

DE LA RECHERCHE À L'INDUSTRIE

cea



FCC week 2018

Block-coil 16T Design for the FCC



The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 654305. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

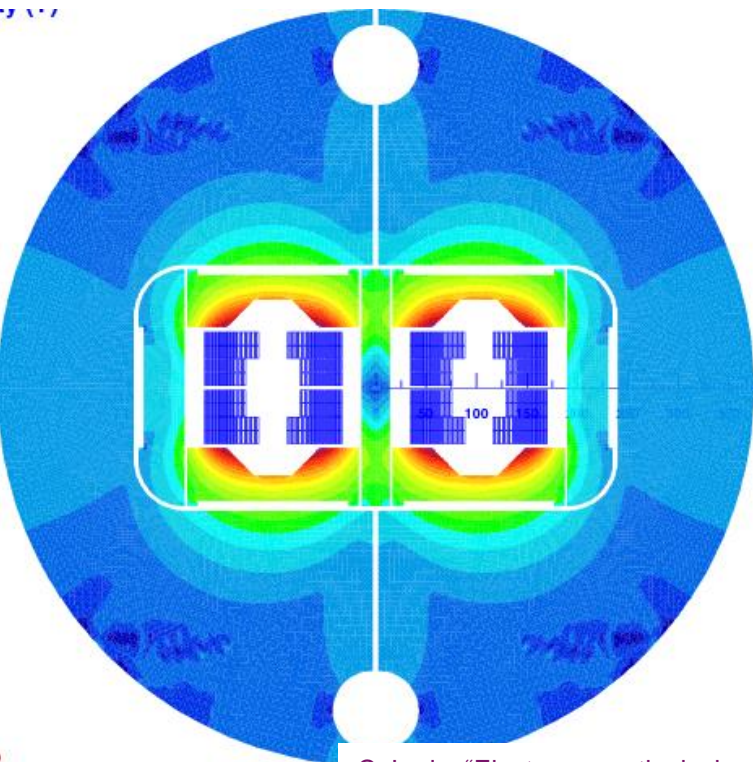


E. Rochepault, M. Segreti,
on behalf of C. Pes, M. Durante, C. Lorin
With contributions of the EuroCirCol collaboration

10/04/2018

- FCC week 2017:
204 mm interbeam
750 yoke diameter
63 mm Al shell

v1ari204

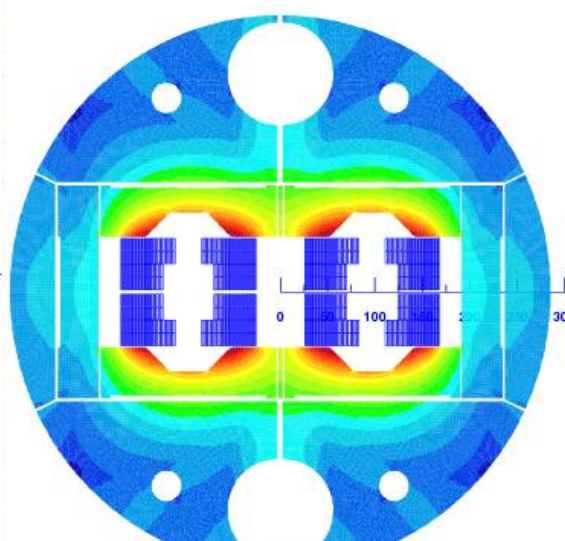


IRFU/DACM/LEAS

C. Lorin, "Electromagnetic design of the block coil option", [FCC week 2017](#)

- Review Oct. 2017:
194 mm interbeam
570 mm yoke diameter
100 mm Al shell

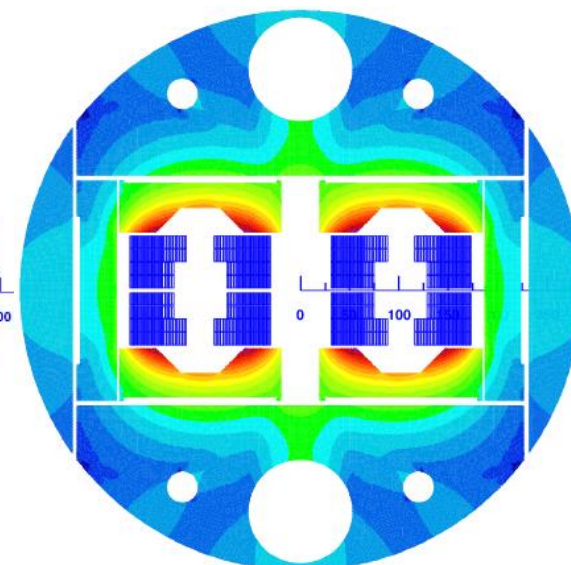
MT2017



C. Lorin, "Block-coil electromagnetic design", [ECC review 2017](#)

- Today:
204 mm interbeam
570 yoke diameter
67 mm Al shell +
20 mm SS shell

v5ari204

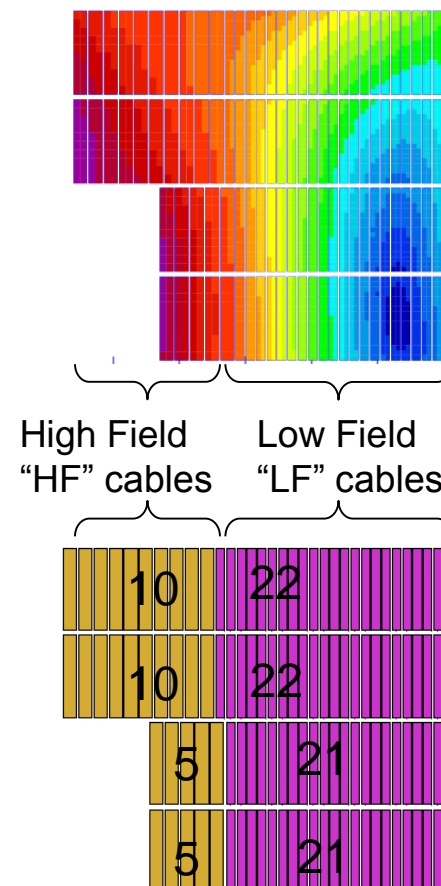


FCC week 2018 - 10/04/2018

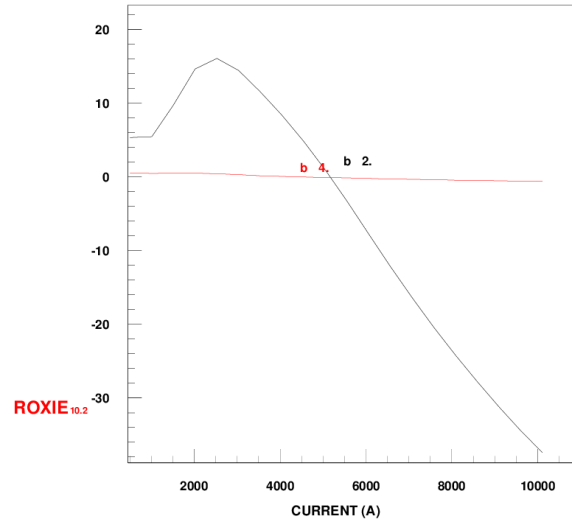
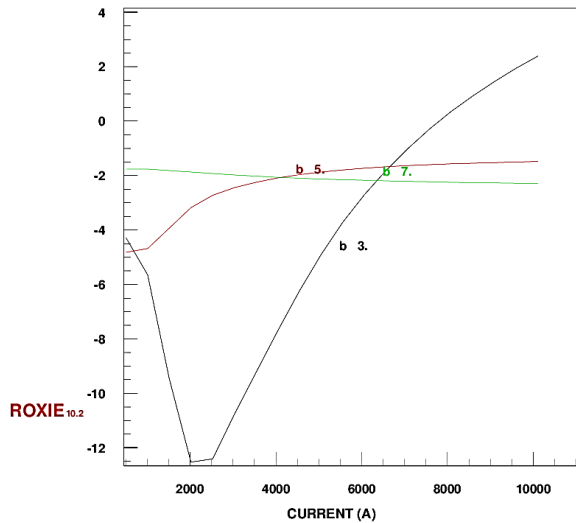
Page 2

Parameter	Value	Unit
Inom	10.123	kA
Nturns	5+10+21+22	-
Bore thickness	1.9 (1.4 + 0.5)	mm
Mid-plane shim	2.28	mm
Conductor area	138	cm ²
Estimated weight*	7.90	kt
Yoke diameter	570	mm
Bcenter	16.00	T
Bpeak	16.75	T
Load-line margin	13.75	%
Diff. inductance	49.1	mH/m

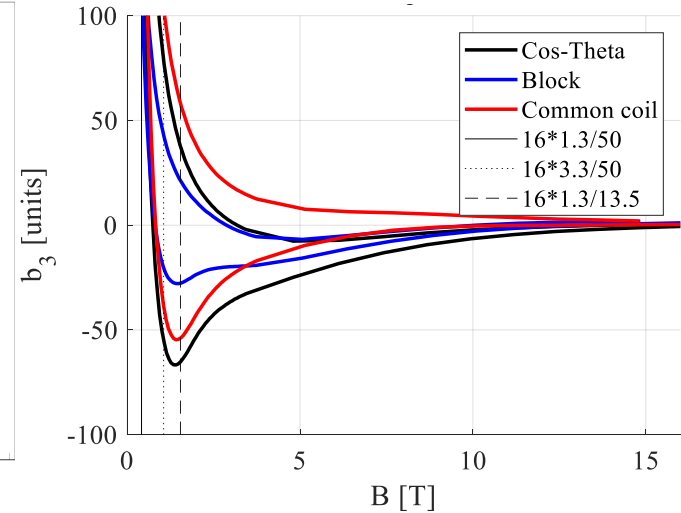
*Area x 4668 dipoles x 14.1m x 8.7 t/m³



- Without persistent currents (geometric + saturation):



