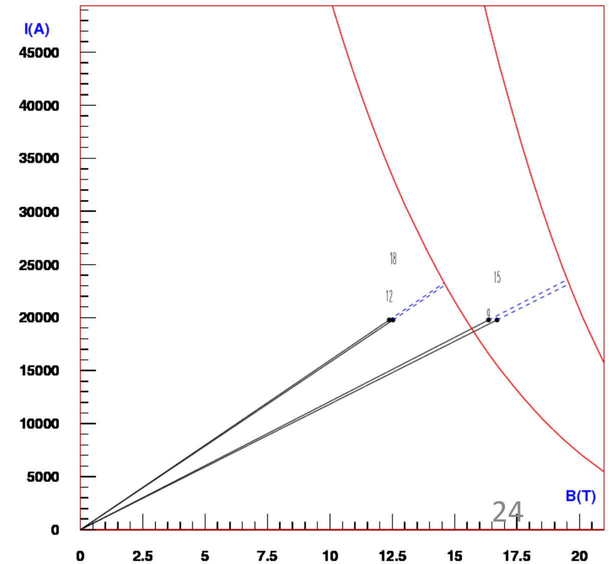
Quantity	old baseline	ASC2016	v20ar	v22ar
strand diameter	1.1 – 0.7	1.1 – 0.7	1.155 – 0.705	1.19 – 0.74
nb of strands	24 – 37	24 – 39	21 – 35	37-60
width	13.85	14.25	13.05	23.25
average thickness	2.0 – 1.25	2.0 – 1.25	2.1 – 1.25	2.15 – 1.35
Cu/nonCu	1.0 – 1.0	0.8 – 1.6	0.8– 2.3	0.8 – 2.25
I_{nom}	8470	10930	10980	19730
B_{peak}	16.56	16.81	16.74	16.70
LL margin (1.9 K)	16.8	13.95	14.01	14.35
Inductance diff. (2 ap)	88.19	48.06	39.80	12.32
Stored energy (2 ap)	3340	3016	2518	2532
Nb of turns	153 = 2+3+9+9 +32+32+33+33	114 = 3+3+9+9 +22+22+23+23	104 = 5+5+10+10 +18+18+19+19	56 = 5+10 +20+21
Fx & Fy (per ½-coil)	8817 & -3703	8473 & -3572	8042 & -3347	7675 & -3538
Hotspot	310	348	348	329
Bore thickness	6.0	6.3	1.75	1.75
Midplane shim	2.0	1.45	1.75	2.55
LdxI (1 aperture)	373	263	218	122
I/Ic HF-LF	-	-	0.47 – 0.61	0.44 – 0.60
Conductor area (2 ap)	**190**	**151.9**	**133.7**	**134.0**
4578 x 14.3 x 8.7 weight	**10820**	**8652**	**7614**	**7633**

