DE LA RECHERCHE À L'INDUSTRIE

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.

EuroCirCol
A key to New Physics

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

10/04/2018

EVOLUTION OF THE DESIGN

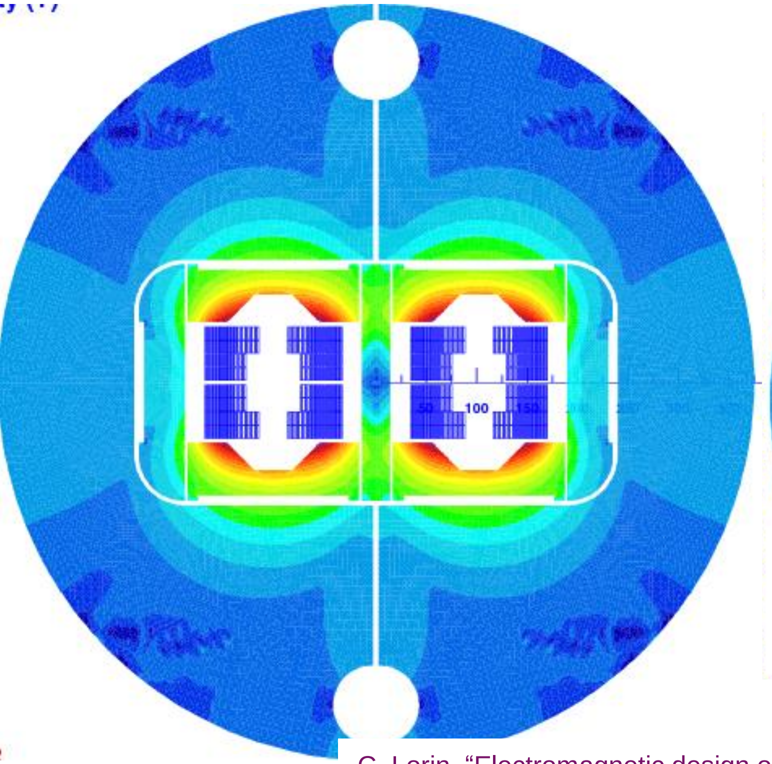
- FCC week 2017:

204 mm interbeam

750 yoke diameter

63 mm Al shell

v1ari204



C. Lorin, “Electromagnetic design of the block coil option”, FCC week 2017

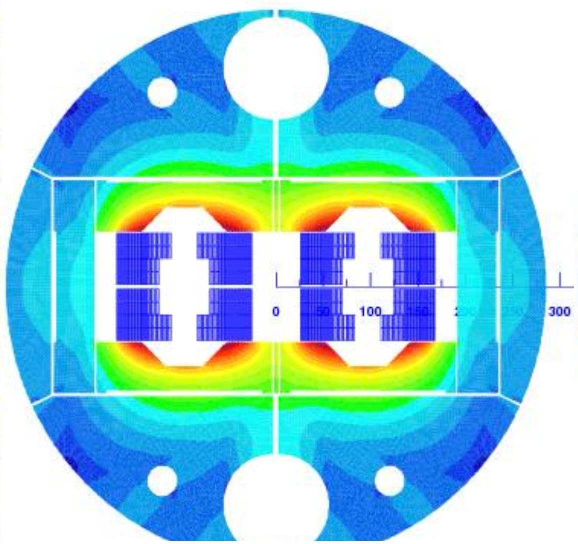
- Review Oct. 2017:

194 mm interbeam

570 mm yoke diameter

100 mm Al shell

MT2017



C. Lorin, “Block-coil electromagnetic design”, ECC review 2017

- Today:

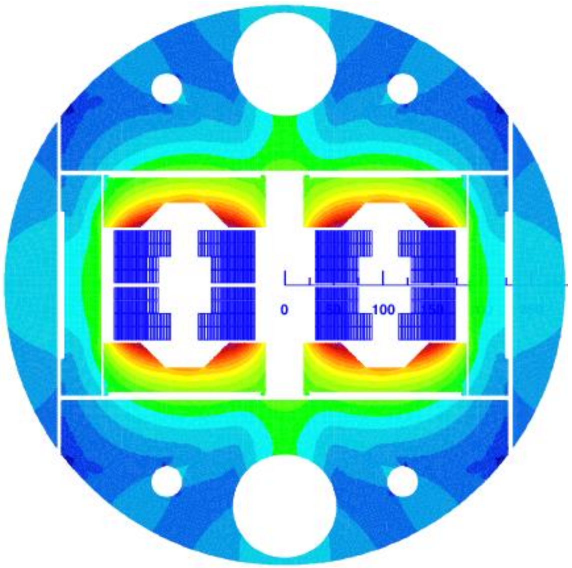
204 mm interbeam

570 yoke diameter

67 mm Al shell +

20 mm SS shell

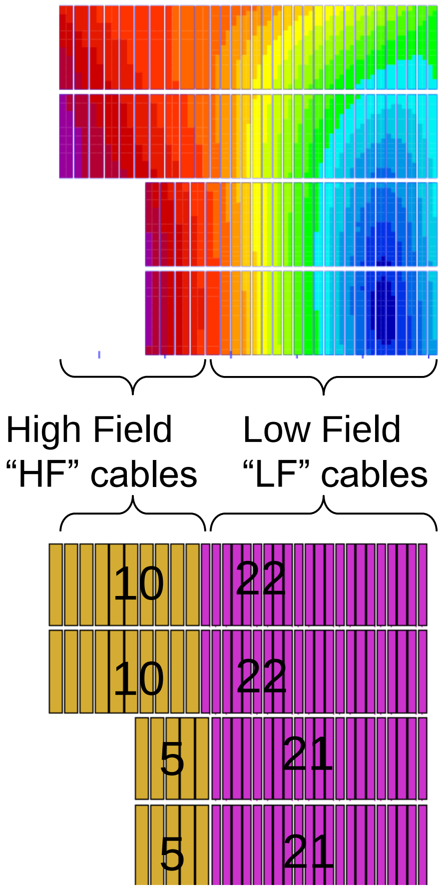
v5ari204



2D MAGNETIC DESIGN – MAIN PARAMETERS

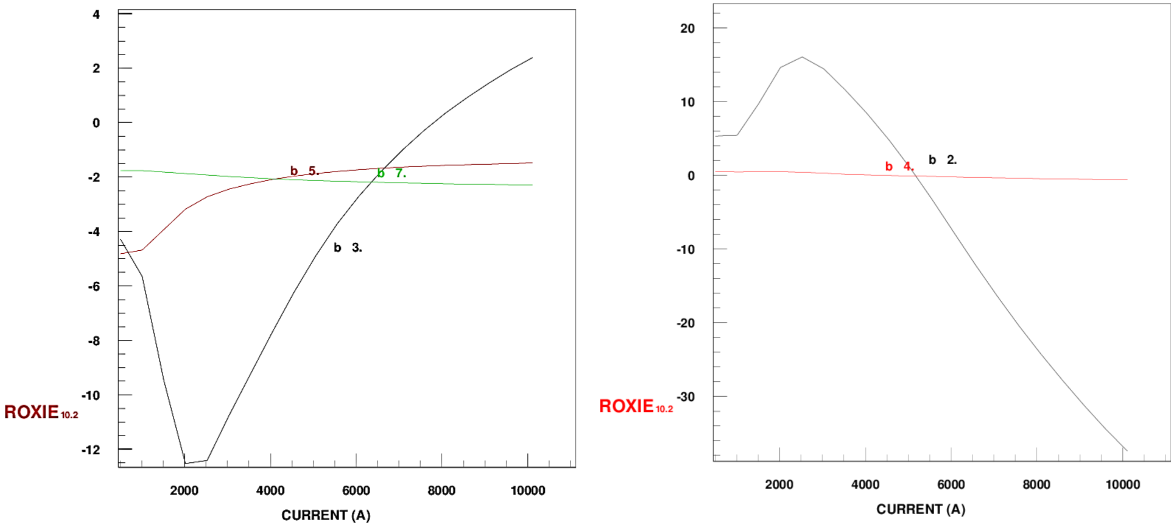
Parameter	Value	Unit
Inom	10.123	kA
Nturns	5+10+21+22	-
Bore thickness	1.9 (1.4 + 0.5)	mm
Mid-plane shim	2.28	mm
Conductor area	138	cm^2
Estimated weight*	7.90	kt
Yoke diameter	570	mm
Bcenter	16.00	T
Bpeak	16.75	T
Load-line margin	13.75	%
Diff. inductance	49.1	mH/m

