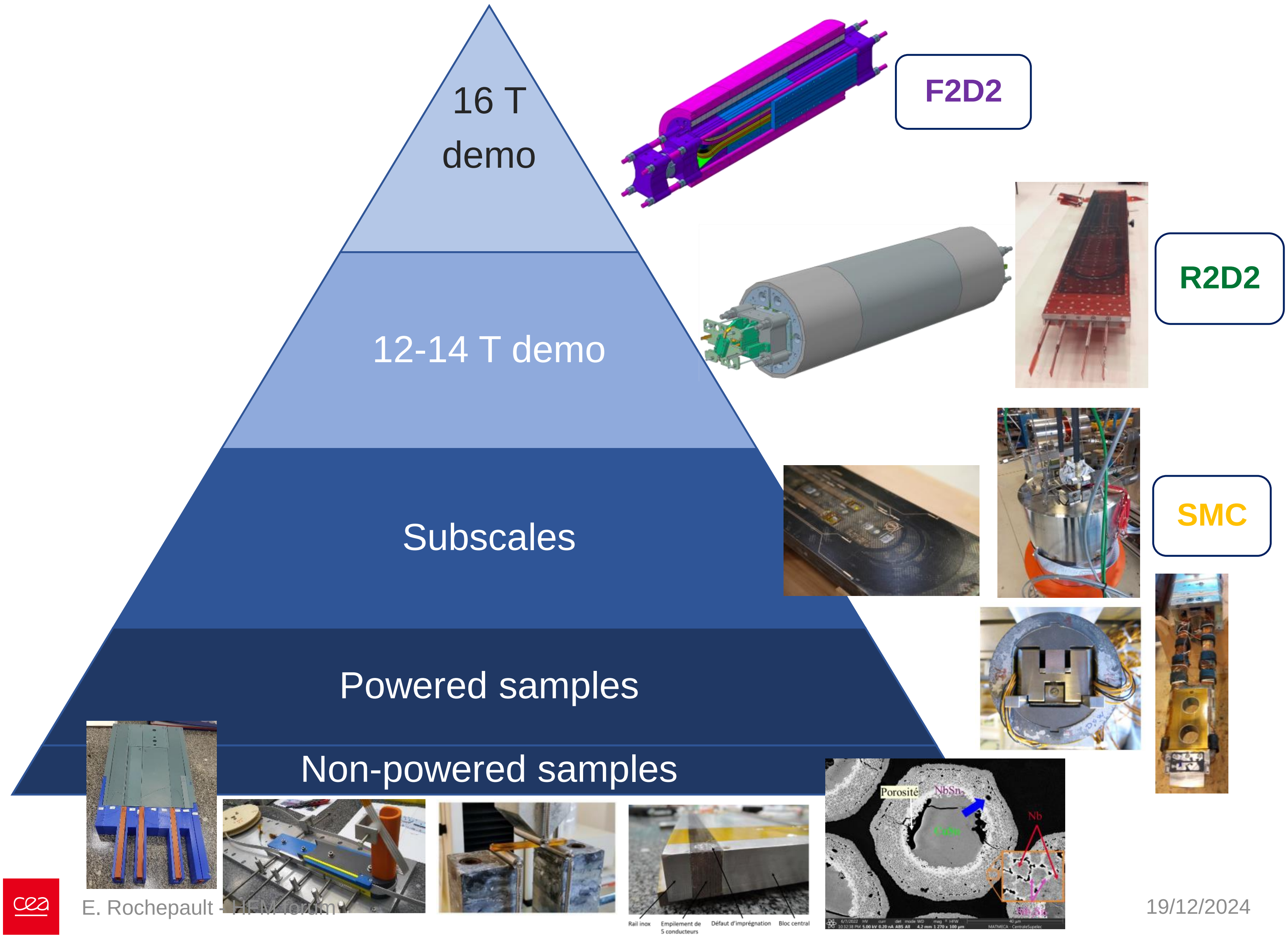
R2D2 and F2D2 magnet design

E. Rochepault, V. Calvelli, G. Campagna, M. Durante, H. Felice, J. Faucheux, T. Guillo, G. Lenoir, G. Minier, S. Perraud, Y. Perron, F. Rondeaux - CEA

J.C. Perez - CERN

HFM forum – 19/12/2024

Development Plan towards 16 T Nb_3Sn Dipoles

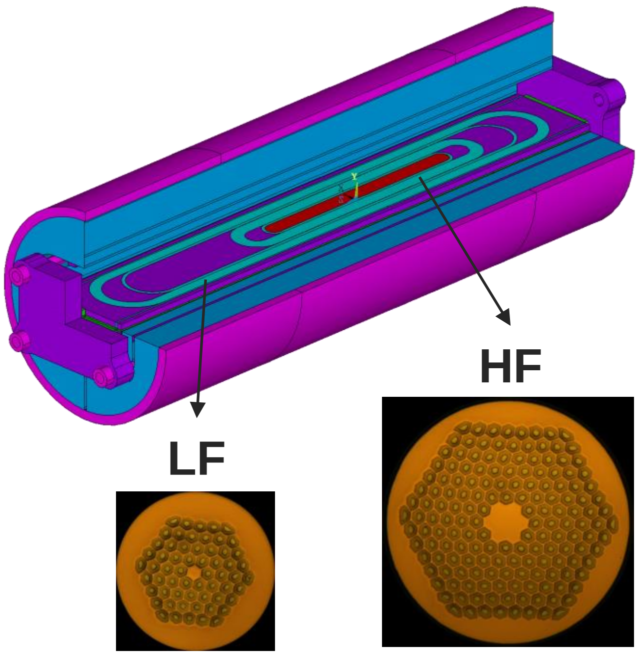


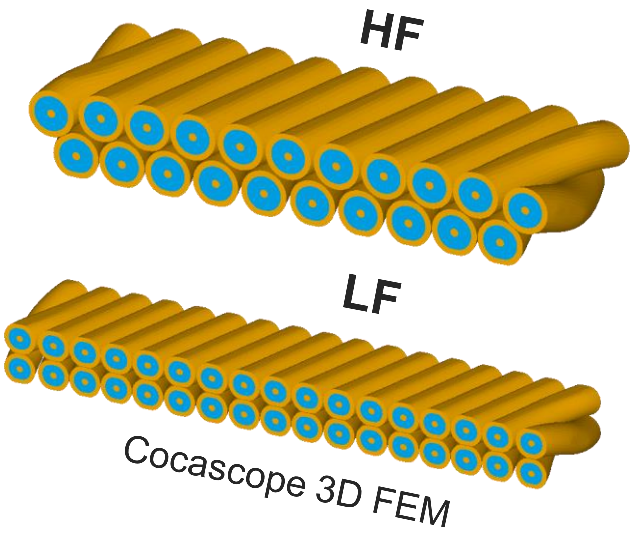
1. R2D2-F2D2 conductors

Conductor production and qualification

- 2 Nb_3Sn RRP conductors for grading
- Same cables for all magnets
- Strand I_c characterization @ CERN
- Cable production @ CERN
- Cable and strand mechanical characterization @ Saclay

	HF	LF	Unit
Strand diameter	1.1	0.7	mm
Jc at 4.2 K and 16 T	1200	1200	A/mm^2
Cu/non Cu ratio	0.8	2	
Cable number of strands	21	34	
Unreacted Bare cable			
Width	12.58	12.58	mm
Thickness	1.97	1.25	mm
Reacted Bare cable			
Width	12.74	12.74	mm
Thickness	2.06	1.31	mm
Insulation Thickness	0.15	0.15	mm





Strand characterization

Explored heat treatments*:

Cycle	Final Plateau		Spools Tested, I_c	
	Temperature (°C)	Time (h)	DEM-1.1	DEM-0.7
3_680_A	680	50	2	0
3_665_B	665	50	37	16
3_665_K	665	30	1	1
3_650_A	**650**	**50**	**5**	**1**
3_650_I	650	30	3	1

- **Chosen for R2D2: 650°C-50h**

→ Higher RRR

→ small decrease of Ic

- Improvement of Ic possible for higher performance

for DEM-1.1:

HT cycle	B_{c2} (T)	I_c at B_p = 12.37 T and 4.25 K		RRR	
		I_c (A)	Degradation relative to 3_665_B	RRR	Increase relative to 3_665_B
3_665_B	26.9	1485	-	279	-
3_650_A	**25.4**	**1446**	**2.6 %**	**335**	**21.8 %**
3_650_I	24.9	1435	4.2 %	342	25.0 %

for DEM-0.7:

B_{c2} (T)	I_c at B_p = 8.089 T and 4.25 K		I_c at B_p = 12 T and 4.25 K	
	I_c (A)	Degradation relative to 3_665_B	I_c (A)	Degradation relative to 3_665_B
25.3	841	-	412	-
24.4	**824**	**2.0 %**	**391**	**5.1%**
24.0	837	0.4 %	391	5.1%

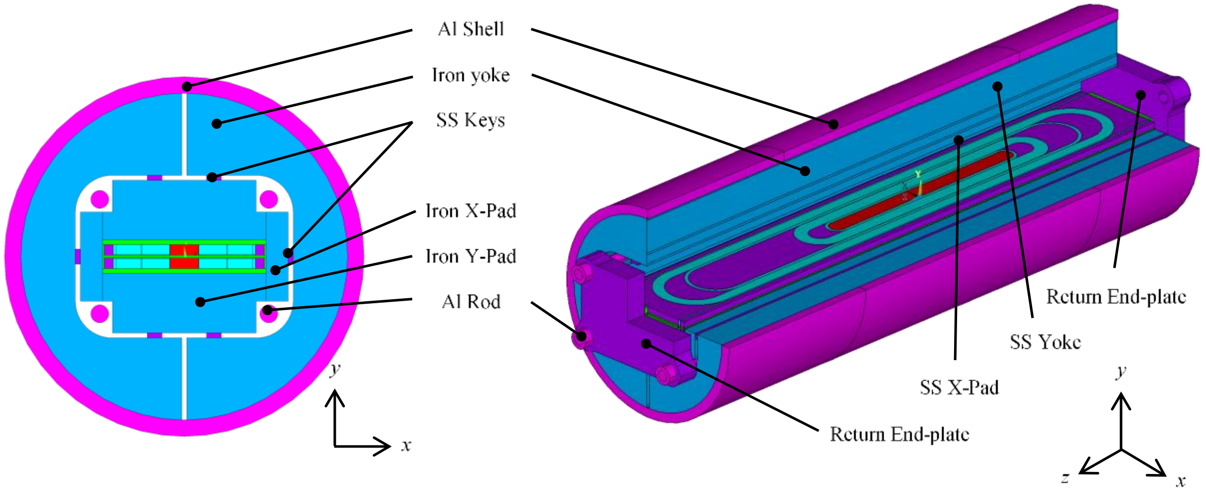
*See for more details: "Performance of Dem-1.1 and Dem-0.7 Wires for R2D2: Heat Treatment Recommendations", S. Hopkins, internal CERN note

2. R2D2

Overview of the R2D2 design

- Conceptual and detailed design at Saclay
- Fabrication, assembly and pre-stress at Saclay
- Tests at cold at CERN
- **Main goal: demonstrate feasibility of grading in block-coils**
  - Winding two cables on top of each other
  - Heat treating two different cables together
  - Jonctions of the 2 cables → 1st option: external Nb_3Sn-NbTi joints

R2D2 = **R**esearch **R**acetrack **D**ipole **D**emonstrator

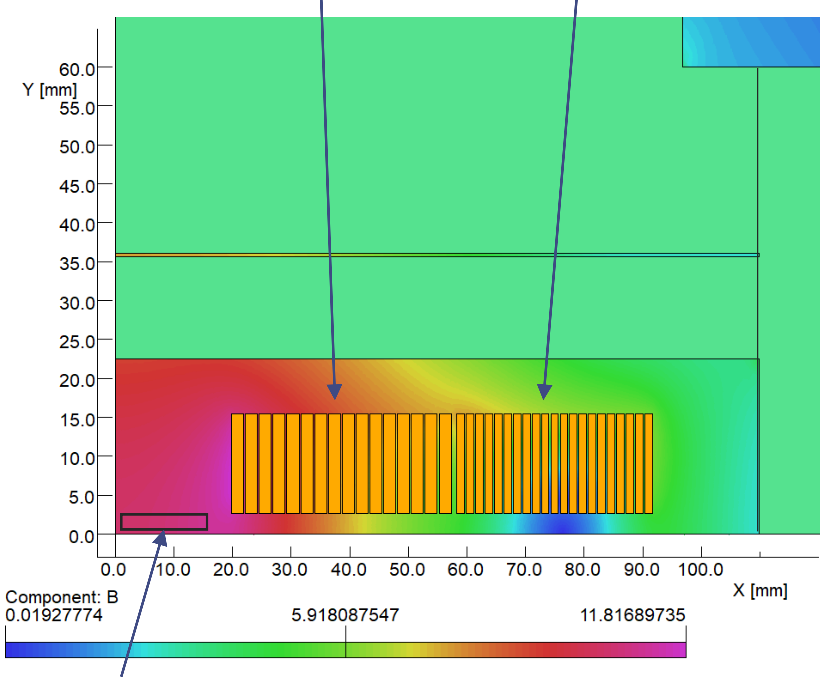


Aperture	None
Outer diameter	480 mm
Structure length	2.0 m
Nominal central field	11.6 T
Ultimate central field	12.1 T

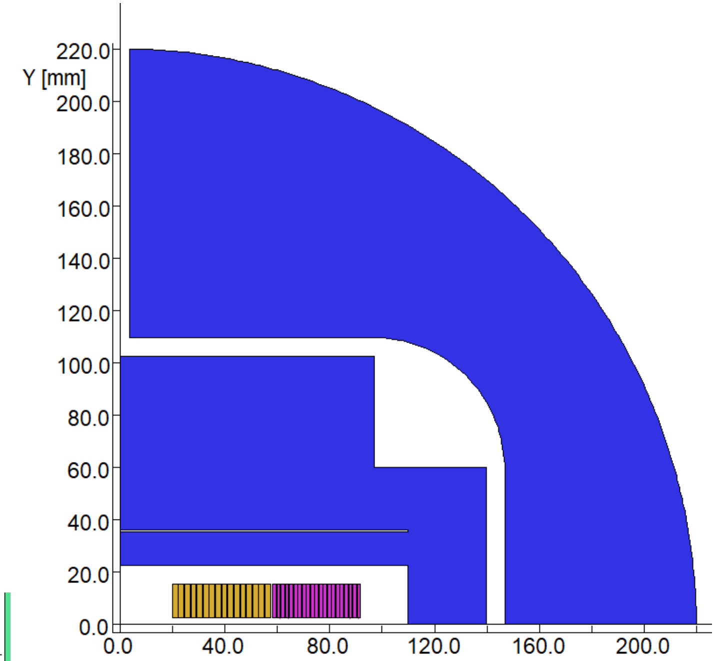
2D Magnetic design

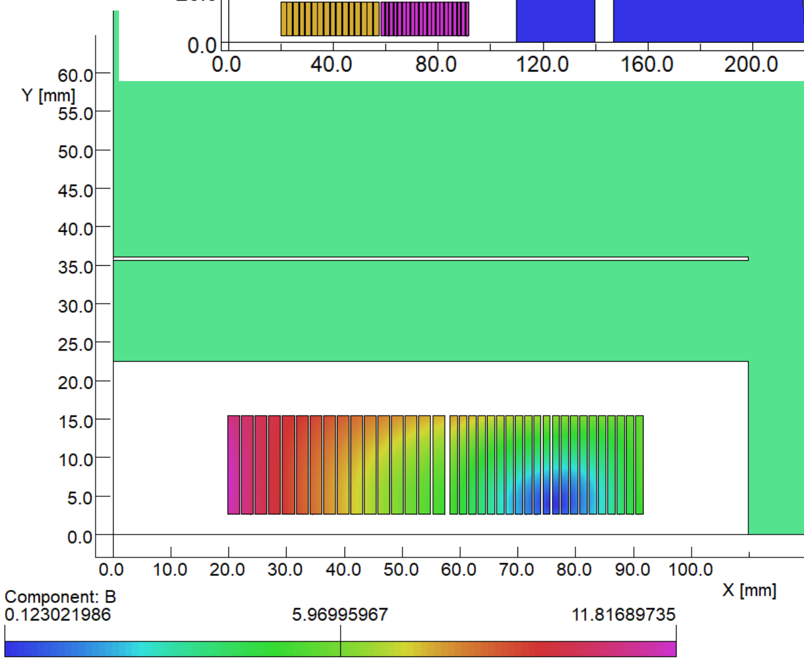
Number of turns optimized to balance the load-line margins:

16 HF **21 LF**

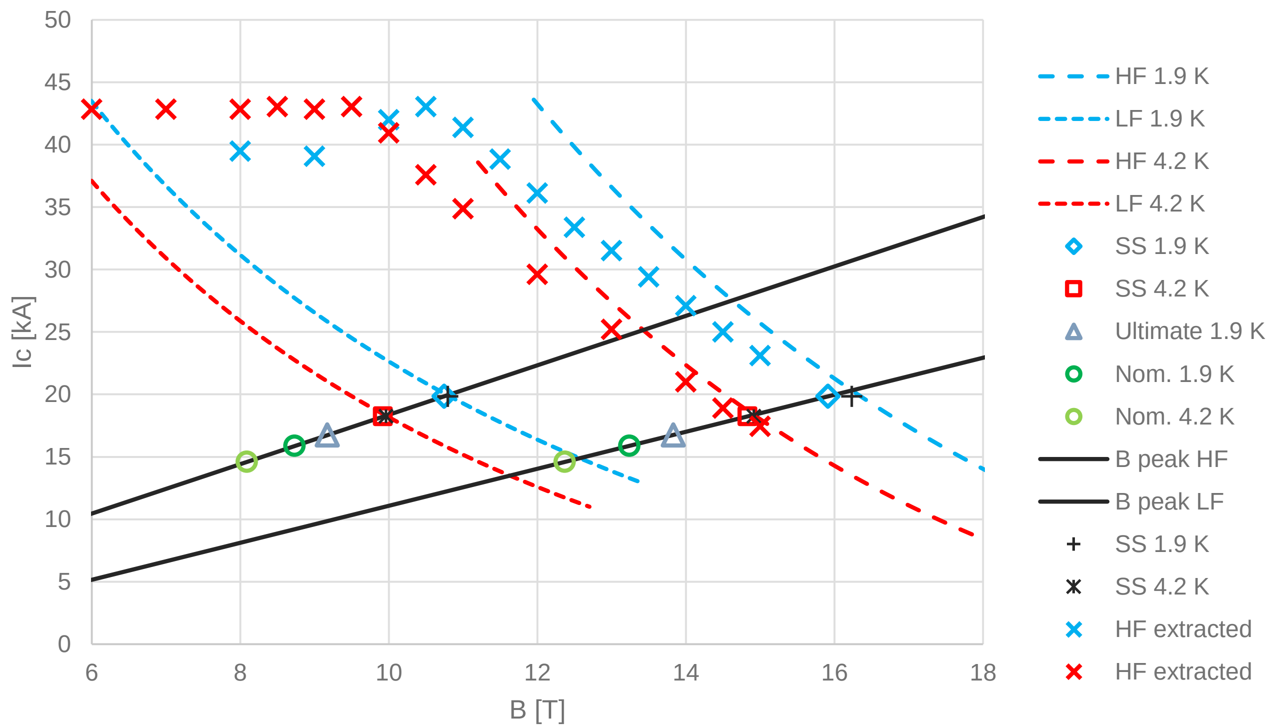


Accessible area for measurements (~30 X 5 mm)





R2D2 Load-lines and margins

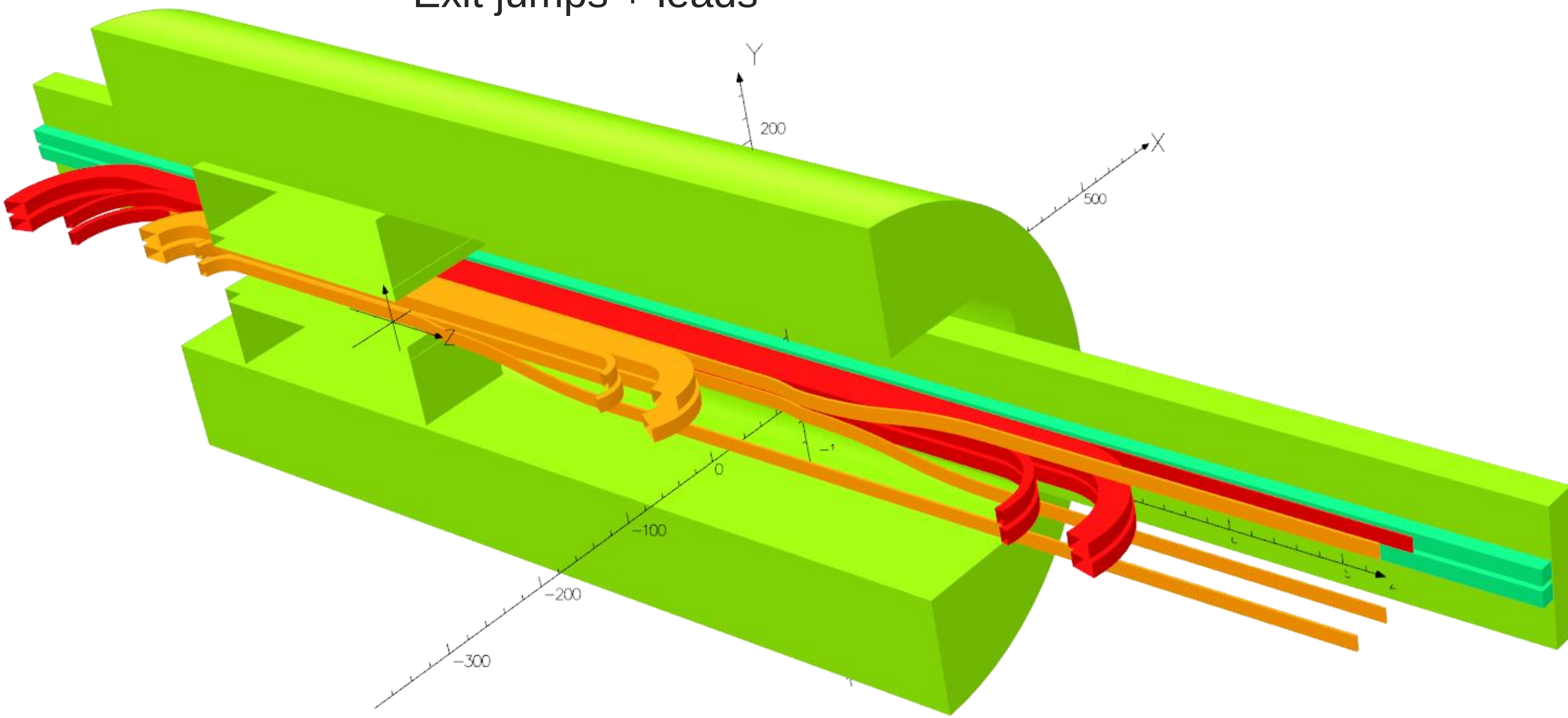


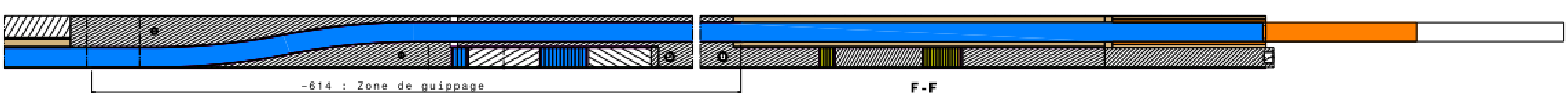
Parameter	Nom.	Nom.	Ultimate*	SS	SS	Unit
	4.2 K	1.9 K	**1.9 K**	4.2 K	1.9 K	
Current [kA]	14.6	15.9	**16.8**	18.2	19.8	kA
LL Margin HF	20.5	21.9	**17.5**	0.7	2.3	%
LL Margin LF	20.3	20.4	**16.0**	0.3	0.5	
B center	10.89	11.62	**12.12**	12.96	13.87	T
B peak HF	12.37	13.24	**13.83**	14.83	15.92	T
B peak LF	8.089	8.73	**9.17**	9.92	10.74	T
J block HF	474.0	515.8	**544.3**	592.5	644.8	A/mm2
J block LF	694.9	756.1	**797.8**	868.6	945.1	A/mm2