- Persistent currents P.C.:



Operation	Case	b2	b3	b5	b7	b9 ¹
Injection (3.3 TeV)	without P. C.	5.2	-3.2	-4.9	-1.7	
	P. C. only	0	-25.5	-2.1	-5.7	-2.5
	with P. C.	5.2	-28.9	-7.0	-7.4	
	Max. target ²	-	60	-	-	-
Collision	negligible P. C.	-37.48	0.49	-1.96	-2.43	-1.59
	Max. target ²	50	4	3	3	3

S. Izquierdo Bermudez, "Field Quality Table Update for EuroCirCol 16 T designs", FCC-hh magnet-beam dynamics coordination meeting 03, 2017

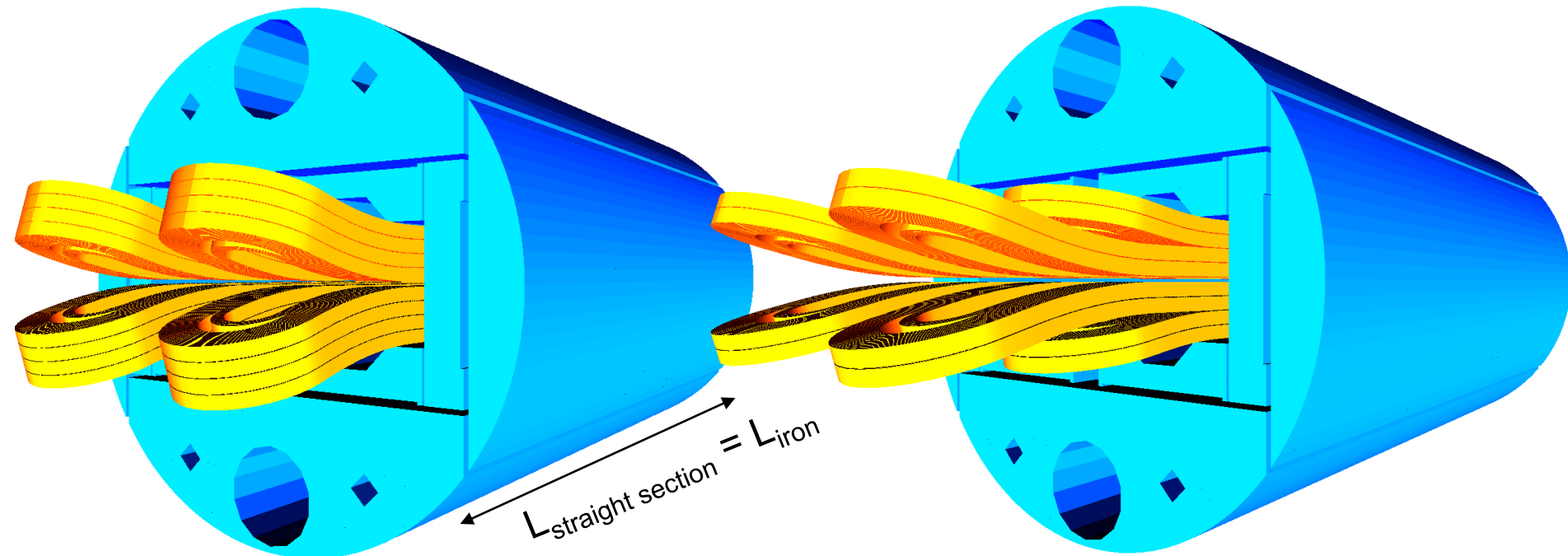
¹Other harmonics <1 unit
²Absolute value

Compact:

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

Long:

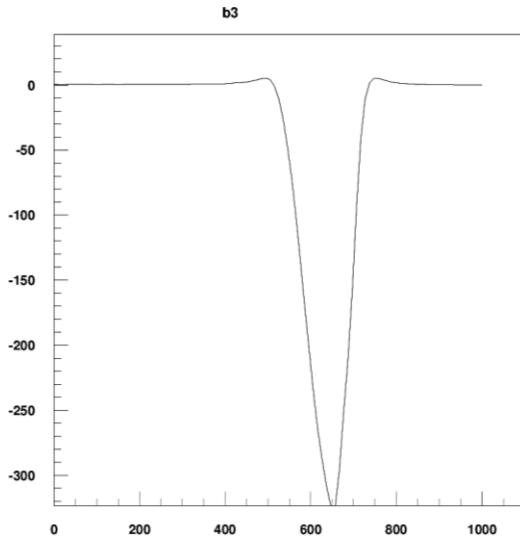
- Extension of coil ends
- Compensation of the b_3 in the ends



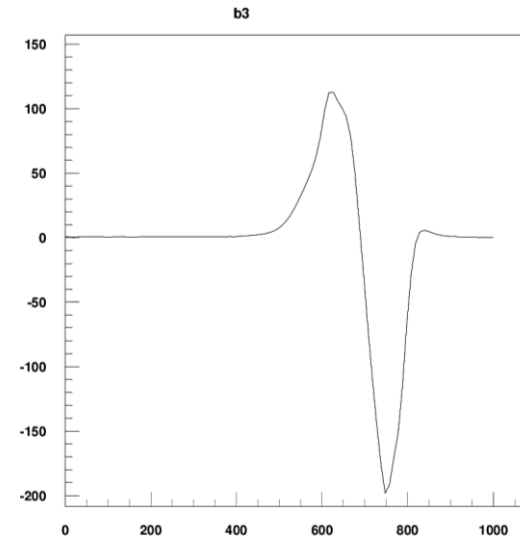
- **Minimum conductor length**
- **Are the harmonics still within spec?**
- **Is the peak field still in the straight section ?**

- **What impact on the lengths? (conductor, coil ends)**
- **What impact on the peak field?**

Compact:



Long:

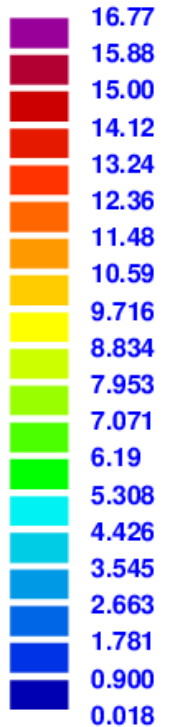


Design	b2	b3	b5	b7	b9
2D	-37.48	0.49	-1.96	-2.43	-1.59
3D, Compact ends	-39.03	-4.59	-2.37	-2.47	-1.58
3D, Long ends	-39.41	0.08	-2.41	-2.51	-1.58
3D compact + compensation	-38.95	-2.70	-1.90	-2.29	-1.57
2D compensation	-37.40	2.39	-1.48	-2.43	-1.59

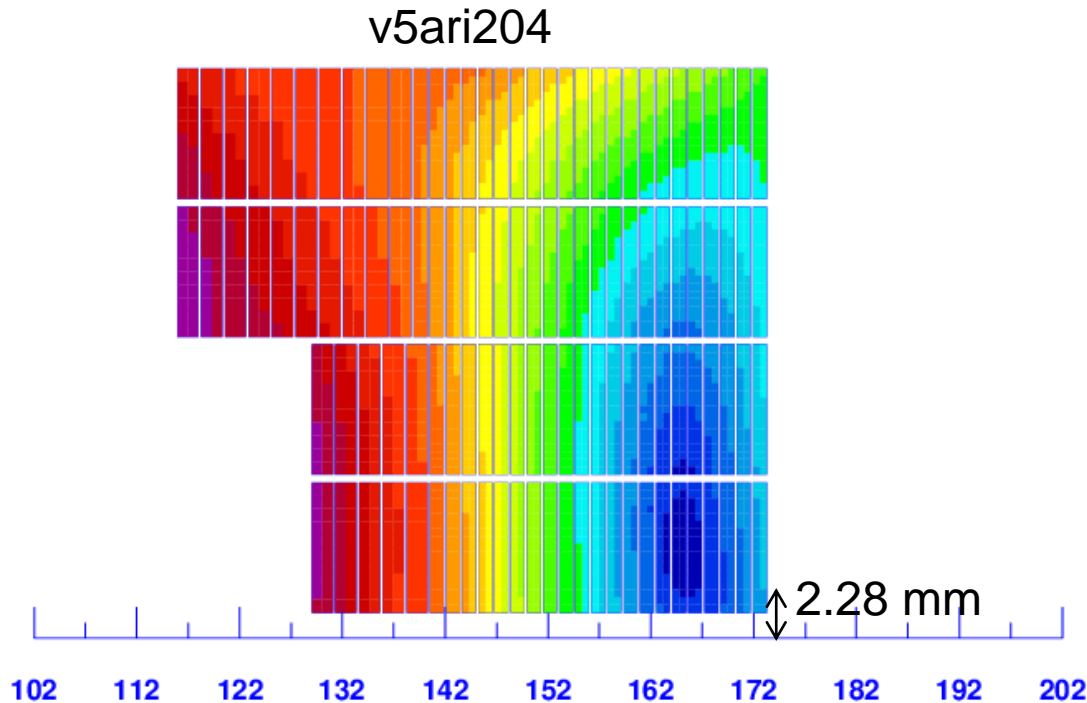
- At collision
- Magnetic length 14 m

Midplane shim 2.35 mm \rightarrow 2.28 mm

- b_3 in the straight section (2d): 0.49 units \rightarrow **2.39 units**
- b_3 integrated -4.59 units \rightarrow **-2.70 units**
- Slightly lower **other harmonics**
- Slightly higher **margin**

