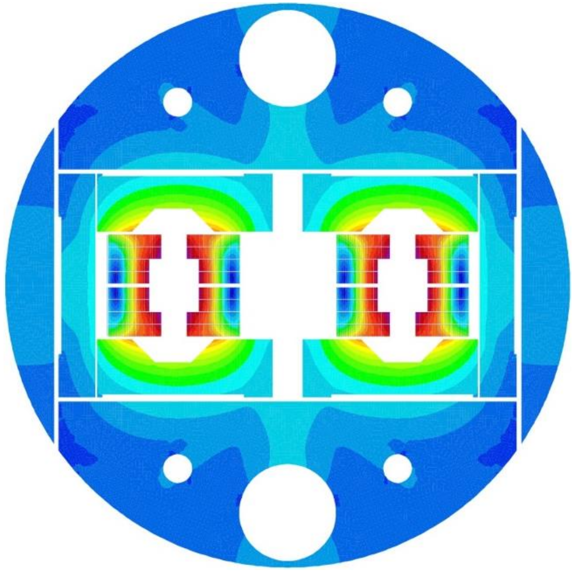
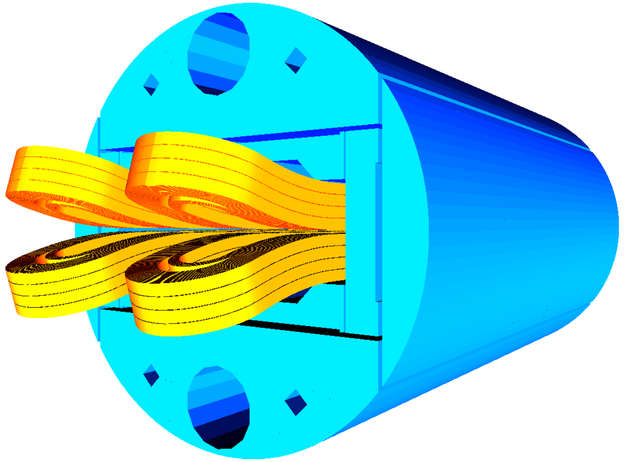


ECC block option



Maria Durante

on behalf of Michel Segreti, Chhon Pes, Etienne Rochepault and Clément Lorin

4th ECC Annual meeting – WP5 meeting - 17/10/2018

Karlsruhe

Overview

- Design version v4ari250 : inter-beam 250
- 2D magnetic design
- Harmonics
- Persistent currents
- Random geometrical errors
- 3D magnetic design
- 2D mechanical design
- 3D mechanical design (ongoing)

v4ari250 : inter-beam 250

High field strand diameter: 1.1 mm (for procurement reason)

Heat treatment dimensional change:

+1% width ; +3% thickness

Bore thickness: 1.9 mm

including 0.5 mm thick ground insulation

Inter-beam distance: 250 mm

Yoke outer diameter: 616 mm

Space for He cooling 2xDN106 + 4xDN32

20 mm SS-shell

Coldmass outer diameter target : 800 mm

v4ari250

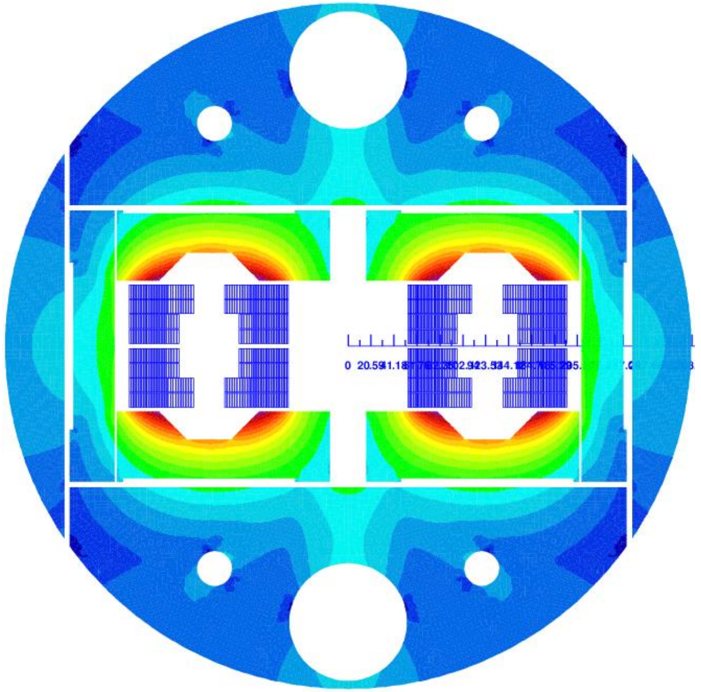
250 mm inter-beam

616 yoke outer diameter

72 mm Al shell +

20 mm SS shell

800 total outer diameter

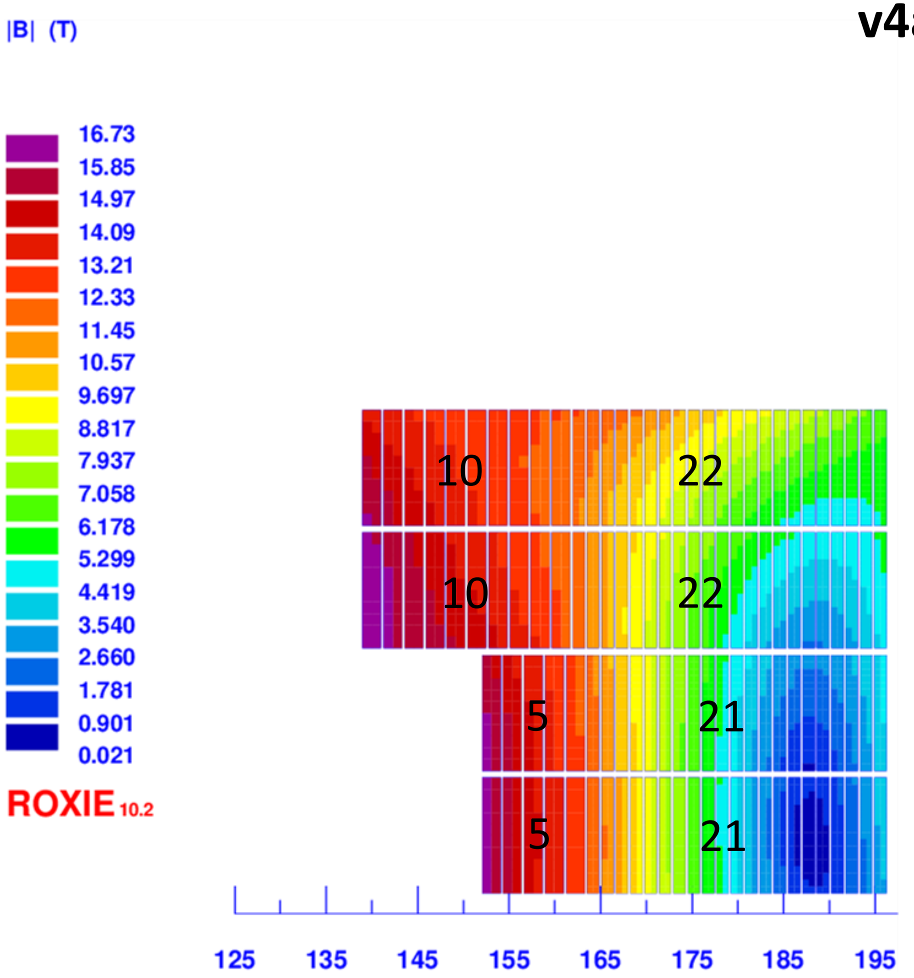


2D magnetic design main parameters

Parameter	v5ari204	v4ari250	Unit
Inom	10.111	10.176	kA
Nb turns	5+10+21+22	5+10+21+22	-
Bore thickness	1.9 (1.4 + 0.5)	1.9 (1.4 + 0.5)	mm
Mid-plane shim	2.28	2.07	mm
Conductor area	138	138	cm^2
Estimated weight*	7.90	7.90	kt
Yoke diameter	570	616	mm
Bcenter	16.00	16.00	T
Bpeak	16.75	16.73	T
Load-line margin (ROXIE)	13.75**	13.73**	%
Diff. inductance	49.1	47.8	mH/m

** Area x 4578 dipoles x 14.3 m x 8.7 kg/m^3

v4ari250

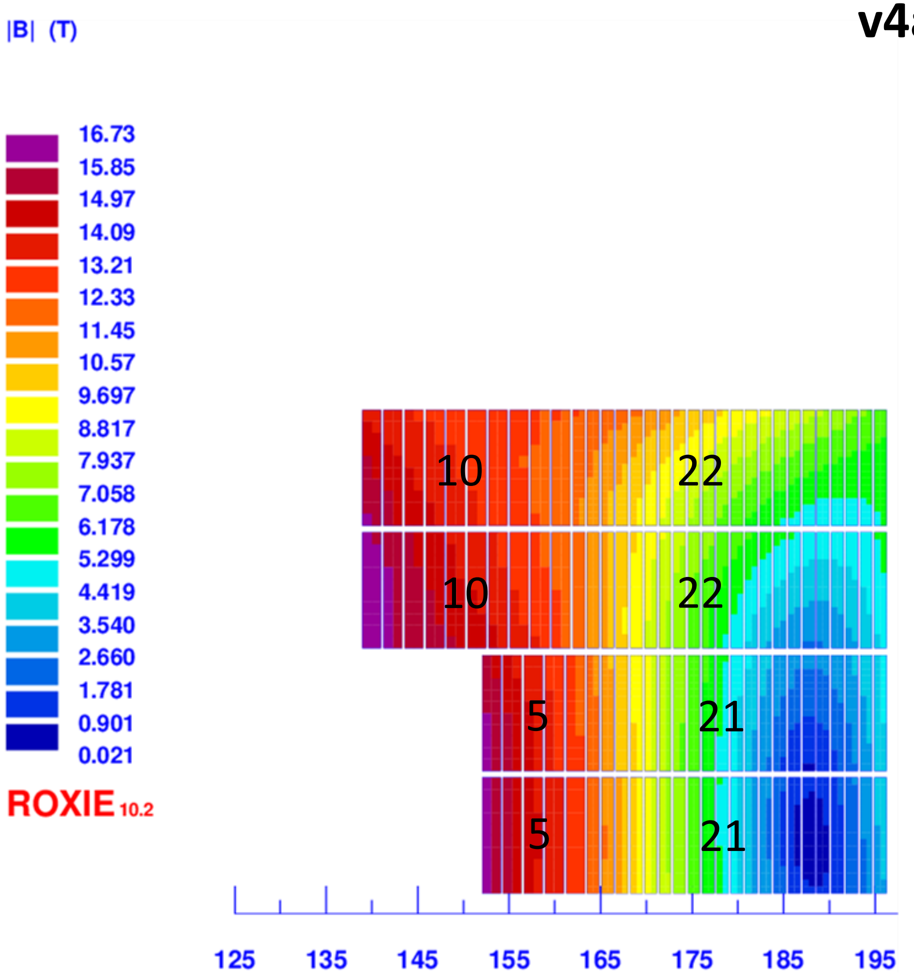


** Estimated by ROXIE, but in fact > 14 % (14.67 %)

HF and LF Cables (unchanged since 2017)