Single double pancake design

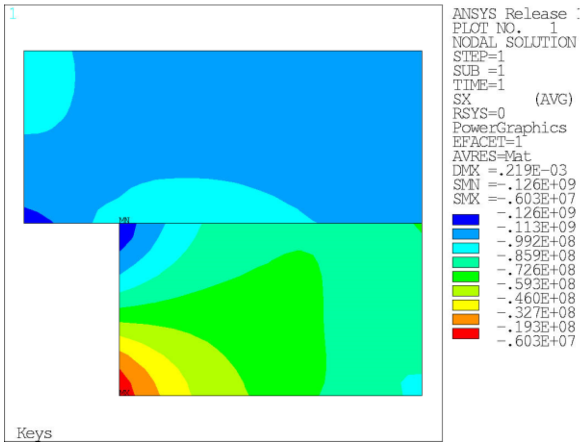


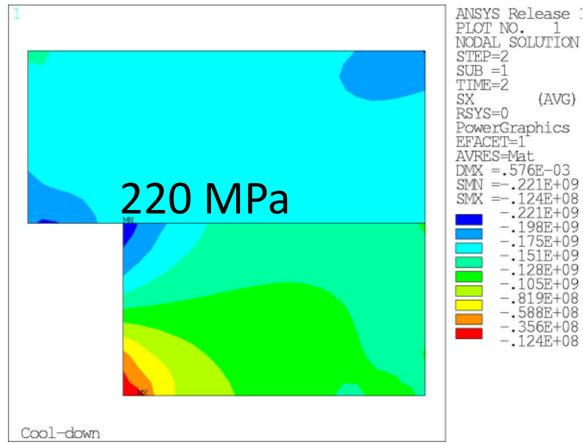


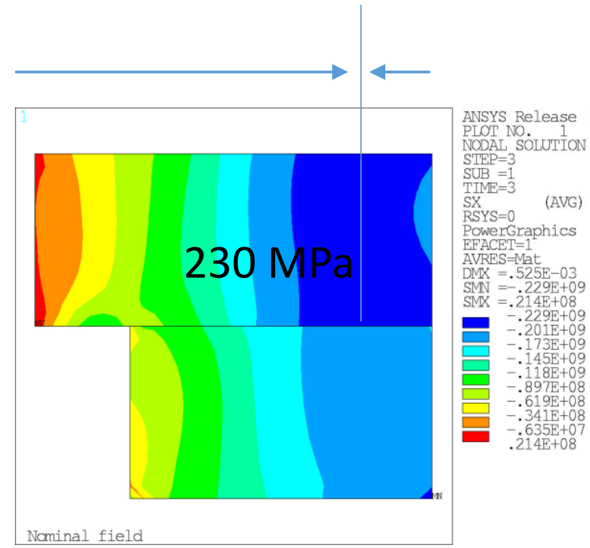


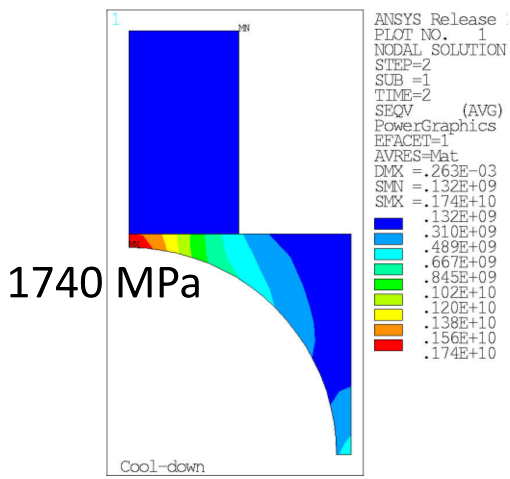


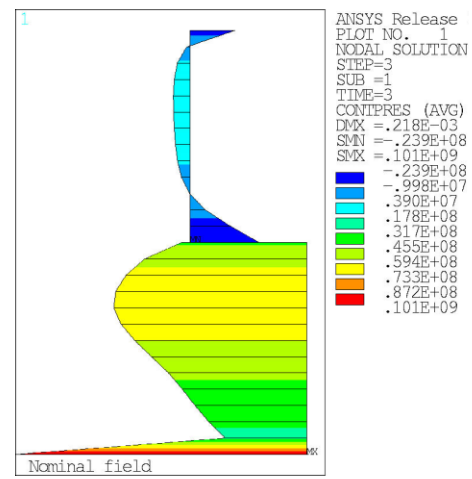
Single double pancake design





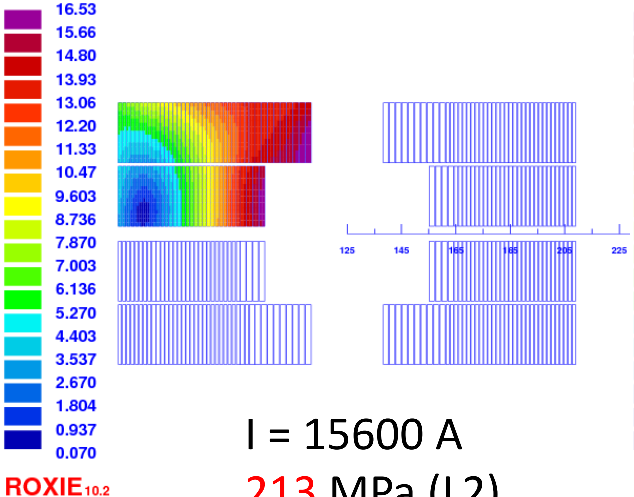






2 block designs

v101

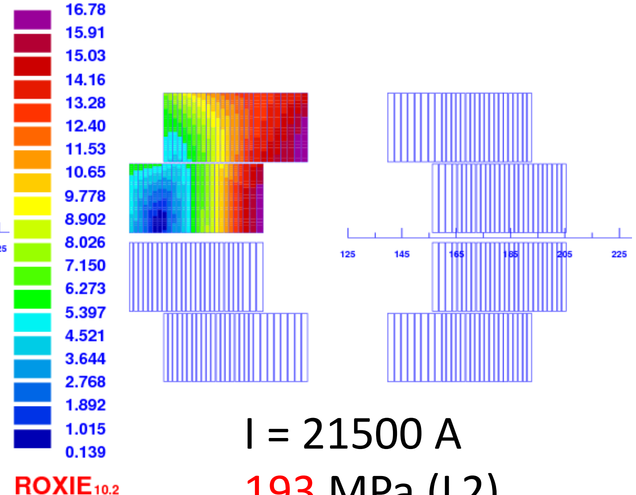


I = 15600 A
213 MPa (L2)
22 mm cable

1.1 mm x 38
0.7 mm x 60

151.3 cm²
8517 tons

v8ar