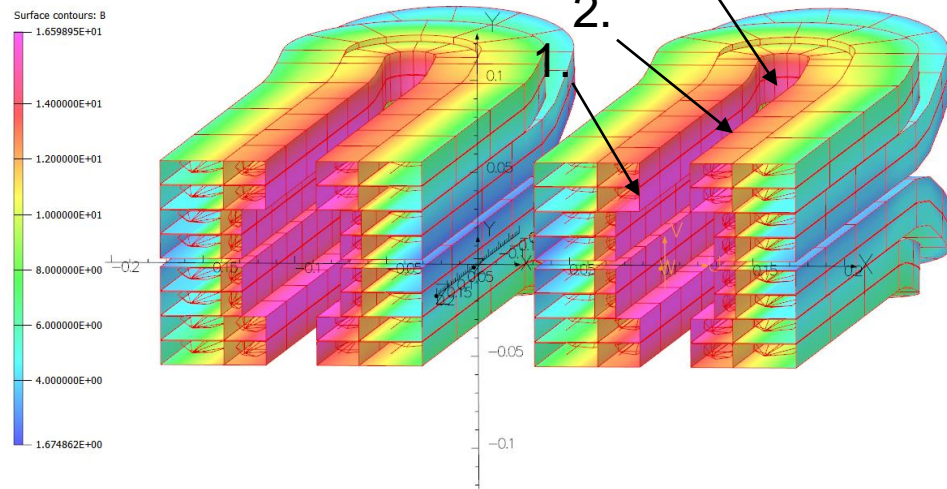
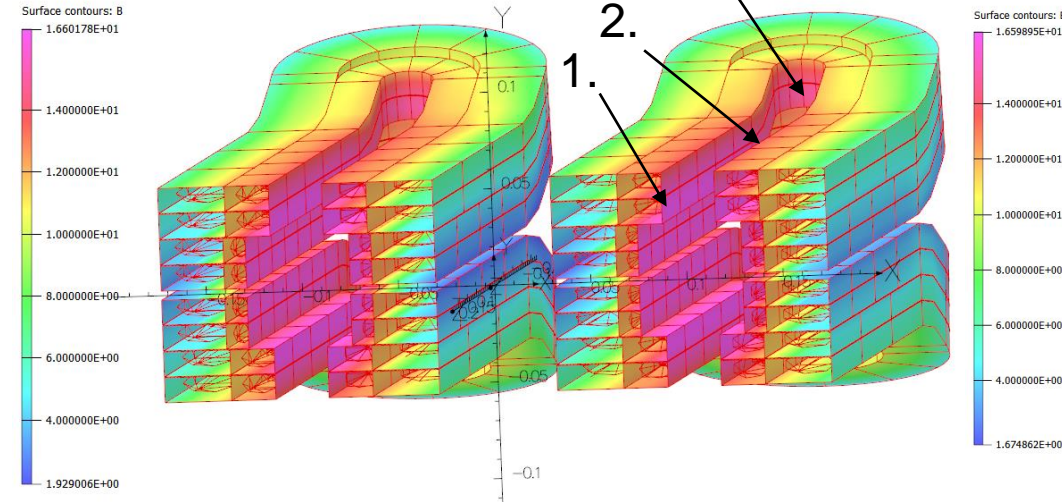


ROXIE_{10.2}



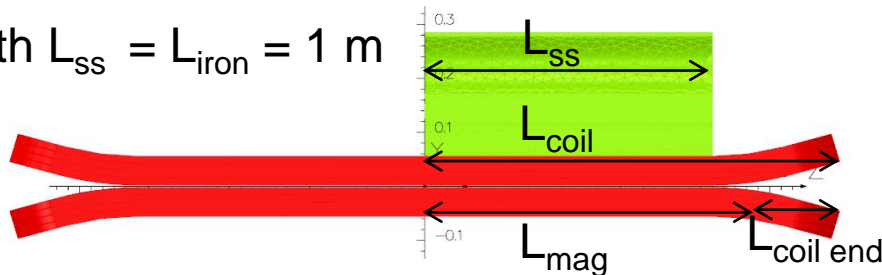
Compact:

Long:



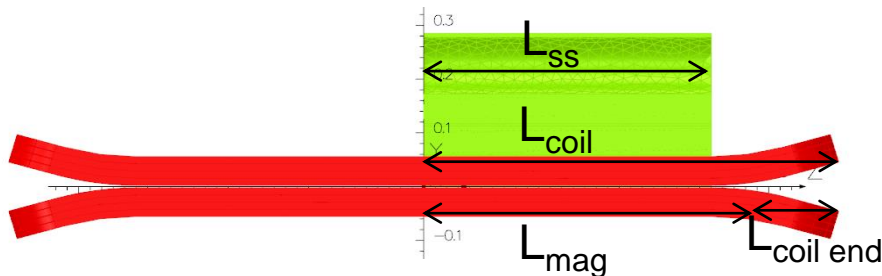
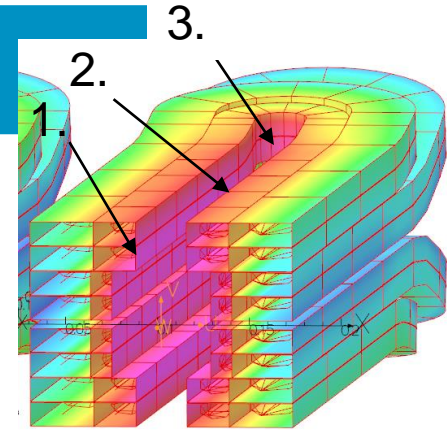
1. Peak field in the center ($z = 0$) = 16.6 T for both cases
2. at the beginning of the coil ends ~16 T
3. Peak field in the pole tip ~15 T

With $L_{ss} = L_{iron} = 1$ m



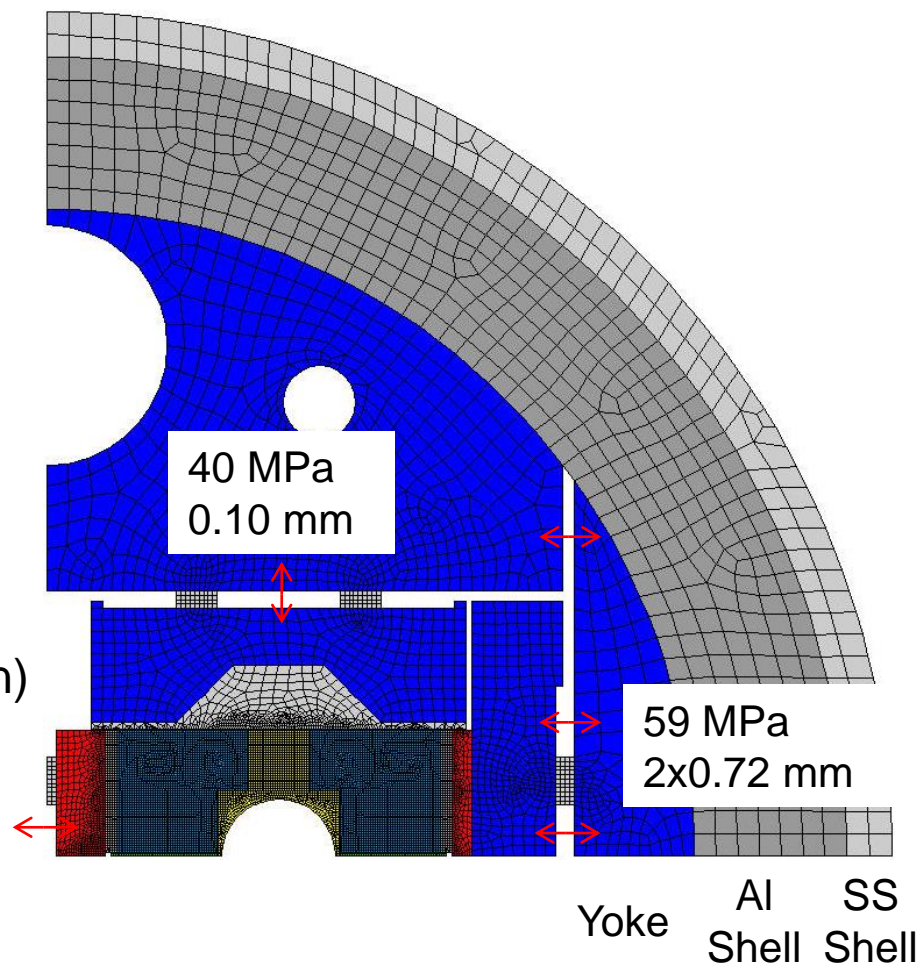
- $B_{\text{peak center}} - B_{\text{peak ends}} = \Delta B_{\text{peak}} > 0.6$ T
- **Additional operational margin in the ends**

Parameter	Compact	Compact compensated	Long	Unit
b3 integrated	-4.59	-2.70	0.08	units
$B_{\text{peak1}}, z=0$	16.6	16.6	16.6	T
$B_{\text{peak2}}, \text{bend}$	15.9	15.9	16.0	T
$B_{\text{peak3}}, \text{tip}$	15.0	15.0	15.2	T
$L_{\text{straight section}}$	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)
$L_{\text{coil end}} = L_{\text{coil}} - L_{\text{mag}}$	80	80	135	mm (per end)