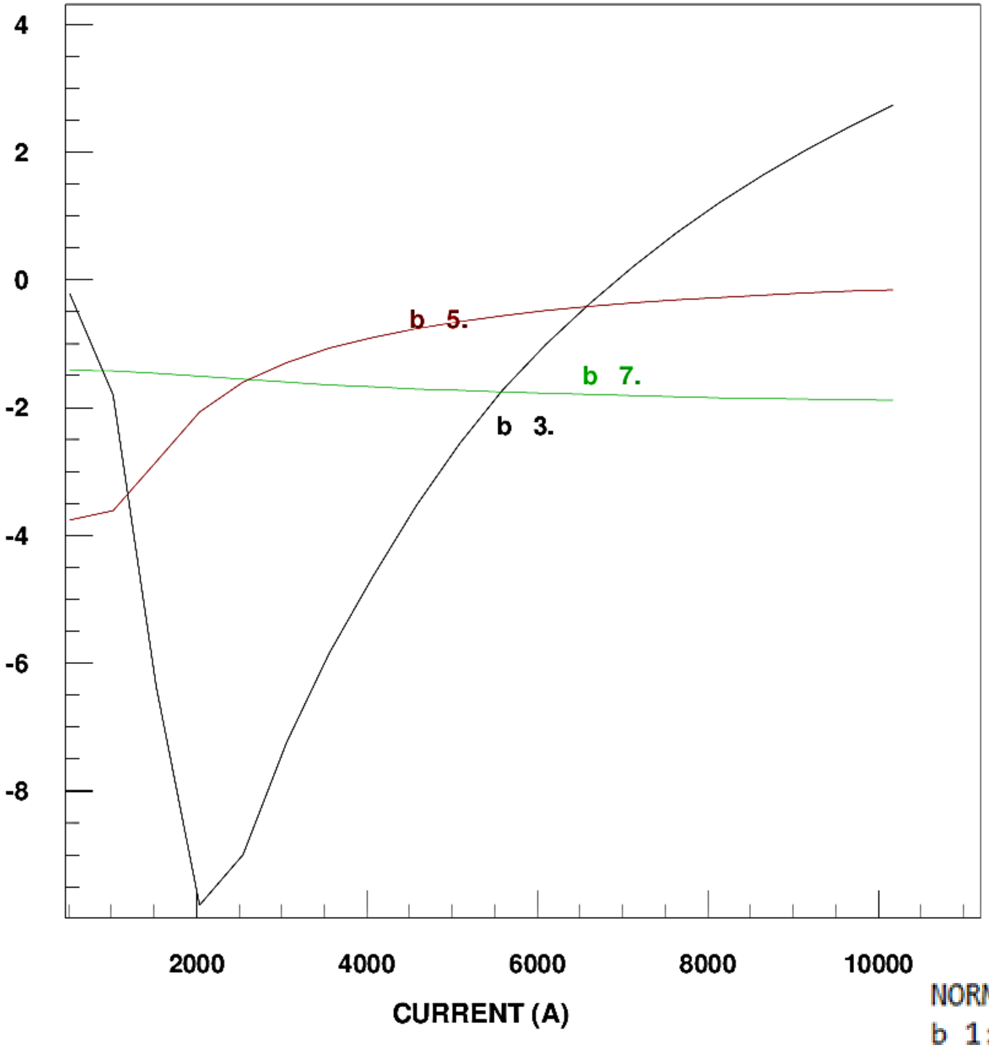
v4ari250

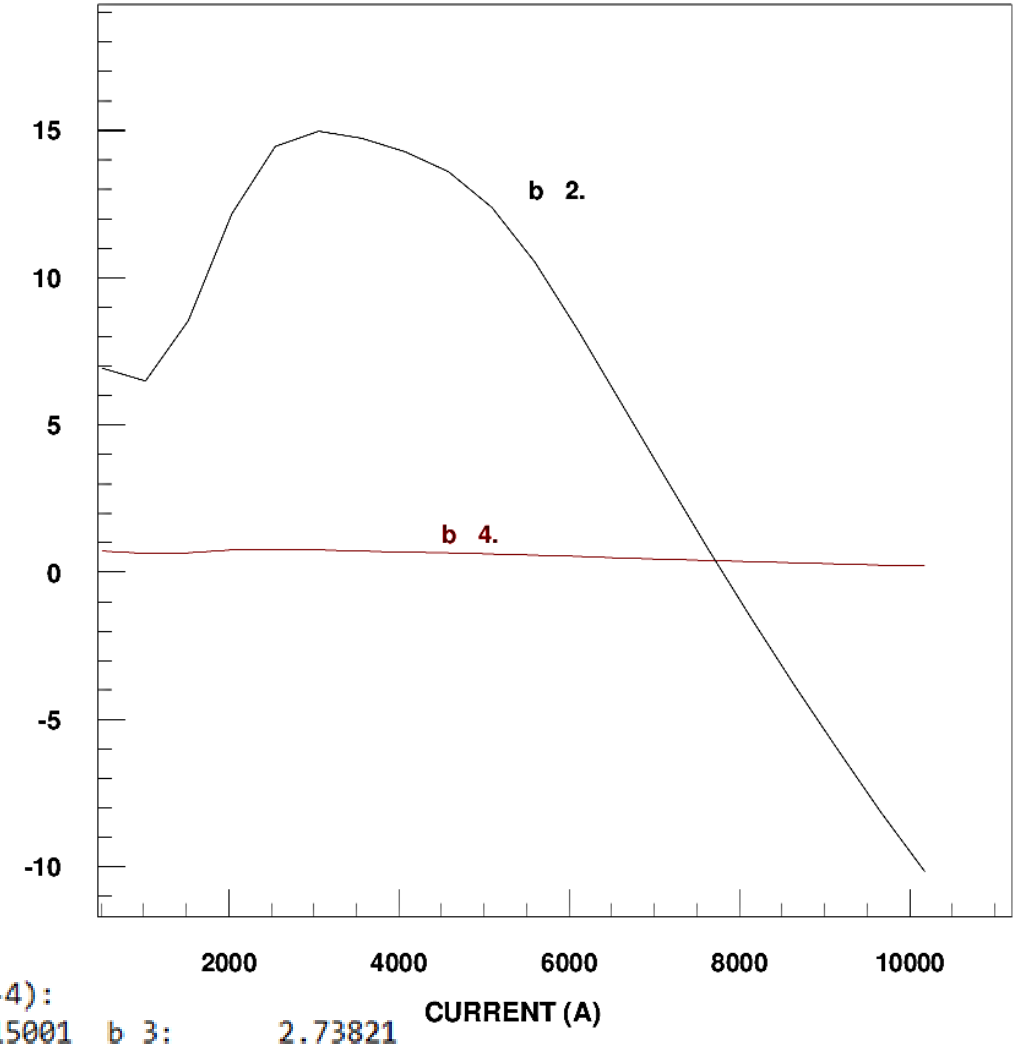
PARAMETER	Values		Unit
Strand diameter	1.1	0.7	mm
Number of strands	21	34	adim
Unreacted width	12.47	12.47	mm
Unreacted thickness	1.94	1.23	mm
Reacted width	12.6	12.6	mm
Reacted thickness	2.00	1.27	mm
Copper/non-Copper ratio	0.8	2.0	adim
Insulation thickness	0.15	0.15	mm
Bare cable compaction	11.8	12.0	%
Packing factor	85.4	88.2	%
Transposition pitch	93	93	mm



Harmonic content

v4ari250





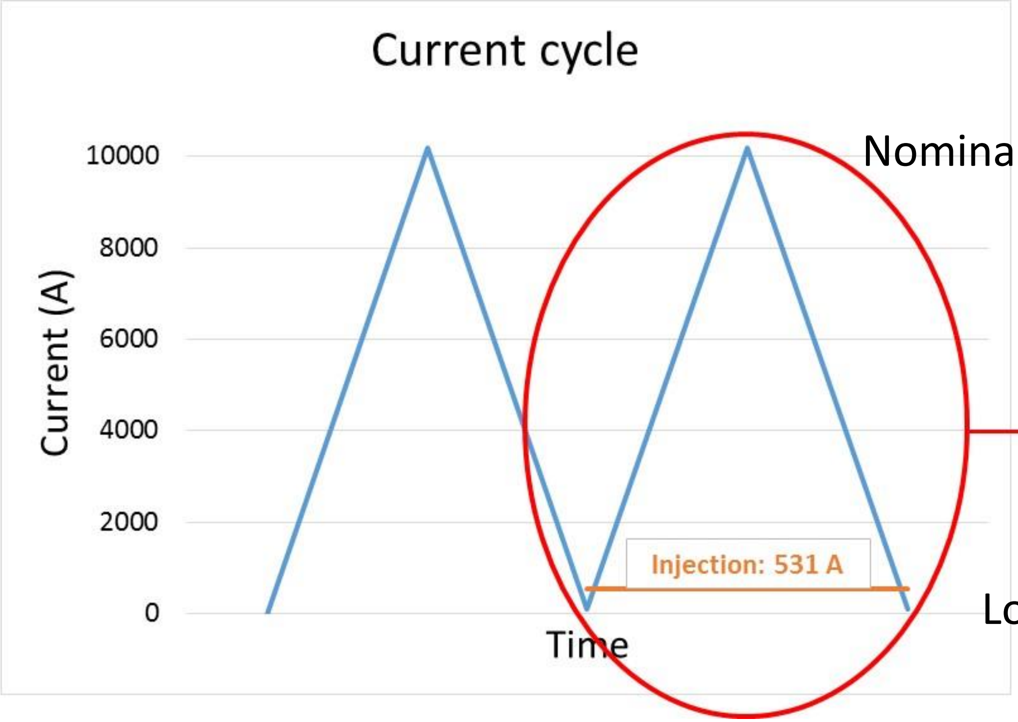
At Inom = 10176 A

```
NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:    -10.15001  b 3:      2.73821
b 4:      0.21845  b 5:     -0.15229  b 6:      0.00854
b 7:     -1.88733  b 8:      0.00002  b 9:     -1.51961
```

Without persistent current

b2 max = 15 units at 3053 A

Persistent currents



v4ari250

Nominal current = 10176 A

Only the second ramp up and second ramp down are studied

Low field turning point (reset current) = 100 A

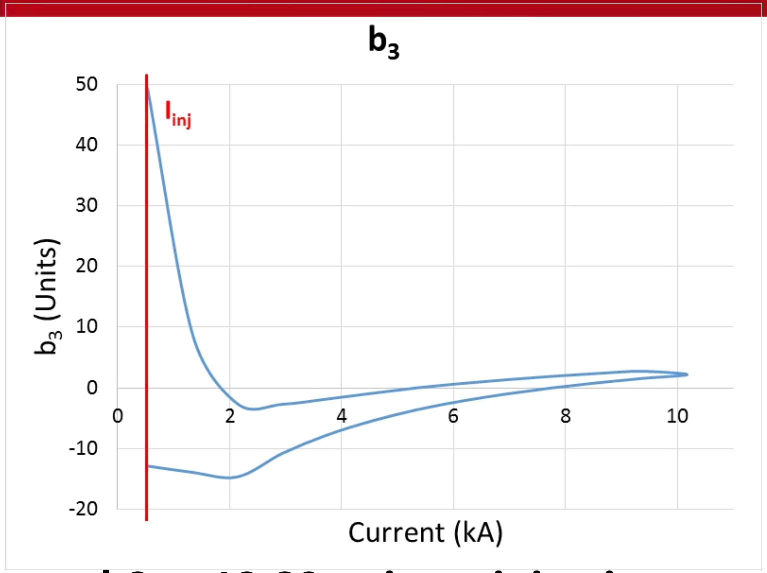
Current cycle: 0 A → 10176 A (first ramp up, pre-cycle) → 100 A (first ramp down, pre-cycle) → 10176 A (second ramp up) → 100 A (second ramp down)

Calculations at the reference radius = 16.67 mm (i.e. at 2/3 of the aperture radius) in the right aperture i.e. at x = 125 mm

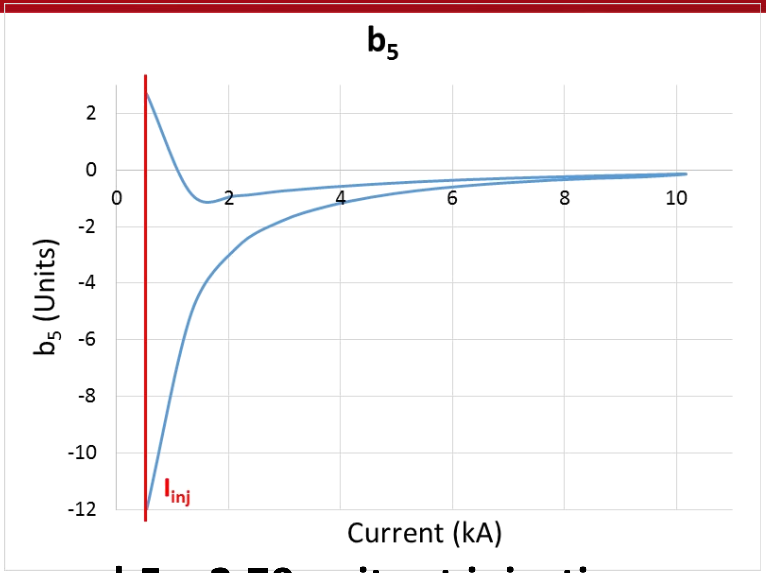
Injection at 3.3 TeV i.e. at 16 T x 3.3 / 50 = 1.056 T (corresponding to **531 A** for the v4ari250 magnetic model)