*Area x 4668 dipoles x 14.1m x 8.7 t/m^3

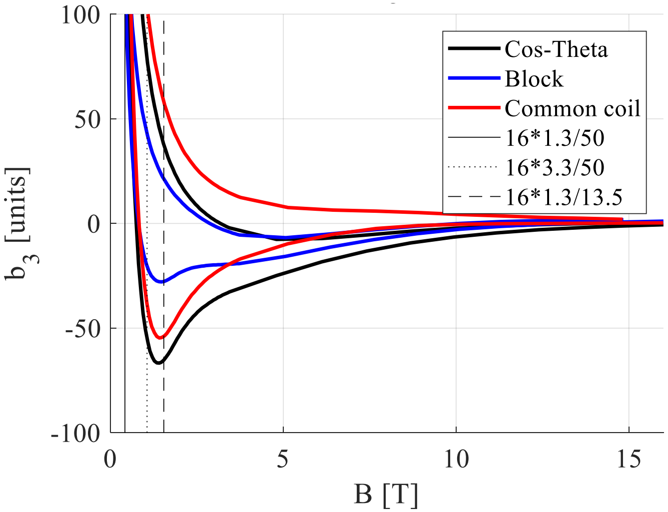


2D MAGNETIC DESIGN – HARMONICS

- 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

[1] Other harmonics <1 unit

[2] Absolute value

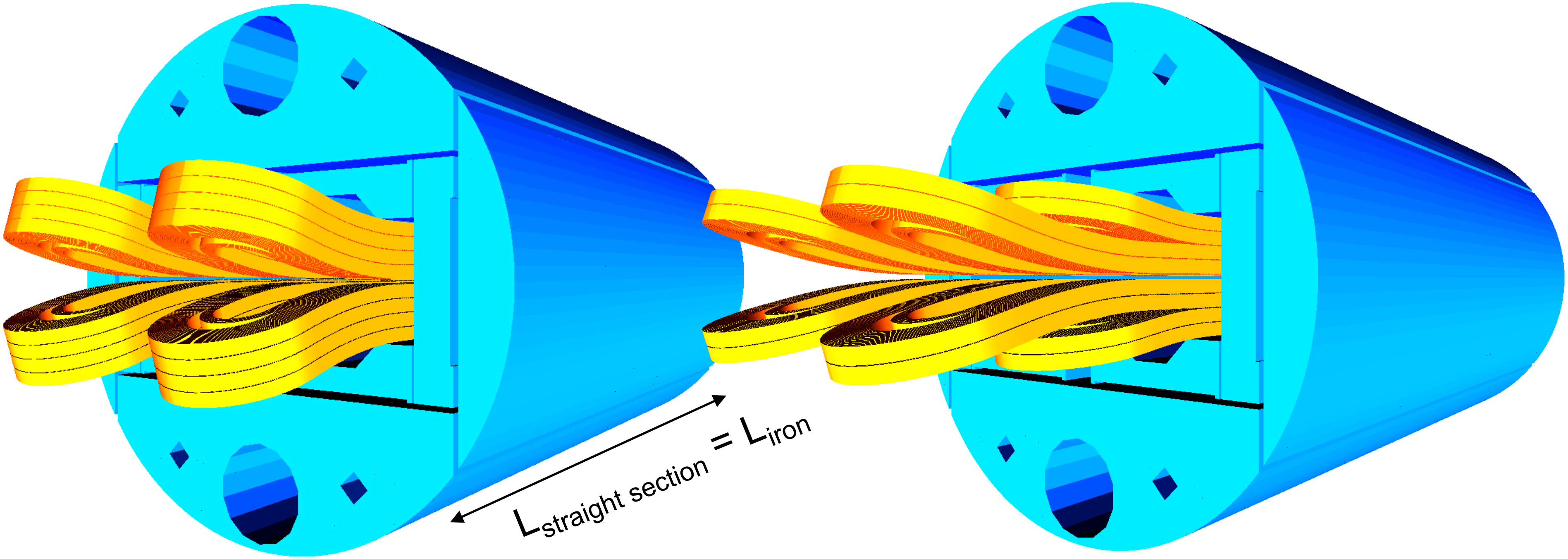
3D MAGNETIC DESIGN – 2 OPTIONS

Compact:

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

Long:

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



→ **Minimum conductor length**

→ **Are the harmonics still within spec?**

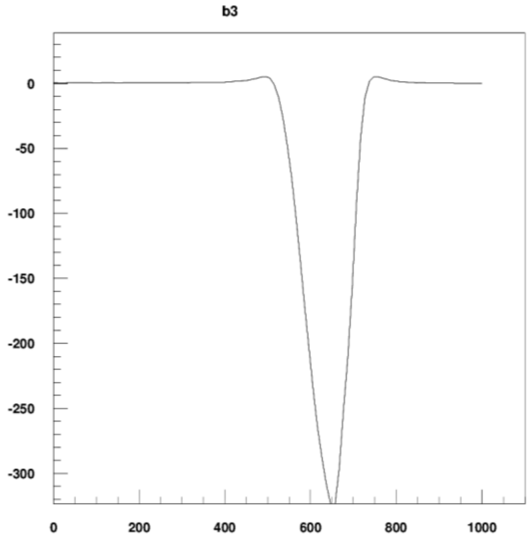
→ **Is the peak field still in the straight section ?**

→ **What impact on the lengths? (conductor, coil ends)**

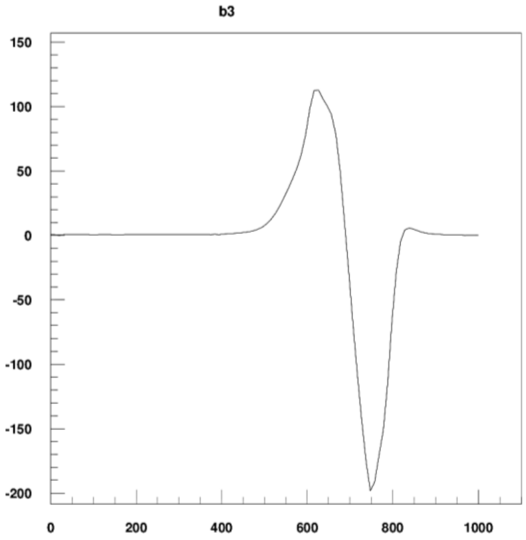
→ **What impact on the peak field?**

3D MAGNETIC DESIGN – HARMONICS

Compact:



Long:



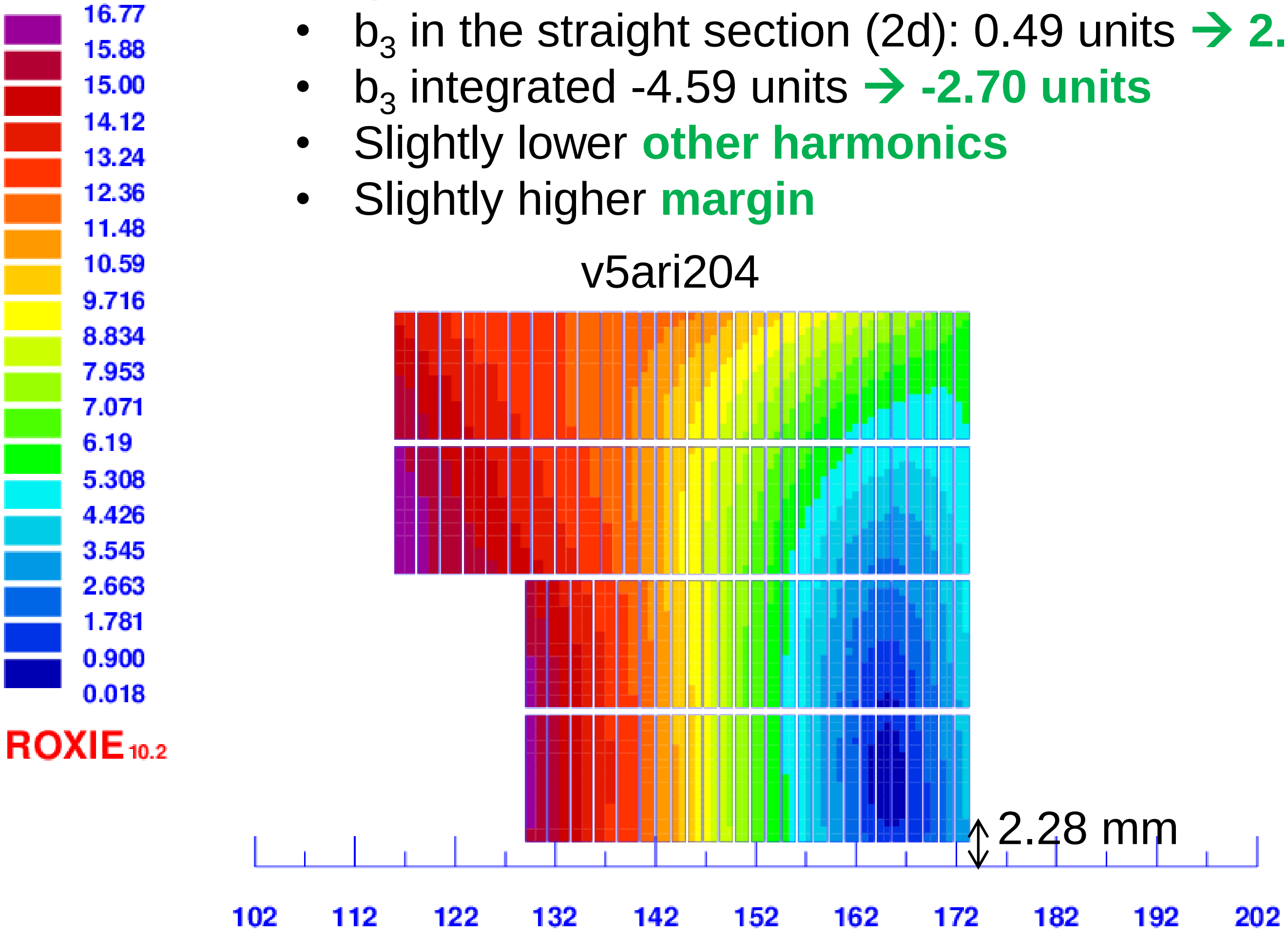
Design	b2	b3	b5	b7	b9
2D	-37.48	0.49	-1.96	-2.43	-1.59
3D, Compact ends	-39.03	**-4.59**	-2.37	-2.47	-1.58
3D, Long ends	-39.41	**0.08**	-2.41	-2.51	-1.58
3D compact + compensation	-38.95	**-2.70**	-1.90	-2.29	-1.57
2D compensation	-37.40	**2.39**	-1.48	-2.43	-1.59