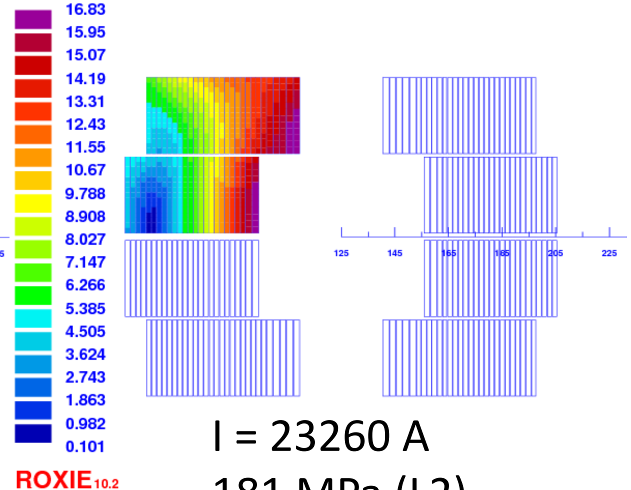


I = 21500 A
193 MPa (L2)
25.2 mm cable

1.2 mm x 40
0.8 mm x 60

143.6 cm²
8178 tons

v9ar



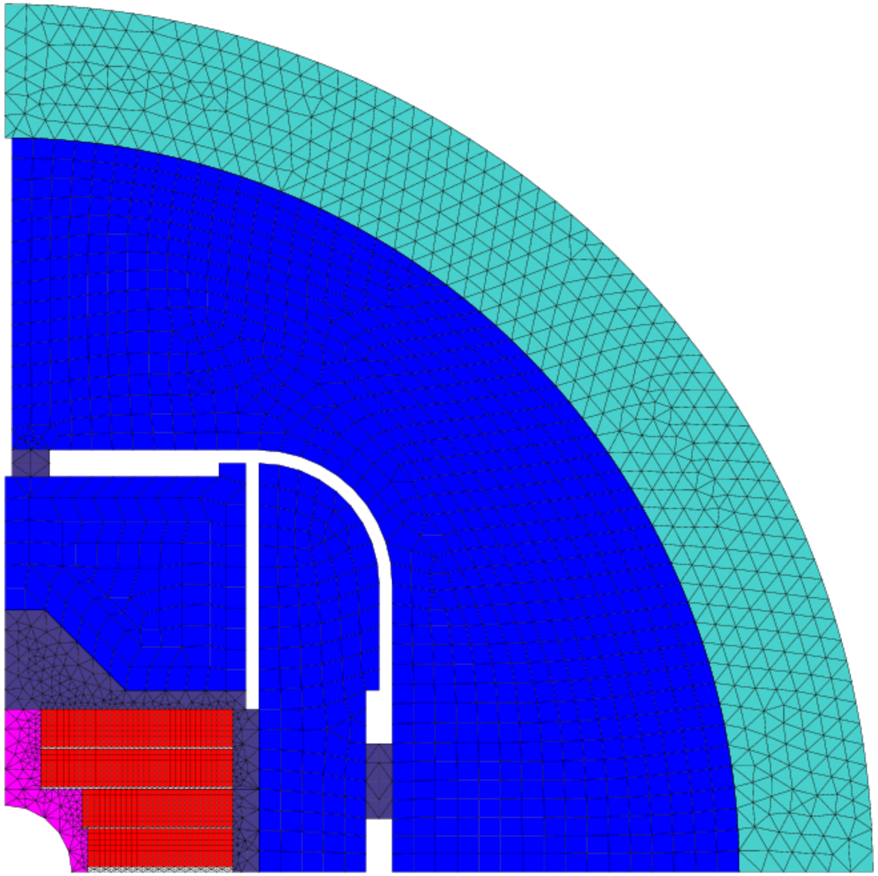
I = 23260 A
181 MPa (L2)
28.35 mm cable

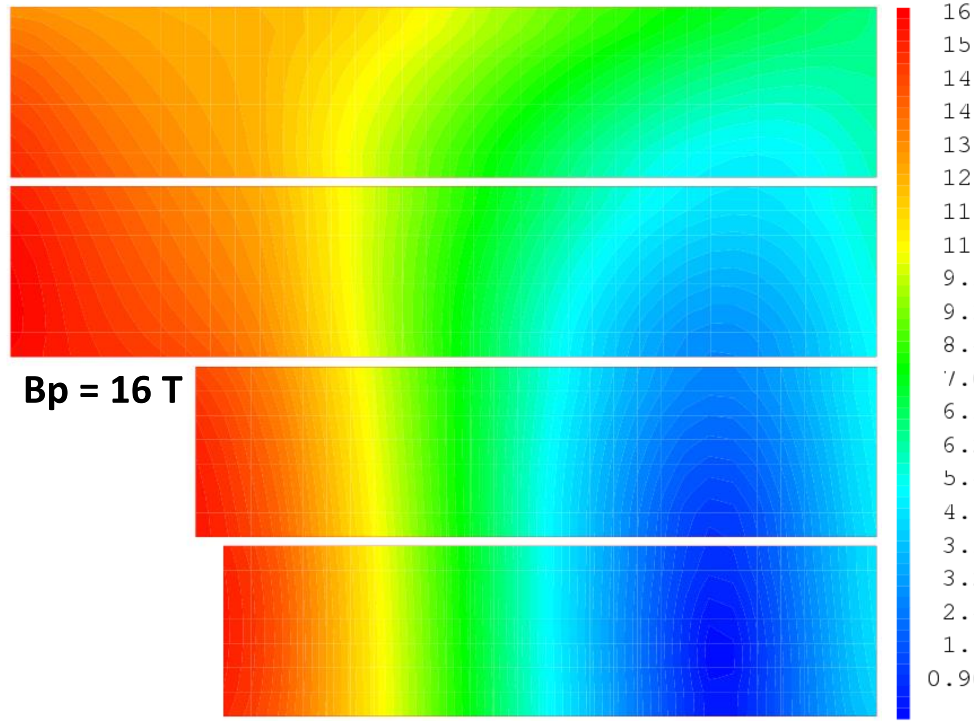
1.2 mm x 45
0.9 mm x 60

169 cm²
9625 tons

Quench induced gradient [K]

CAST3M

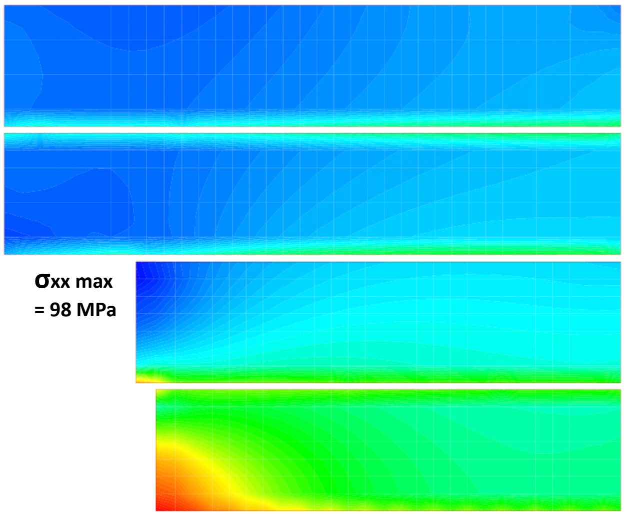




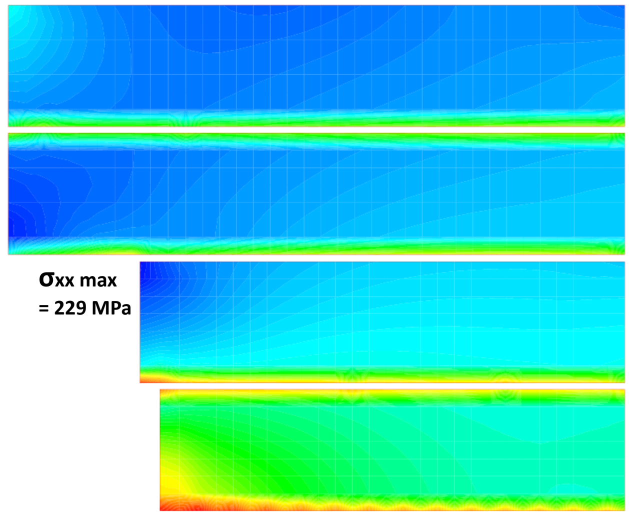
The full analysis was performed by Michel Segreti