Persistent currents

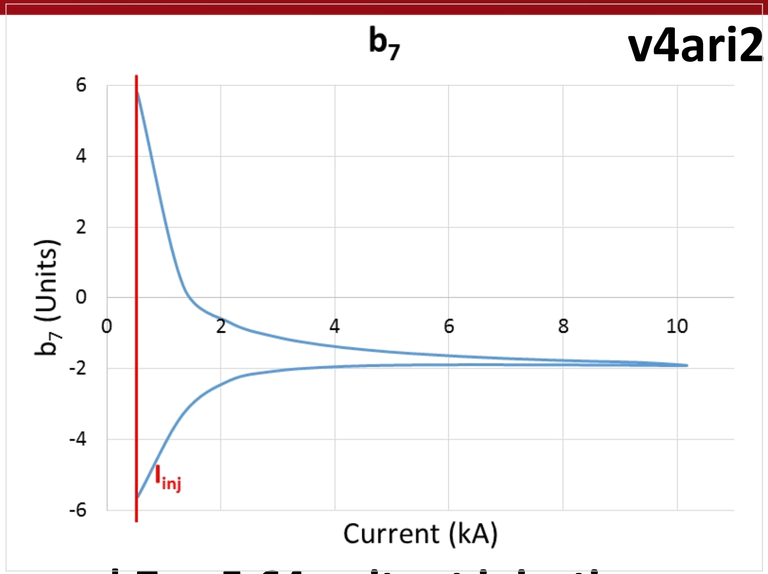
v4ari250



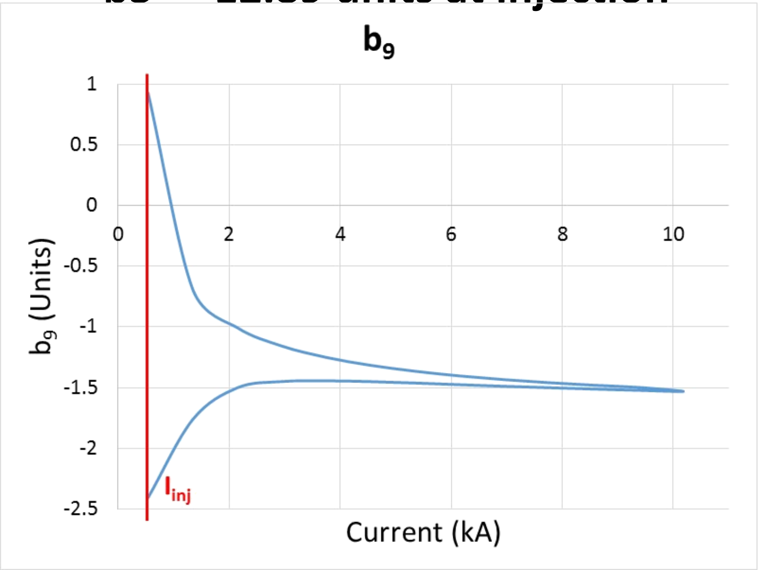
b3 = -12.89 units at injection



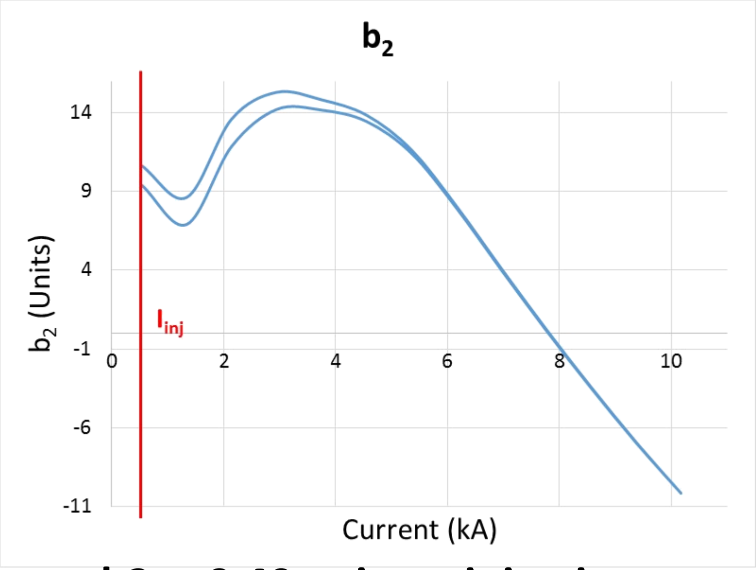
b5 = 2.70 units at injection



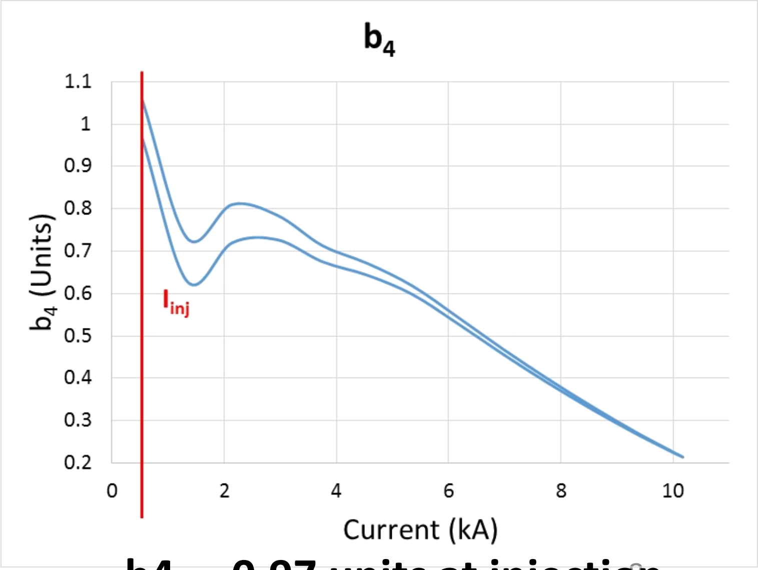
b7 = -5.64 units at injection



b9 = -2.40 units at injection



b2 = 9.40 units at injection

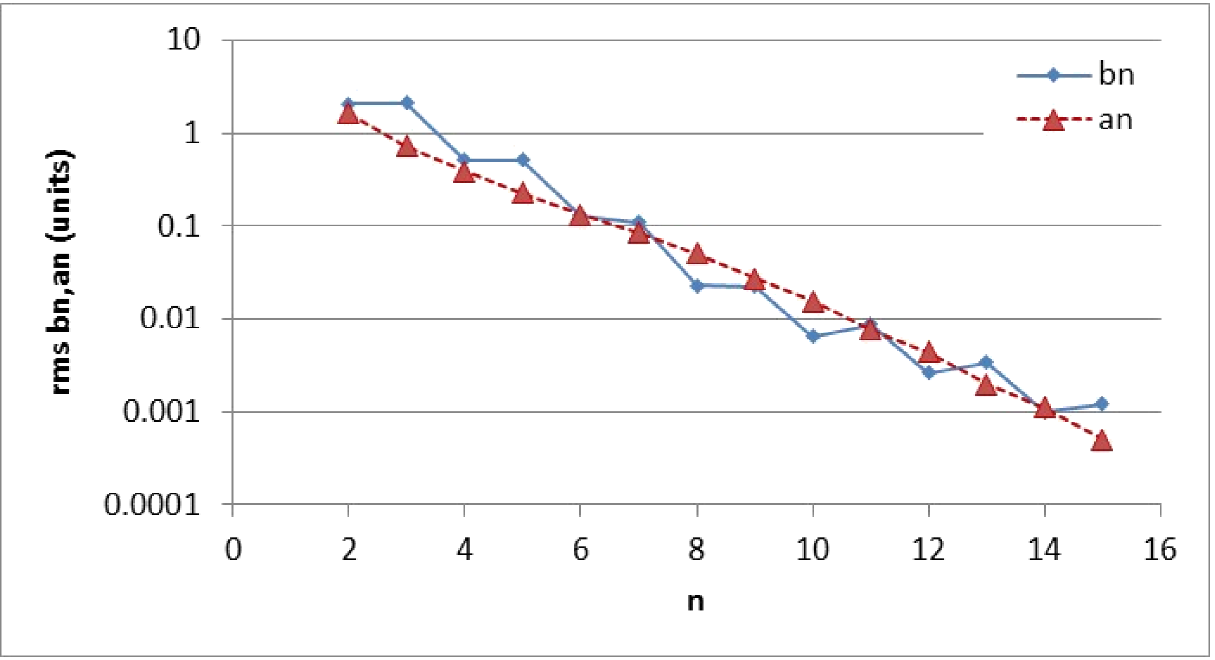


b4 = 0.97 units at injection

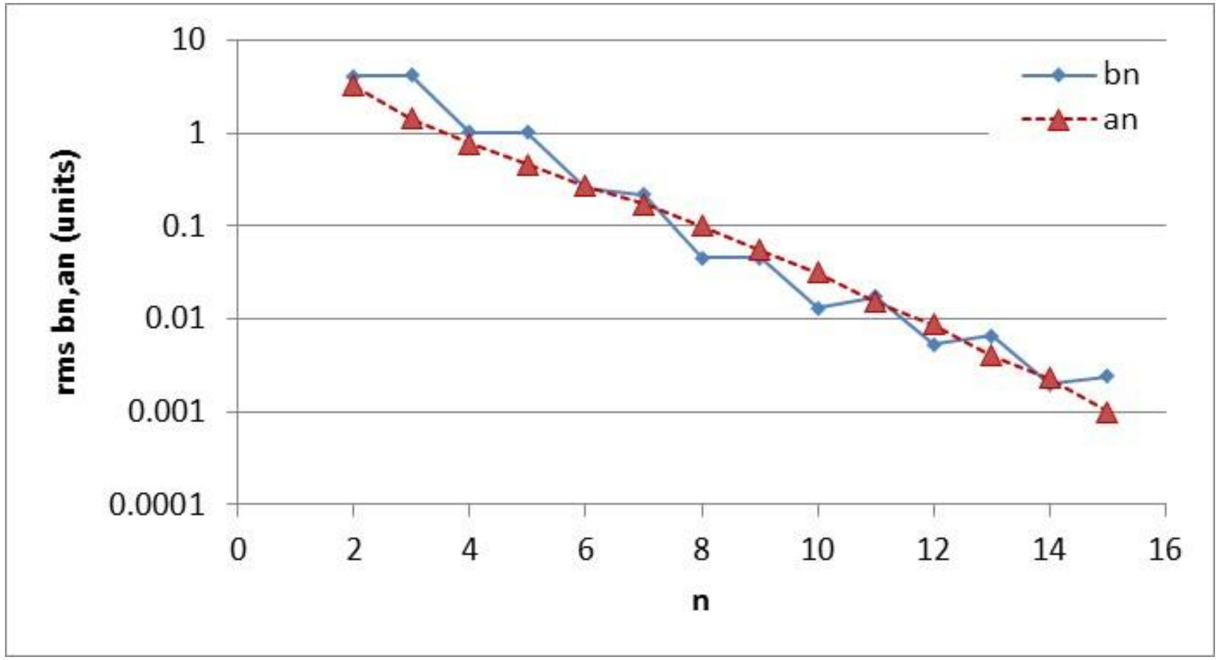
Random geometric errors

v4ari250

- Modeling of random geometric errors with ROXIE



Results for rms of 50 µm

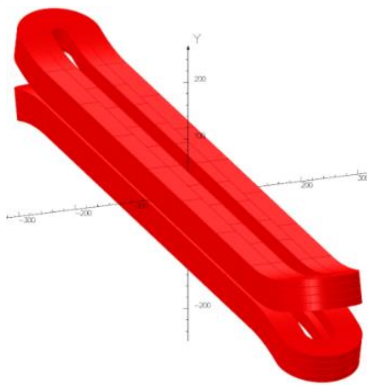


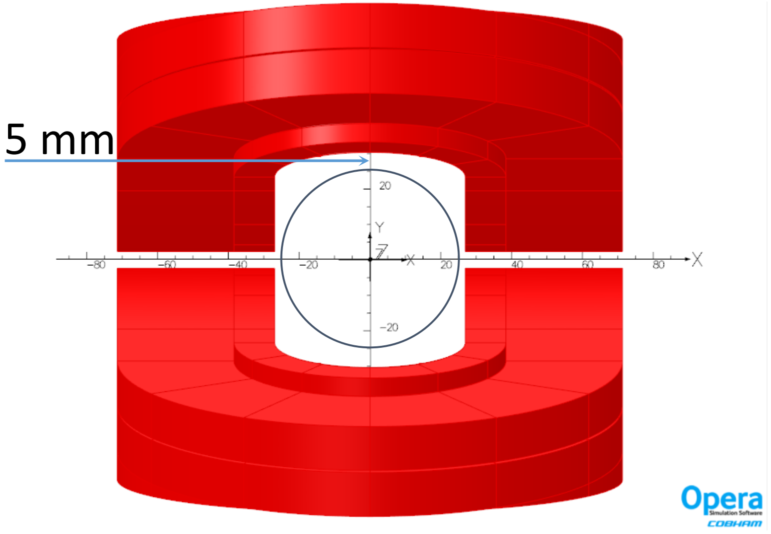
Results for rms of 100 µm

- Calculations with Opera are ongoing

3D magnetic design - Assumptions

- Assumptions:
  - Return ends – 1000 mm straight section
  - Hardway bend : Rmin = 450 mm in upper layer (w = 12.6 mm)
    - Strain 13.8 mm/m
      (HD2: 30.6 mm/m HD3: 12.4 mm/m Fresca2: 15.3 mm/m)
  - Coil-to-aperture y-direction: 5 mm
  - Double pancake end





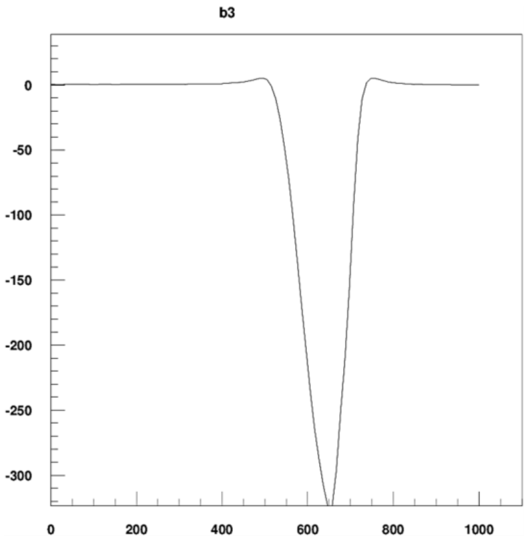
3D Magnetic Design – Options

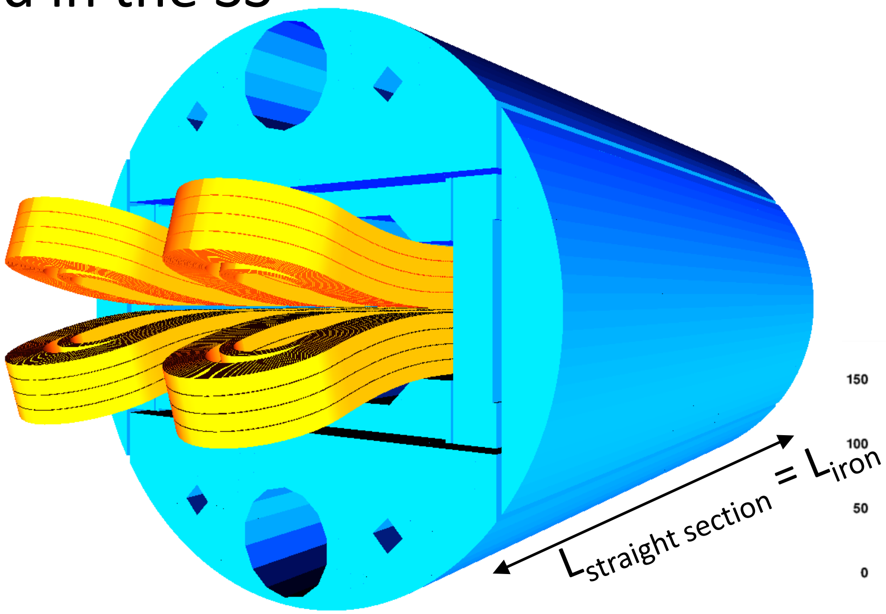
<u>Compact</u>: → **Minimum conductor length**

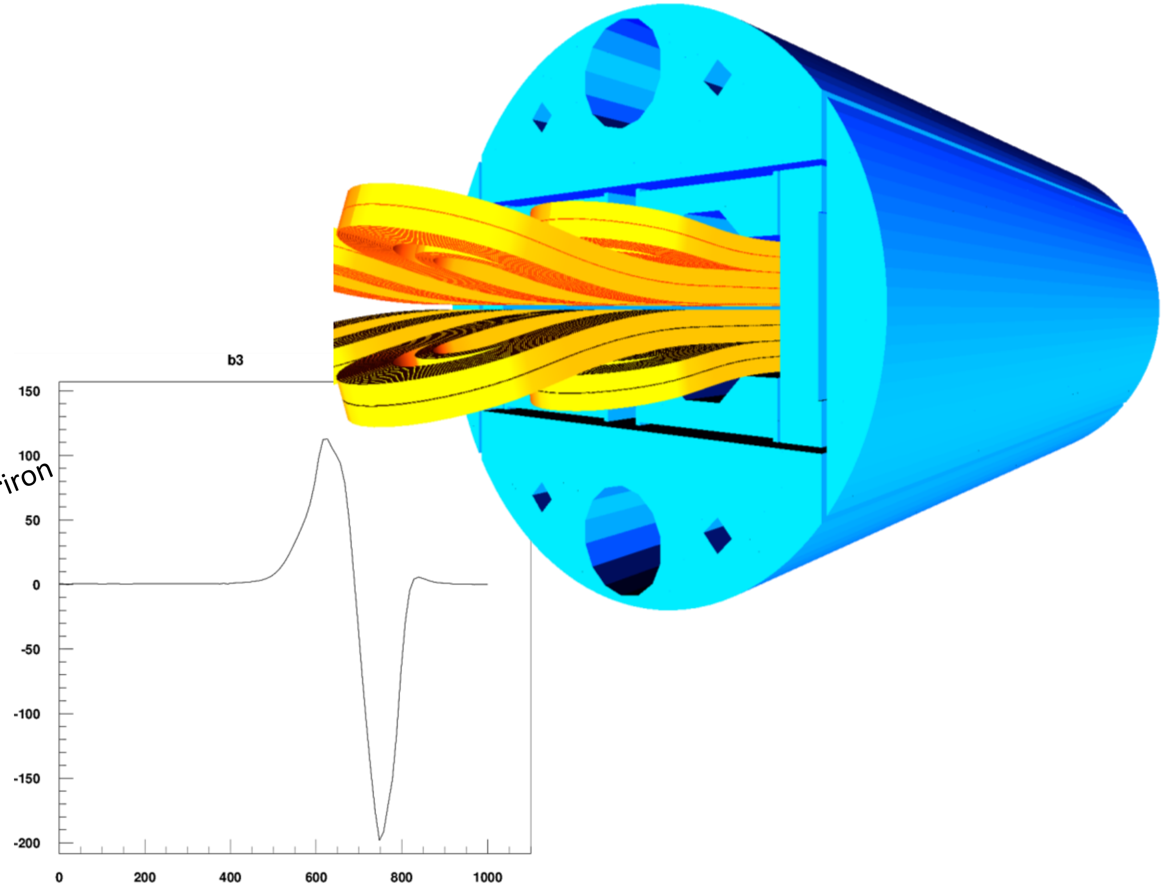
- Coil ends to the shortest
- Room in the spacers for internal joints
- b3 compensated in the SS

<u>Long</u>:

- Extension of coil ends
- Compensation of the b3 in the ends

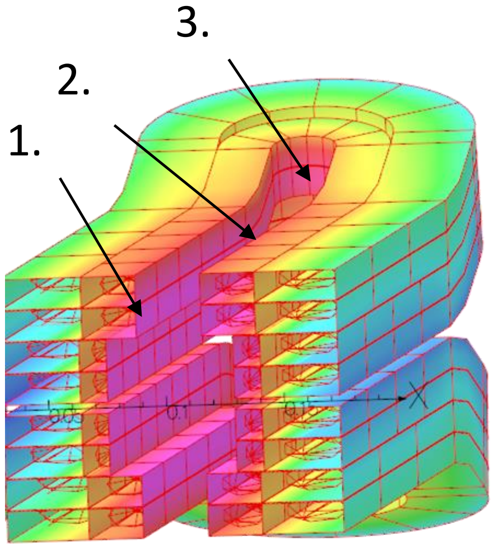


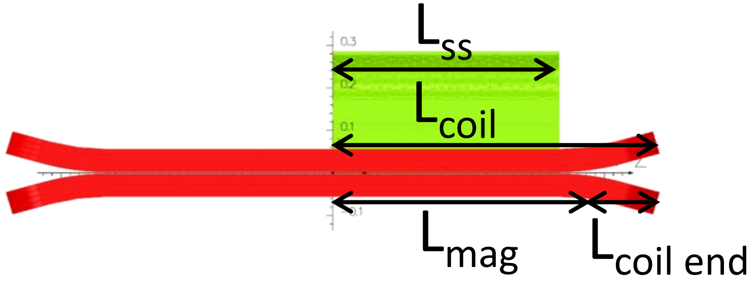




3D Magnetic Design – Options

Parameter	Compact	Compact compensated	Long	Unit
b3 integrated	-4.59	-3.00	0.08	units
Midplane shim	2.35	2.28	2.35	mm
$B_{peak}1$, z=0	16.60	16.60	16.60	T
$B_{peak}2$, HW bend	15.94	15.94	15.99	T
$B_{peak}3$, tip	15.03	15.03	15.23	T
$L_{straight\ section}$	500	500	500	mm (half length)
L_{iron}	500	500	500	mm (half length)
L_{coil}	722	722	813	mm (half length)
L_{mag}	642	642	678	mm (half length)
$L_{coil\ end} = L_{coil} - L_{mag}$	**80**	**80**	**135**	**mm (per end)**