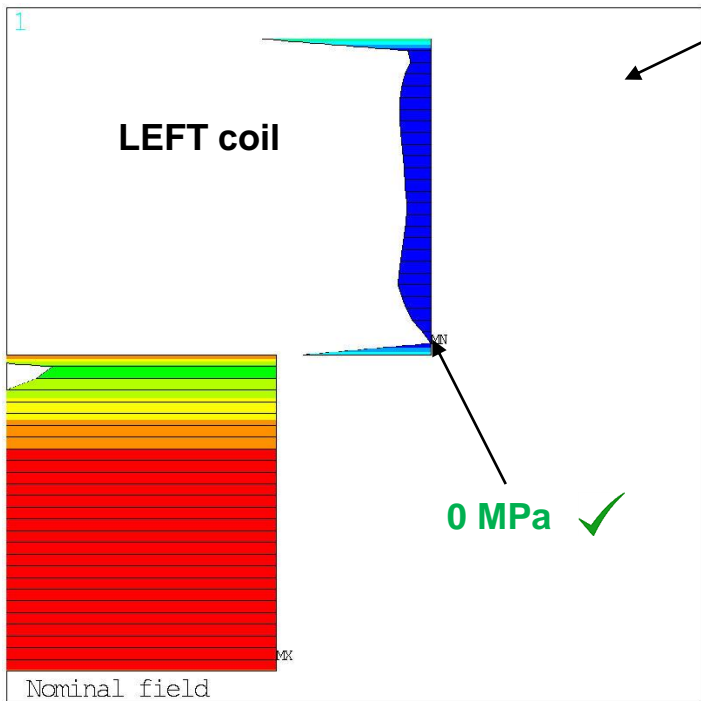
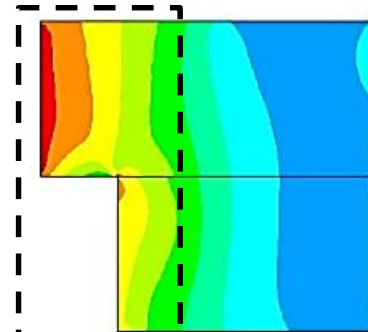
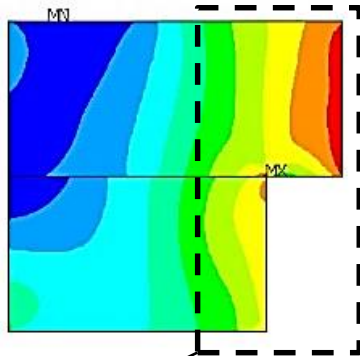


- Nominal:**
- Short ends
 - Low harmonics
 - Margin ($\Delta B_{\text{peak}} > 0.6 \text{ T}$)

- Geometry:
 - Interbeam distance = 204 mm
 - Outer yoke $\varnothing = 570$ mm
 - 67 mm Al shell + 20 mm SS shell
- ECC Coil properties (293K/4.2K):
 - $E_x = 25$ GPa / 27.5 GPa
 - $E_y = 30$ GPa / 33 GPa
- Pre-load:
 1. Bladders without SS shell
 2. 2 Horizontal + 2 Vertical keys
 3. Imposed displacement on SS shell bottom = -0.2 mm (260 MPa tension)
- Contacts:
 - Bonded: inside the coils, with the poles
 - Separation allowed with 0.2 friction: between the coils, with the structure

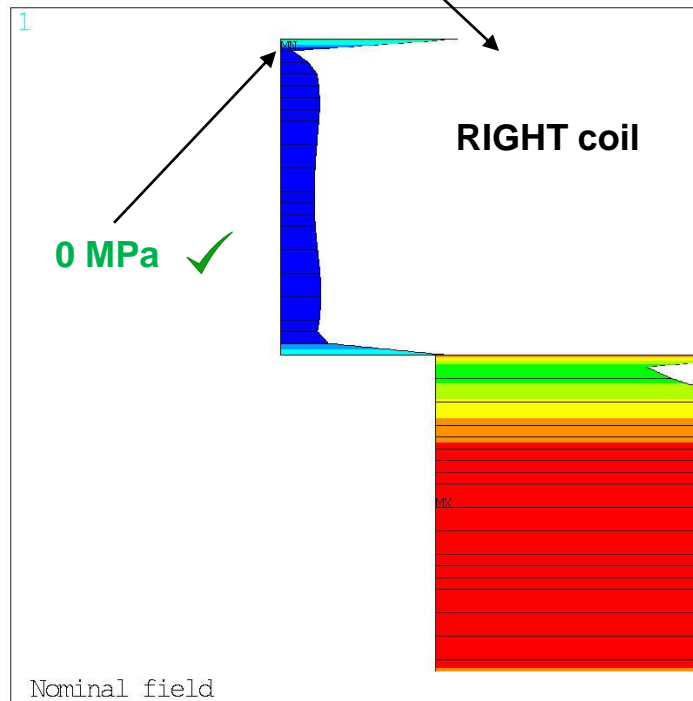


- Pre-load: **interference tuned**
- Operation at 16 T: **contact pressure >0**



ANSYS Release
Build 19.0
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =1
TIME=3
CONTIPRES (AVG)
DMX =.329E-03
SMN =8936.27
SMX =.481E+08

Blue	8936.27
Light Blue	.536E+07
Light Cyan	.107E+08
Cyan	.161E+08
Green	.214E+08
Light Green	.267E+08
Yellow-Green	.321E+08
Yellow	.374E+08
Orange	.428E+08
Red	.481E+08



ANSYS Release
Build 19.0
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =1
TIME=3
CONTIPRES (AVG)
DMX =.302E-03
SMN =.118E+07
SMX =.470E+08

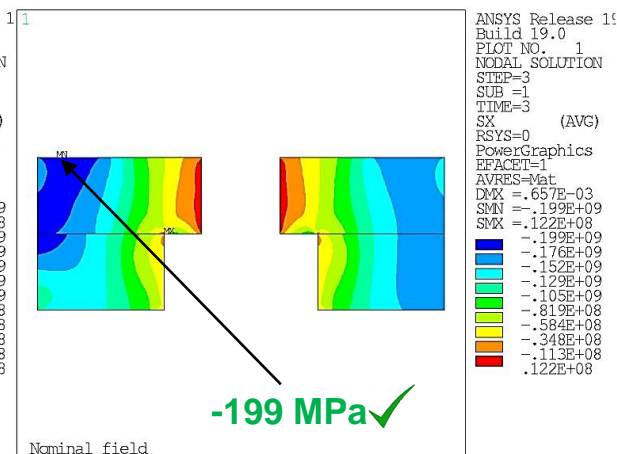
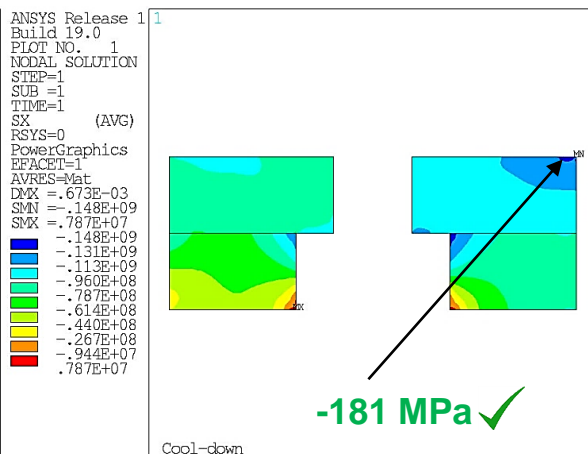
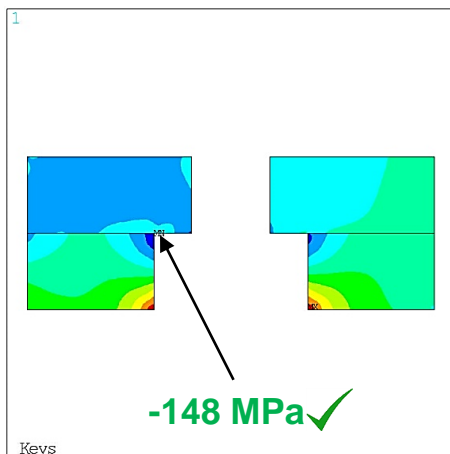
Blue	.118E+07
Light Blue	.627E+07
Light Cyan	.114E+08
Cyan	.164E+08
Green	.215E+08
Light Green	.266E+08
Yellow-Green	.317E+08
Yellow	.368E+08
Orange	.419E+08
Red	.470E+08

Room-temperature pre-load

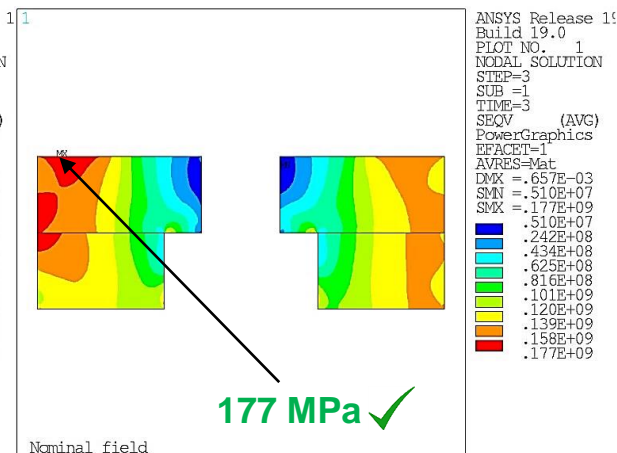
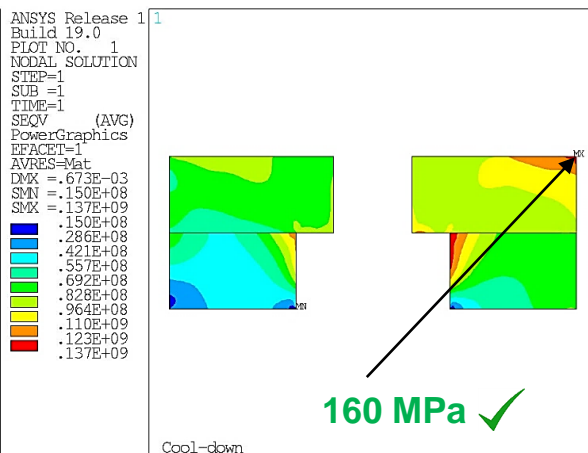
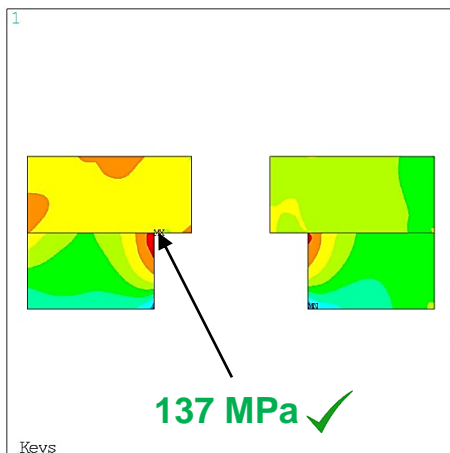
Cool-down to 1.9K