Normal stress distribution

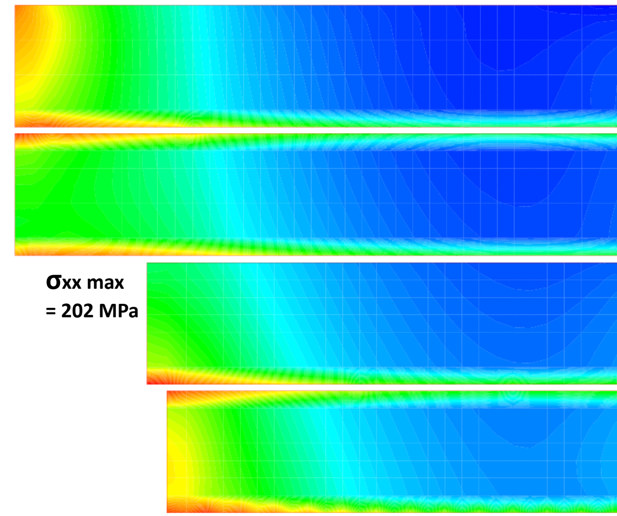
σxx distribution



Key insertion



Cool-down



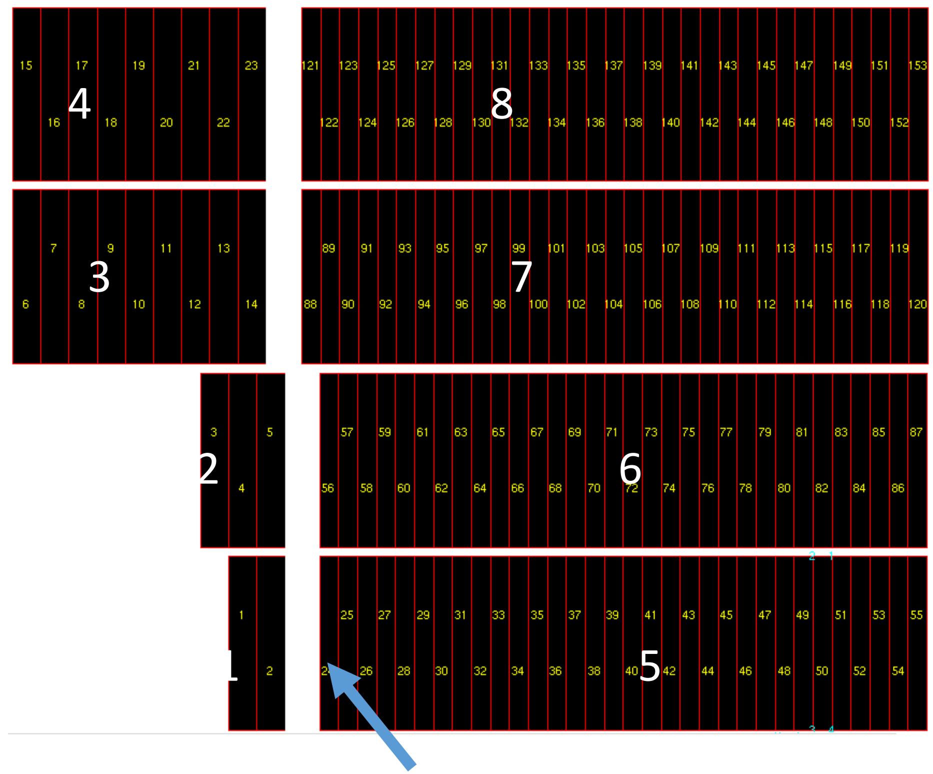
Energization

2 extrem cases 1/2

Tiina gives us the temperature distribution at each conductor after a quench

Peak gradient at the end t = 500 ms (gradient values almost constant from t = 400 ms to t = 500 ms)

Block	Temp [K] at the block interfaces t = 500 ms	Average Temp [K] in associated block t = 500 ms
1	74	75
2	73	74
3	72	74
4	70	72
5	**307**	141
6	186	141
7	182	154
8	179	157



Hot spot localization (conductor 24)

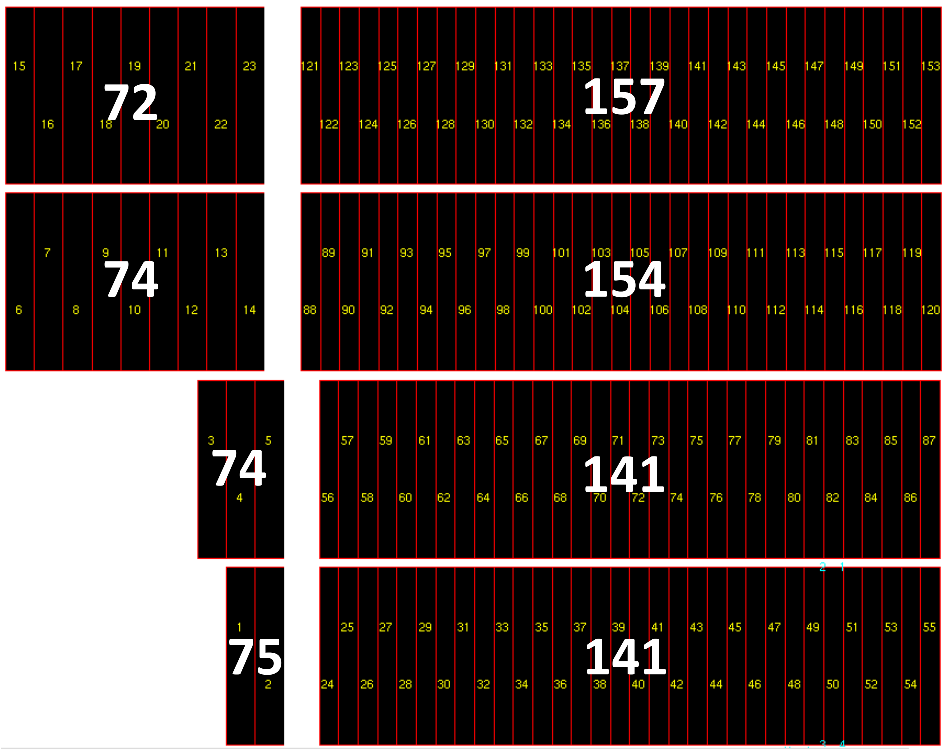
	Max gradient [K] at the block interfaces t = 500 ms
1-5	233 K
2-6	113 K
3-7	110 K
4-8	109 K

2 extrem cases 2/2

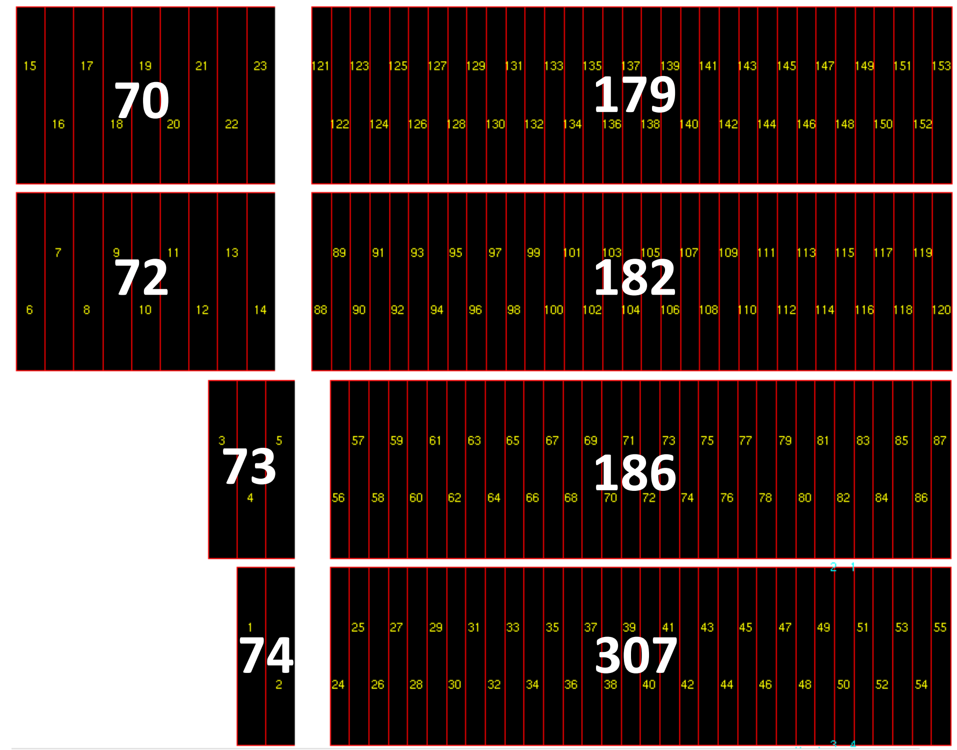
As the mechanical model is discretized from coil block (not from each conductor) → 2 cases are studied for the mechanical computation after a quench:

Case a) The average temperature in each block is imposed → especially to see the impact on SigmaXX

Case b) The temp at the block interfaces is imposed in each block (this correspond to the max temp gradient)
→ especially to see the impact on SigmaXY



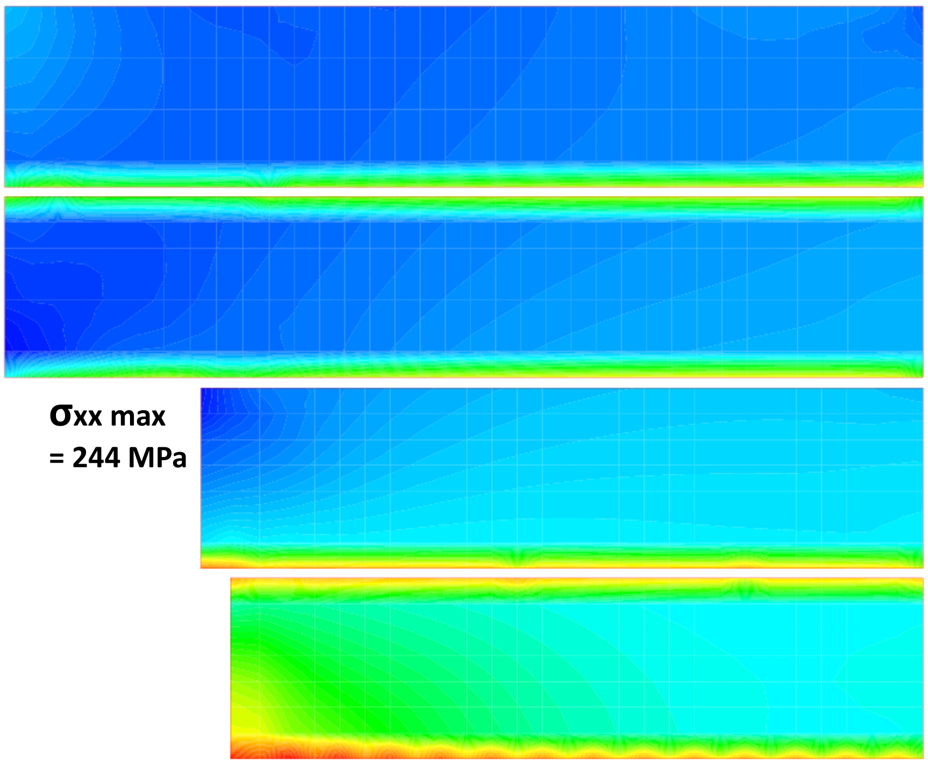
Case a



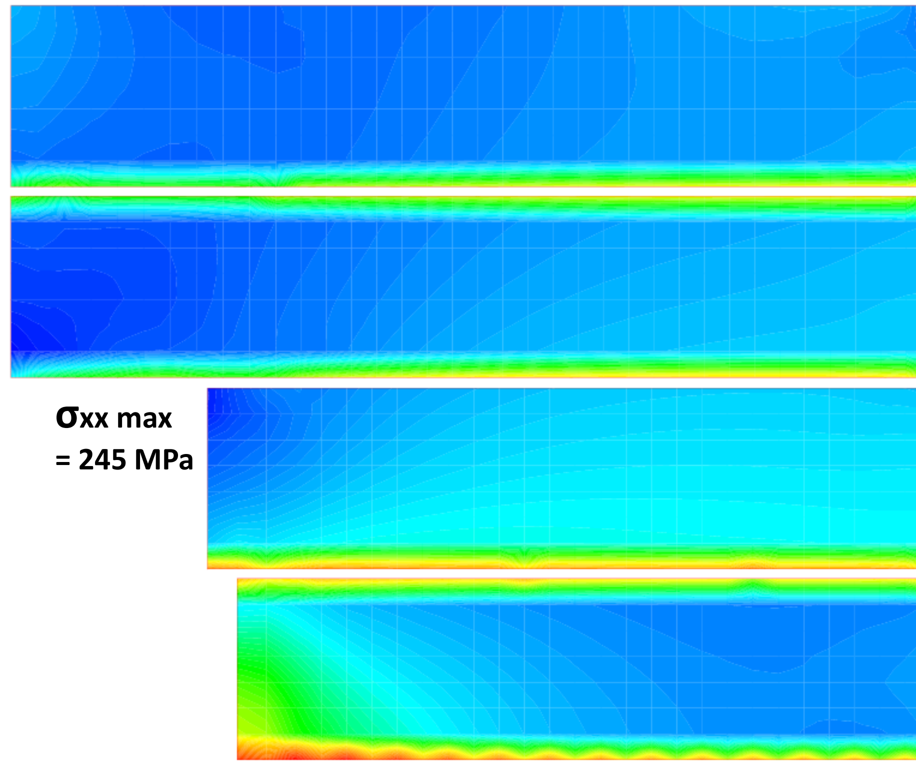
Case b

Impact of 'natural' quench 1/2

σxx distribution: no impact



Case a

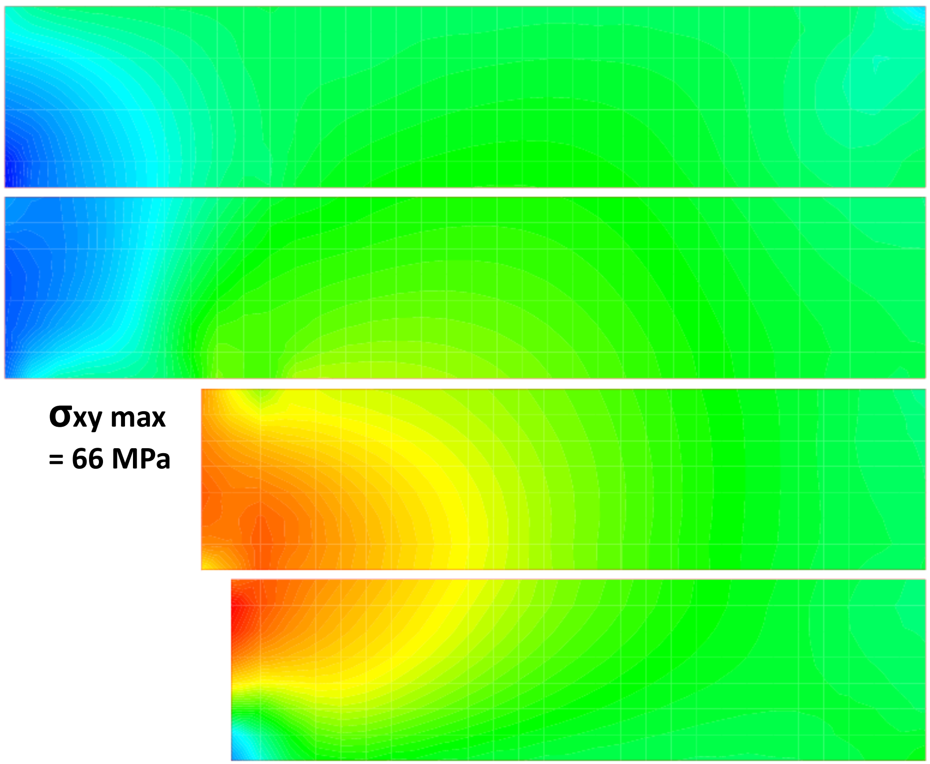


Case b

Impact of ‘natural’ quench 1/2

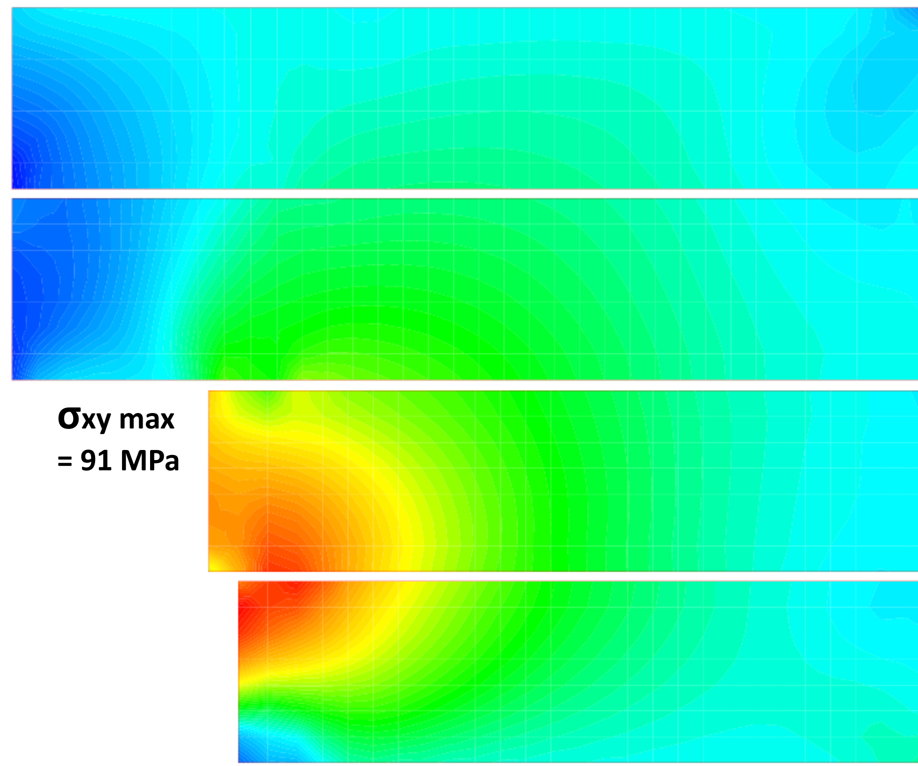
σxy distribution: 50 % higher

σxy max
= 66 MPa



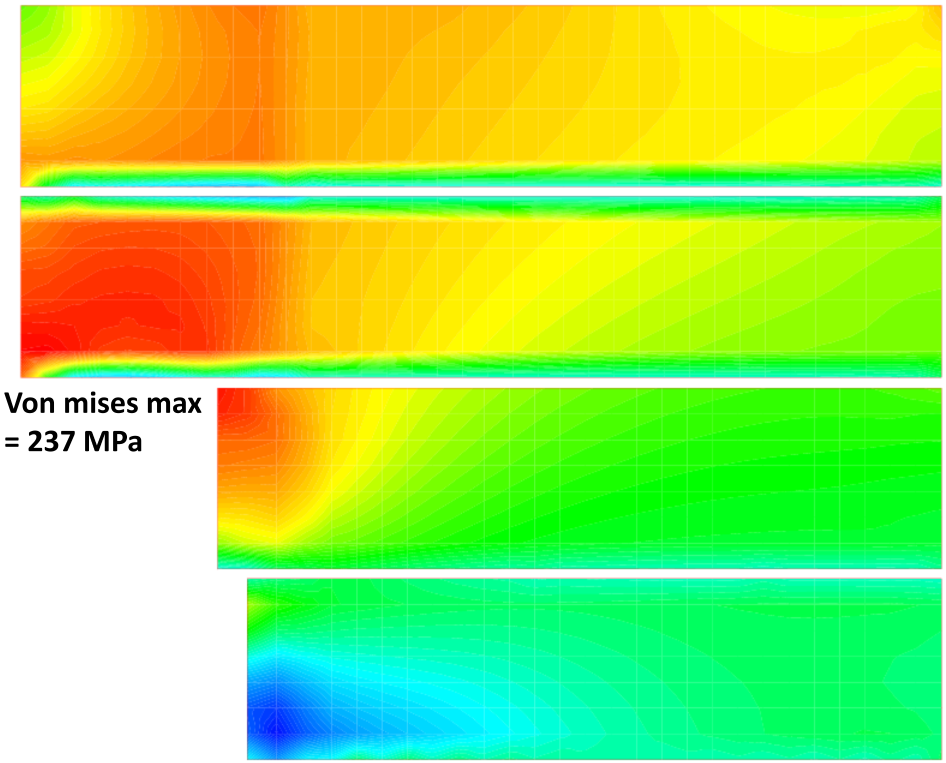
Case a

σxy max
= 91 MPa