- At collision
- Magnetic length 14 m

COMPENSATION OF b_3 IN 2D

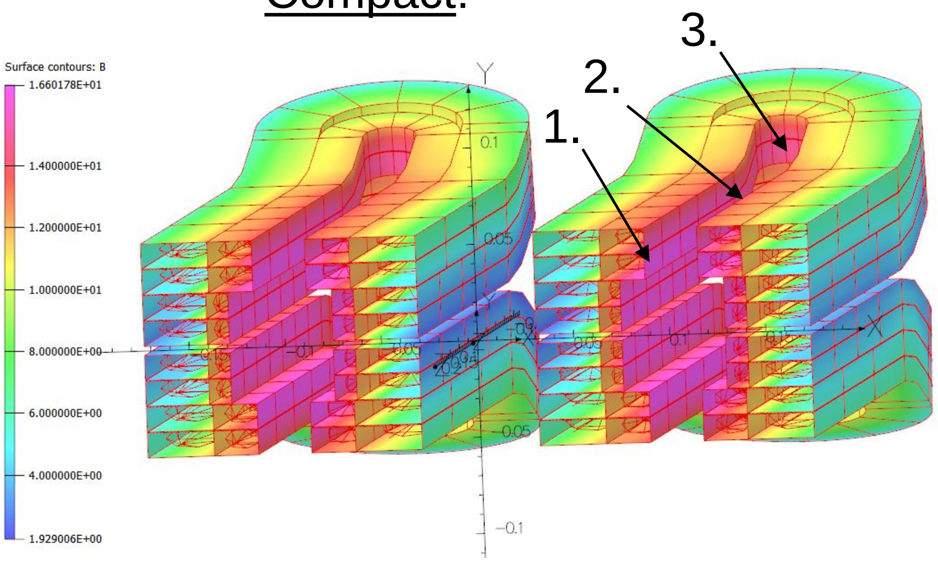
Midplane shim 2.35 mm → 2.28 mm

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

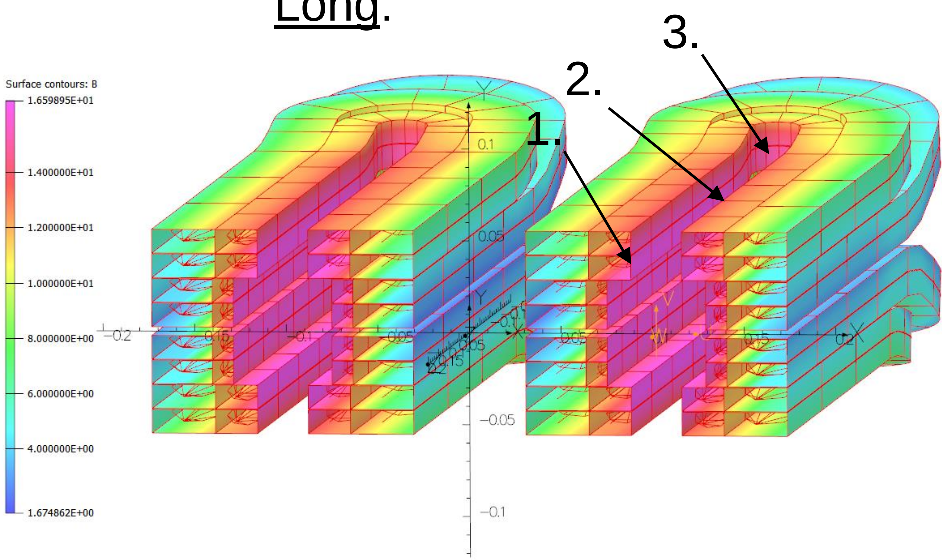


3D MAGNETIC DESIGN – PEAK FIELD

Compact:

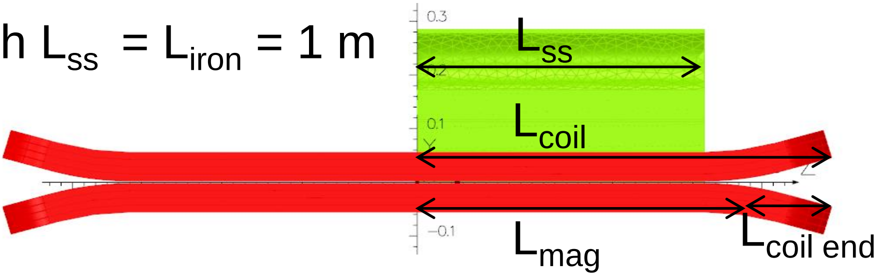


Long:



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

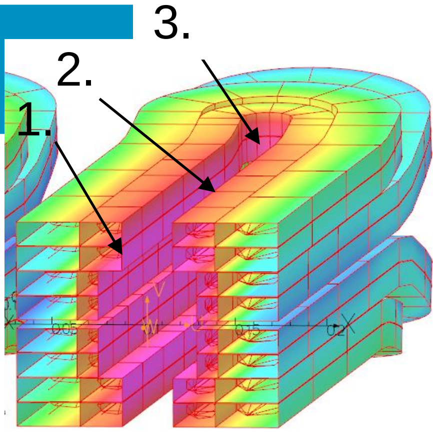
With L_{ss} = L_{iron} = 1 m

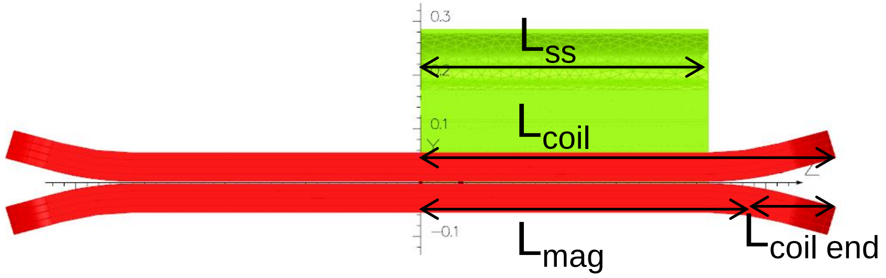


- **$B_{peak\ center} – B_{peak\ ends} = \Delta B_{peak} > 0.6$ T**
- **Additional operational margin in the ends**

3D MAGNETIC DESIGN – SUMMARY

Parameter	Compact	Compact compensated	Long	Unit
b3 integrated	-4.59	-2.70	0.08	units
B_{peak1}, z=0	16.6	16.6	16.6	T
B_{peak2}, bend	15.9	15.9	16.0	T
B_{peak3}, tip	15.0	15.0	15.2	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)**



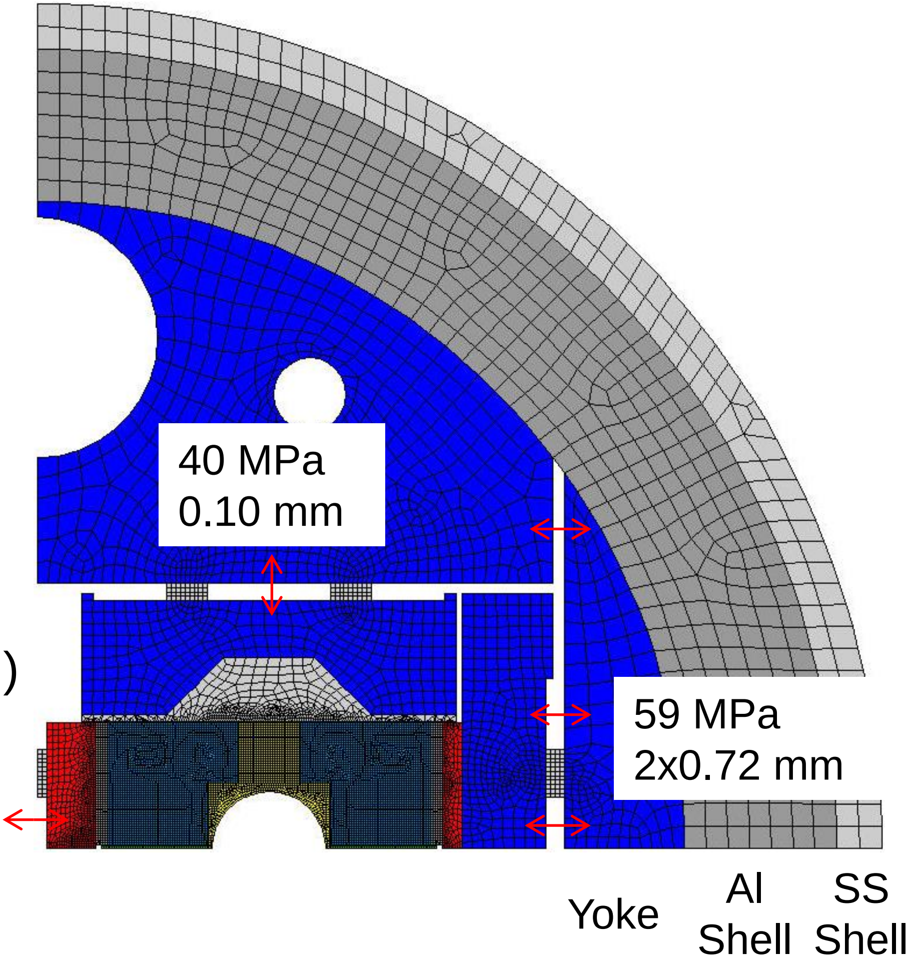


Nominal:

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

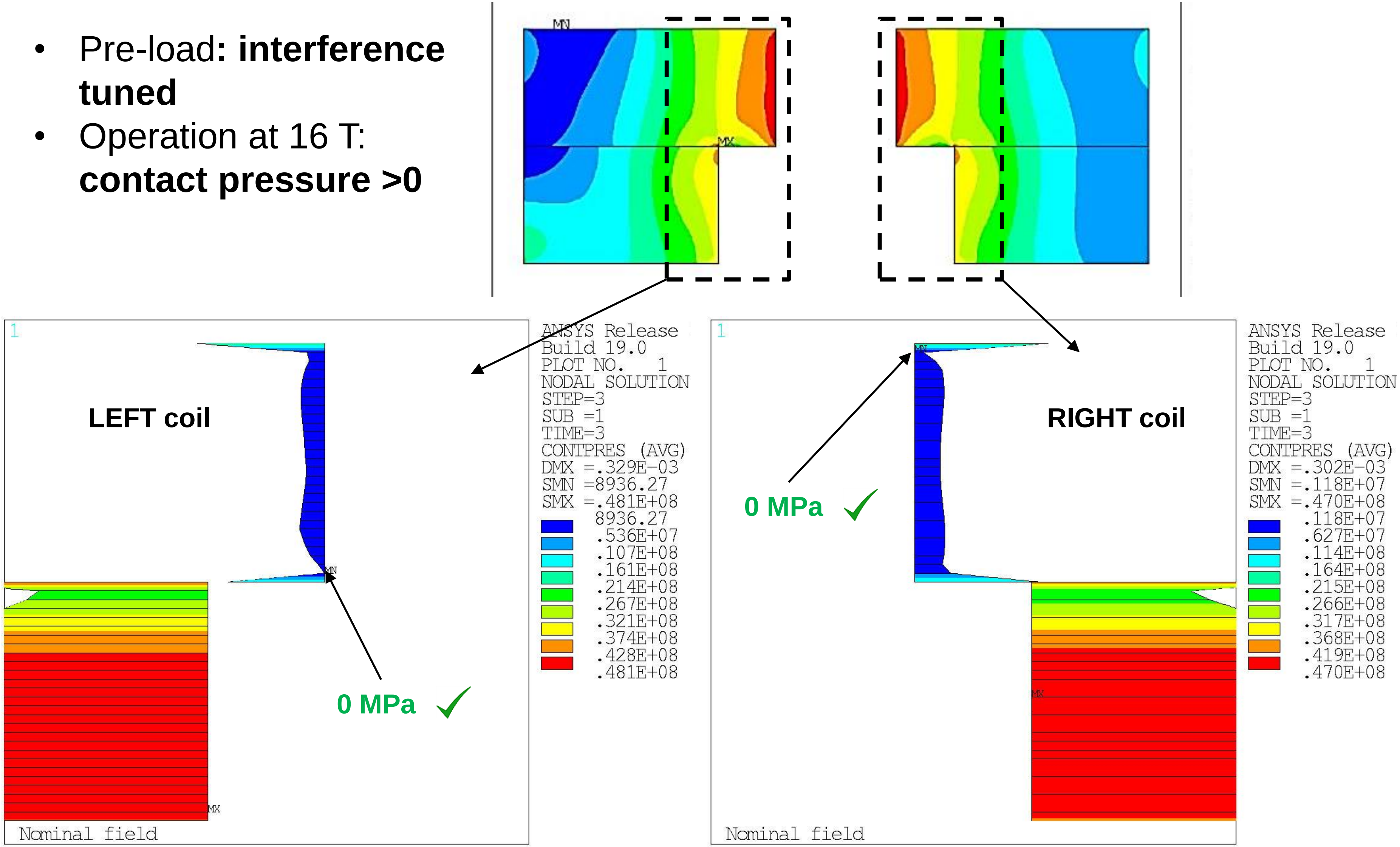
2D MECHANICAL DESIGN – MODEL

- Geometry:
  - Interbeam distance = 204 mm
  - Outer yoke Ø = 570 mm
  - 67 mm Al shell + 20 mm SS shell
- ECC Coil properties (293K/4.2K):
  - Ex = 25 GPa / 27.5 GPa
  - Ey = 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



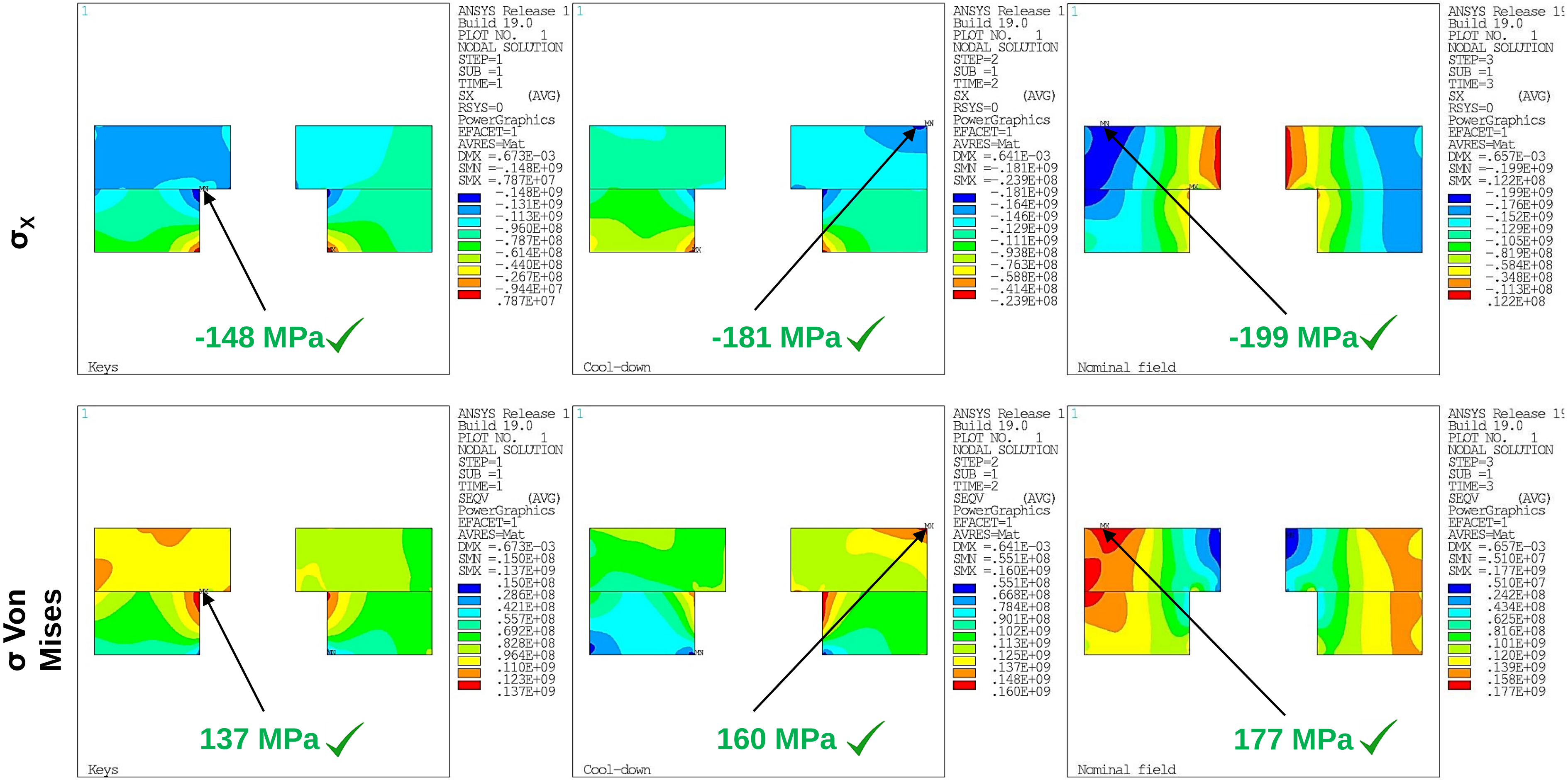
2D MECHANICAL DESIGN – COIL-POLE CONTACT