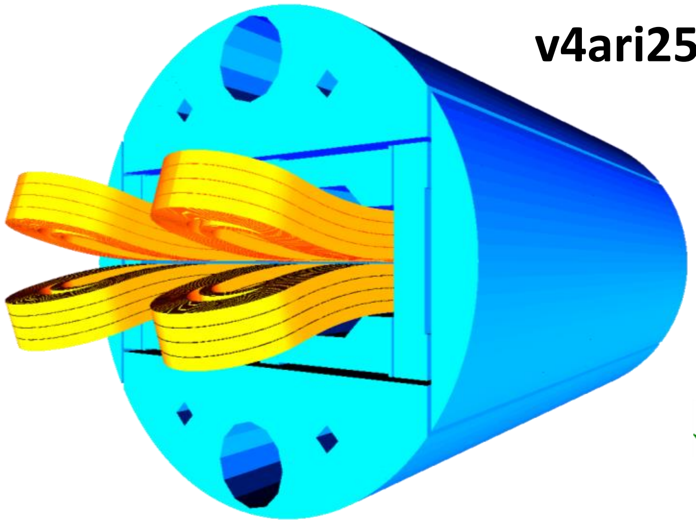


Baseline:
- **Short ends**
- **Low harmonics**
- **Margin (ΔB_{peak} > 0.6 T)**

3D Magnetic Design main parameters

Peak field in straight part:
16.7 T (ROXIE 2D)
16.6 T (OPERA 3D)
Peak field in ends:
15.8 T (OPERA 3D)

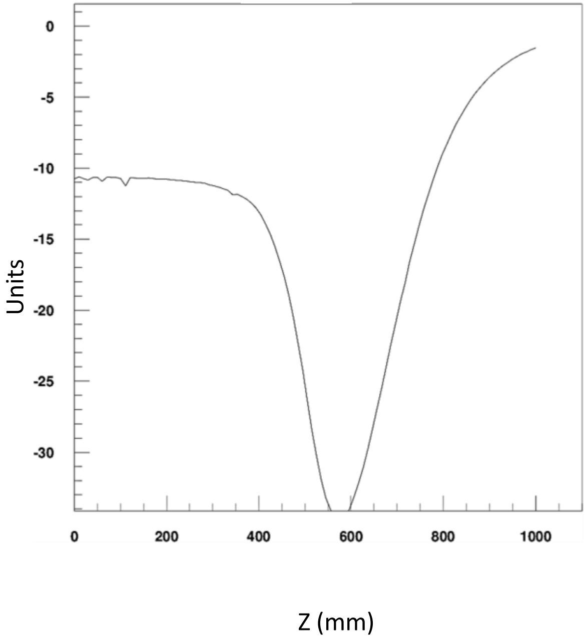
v4ari250



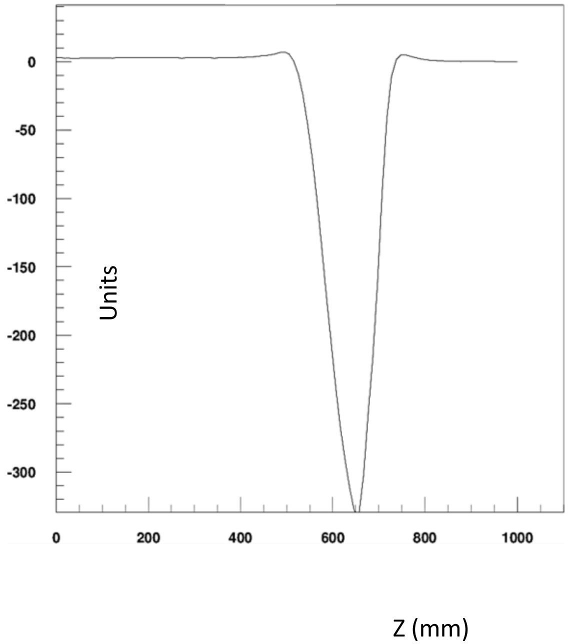
At Inom = 10176 A

```
ROXIE 2D

BLOCK NUMBER .......................................          30
PEAK FIELD IN CONDUCTOR  399 (T) ..................      16.7336
MAXIMUM LOADLINE IN BLOCK   30 (%) ................      86.2746
REFERENCE RADIUS (mm) .............................      16.6700
MAIN FIELD (T) ....................................   -16.000242
NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:    -10.15001  b 3:     2.73821
b 4:      0.21845  b 5:     -0.15229  b 6:     0.00854
b 7:     -1.88733  b 8:      0.00002  b 9:    -1.51961

ROXIE 3D

REFERENCE RADIUS (mm) .............................      16.6700
3D REFERENCE MAIN FIELD (T) .......................     -15.9922
MAGNETIC LENGTH (mm) ..............................     637.9365

NORMAL 3D INTEGRAL RELATIVE MULTIPOLES (1.D-4):
Version 1.29/04 of HIGZ started
b 1:  10000.00000  b 2:    -22.59054  b 3:   -54.10176
b 4:      0.05800  b 5:     -4.99637  b 6:     0.01294
b 7:     -2.41246  b 8:     -0.00946  b 9:    -1.42072

NORMAL INTEGRAL RELATIVE MULTIPOLES (1.D-4) ON 14 m (magnetic length):
b 2 = [12.72 x (-10.15) + 2 x 0.64 x (-22.59)] / 14.00 = -11.29 < 20 units
b 3 = [12.72 x 2.74 + 2 x 0.64 x (-54.10)] / 14.00     = -2.46 < 3 units
b 5 = [12.72 x (-0.15) + 2 x 0.64 x (-5.00)] / 14.00   = -0.59 < 3 units
b 7 = [12.72 x (-1.89) + 2 x 0.64 x (-2.41)] / 14.00   = -1.94 < 3 units
```

b2



b3



2D Mechanical model - Bladder inflation

ANSYS MODEL V4ari250

with outer yoke Ø = 616 mm

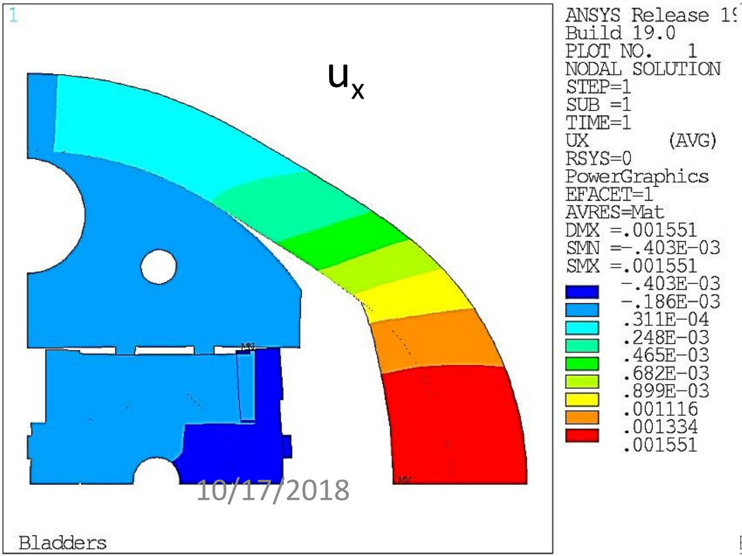
72 mm thick Al shell

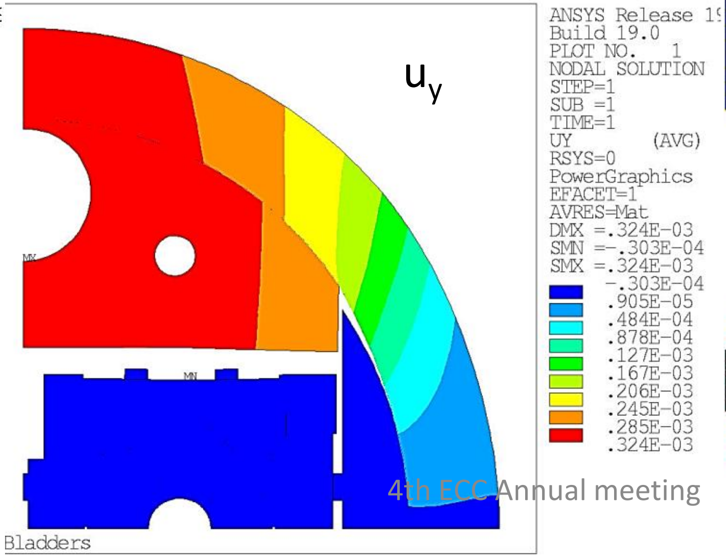
3 horizontal bladders: 1800 µm for 1600 µm

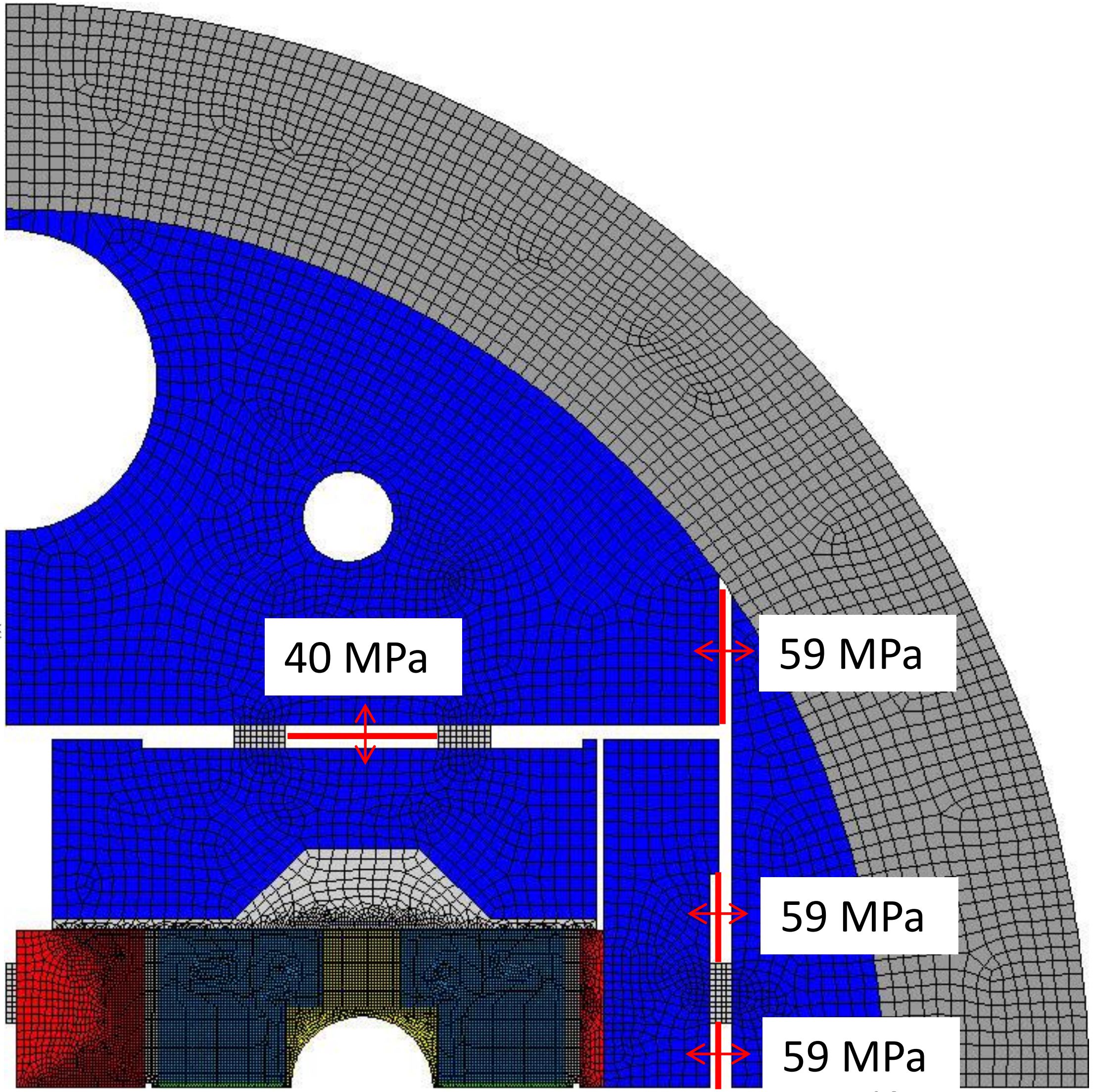
1 vertical bladder: 330 µm for 100 µm

No 20 mm thick SS shell for bladder inflation

→ peak von Mises stress in coil < 100 MPa







2D Mechanical model – Keys and SS shell

ANSYS MODEL V4ari250

with outer yoke Ø = 616 mm

72 mm thick Al shell + 20 mm thick SS shell

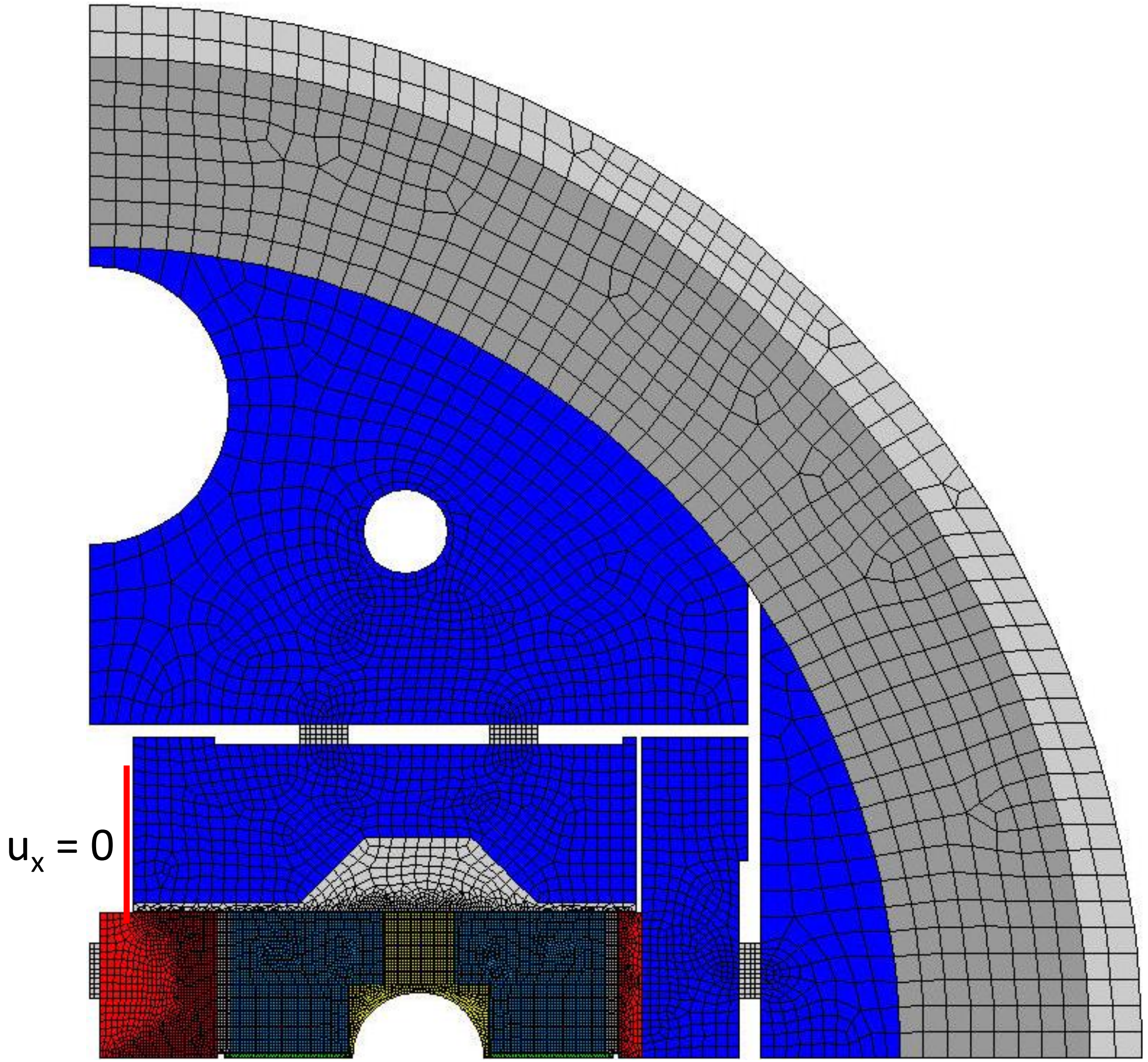
2 horizontal keys → 412 µm + 1185 µm ←

Vertical keys 100 µm ↓

Imposed displacement on SS shell bottom: -0.2 mm

Contacts/symmetry:

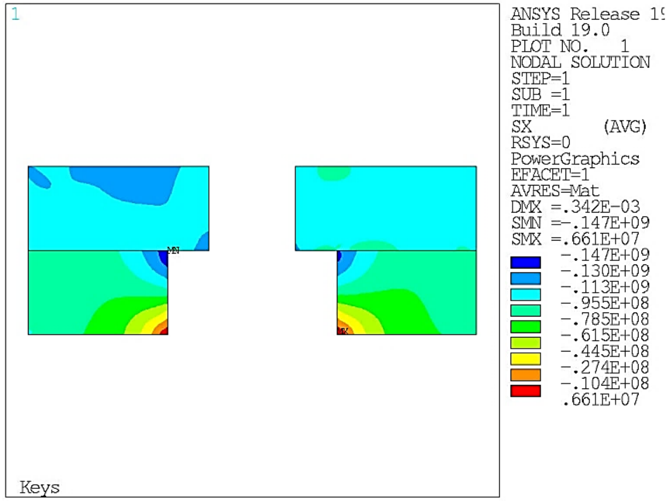
- Bonded: inside the coils, with the poles
- Separation allowed with 0.2 friction: between the coils, with the structure
- ¼ of the structure



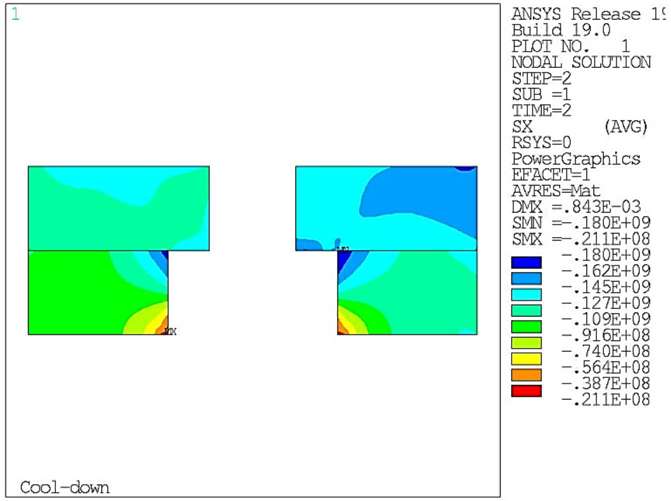
Stress distribution - Coils

Key + SS shell | **Cold – 4.2 K** | **16 T**

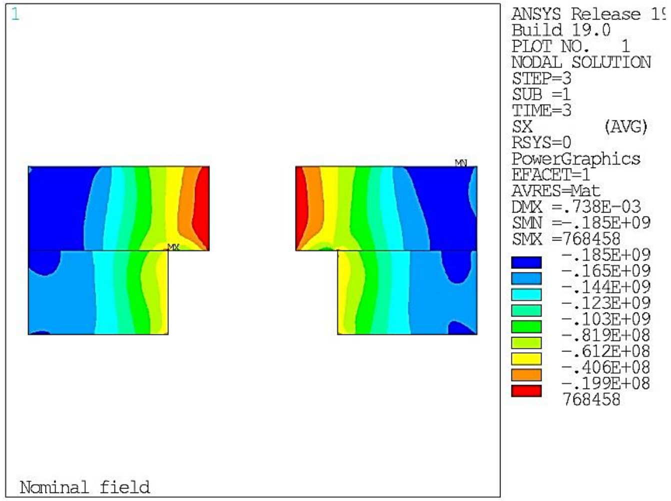
σ_x



-147 MPa

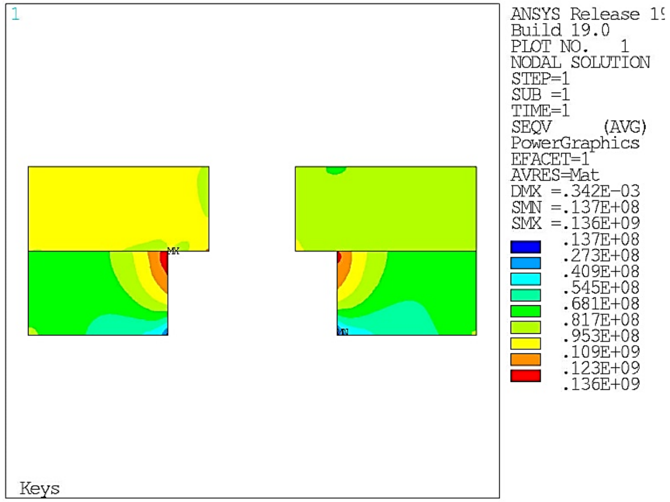


-180 MPa

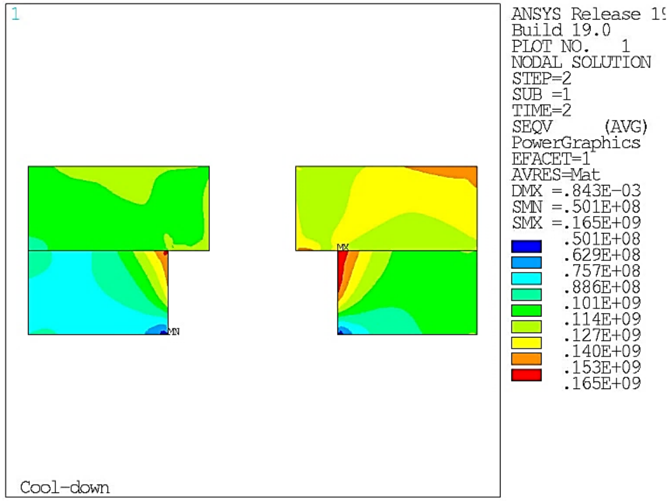


-185 MPa

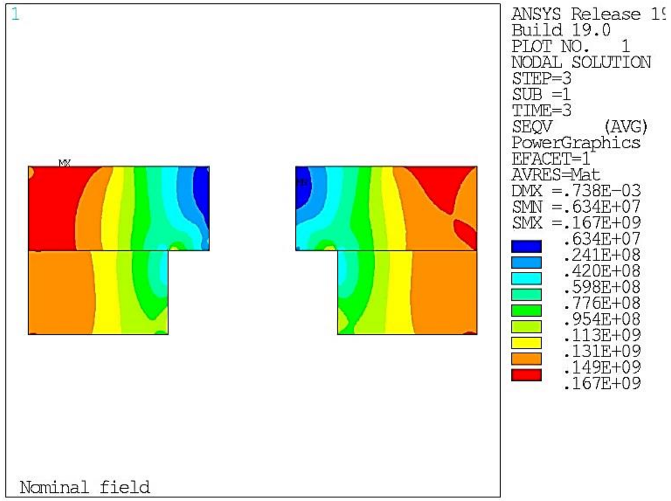
von Mises



+136 MPa



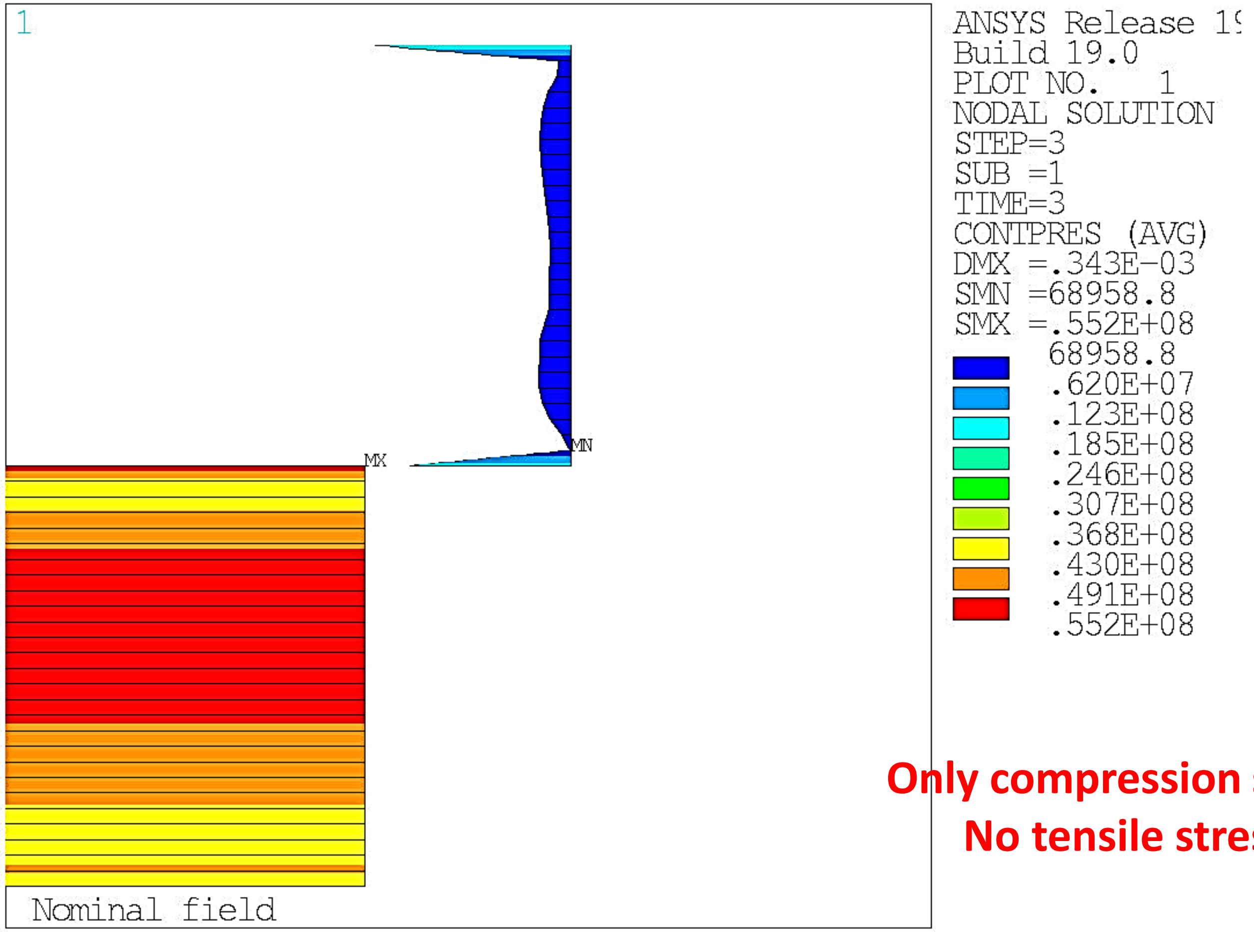
+165 MPa



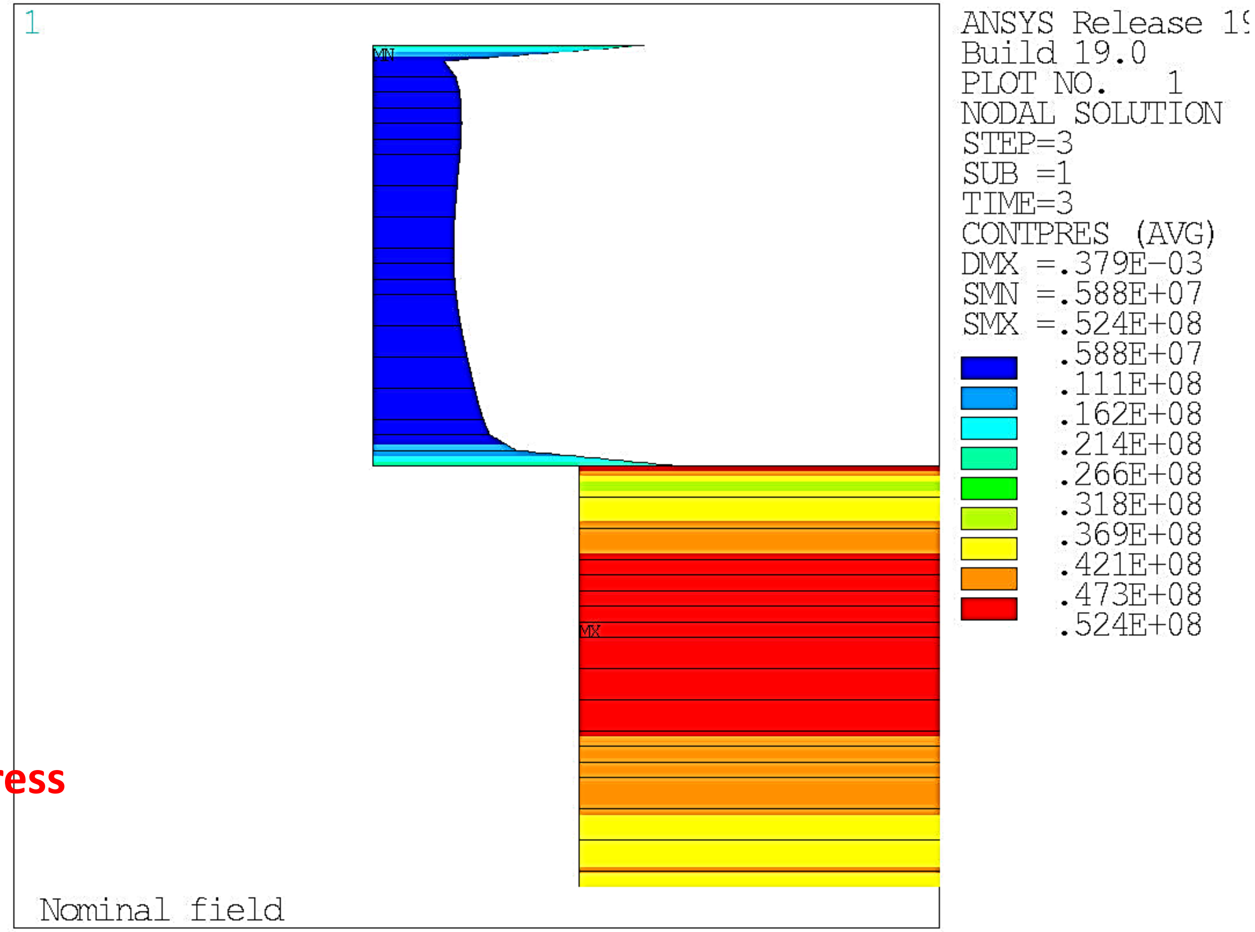
+167 MPa

σ_x at coil / pole interface

LEFT



RIGHT

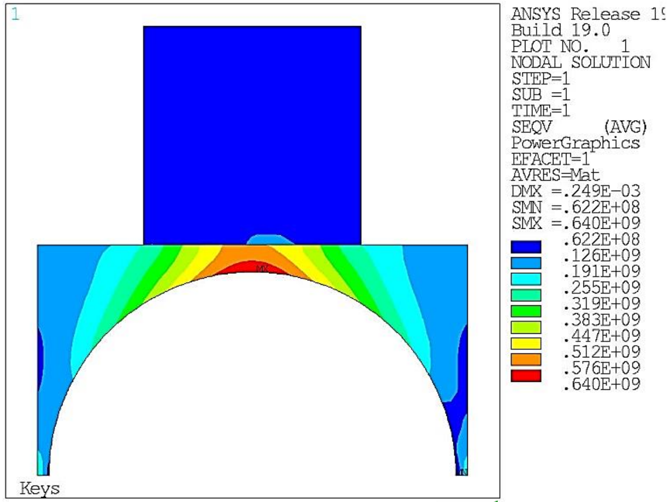


Only compression stress
No tensile stress

Von Mises stress distribution – Ti Poles

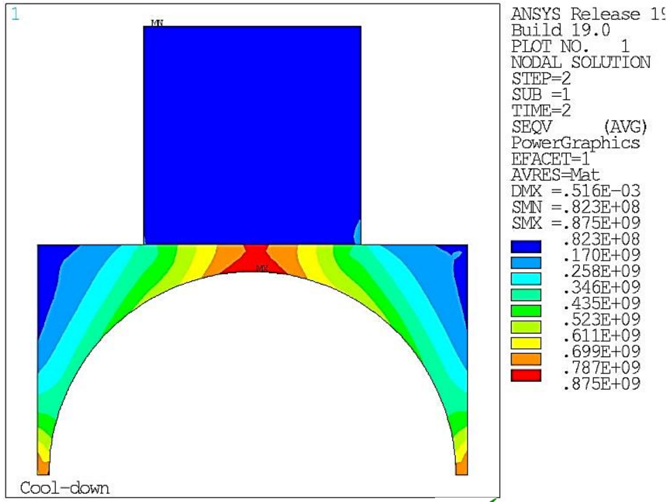
von Mises

Key + SS shell