***ultimate**:
- adiabatic hotspot = 350 K
- Peak stress = 180 MPa

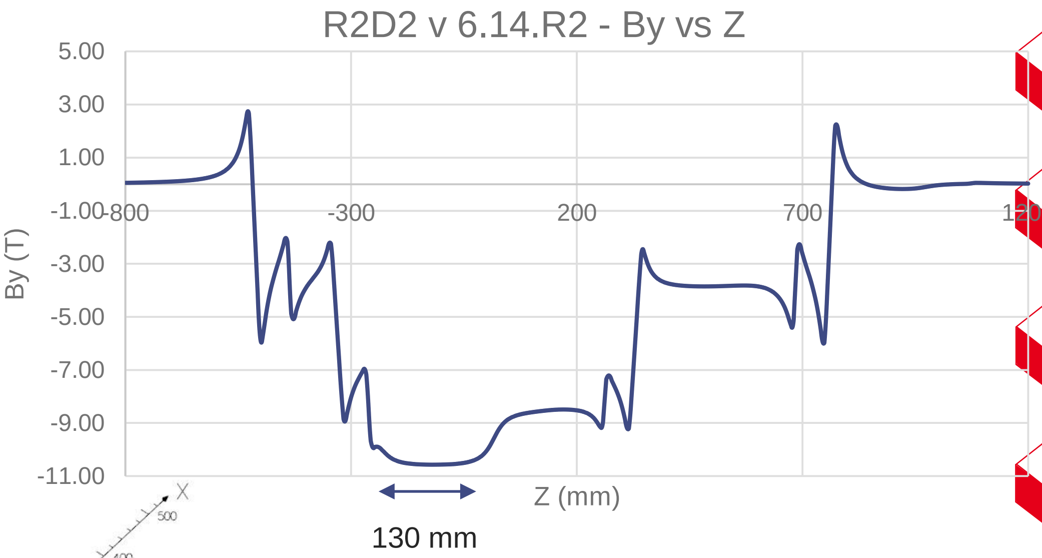
3D Magnetic design

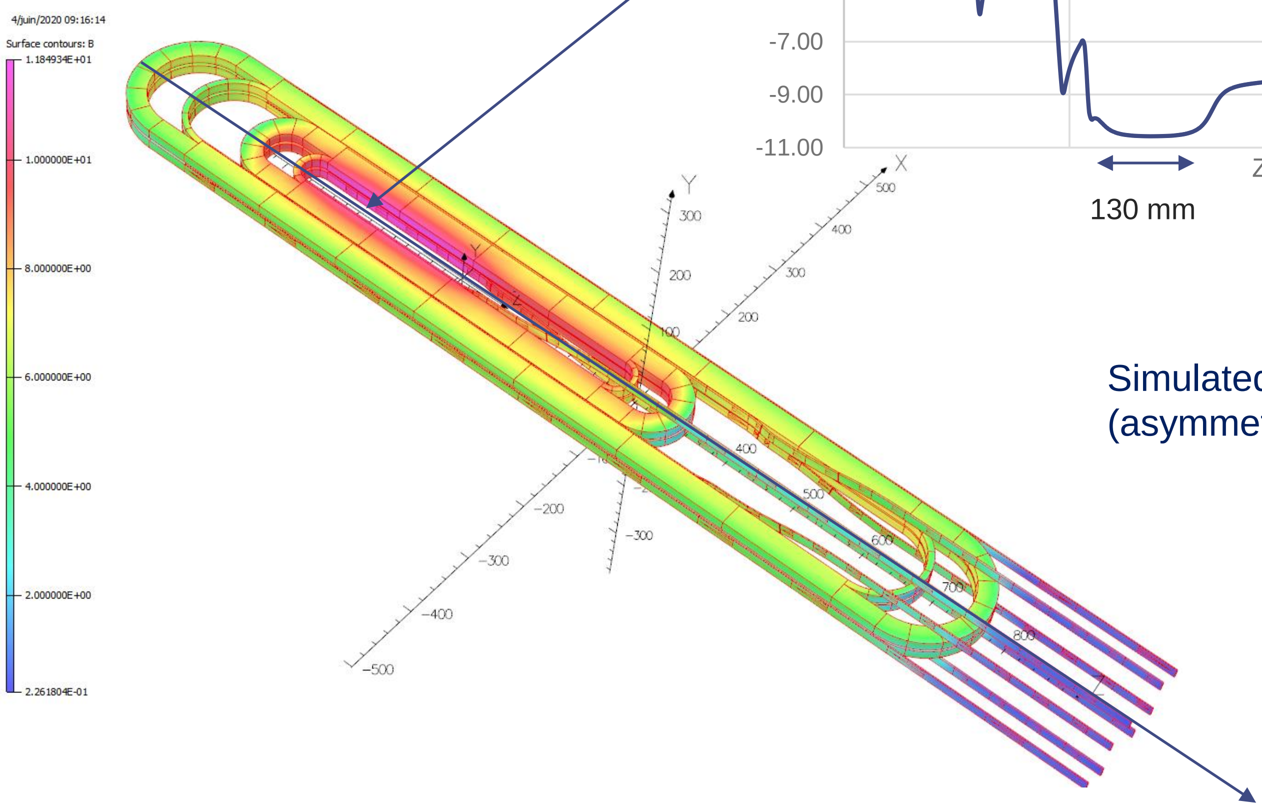
- R2D2 magnet = single-layer coils x2
- 2 coils modelled
- 2 sides RE+LE
- Exit jumps + leads