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



2D MECHANICAL DESIGN – COIL PEAK STRESS

Room-temperature pre-load | **Cool-down to 1.9K** | **Operation at 16 T**



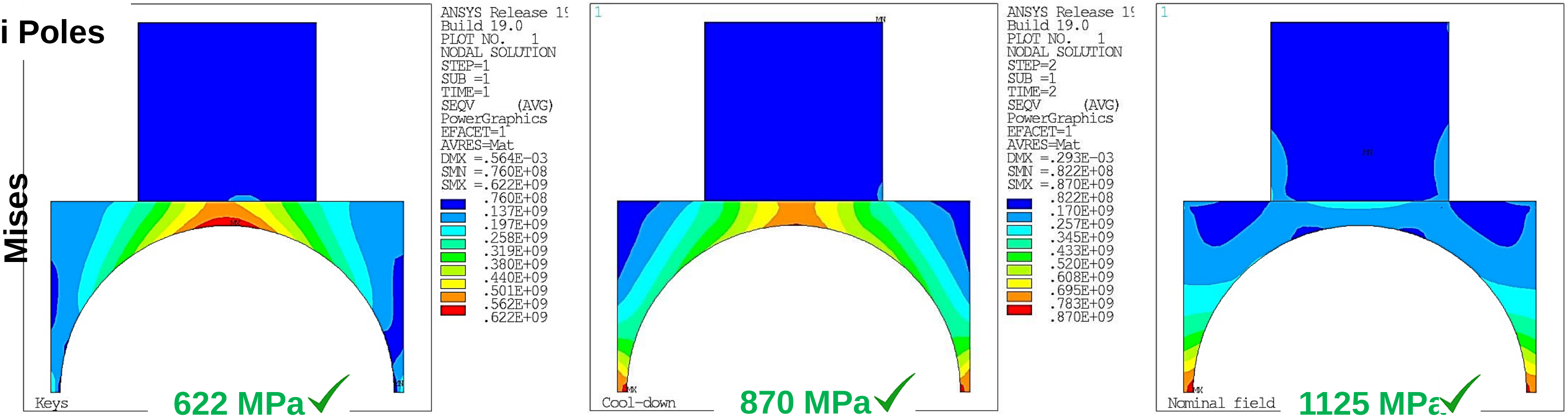
Criteria: <150 MPa | <200 MPa | <200 MPa

2D MECHANICAL DESIGN – STRUCTURE

Room-temperature pre-load | **Cool-down to 1.9K** | **Operation at 16 T**

Ti Poles

σ Von Mises

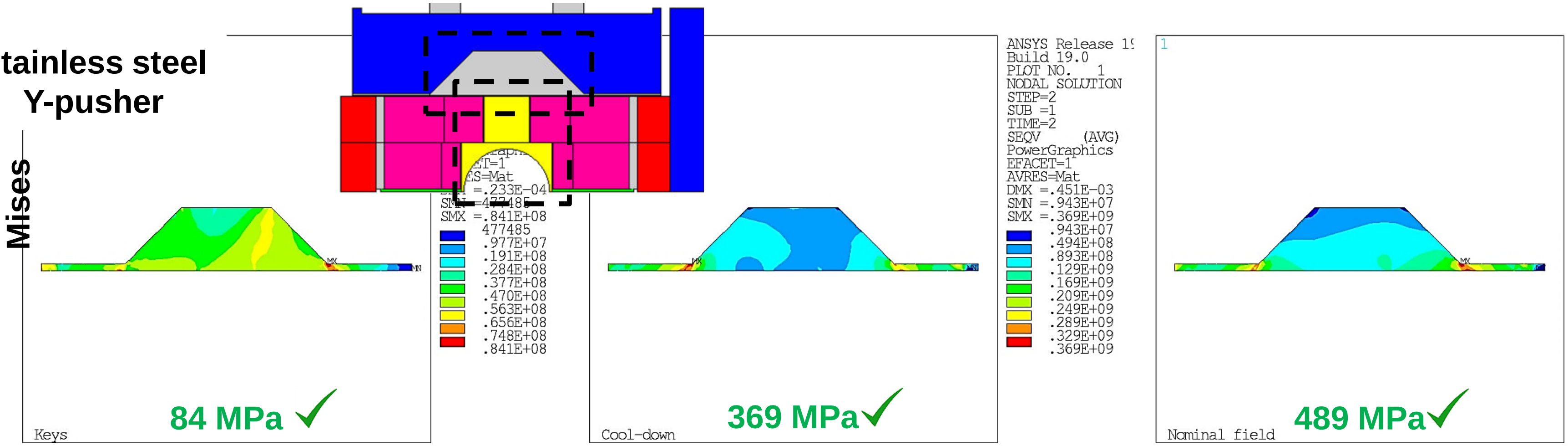


622 MPa ✓ | **870 MPa** ✓ | **1125 MPa** ✓

Criteria: <800 MPa | <1650 MPa | <1650 MPa

Stainless steel Y-pusher

σ Von Mises



84 MPa ✓ | **369 MPa** ✓ | **489 MPa** ✓

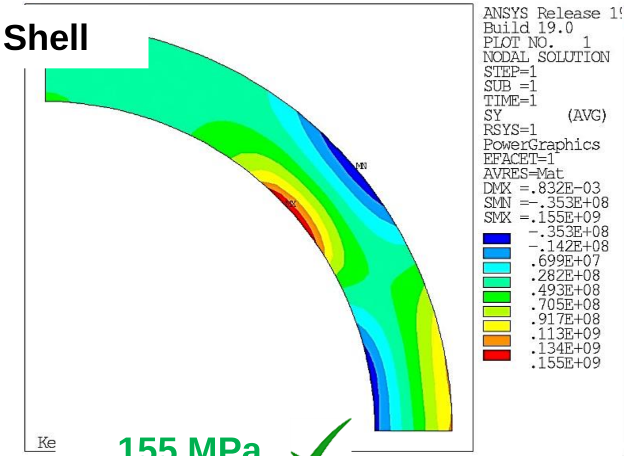
Criteria: <350 MPa | <1050 MPa | <1050 MPa

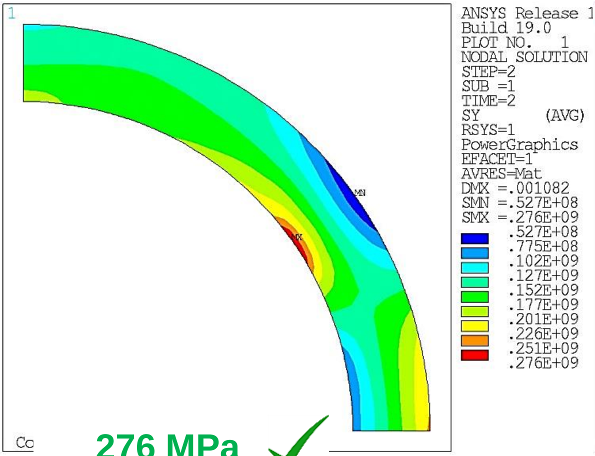
2D MECHANICAL DESIGN – STRUCTURE

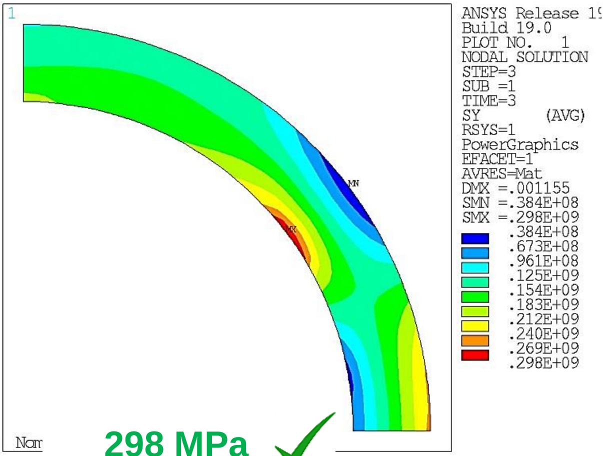
Room-temperature pre-load | **Cool-down to 1.9K** | **Operation at 16 T**

Al Shell

σ_θ





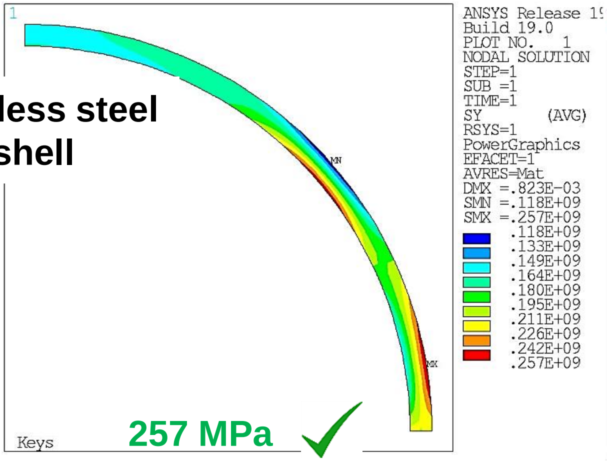


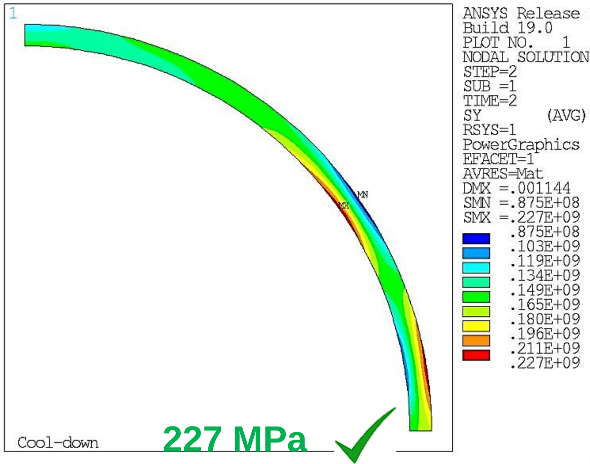
155 MPa ✓ | **276 MPa** ✓ | **298 MPa** ✓