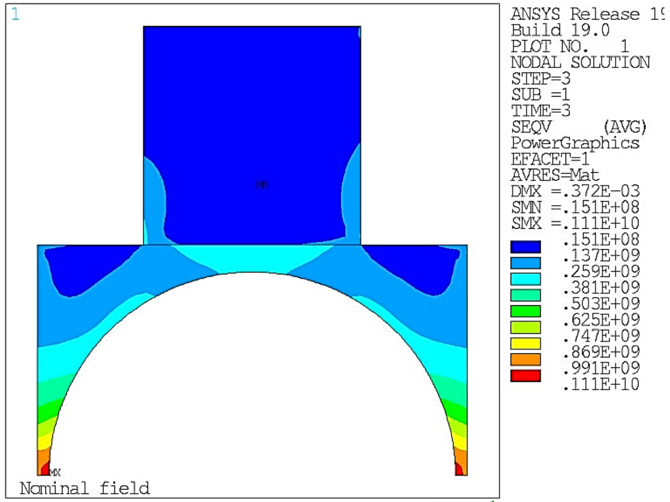
640 MPa ✓

Cold – 4.2 K



875 MPa ✓

16 T



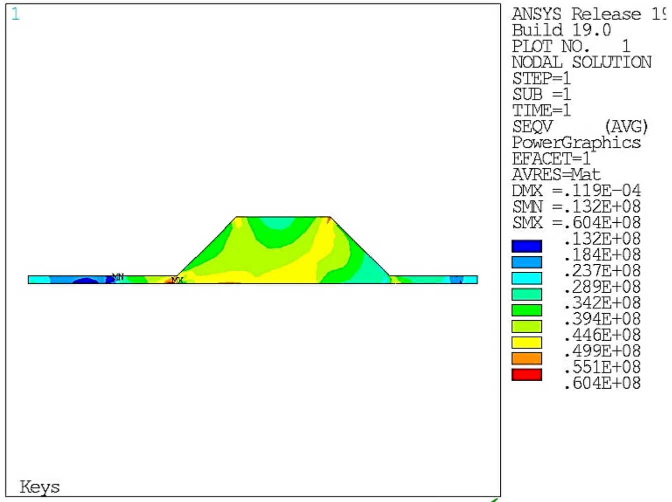
1110 MPa ✓

POLE	293 K	4.3 K
Ti 6Al 4V	800	1650

Von Mises stress distribution – Y pusher

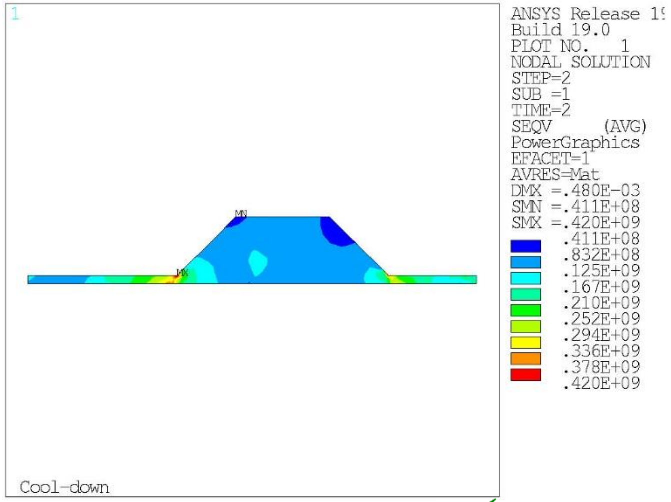
von Mises

Key + SS shell



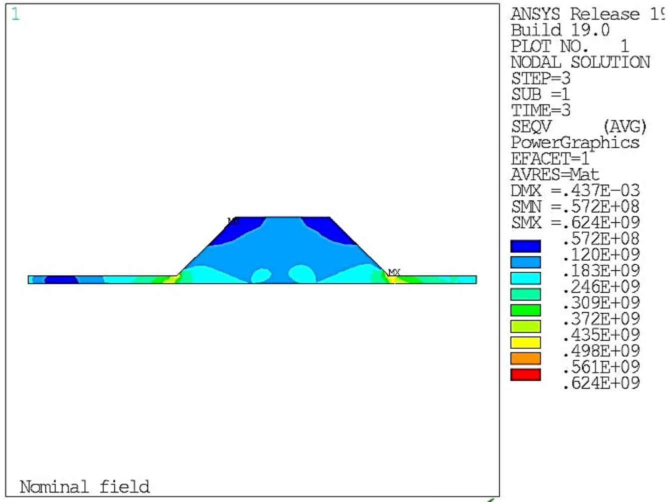
60 MPa ✓

Cold – 4.2 K



420 MPa ✓

16 T



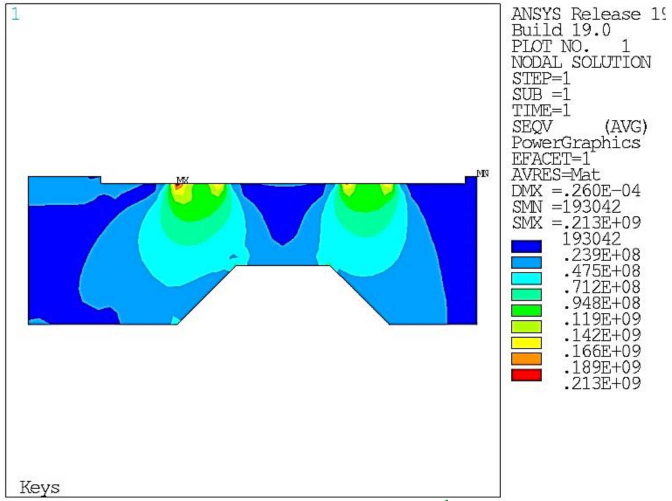
624 MPa ✓

PUSHER	293 K	4.3 K
SS 316 LN	350	1050

Stress distribution – Iron Y-pad

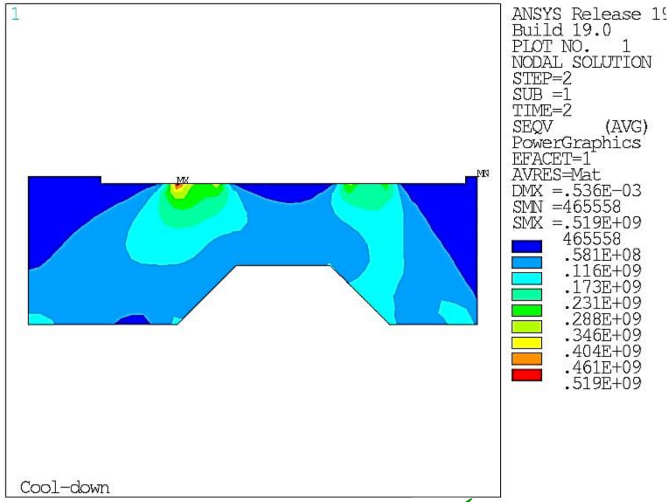
von Mises

Key + SS shell



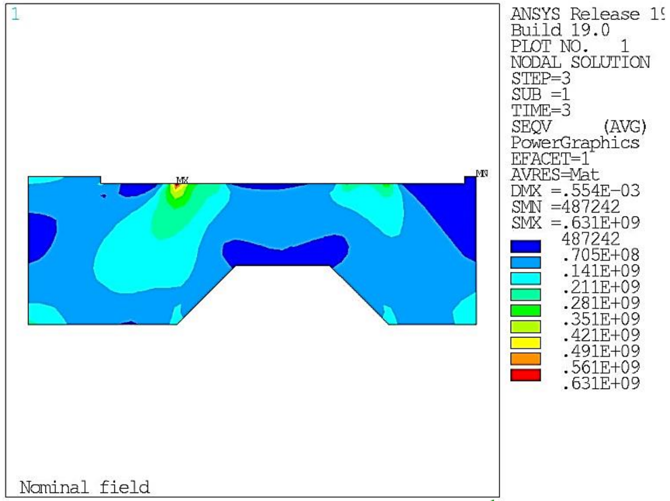
213 MPa ✓

Cold – 4.2 K



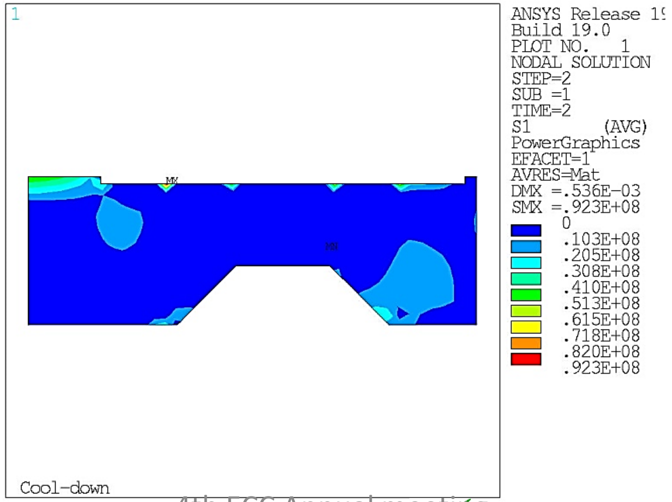
519 MPa ✓

16 T

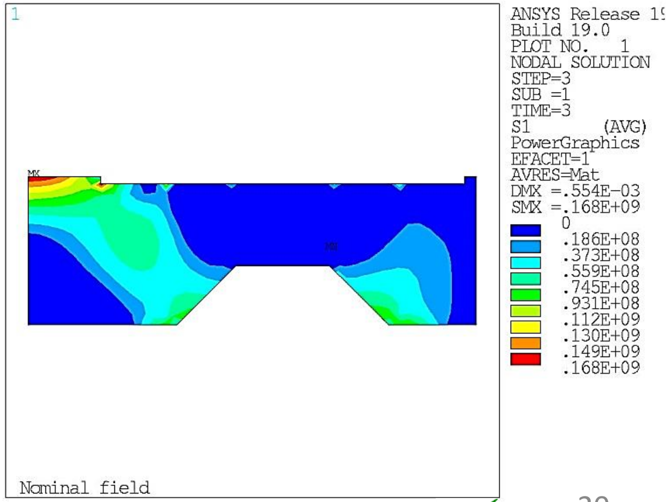


631 MPa ✓

Sigma I



92 MPa ✓



168 MPa ✓

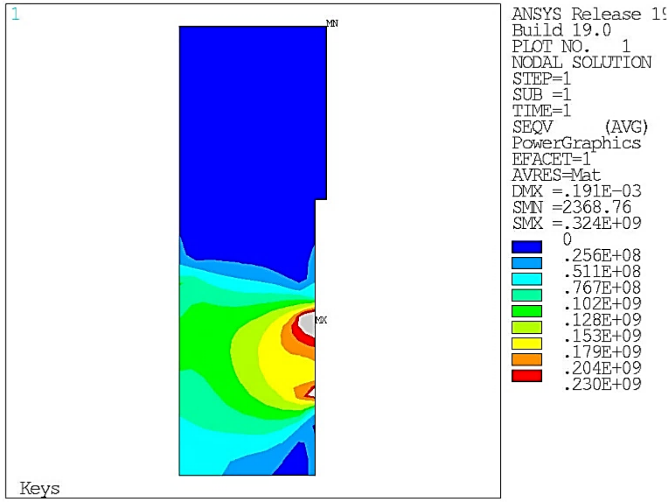
PADS	293 K	4.3 K
Ferromagnetic iron	230	720*