3D Magnetic design

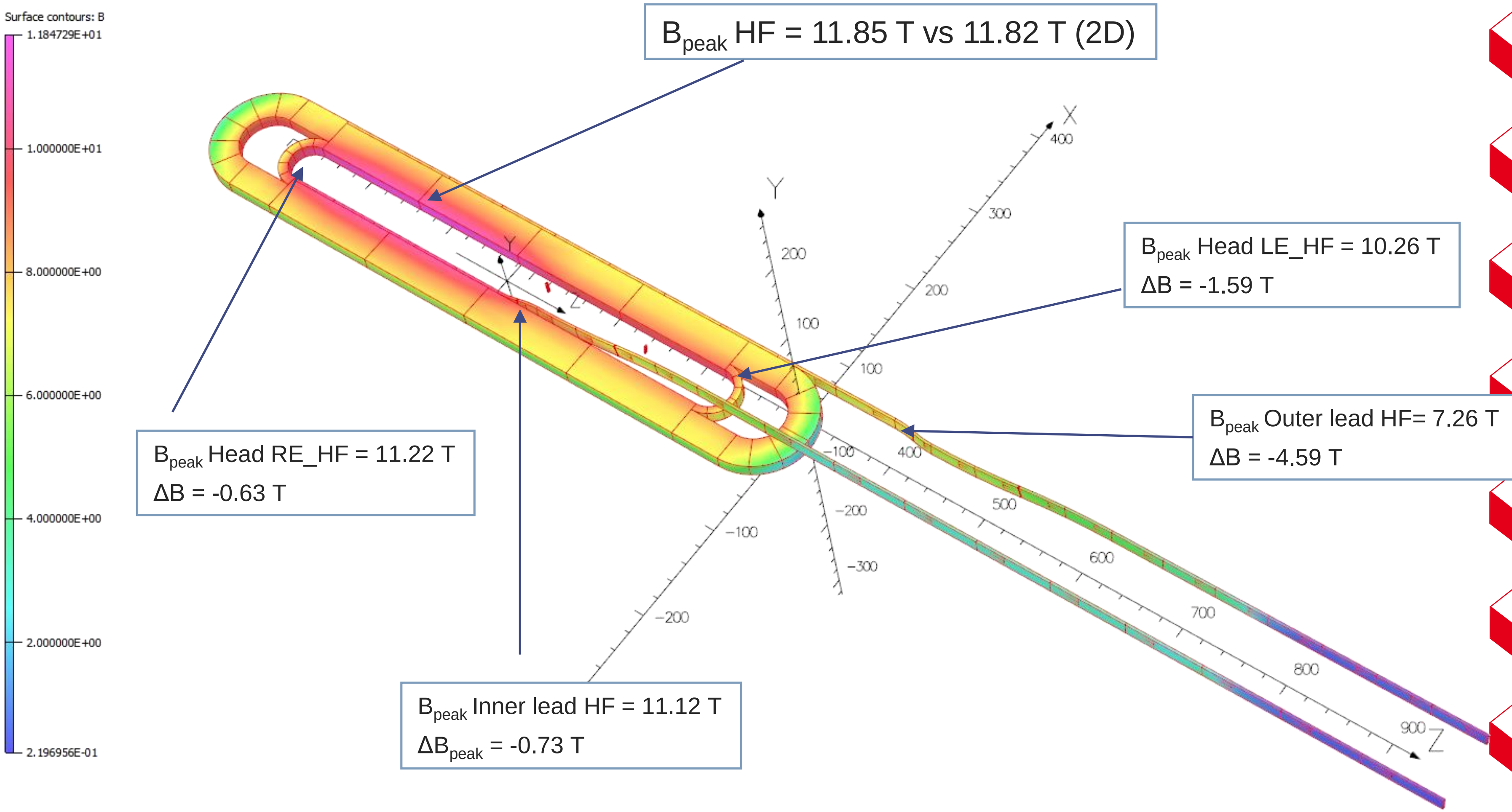




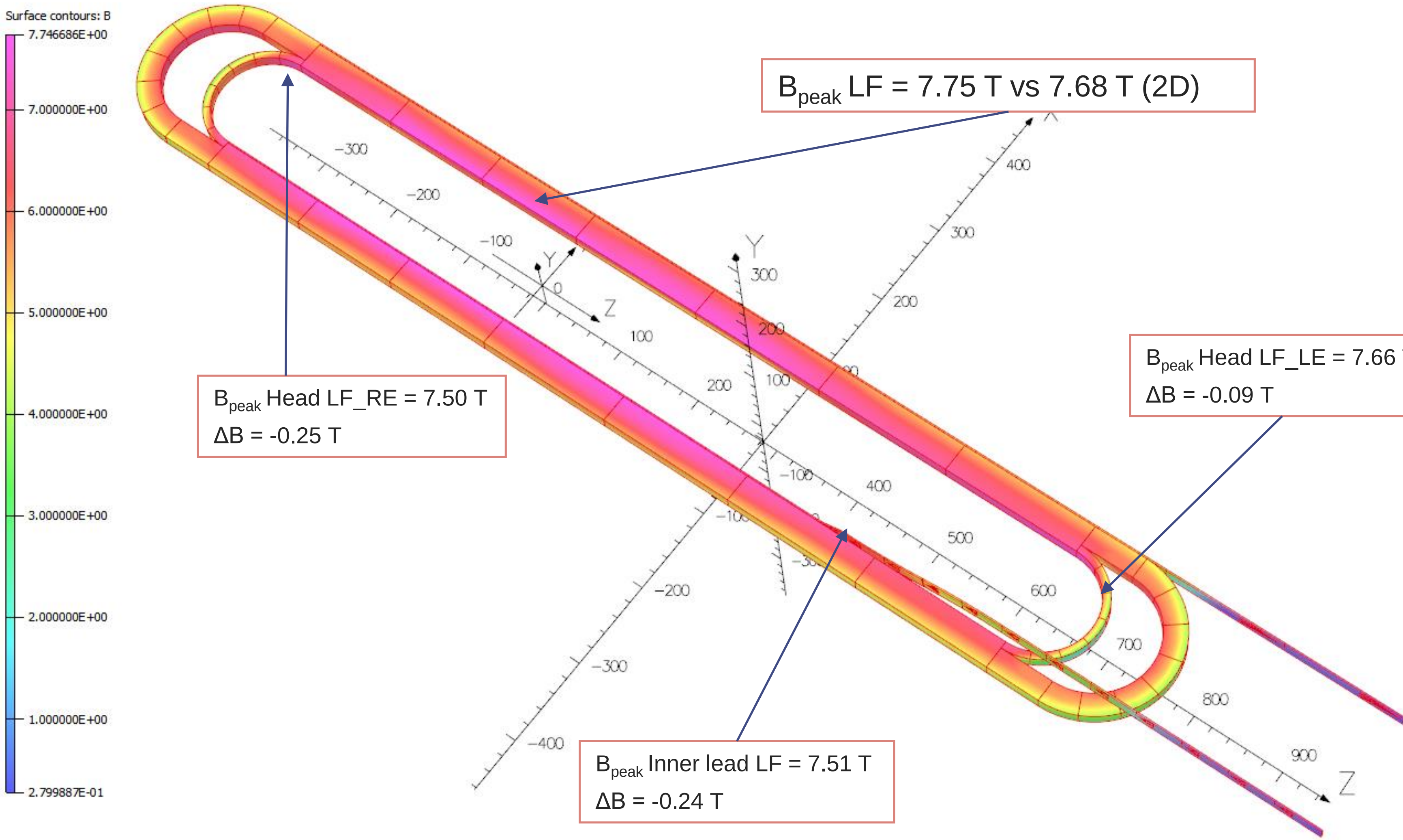
Simulated considering both poles (asymmetric due to the exit leads)

3D Magnetic design

Design optimized to lower the peak fields in critical areas :
→ Coil ends, Leads, and exit jumps