Operation at 16 T

σ_x



σ Von Mises



Criteria: <150 MPa

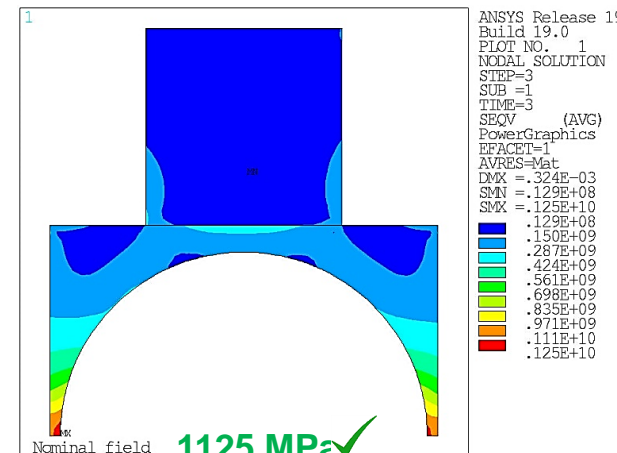
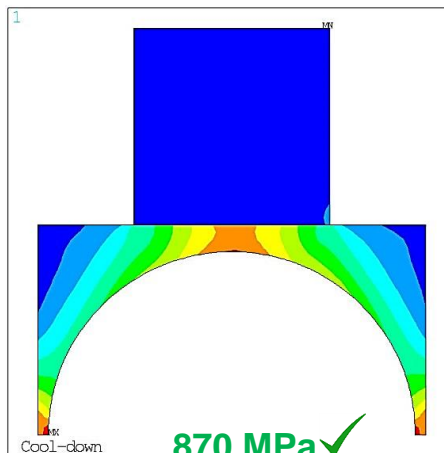
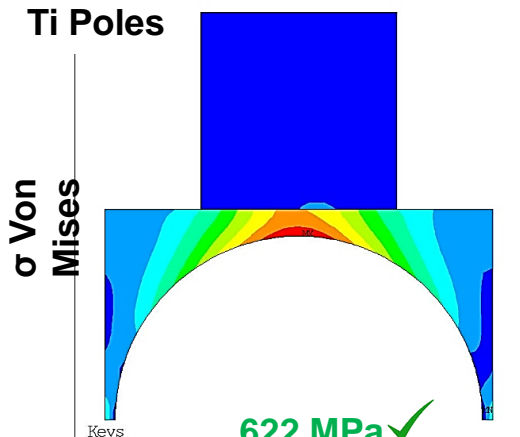
<200 MPa

<200 MPa

Room-temperature pre-load

Cool-down to 1.9K

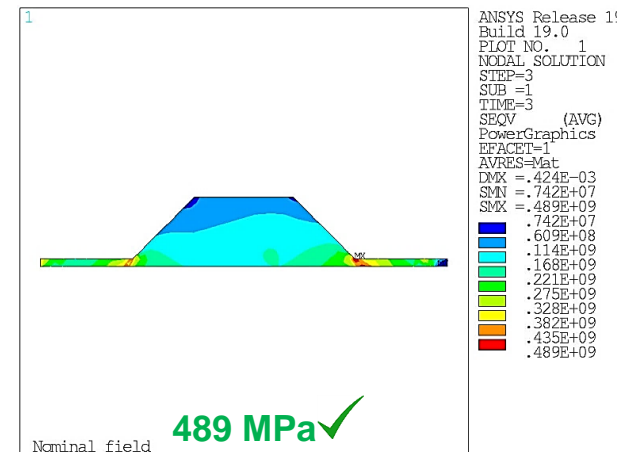
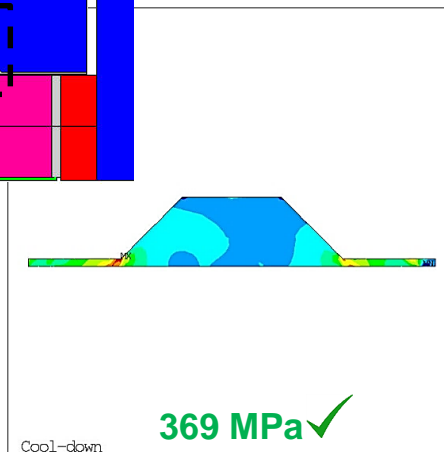
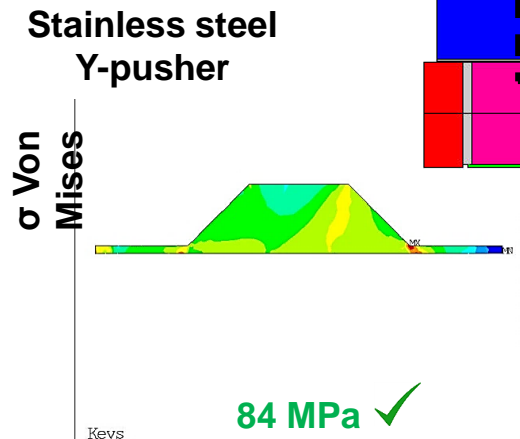
Operation at 16 T



Criteria: <800 MPa

<1650 MPa

<1650 MPa

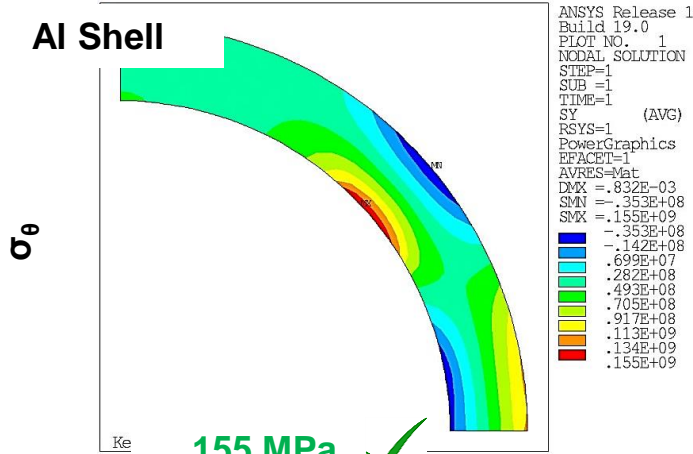


Criteria: <350 MPa

<1050 MPa

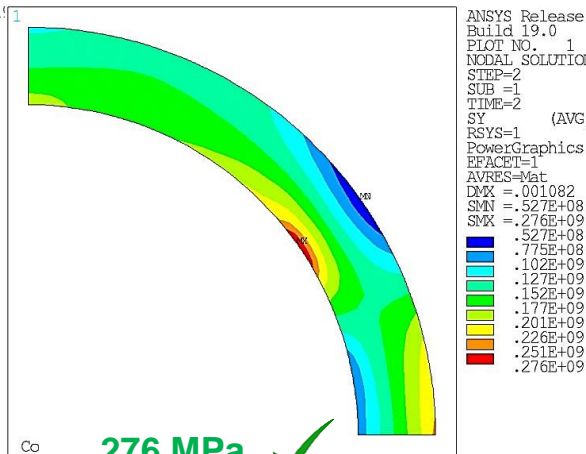
<1050 MPa

Room-temperature pre-load



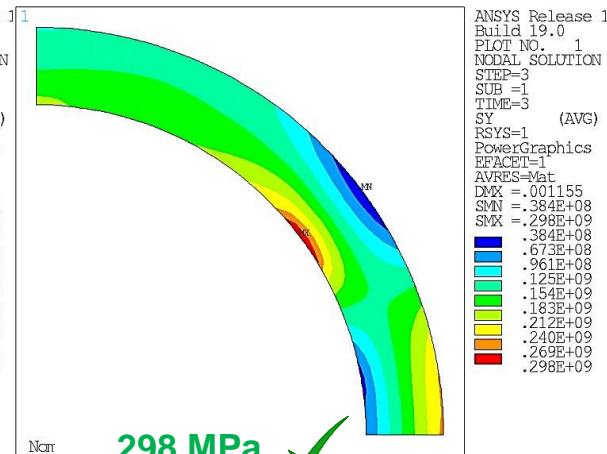
155 MPa ✓
<480 MPa

Cool-down to 1.9K



276 MPa ✓
<690 MPa

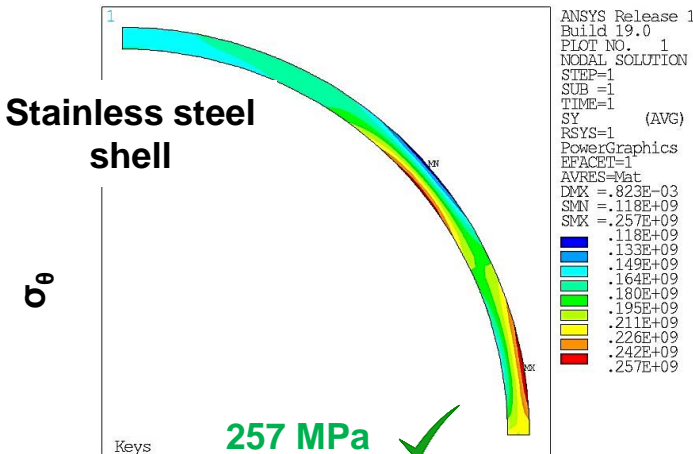
Operation at 16 T



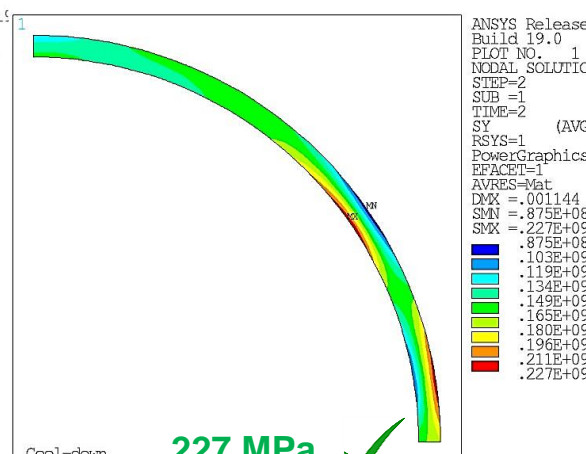
298 MPa ✓
<690 MPa

Criteria:

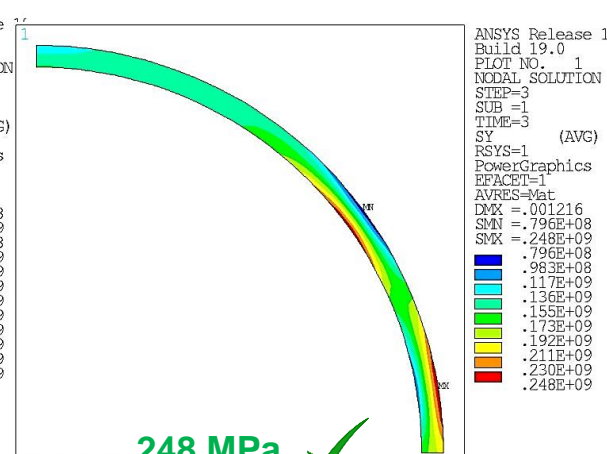
Stainless steel shell



257 MPa ✓
<350 MPa



227 MPa ✓
<1050 MPa

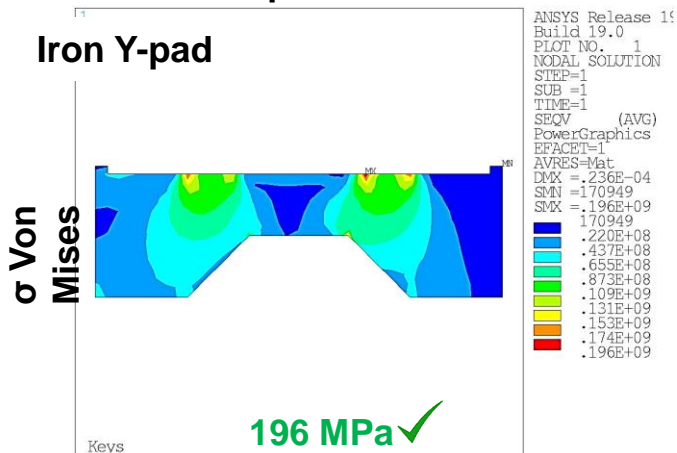


248 MPa ✓
<1050 MPa

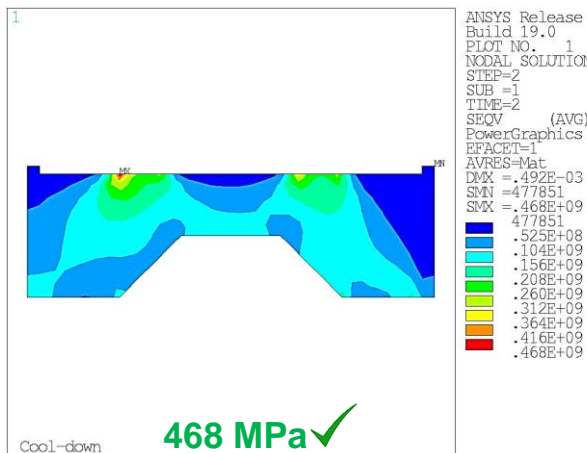
Criteria:

Room-temperature pre-load

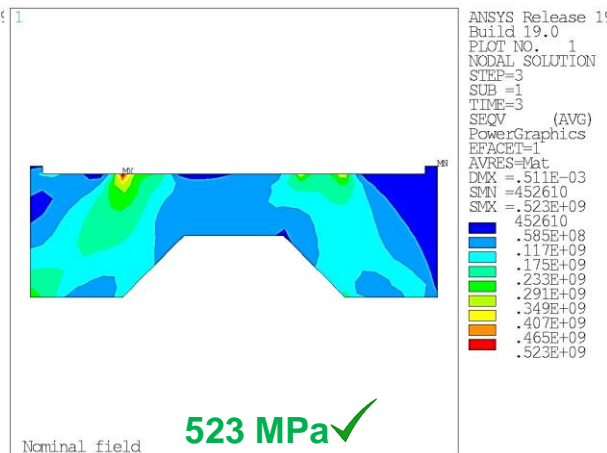
Iron Y-pad



Cool-down to 1.9K



Operation at 16 T

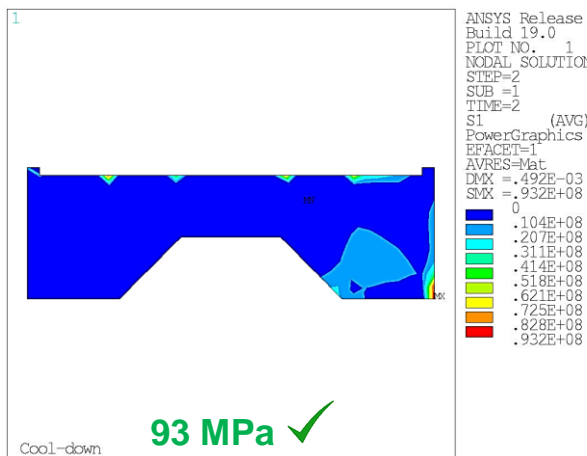
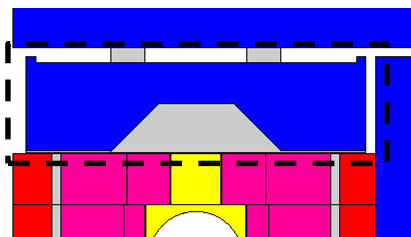