*σ_I < 380 MPa

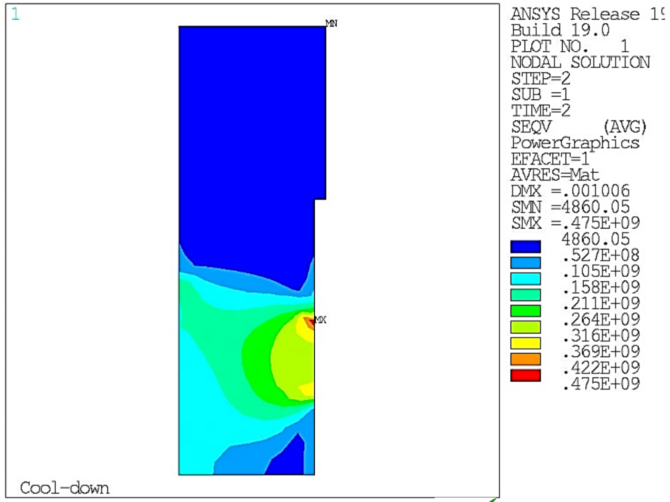
Stress distribution – Iron X-pad

Key + SS shell	Cold – 4.2 K	16 T

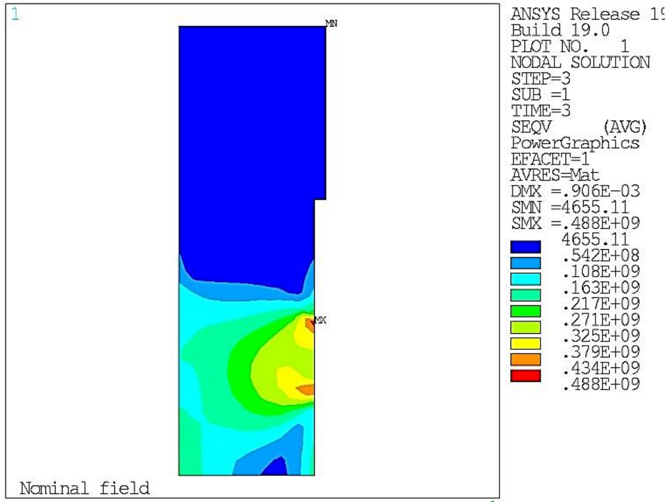
von Mises



324 MPa ✗

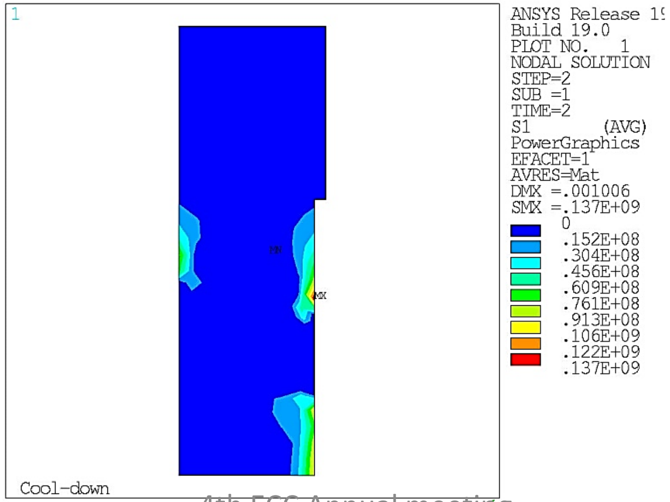


475 MPa ✓

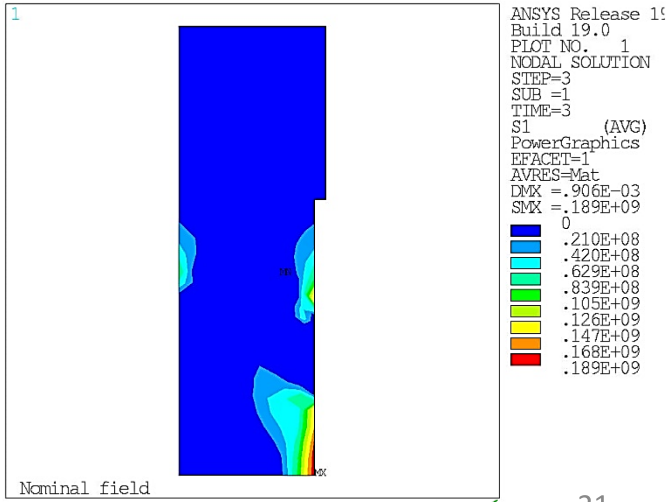


488 MPa ✓

Sigma I



137 MPa ✓



189 MPa ✓

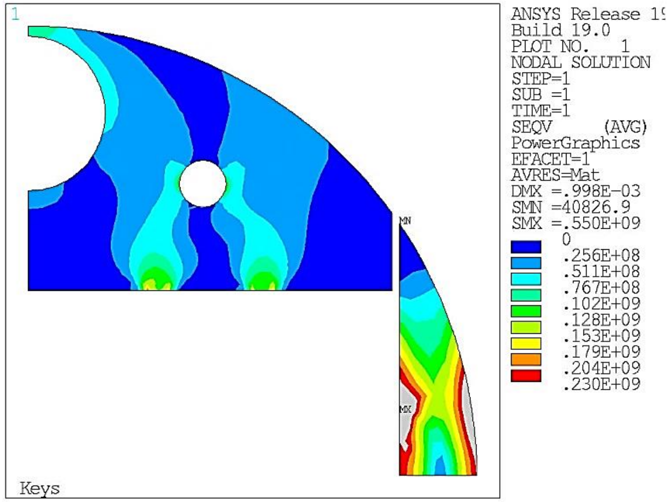
PADS	293 K	4.3 K
Ferromagnetic iron	230	720*

*σ_I < 380 MPa

Stress distribution - Yoke

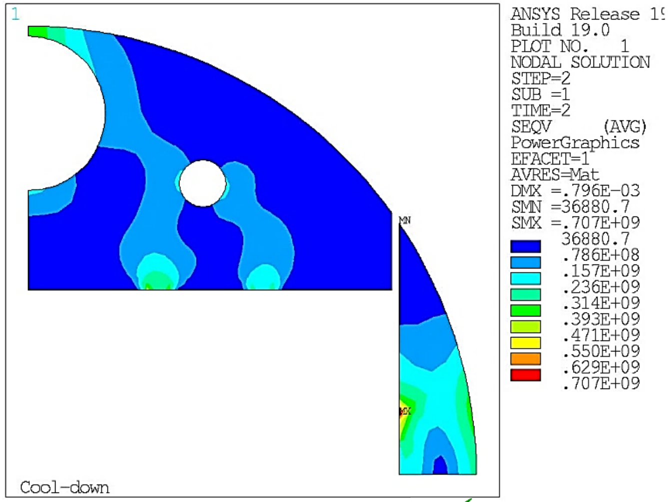
von Mises

Key + SS shell



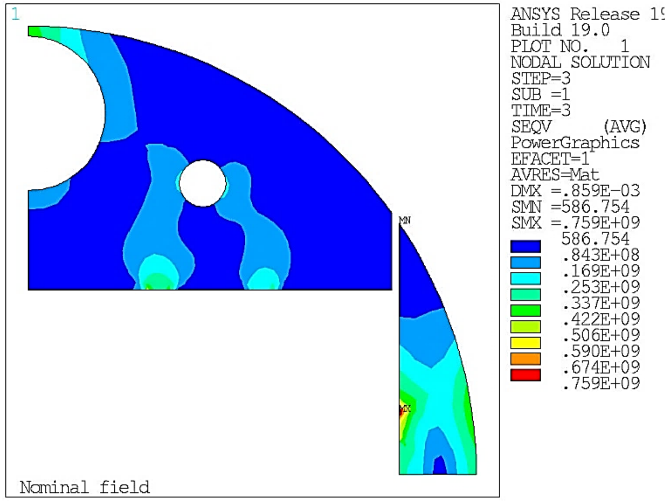
550 MPa ✗

Cold – 4.2 K



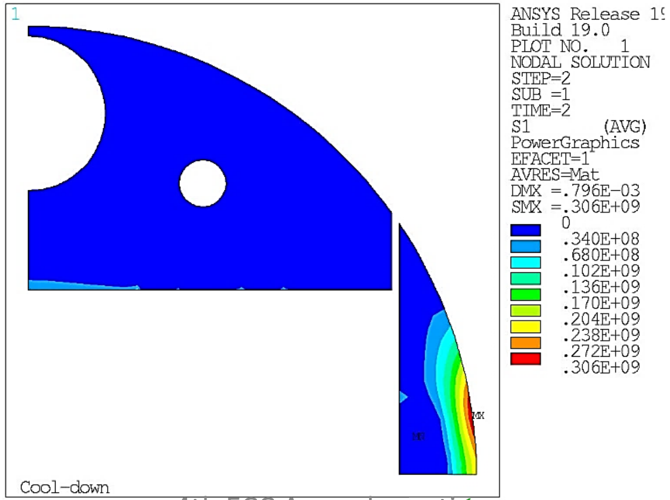
707 MPa ✓

16 T

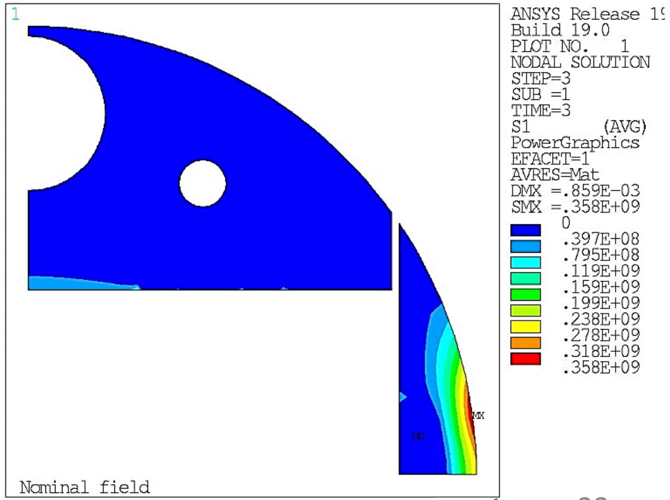


759 MPa ✗

Sigma I



306 MPa ✓



358 MPa ✓

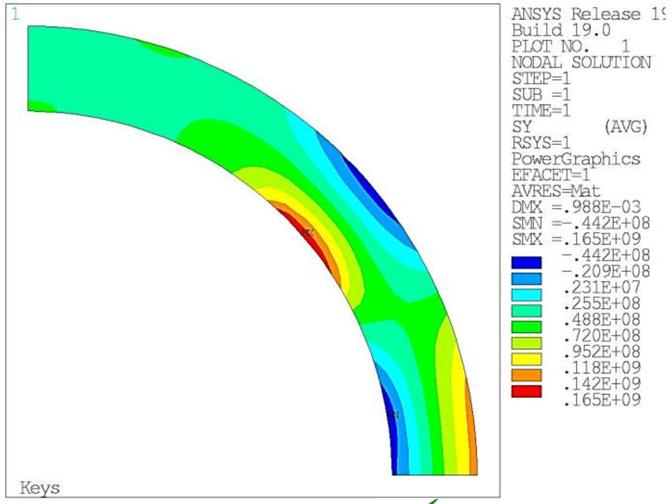
YOKE	293 K	4.3 K
Ferromagnetic iron	230	720*

*σ_I < 380 MPa

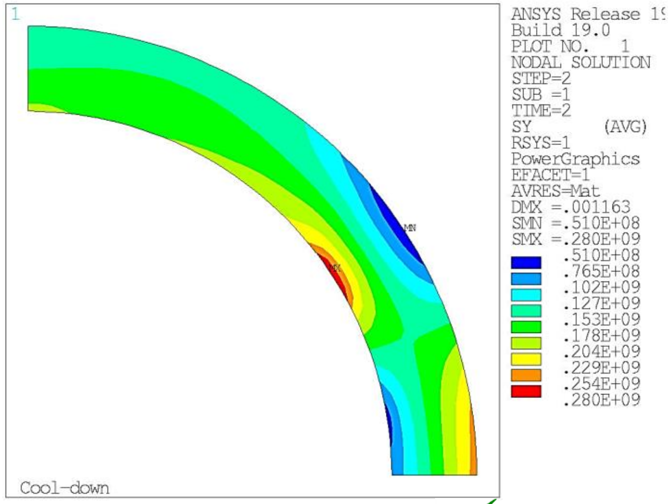
Azimuthal stress distribution – Al shell

σ_θ

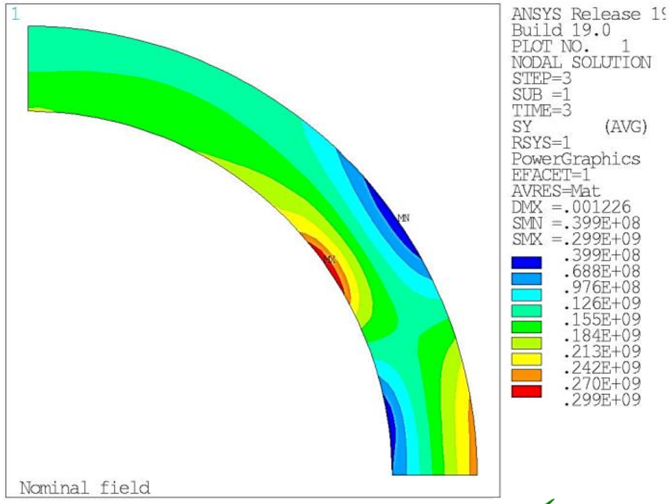
Key + SS shell	**Cold – 4.2 K**	**16 T**



165 MPa ✓



280 MPa ✓

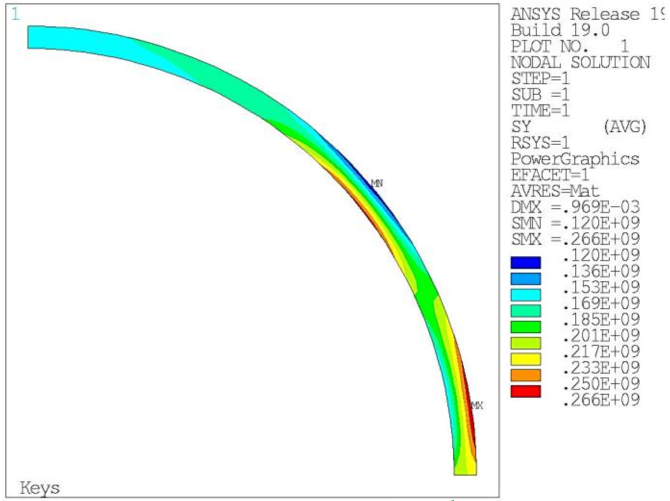
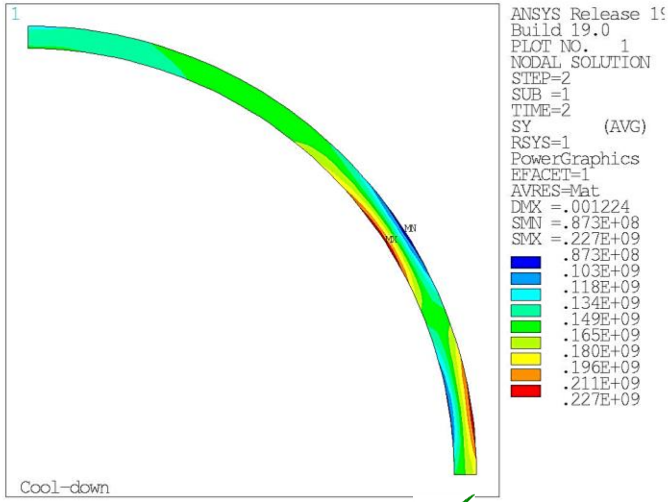
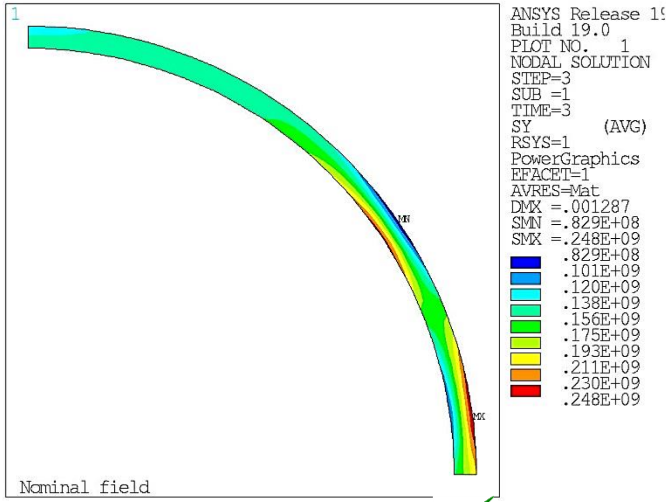