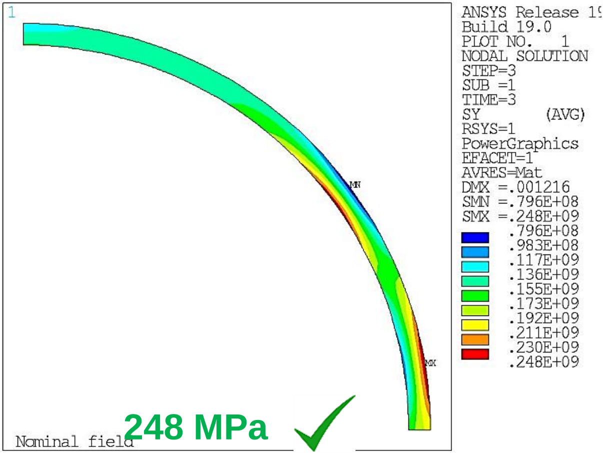
Criteria: <480 MPa | <690 MPa | <690 MPa

Stainless steel shell

σ_θ







257 MPa ✓ | **227 MPa** ✓ | **248 MPa** ✓

Criteria: <350 MPa | <1050 MPa | <1050 MPa

2D MECHANICAL DESIGN – STRUCTURE

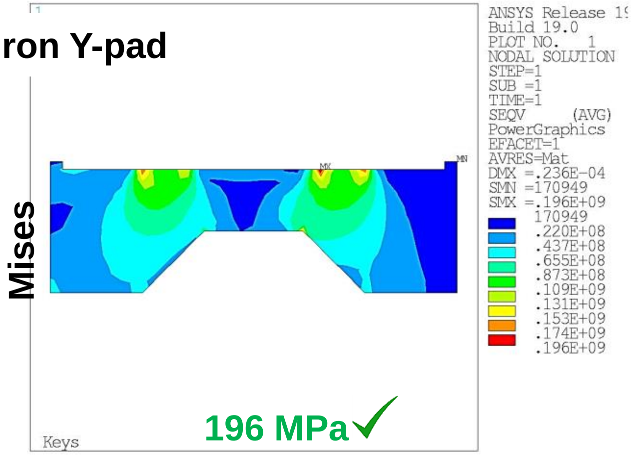
Room-temperature pre-load

Cool-down to 1.9K

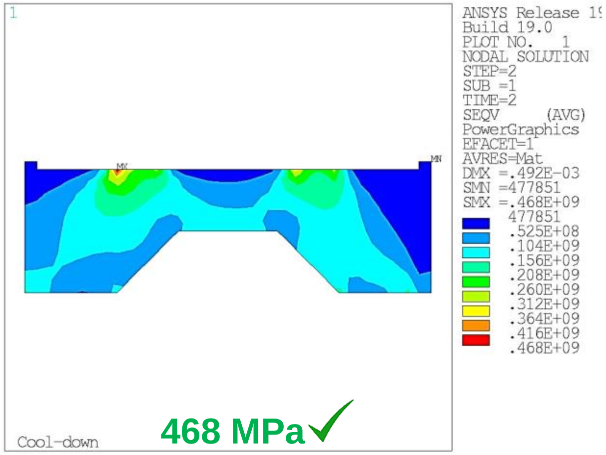
Operation at 16 T

Iron Y-pad

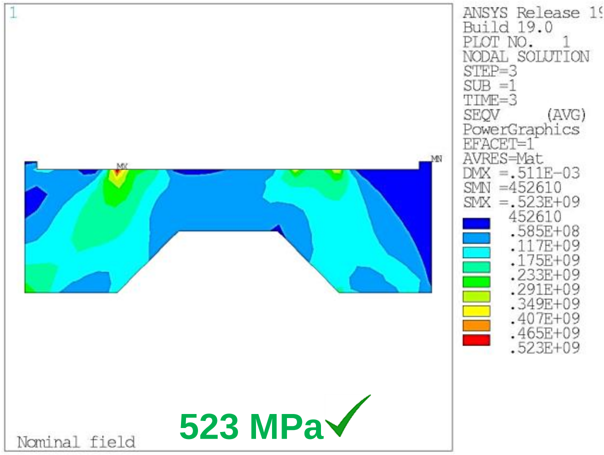
σ Von Mises



196 MPa ✓



468 MPa ✓



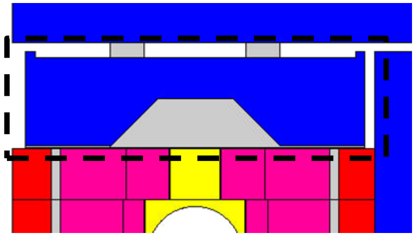
523 MPa ✓

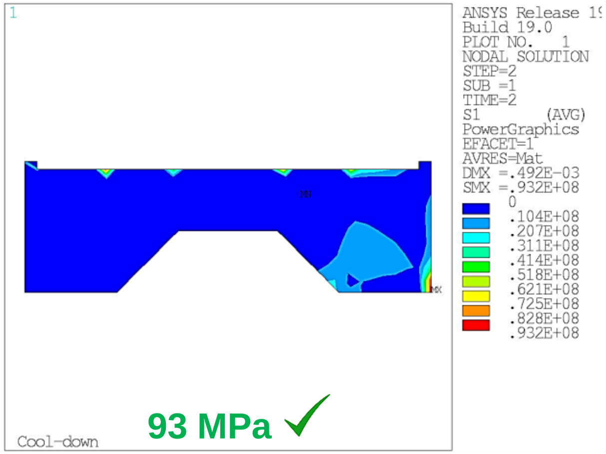
Criteria: <230 MPa

<720 MPa

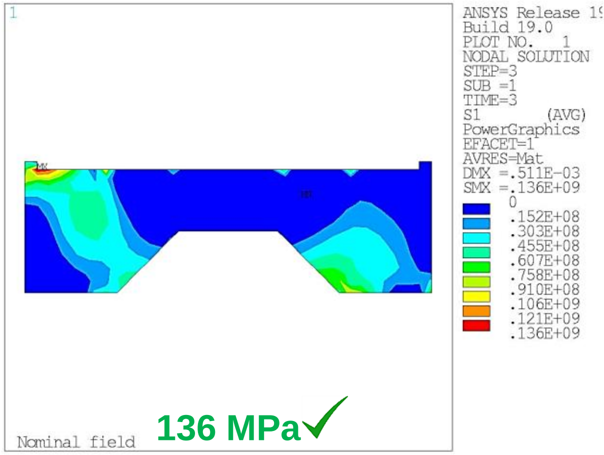
<720 MPa

Sigma I: pure tension





93 MPa ✓



136 MPa ✓

<380 MPa

<380 MPa

2D MECHANICAL DESIGN – STRUCTURE

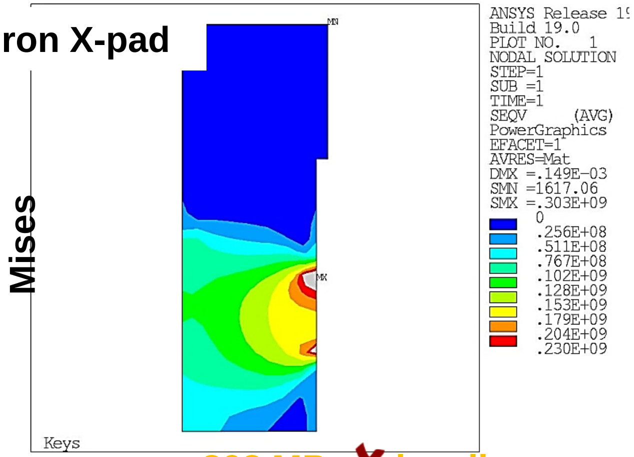
Room-temperature pre-load

Cool-down to 1.9K

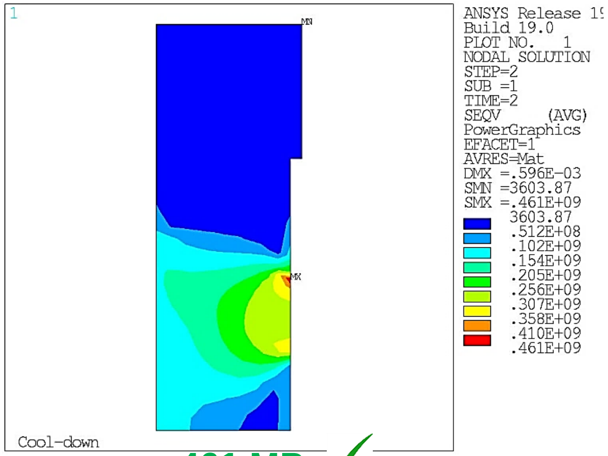
Operation at 16 T

Iron X-pad

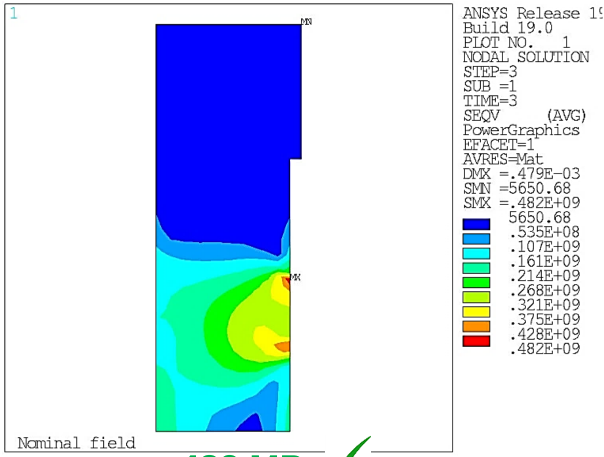
σ Von Mises



303 MPa ✗ locally