Criteria: <230 MPa

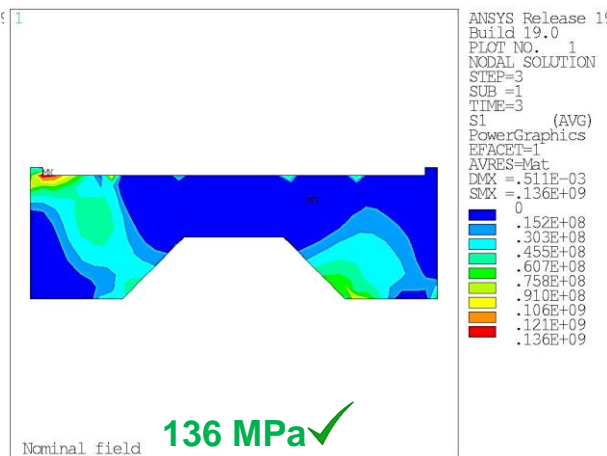
<720 MPa

<720 MPa

Sigma I: pure tension



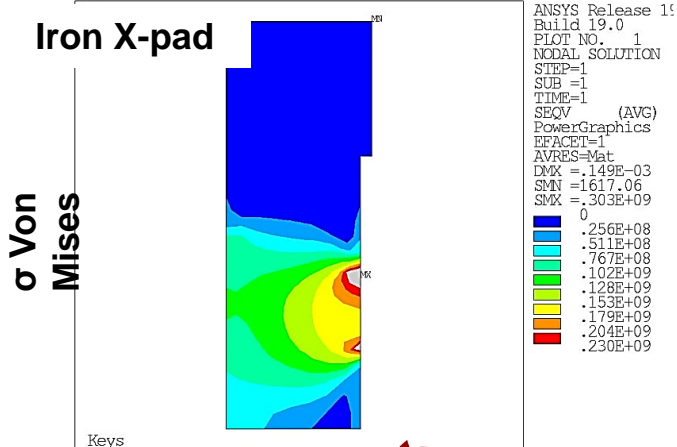
<380 MPa



<380 MPa

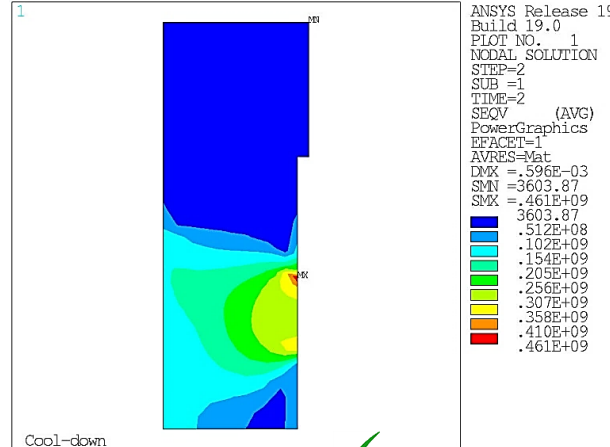
Room-temperature pre-load

Iron X-pad



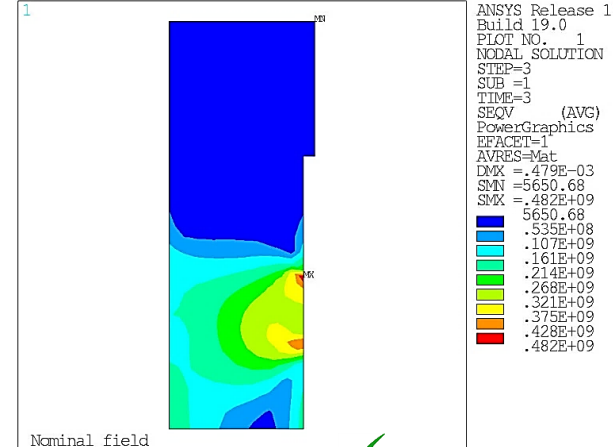
303 MPa ~~X~~ locally

Cool-down to 1.9K



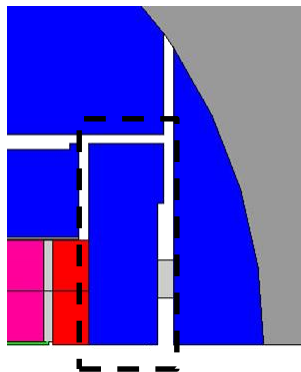
461 MPa ✓

Operation at 16 T



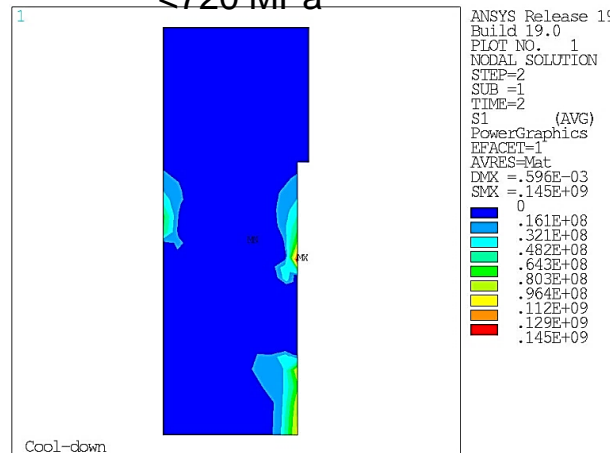
482 MPa ✓

Criteria: <230 MPa



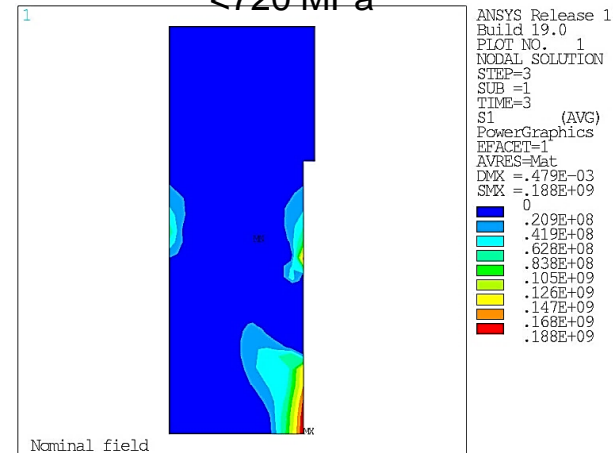
Sigma I: pure tension

<720 MPa



<380 MPa

<720 MPa

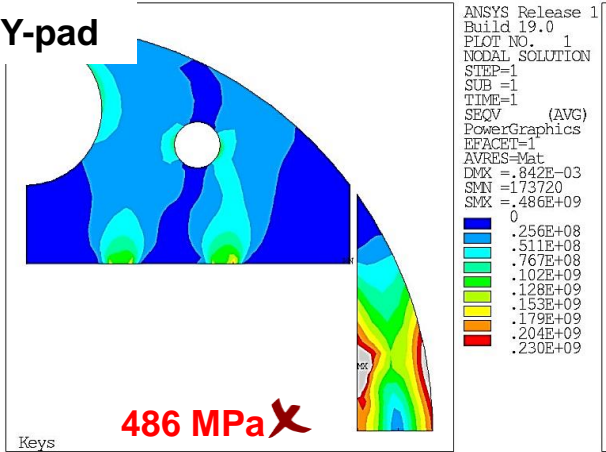


<380 MPa

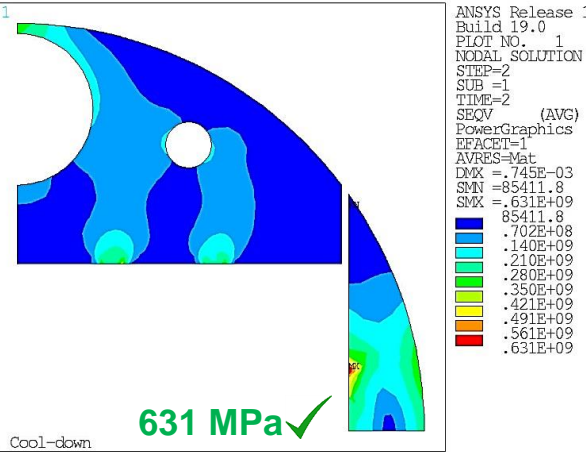
Room-temperature pre-load

Iron Y-pad

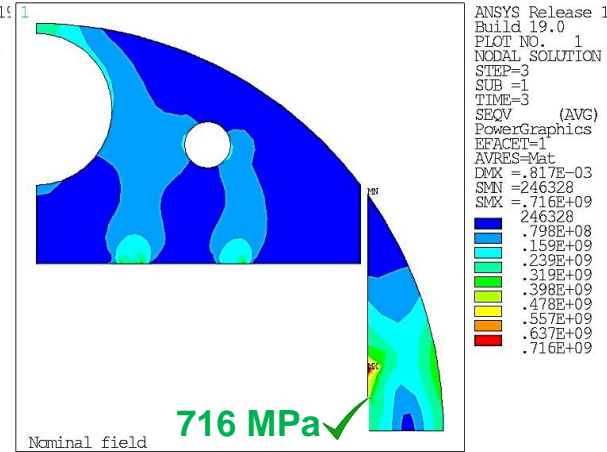
σ Von Mises



Cool-down to 1.9K

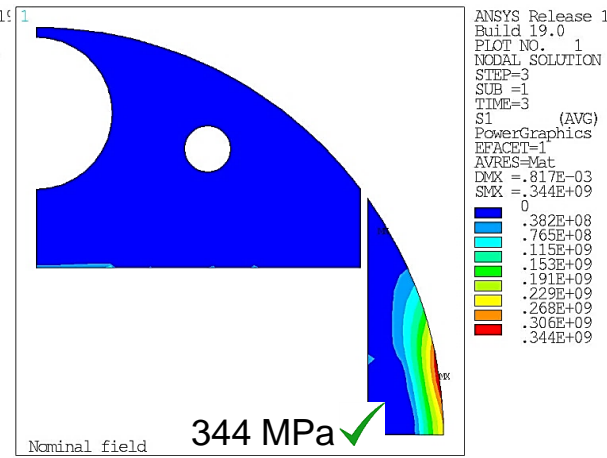
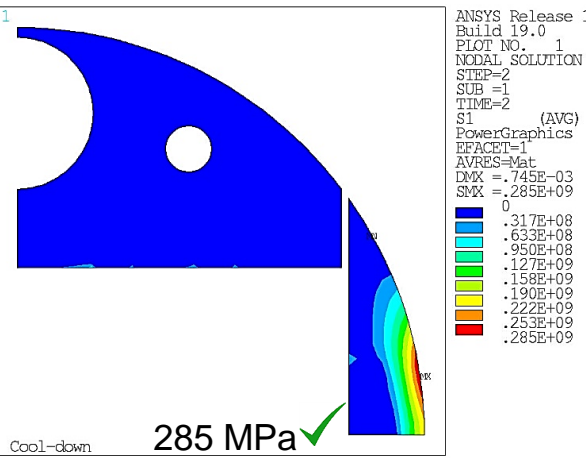
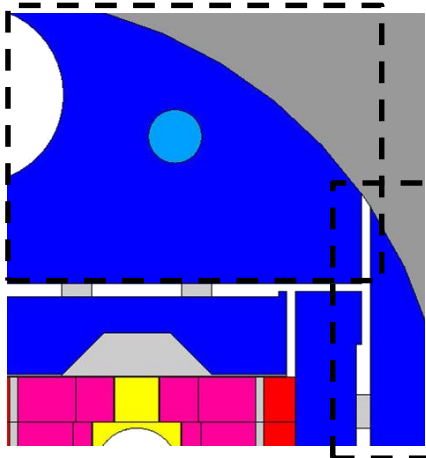


Operation at 16 T



Criteria: <230 MPa <720 MPa <720 MPa

Sigma I: pure tension



<380 MPa <380 MPa

- 2d magnetic design:
 - **16 T at 14 %** of LL margin at 1.9 K
 - At collision: **b3 and higher orders < 3 units** (absolute value)
b2 ~ -40 units
 - At injection: **b3 ~ -30 units**
→ **block-coil more favorable** than other designs
b5 and higher orders < 10 units
- 3d magnetic design:
 - **Compact ends**
 - **Similar values for integrated harmonics**
 - **Additional margin in coil ends** ($\Delta B_{\text{peak}} > 0.6 \text{ T}$)
- 2d mechanical design:
 - **Coil stress < criteria**
 - **Iron X-Pad + Yoke: locally > criterion at warm**
 - **Other components: stress < criteria**

Short-term future (2018-2019)

- Coil end design to be validated by a 3D mechanical study
 - Compact ends favorable for:
 - Limited number of parts
 - Easier pre-load because of aligned blocks
 - EM Forces more balanced between the blocks
- Protection:
 - To be updated by protection team
 - should stay below the limits (minor modifications wrt previous designs)

Mid-term future (~2022)

- F2D2: a block-coil short model dipole toward FCC
- See presentation « The CEA 16T model for the FCC », E. Rochepault