299 MPa ✓

Al SHELL	293 K	4.3 K
Al 7075	480	690

Azimuthal stress distribution – SS Shell

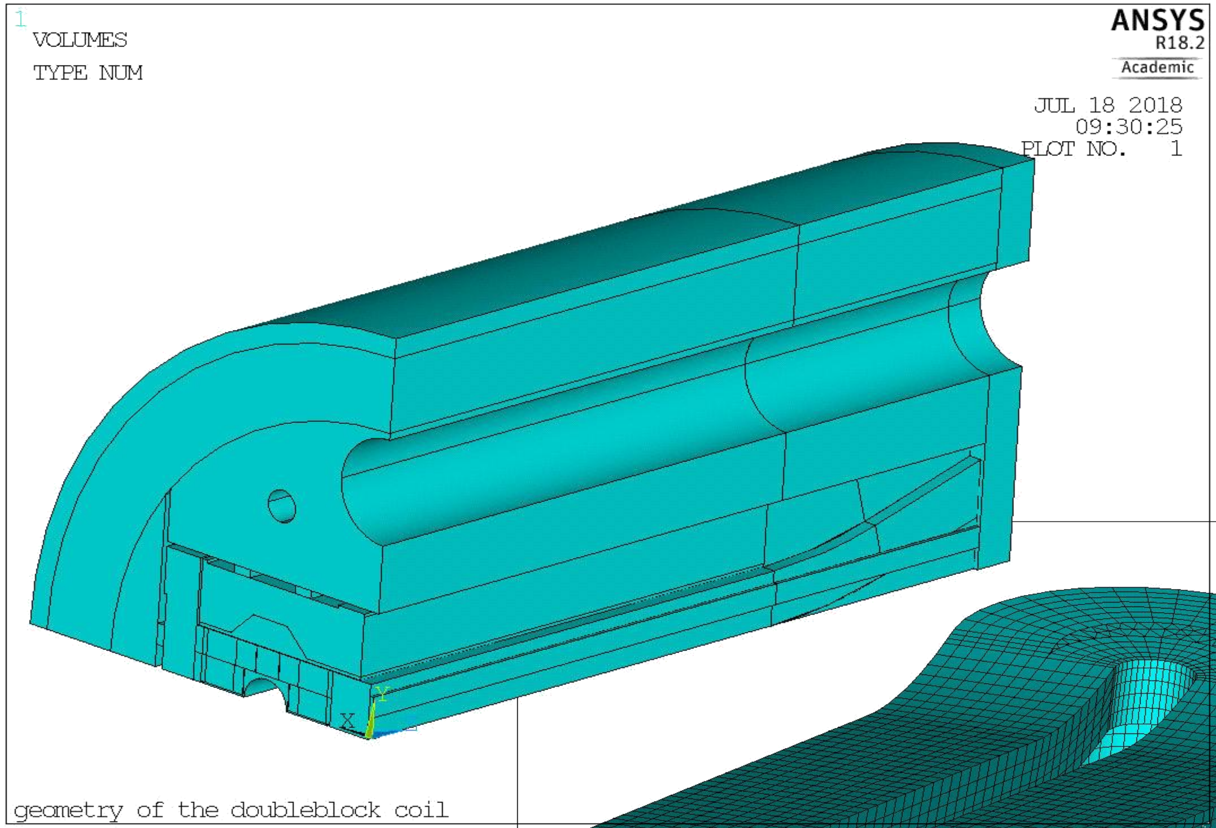
σ_θ

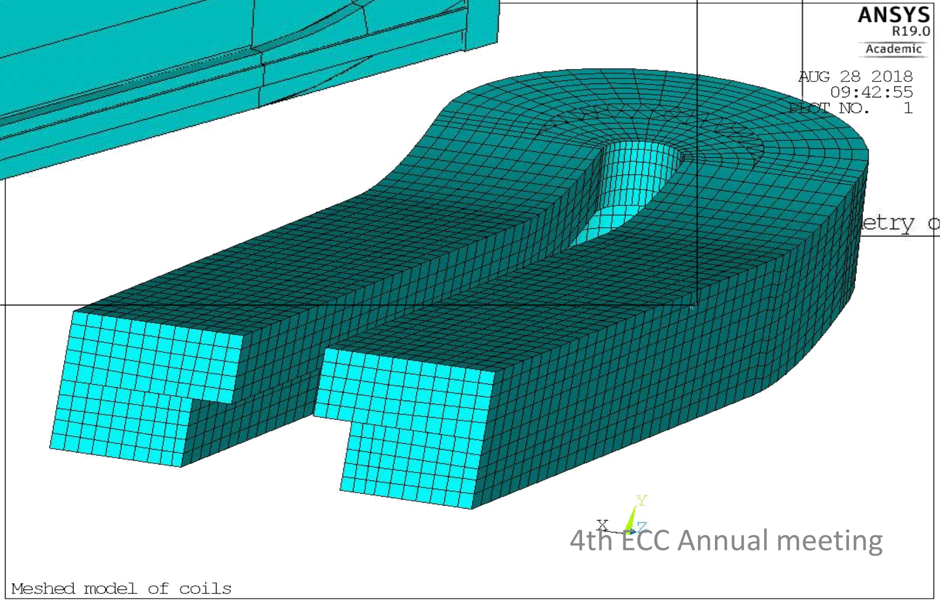
Key + SS shell	Cold – 4.2 K	16 T
		
266 MPa	227 MPa	248 MPa

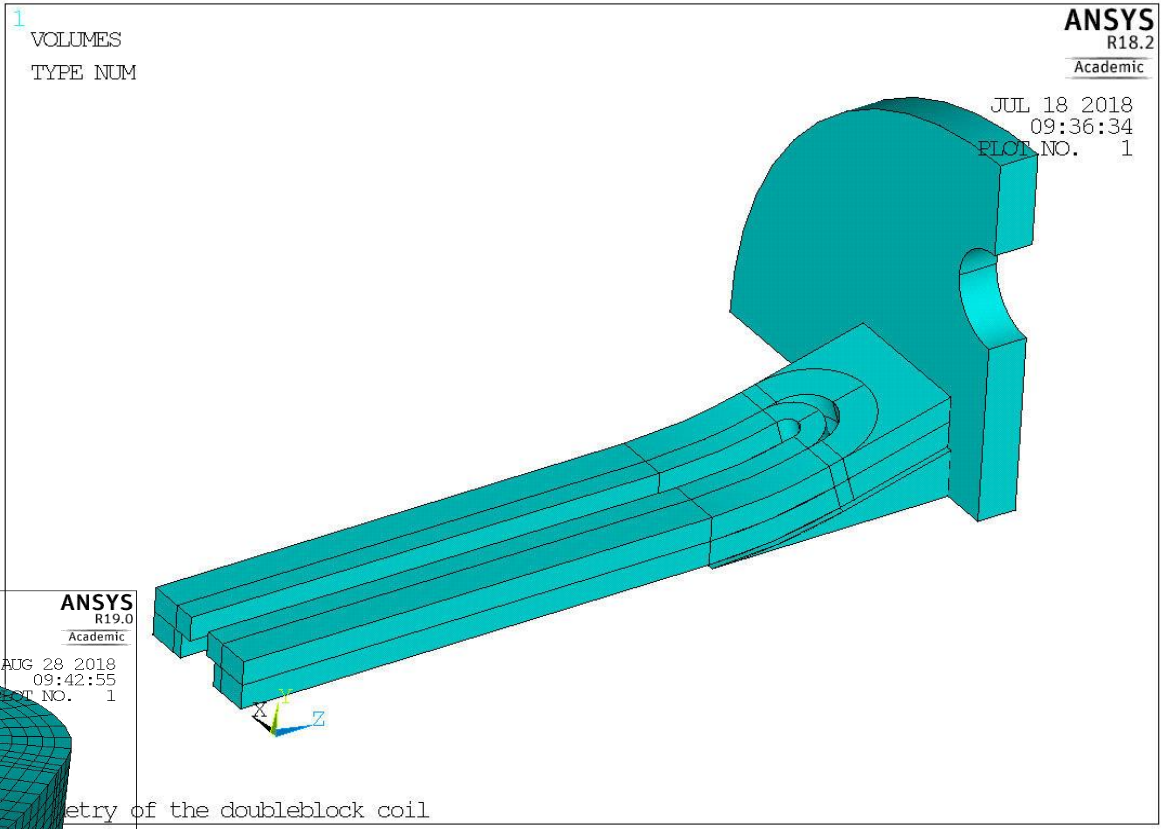
SS SHELL	293 K	4.3 K
SS 316 LN	350	1050

3D Mechanical design (ongoing)

- Ansys 3D model







Contacts/symmetry:

- Bonded: inside the coils, with the poles
- Separation allowed with 0.2 friction: between the coils, with the structure
- ¼ of the structure

3D Mechanical design - Next steps

- Comparison between 2D and 3D @ z = 0 results
- Impact of the SS length on coil-ends results
  - 1 m and 2 m SS models
- Axial stress
- 3D Mechanical design :
  - End-shoe/end plate interference,
  - x interference increase,

needed to keep end shoe and end plate in contact

Conclusion for the magnetic design

- A 3D double aperture electromagnetic model has been developed by optimizing the field quality and the magnetic and physical lengths (coil ends as short as possible)
- Persistent current is taken into account with ROXIE 2D
- A random geometric errors analysis with ROXIE has been realized
  - Calculations results with Opera are foreseen soon
- As the block coil is the same than for the v2ari194 model presented last year, we assume that Hotspot and Voltage to ground remain below the limit

Conclusion for the mechanical design

- Investigation of a double aperture 2D mechanical design with 250 mm inter-beam distance, @ 16 T
- Total outer diameter of 800 mm (SS shell outer diameter)
- Bladder pressure of 59 MPa in operation
- Peak stress in Nb_3Sn coil below the limit
- Peak stress in the horizontal iron components above the limit at warm (key contact with lateral yoke and horizontal pad)
- Almost operational Ansys 3D model

Thanks for your attention

Random geometric errors

Inputs for ROIXE 2D for rms of 100 µm and 50 µm

v4ari250

rms of 100 µm		Block1HF	Block1LF	Block2HF	Block2LF	Block3HF	Block3LF	Block4HF	Block4LF
X (mm)	xl	26.800	38.300	26.800	38.300	13.730	36.730	13.730	36.730
	xu	27.000	38.500	27.000	38.500	13.930	36.930	13.930	36.930
	xs	26.900	38.400	26.900	38.400	13.830	36.830	13.830	36.830
Y (mm)	xl	14.870	14.870	28.270	28.270	41.670	41.670	55.070	55.070
	xu	15.070	15.070	28.470	28.470	41.870	41.870	55.270	55.270
	xs	14.970	14.970	28.370	28.370	41.770	41.770	55.170	55.170
Inclination angle (deg)	xl	-91.2789	-91.2789	-91.2789	-91.2789	-91.2789	-91.2789	-91.2789	-91.2789
	xu	-88.7211	-88.7211	-88.7211	-88.7211	-88.7211	-88.7211	-88.7211	-88.7211
	xs	-90.0000	-90.0000	-90.0000	-90.0000	-90.0000	-90.0000	-90.0000	-90.0000

rms of 50 µm		Block1HF	Block1LF	Block2HF	Block2LF	Block3HF	Block3LF	Block4HF	Block4LF
X (mm)	xl	26.850	38.350	26.850	38.350	13.780	36.780	13.780	36.780
	xu	26.950	38.450	26.950	38.450	13.880	36.880	13.880	36.880
	xs	26.900	38.400	26.900	38.400	13.830	36.830	13.830	36.830
Y (mm)	xl	14.920	14.920	28.320	28.320	41.720	41.720	55.120	55.120
	xu	15.020	15.020	28.420	28.420	41.820	41.820	55.220	55.220
	xs	14.970	14.970	28.370	28.370	41.770	41.770	55.170	55.170
Inclination angle (deg)	xl	-90.6395	-90.6395	-90.6395	-90.6395	-90.6395	-90.6395	-90.6395	-90.6395
	xu	-89.3605	-89.3605	-89.3605	-89.3605	-89.3605	-89.3605	-89.3605	-89.3605
	xs	-90.0000	-90.0000	-90.0000	-90.0000	-90.0000	-90.0000	-90.0000	-90.0000

Material properties (Davide 3rd FCC week)

Coil maximum stress

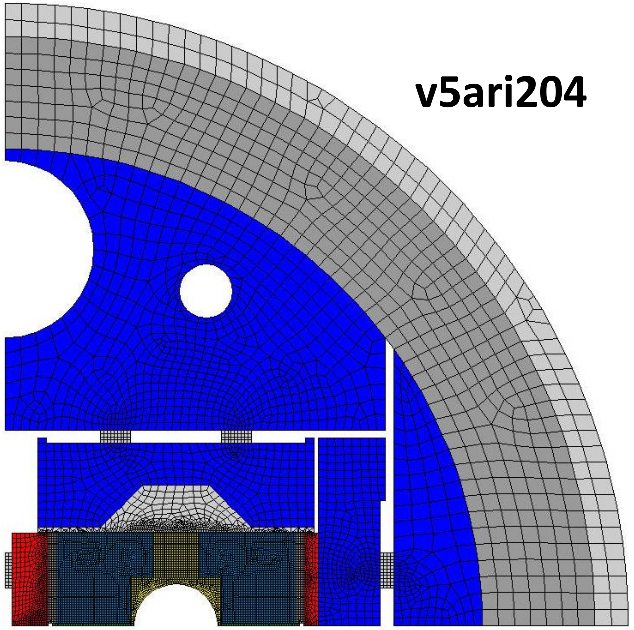
- @ 4.2 K: 200 MPa
- @ 300 K: 150 MPa

Material	$R_{p\,0.2}$ [MPa]	
	293 K	4.3 K
Al 7075	480	690
SS 316 LN	350	1050
NITRONIC 40	350	1240
Ferromagnetic iron	230	720*
Ti 6Al 4V	800	1650

Material	E [GPa]		pr	$(L_{4.3K}-L_{293K})/L_{293K}$
	293 K	4.3 K	293K/4.3K	293 K -> 4.3K
Coil	EX = 25 EY = 30 GXY = 21	EX = 27.5 EY = 33 GXY = 21	0.3	X = 3.36e-3 Y = 3.08e-3
StSt	193	210	0.28	2.84e-3
Iron	213	224	0.28	1.97e-3
Aluminum	70	79	0.34	4.2e-3
Titanium	115	126.5	0.3	1.74e-3
Nitronic 40	210	225	0.28	2.6e-3

*Ferromagnetic iron @ 4.2 K stress < 380 MPa in tension (1st principal stress)

Synthesis of 2D mechanical designs



Interbeam distance = 204 mm

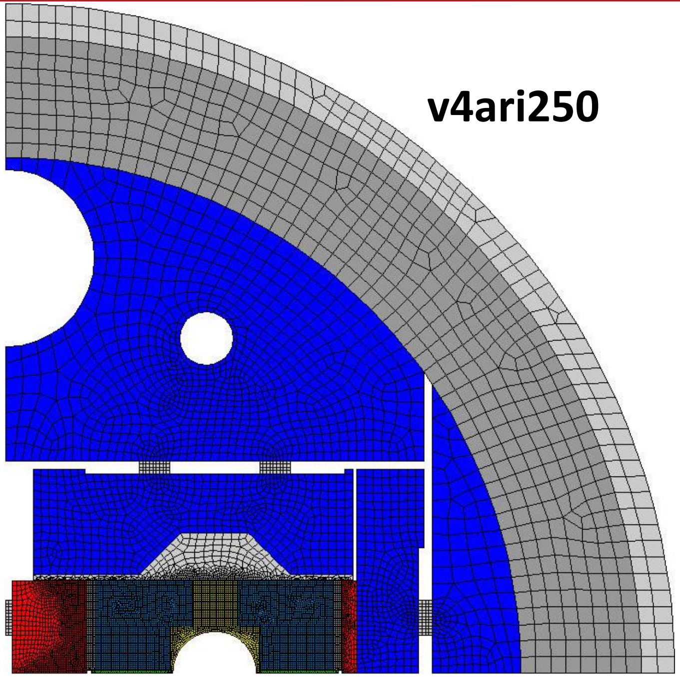
$\varnothing_{ext}$ iron yoke = 570 mm

Total $\varnothing_{ext}$ = 744 mm

67 + 20 mm thick shells

→ 2 x 720 µm ←

	σ_X max	σ Von Mises max
Keys + SS shell	-148	137
Cool-down	-181	160
Energization 16 T	-199	177



Interbeam distance = 250 mm

$\varnothing_{ext}$ iron yoke = 616 mm

Total $\varnothing_{ext}$ = 800 mm

72 + 20 mm thick shells

→ 412 µm + 1185 µm ←

	σ_X max	σ Von Mises max
Keys + SS shell	-147	136
Cool-down	-180	165
Energization 16 T	-185	167