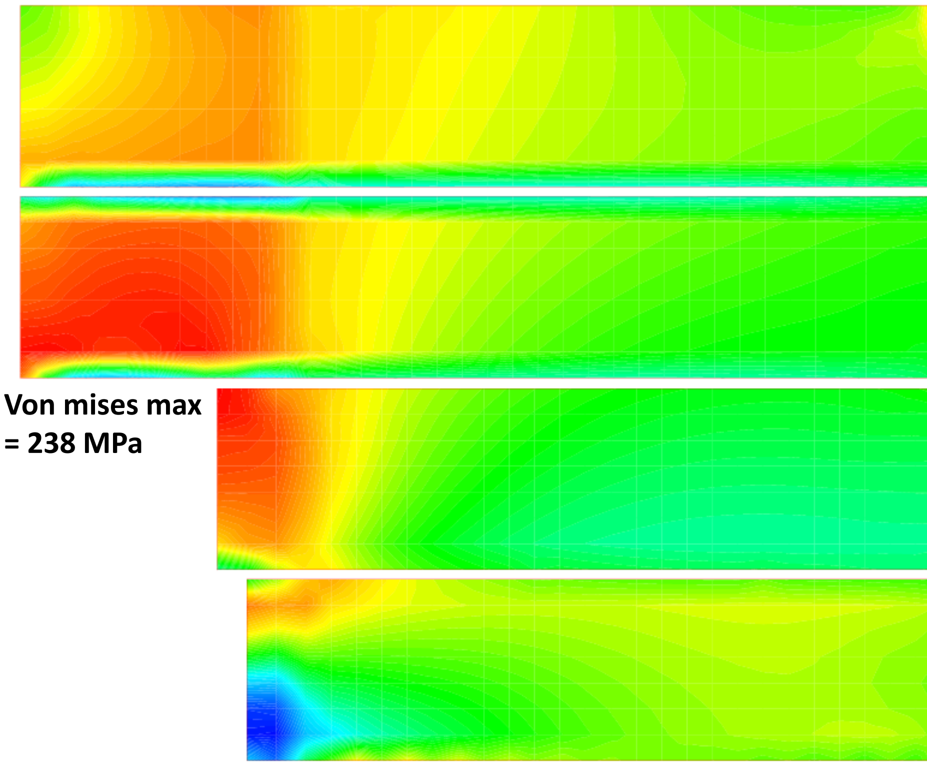
Case b

Von Mises distribution



Von mises max = 237 MPa

Case a



Von mises max = 238 MPa

Case b

Stress in blocks	Collaring (MPa)	Cool-down (MPa)	Energization (MPa)	After quench	
				Case a	Case b
σxx max	98	229	202	244	245
σyy max	48	60	87	124	175
σxy max	29	59	59	66	91
Von Mises max	90	225	204	237	238

As σxx max is the same in cases a and b → it seams not necesary to discretize up to the conductor level for the mechanical computation after a quench

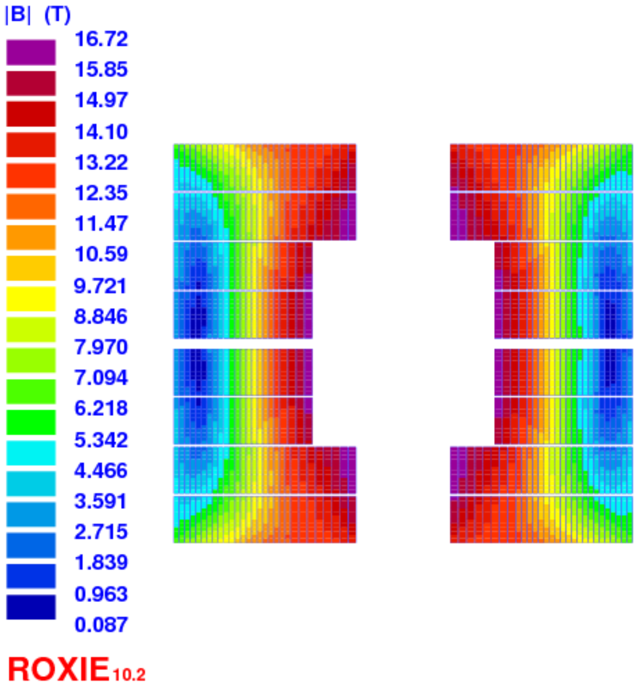
Questions:

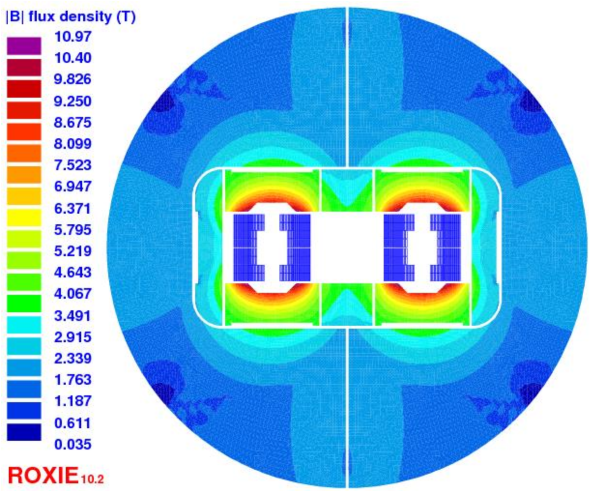
1) **What is the max acceptable compression stress in the coil blocks after a quench (150 MPa or 200 MPa)? The hot spot temp in one conductor is 307 K i.e. a little more than room temp**
2) **What is the max acceptable shear stress in the coil blocks at each main step and especially after a quench?**

50 mm aperture

Cable parameter	value	unit
strand diameter	1.1 – 0.7	mm
nb of strands	22 – 35	N/A
width	12.86 – 12.86	mm
average thickness	2.0 – 1.25	mm
insulation	0.15	mm
Cu/nonCu	0.8– 1.9	N/A
I_{nom}	10625	A
B_{peak}	16.72	T
LL margin (1.9 K)	13.8	%
Inductance diff. (2 ap)	38.5	mH/m
Stored energy (2 ap)	2295	kJ/m
Conductor area (2 ap)	**126.4**	cm²
Nb of turns	104 = 4+4+8+8 +19+19+21+21	-
Fx (per ½-coil)	7771	kN/m
Fy (per ½-coil)	-2971	kN/m
Hotspot	348	K
Wall thickness	0.3	mm