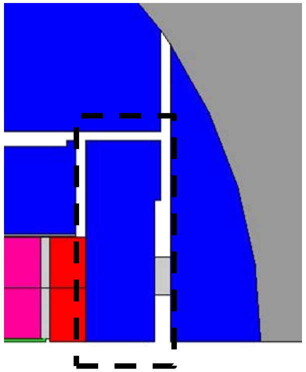
461 MPa ✓

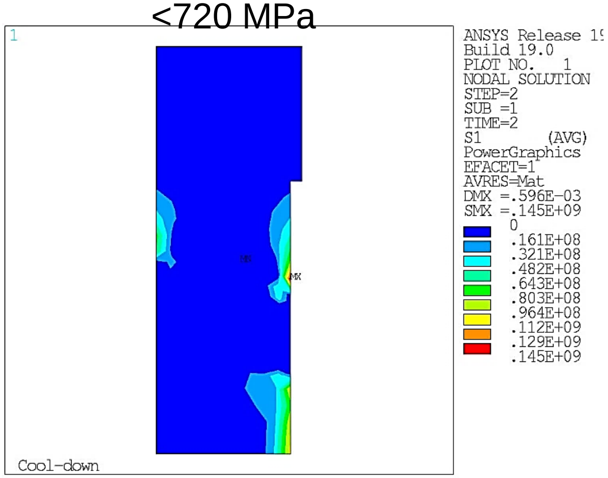


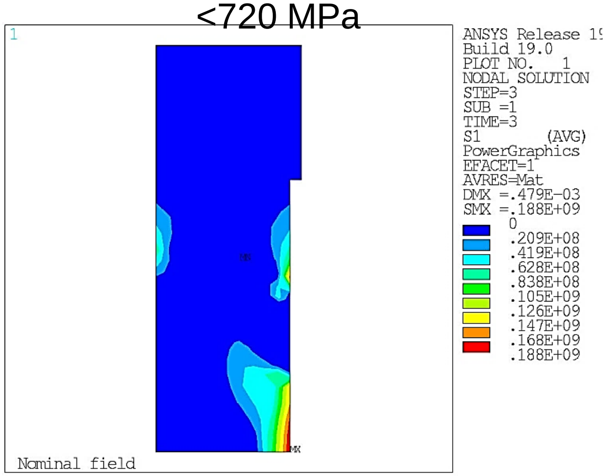
482 MPa ✓

Criteria: <230 MPa <720 MPa <720 MPa

Sigma I: pure tension







<380 MPa <380 MPa

2D MECHANICAL DESIGN – STRUCTURE

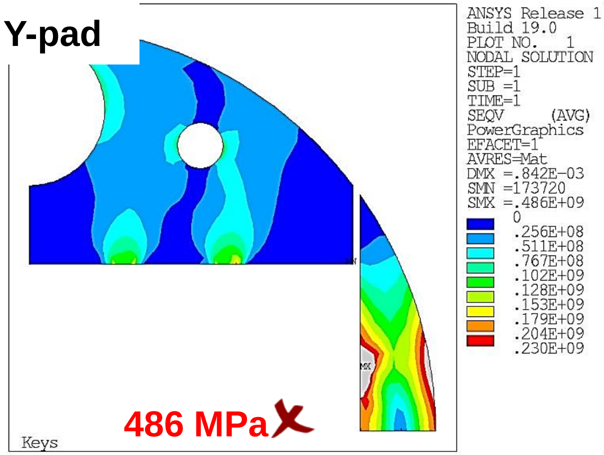
Room-temperature pre-load

Cool-down to 1.9K

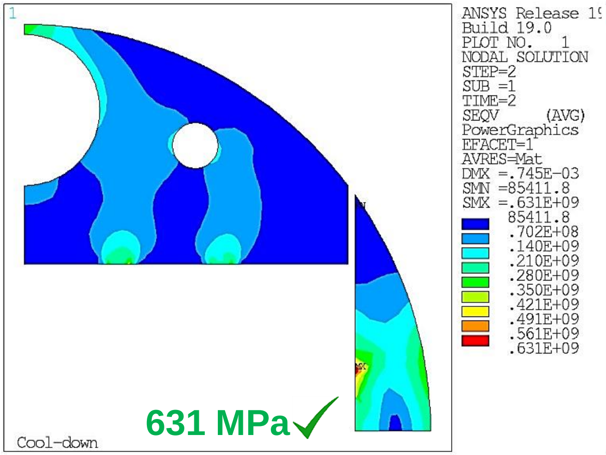
Operation at 16 T

Iron Y-pad

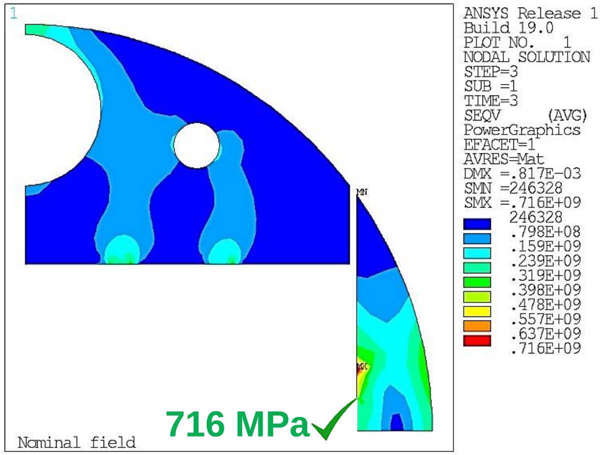
σ Von Mises



486 MPa ✗



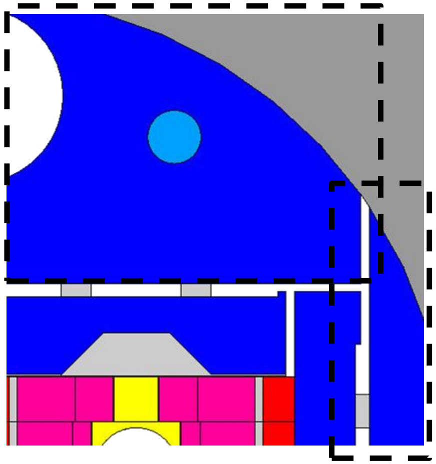
631 MPa ✓

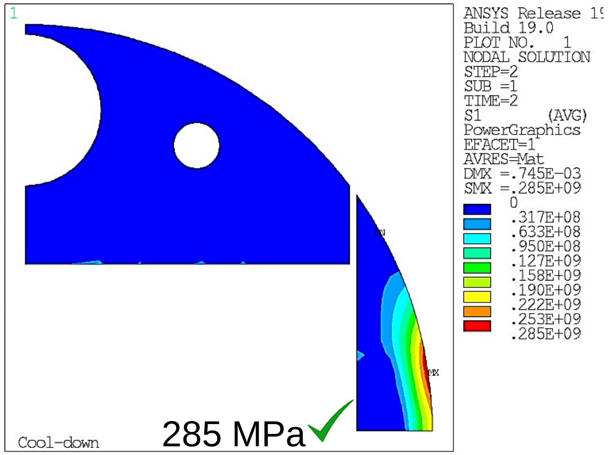


716 MPa ✓

Criteria: <230 MPa <720 MPa <720 MPa

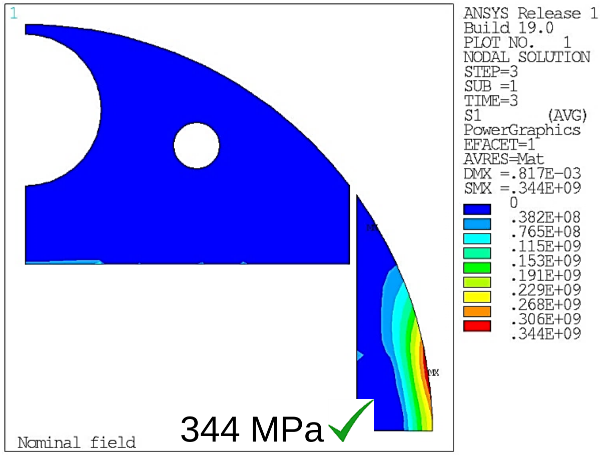
Sigma I: pure tension





285 MPa ✓

<380 MPa



344 MPa ✓

<380 MPa

CONCLUSION

- 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** (ΔB_{peak} > 0.6 T)
- 2d mechanical design:
  - **Coil stress < criteria**
  - **Iron X-Pad + Yoke: locally > criterion at warm**
  - **Other components: stress < criteria**