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BACKUP SLIDES

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

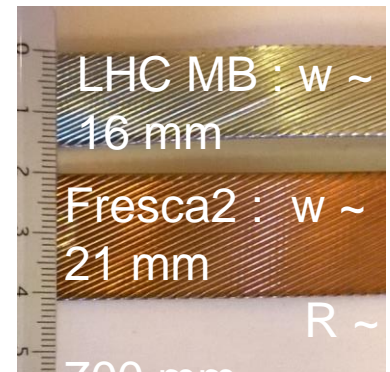
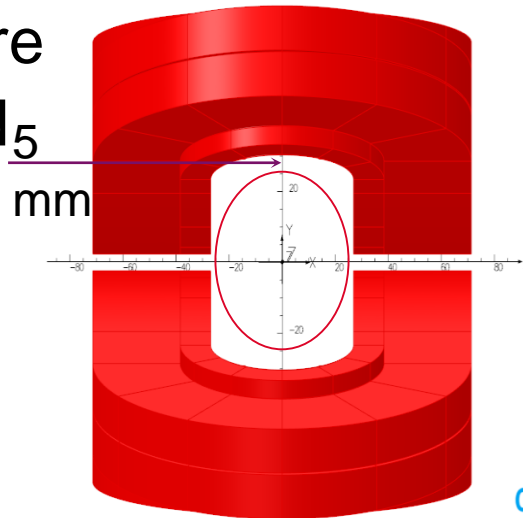
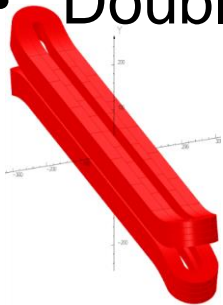
C. Lorin,
Oct 17 review

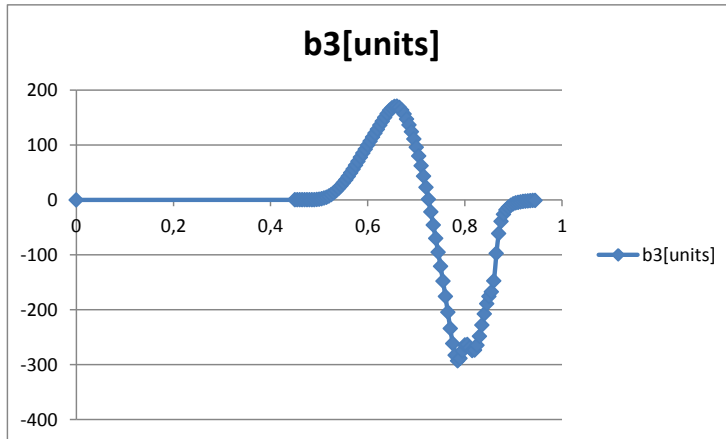
J. Fleiter: Rutherford cable design approach and experience at CERN ([here](#))

Parameter	Unit	11 T RRP for LS2	11 T PIT for LS2	MQXF (PIT and RRP)	FRESCA2	ERMC	SMC
Number of strands	(-)	40	40	40	40	40	18
Strands diameter	mm	0.70	0.70	0.85	1.0	1.0	1.0
Cable bare width	mm	14.70	14.70	18.15	20.9	20.9	10
Cable bare thickness	mm	1.250	1.250	1.525	1.82	1.82	1.81
Keystone angle	°	0.79	0.50	0.40	0.0	0.0	0.0
Thin edge compaction*	%	17.95	15.3	14.02	9.0	9.0	9.5
Thick edge compaction*	%	3.48	6.13	6.57			
Transposition pitch	mm	100	100	109	120	120	63
SS Core width (thickness)	mm		12 (0.0025)		NO	14 (0.0025)	NO

3D magnetic design

- Assumptions:
 - Return ends – 1000 mm straight section
 - Hardway bend : $R_{min} = 450$ 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-dire
 - Double pancake end₅





$$Ib_n = \frac{\int B_n(z) dz}{\int B_1(z) dz} = \frac{\int B_n(z) dz}{L_{mag} \cdot B_{ref}} = \frac{\int b_n(z) dz}{L_{mag}}$$

$$Ib_{n,short} = \frac{\int_{short} b_n(z) dz}{L_{mag,short}}$$

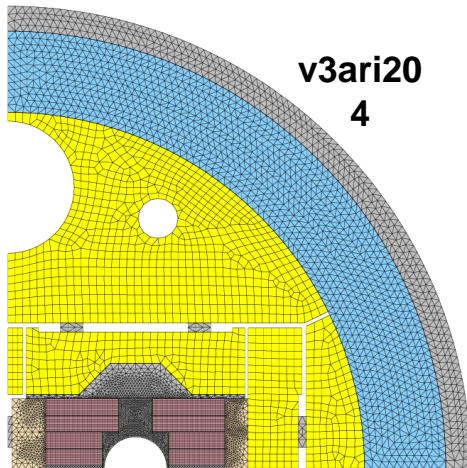
$$Ib_n = \frac{\int_{short} b_n(z) dz + b_n(0) \cdot (L_{mag} - L_{mag,short})}{L_{mag}}$$

$$Ib_n = \frac{Ib_{n,short} \cdot L_{mag,short} + b_n(0) \cdot (L_{mag} - L_{mag,short})}{L_{mag}}$$

Ex: -10 units on a short length

$$Ib_3 = [-10 \text{ units} \times 0.68 \times 2 - 0.8 \text{ units} \times (14.069 - 0.68 \times 2)] / 14.069$$

$$= \mathbf{-1.69 \text{ units}}$$



v3ari20
4

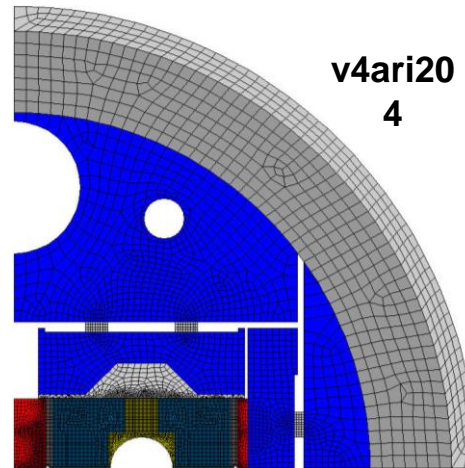
Interbeam distance = 204 mm

\varnothing_{ext} iron yoke = 570 mm

Total \varnothing_{ext} = 740 mm

65 + 20 mm thick shells

→ 2 x 0.67 mm ←



v4ari20
4

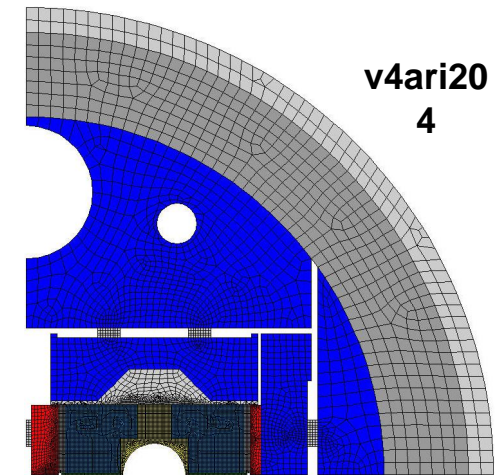
Interbeam distance = 204 mm

\varnothing_{ext} iron yoke = 570 mm

Total \varnothing_{ext} = 740 mm

65 + 20 mm thick shells

1.51mm ←



v4ari20
4

Interbeam distance = 204 mm

\varnothing_{ext} iron yoke = 570 mm

Total \varnothing_{ext} = 744 mm

67 + 20 mm thick shells

→ 2 x 0.72 mm ←

	σ_x max	σ Von Mises max
Keys + SS shell	-170	149
Cool-down	-205	188
Energization 16 T	-188	178

	σ_x max	σ Von Mises max
Keys + SS shell	-135	123
Cool-down	-184	170
Energization 16 T	-214	186

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

Material properties

(Davide 3rd FCC week)

Coil maximum stress

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

Material	R _{p0.2} [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

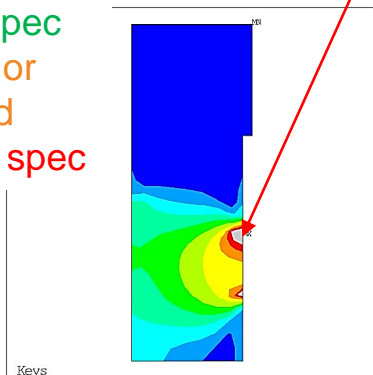
Material	E [GPa]		pr	(L _{4.3K} -L _{293K})/L _{293K}
	293 K	4.3 K		293 K -> 4.3K
Coil	EX = 25 EY = 30 GXY = 21	EX = 27.5 EY = 33 GXY = 21	0.3	X = 3.36e-3 Y = 3.08e-3
StSt	193	210	0.28	2.84e-3
Iron	213	224	0.28	1.97e-3
Aluminum	70	79	0.34	4.2e-3
Titanium	115	126.5	0.3	1.74e-3
Nitronic 40	210	225	0.28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

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

Von Mises [MPa]

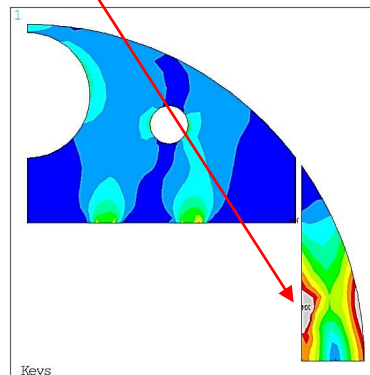
Component	Material	Pre-load	1.9 K	16 T	Crit. 293K	Crit 1.9 K
Poles	Ti6Al4V	622	870	1125	800	1650
Y-Pusher	Stainless steel	84	369	489	350	1050
Y-Pad	Iron	196	468	423	230	720
X-Pad	Iron	303	461	482	230	720
Yokes	Iron	486	631	716	230	720
Al shell	Al	155	275	289	480	690
SS shell	Stainless steel	260	230	250	350	1050

Within spec
At spec or localized
Outside spec



IRFU/DACM/LEAS

```
ANSYS Release 11
Build 19.0
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEGV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.149E-03
SMN =.1617E+06
SMX =.303E+09
0
.256E+08
.511E+08
.767E+08
.102E+09
.128E+09
.153E+09
.179E+09
.204E+09
.230E+09
```



FCC week 2018 - 10/04/2018

```
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.153E+09
.179E+09
.204E+09
.230E+09
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