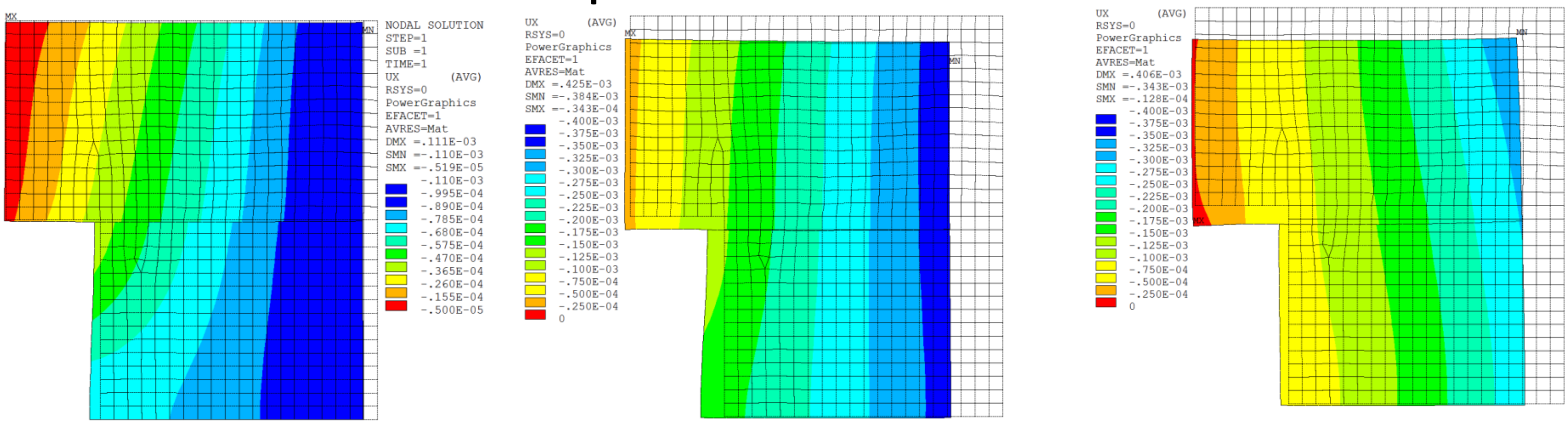
```
MAIN FIELD (T) ....................................   -16.003346
MAGNET STRENGTH (T/(m^(n-1)) ......................     -16.0033

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:     16.77678  b 3:     -1.59701
b 4:      0.87612  b 5:      4.23708  b 6:      0.02142
b 7:     -2.03167  b 8:      0.00017  b 9:     -1.71466
b10:     -0.00001  b11:     -0.31116  b12:     -0.00000
```

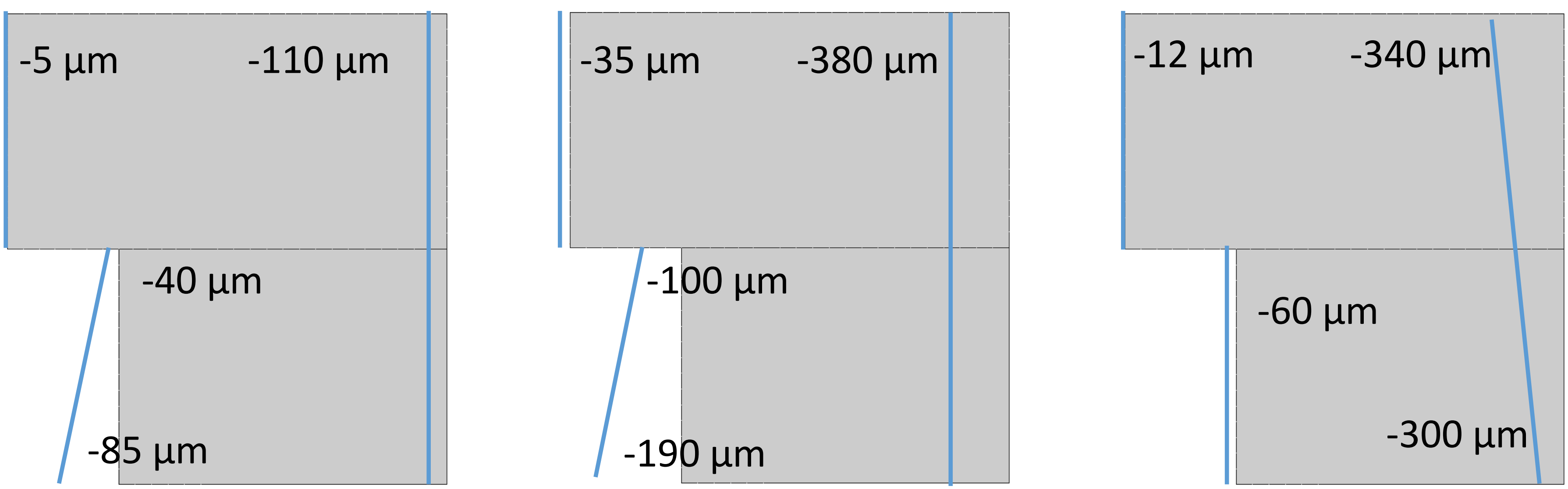




v19ar – Displacement

- Coil horizontal displacement





Critical surface Nb_3Sn

- Jc (1.9 K, 16 T) = 2245 A/mm²
- no cabling degr.
- C0 = 267845 AT/mm²

$$\begin{cases} J_c = \dfrac{C(t)}{B} b^{0.5} (1-b)^2 \\ B_{c2}(T) = B_{c20}(1-t^{1.52}) \\ C(t) = C_0 (1-t^{1.52})^{\alpha} (1-t^2)^{\alpha} \end{cases}$$

where $t = T/T_{c0}$ and $b = B/B_{c2}(t)$ with B the magnetic flux density on the conductors. T_{c0} = 16 K, B_{c20} = 29.38 T, α = 0.96, are fitting parameters computed from the analysis of measurements on the conductor.

- Similarly:
  - Jc (1.9 K, 16 T) = 2312 A/mm²
  - 3% cabling degr.
  - C0 = 275880 AT/mm²