3D Magnetic design

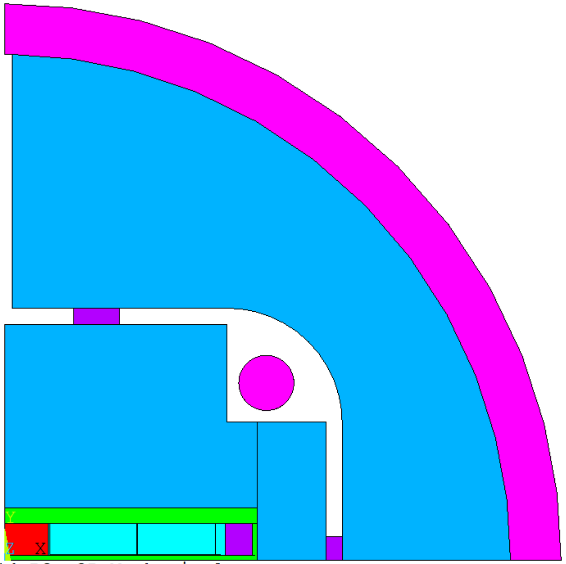


3D Mechanical design

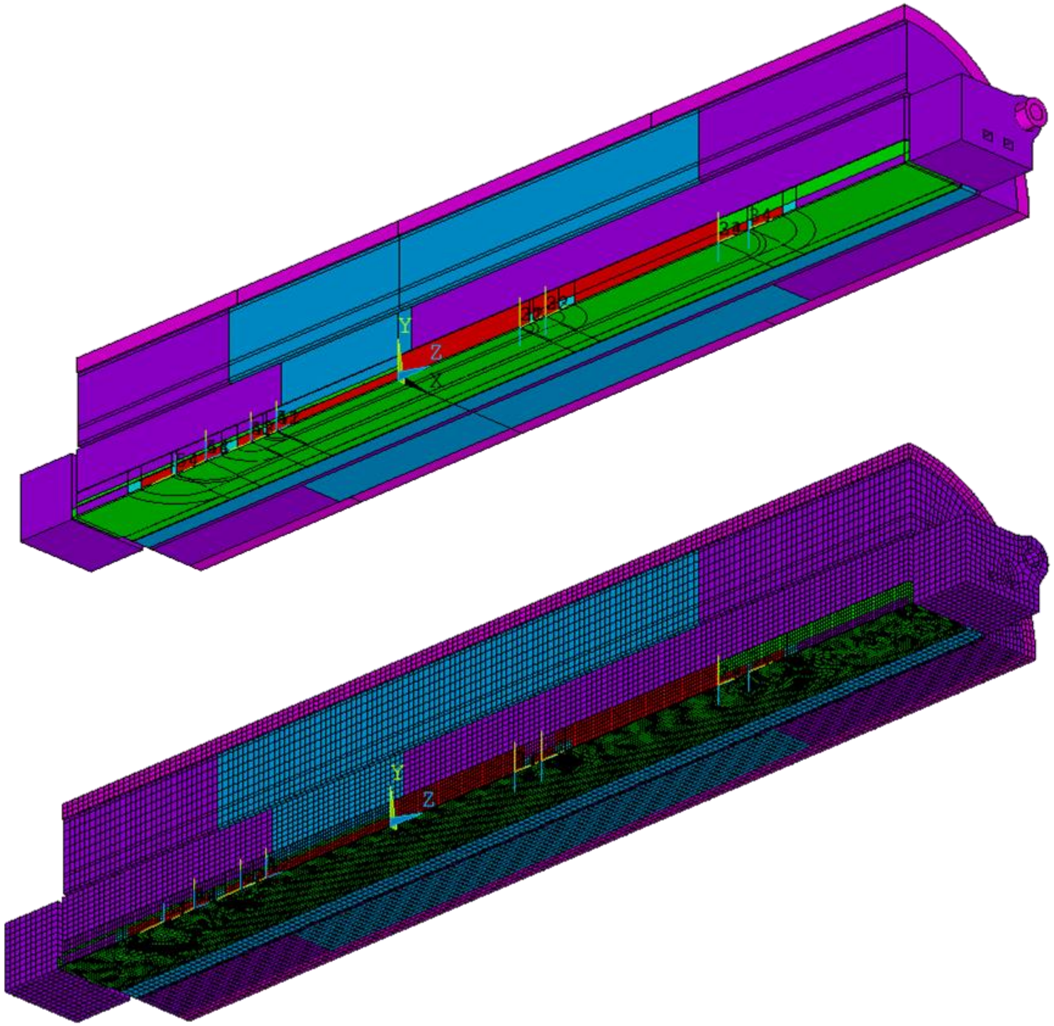
Several models:

- Return End model
- Lead End model
- Asymetric coils → Both ends modelled

→ All models consistent

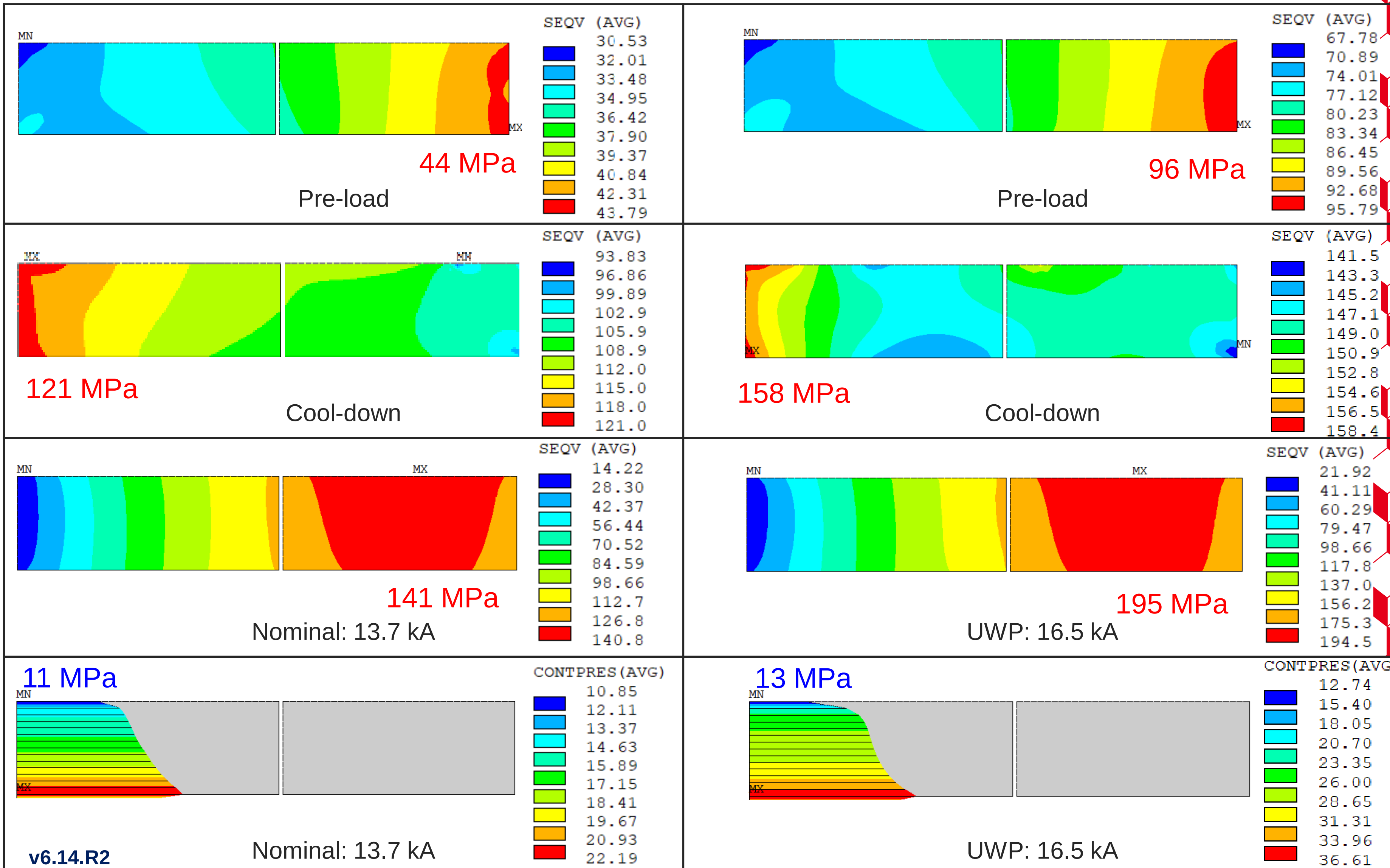


6p14pR2, 2D Mechanical

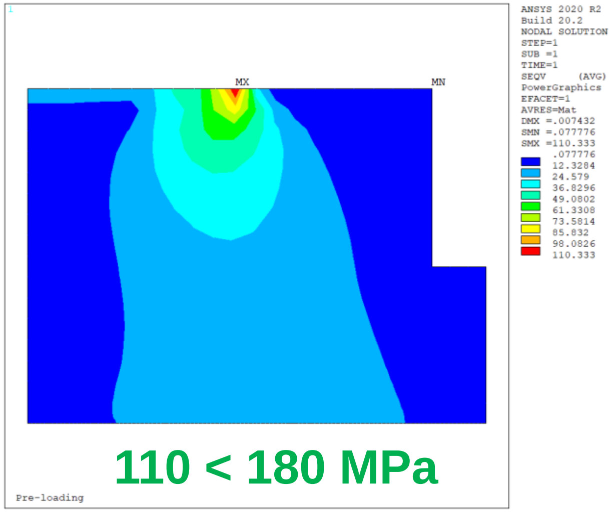


Version 6p14_R2, 3D Mechanical

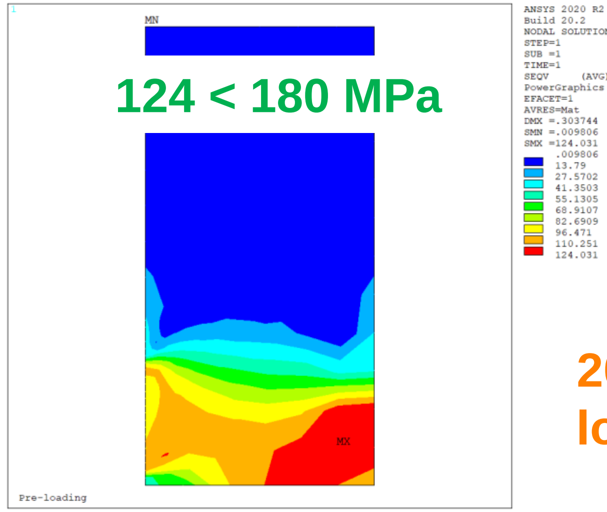
Peak stress in coil and Contacts (Nom.+UWP)