OUTLOOKS

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

DE LA RECHERCHE À L'INDUSTRIE

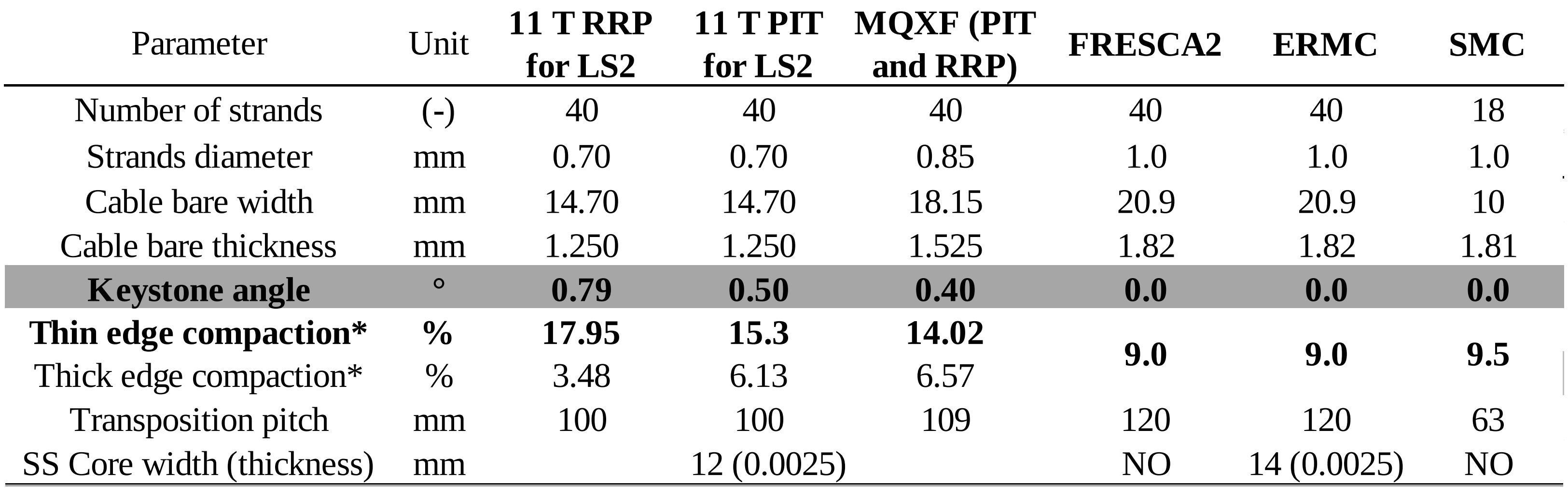
BACKUP SLIDES

CONDUCTOR PARAMETERS

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

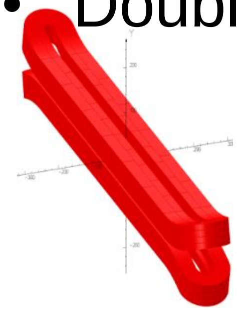
J. Fleiter: Rutherford cable design approach and experience at CERN (here)

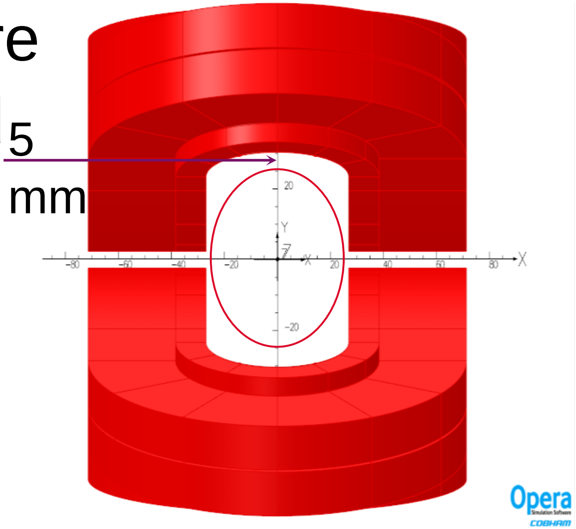


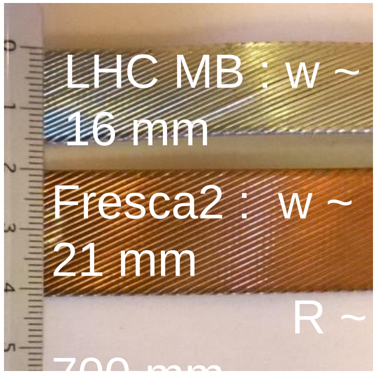
Parameter	Unit	11 T RRP for LS2	11 T PIT for LS2	MQXF (PIT and RRP)	FRESCA2	ERMC	SMC
Number of strands	(-)	40	40	40	40	40	18
Strands diameter	mm	0.70	0.70	0.85	1.0	1.0	1.0
Cable bare width	mm	14.70	14.70	18.15	20.9	20.9	10
Cable bare thickness	mm	1.250	1.250	1.525	1.82	1.82	1.81
Keystone angle	**°**	**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

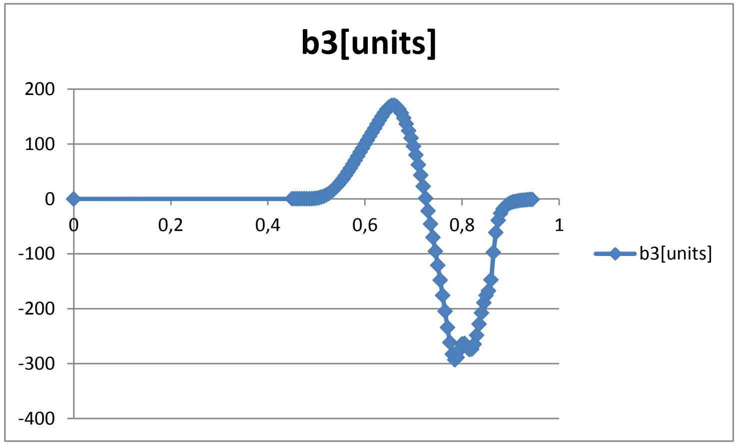
- Assumptions:
  - Return ends – 1000 mm straight section
  - Hardway bend : Rmin = 450 mm in upper layer (w = 12.6 mm)
    - Strain 13.8 mm/m (HD2: 30.6 mm/m HD3: 12.4 mm/m Fresca2: 15.3 mm/m)
  - Coil-to-aperture y-dire
  - Double pancake end







3D HARMONICS



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

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

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

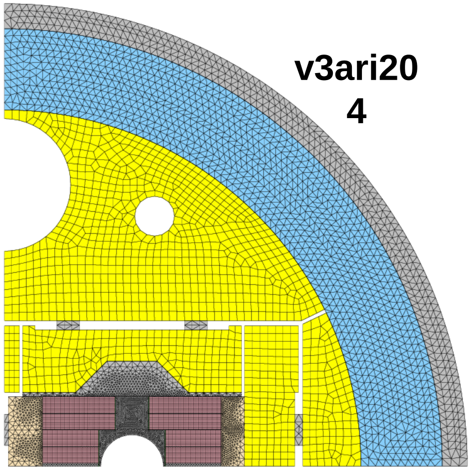
$$Ib_n = \frac{Ib_{n,short}.L_{mag,short} + b_n(0).(L_{mag} - L_{mag,short})}{L_{mag}}$$

Ex: -10 units on a short length

Ib_3 = [-10 units x 0.68x2 -0.8 units x (14.069-0.68x2)] / 14.069

= **-1.69 units**

2D MECHANICAL DESIGNS



Interbeam distance = 204 mm

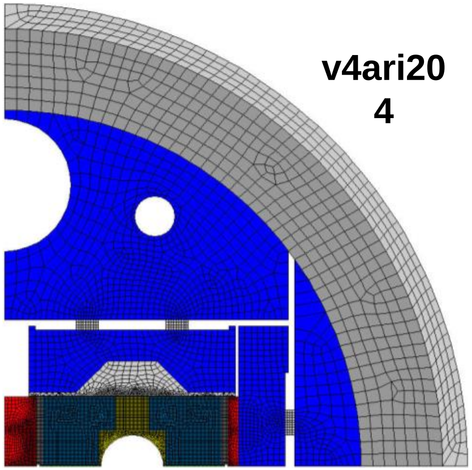
Ø$_{ext}$ iron yoke = 570 mm

Total Ø$_{ext}$ = 740 mm

65 + 20 mm thick shells

→ 2 x 0.67 mm ←

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



Interbeam distance = 204 mm

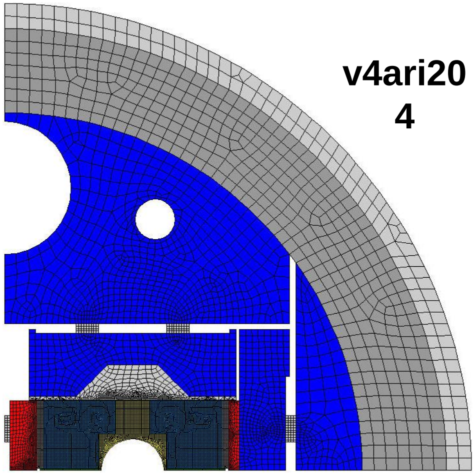
Ø$_{ext}$ iron yoke = 570 mm

Total Ø$_{ext}$ = 740 mm

65 + 20 mm thick shells

1.51mm ←

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



Interbeam distance = 204 mm

Ø$_{ext}$ iron yoke = 570 mm

Total Ø$_{ext}$ = 744 mm

67 + 20 mm thick shells

→ 2 x 0.72 mm ←

	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	$R_{p\ 0.2}$ [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)

2D MECHANICAL DESIGN – STRUCTURE

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