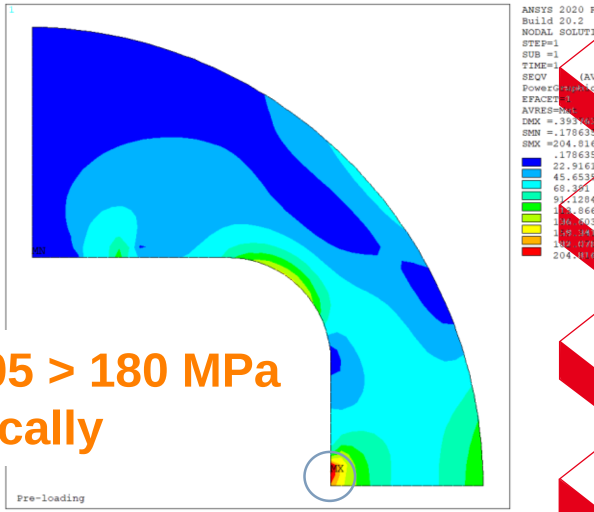
Peak stresses in structure (SS 1.9 K)



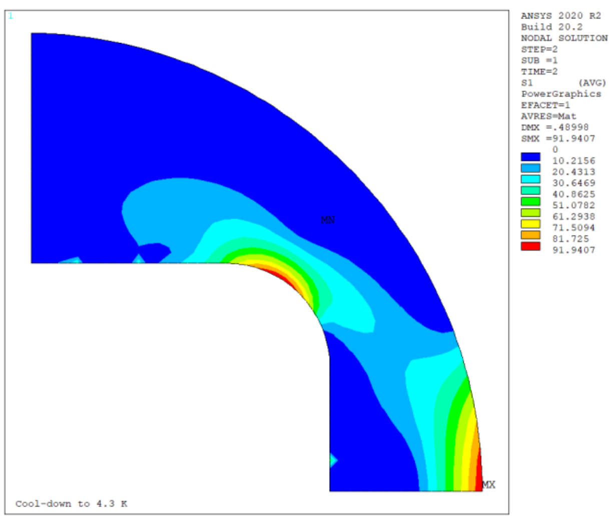
110 < 180 MPa



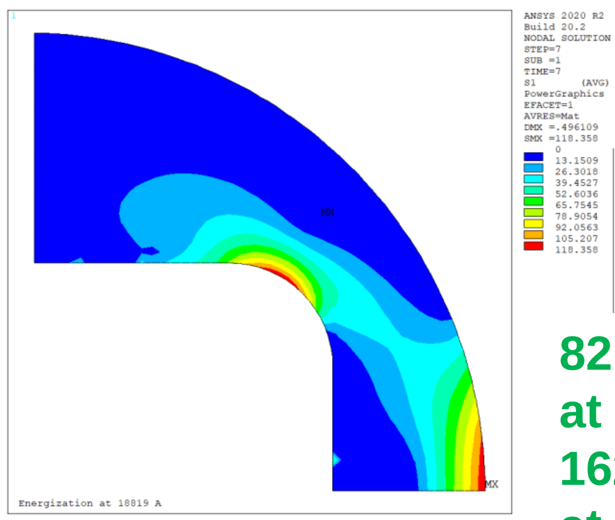
124 < 180 MPa



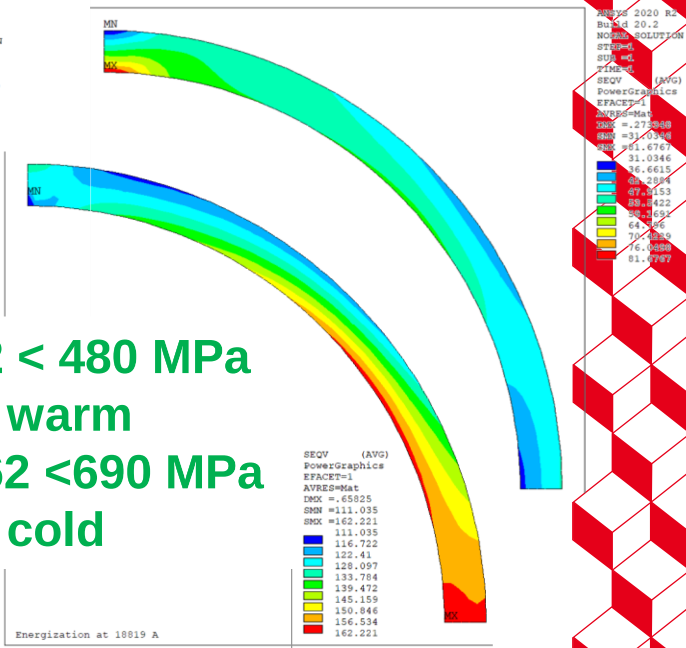
205 > 180 MPa locally



S1 = 92 < 200 MPa at cold

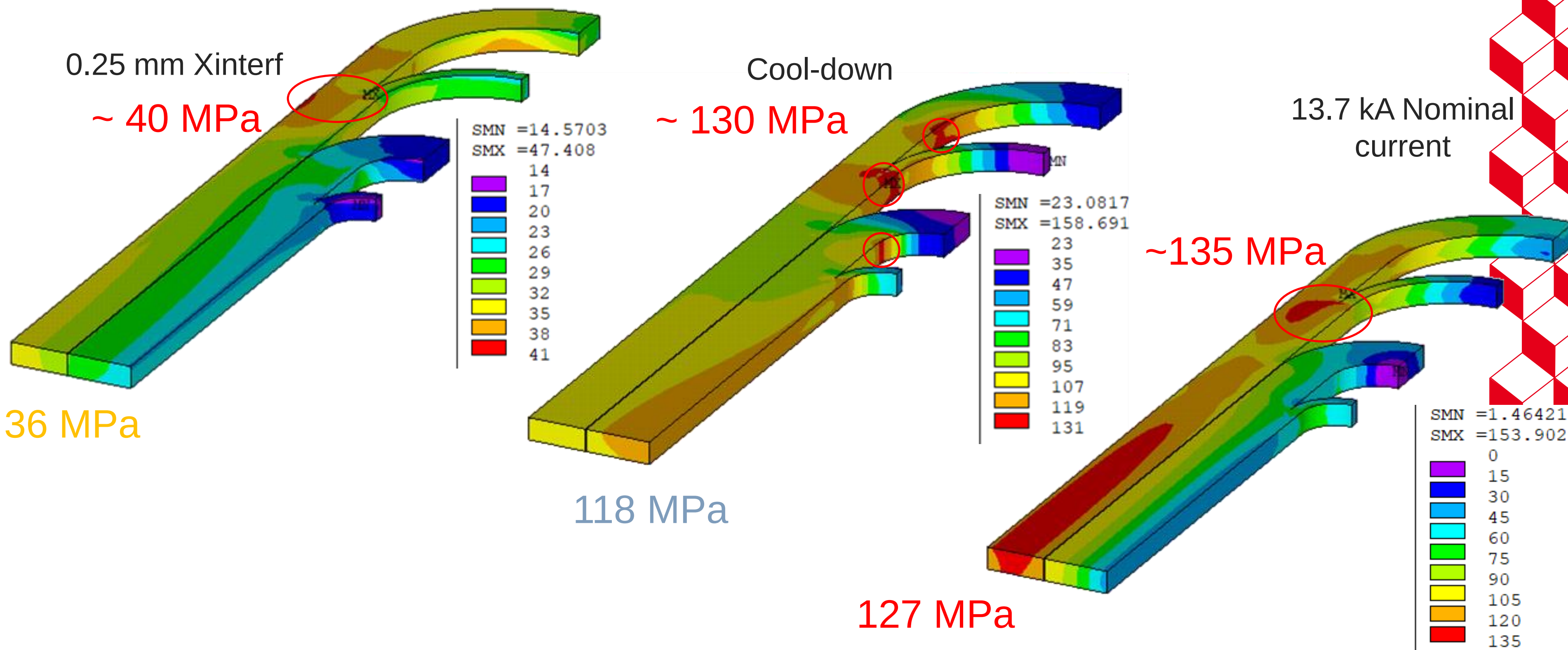


S1 = 118 < 200 MPa at SS



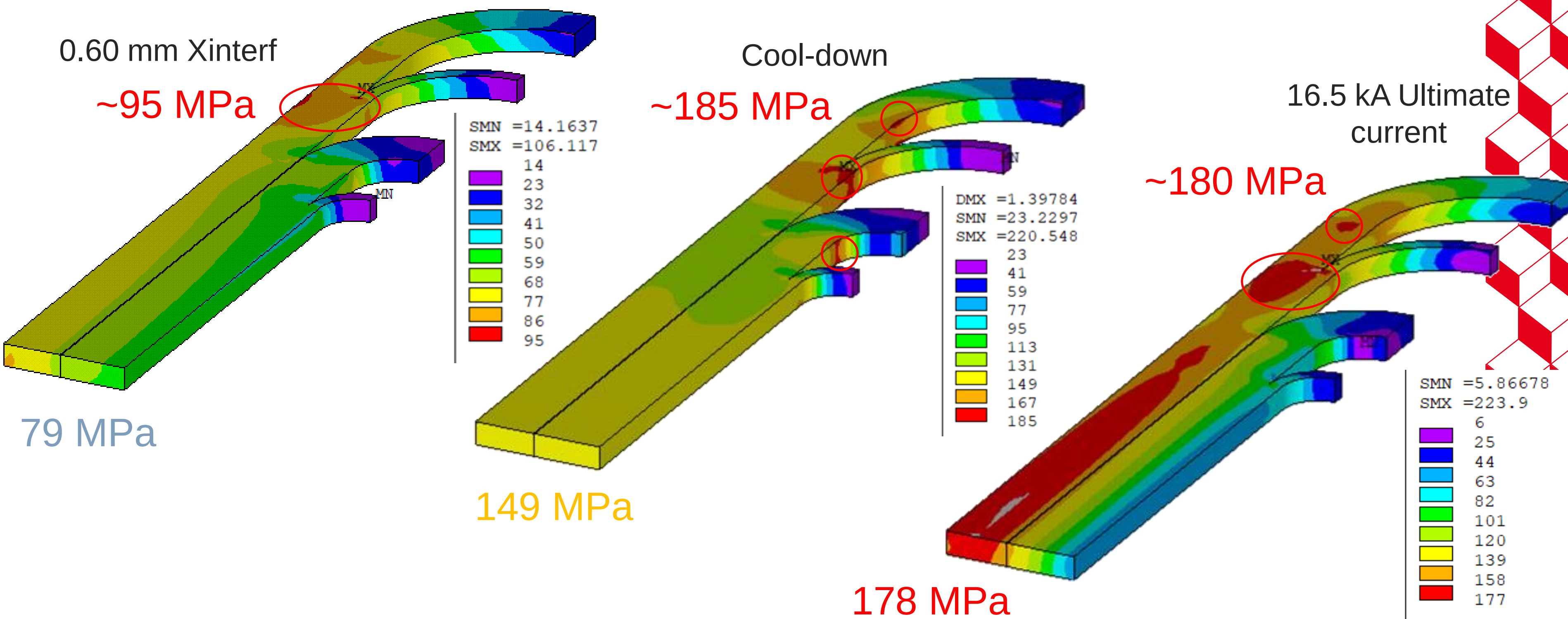
82 < 480 MPa at warm
162 <690 MPa at cold

VM Stress – 3D (Nominal)



- Higher stresses in coil-ends than in straight section
- Peak stress still < 150 MPa at Nominal

VM Stress – 3D (Ultimate)

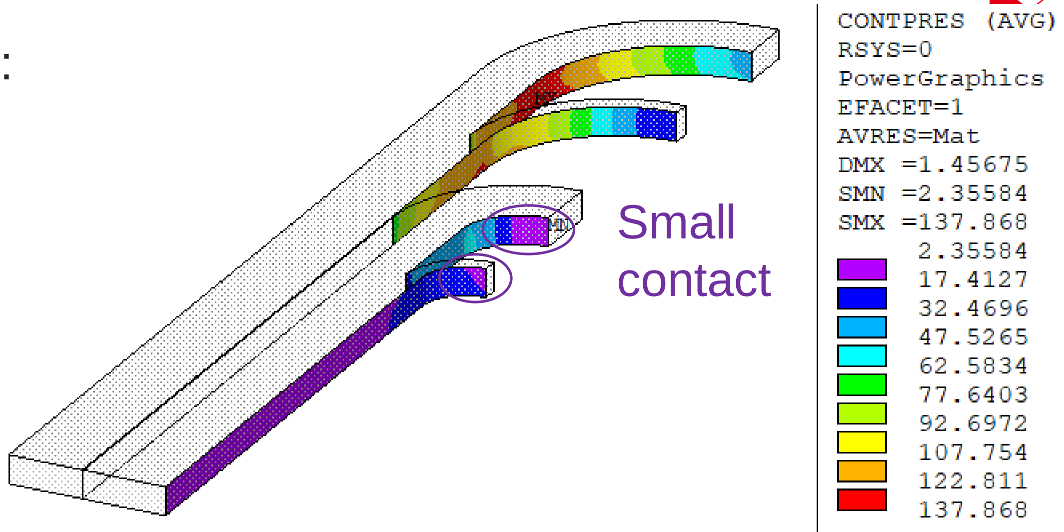


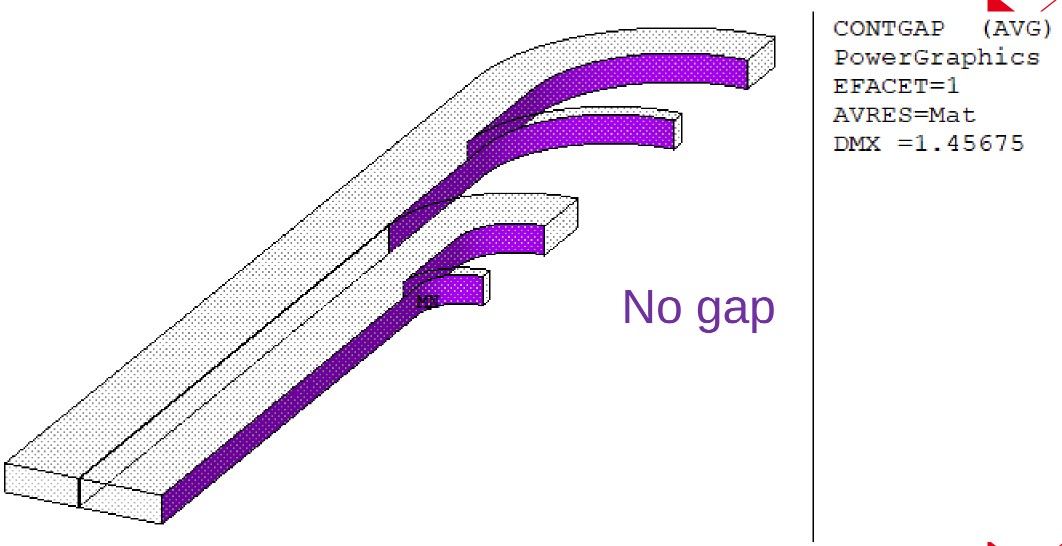
- Higher stresses in coil-ends than in straight section
- Peak stress still < 200 MPa at ultimate

Pole contact pressure – 3D (Nominal)

- Lorentz forces @ **Nominal** current:
  $F_{z,mag}$ = 350 kN /end
- Xpreload: 0.25 mm interf.
- Z Preload:
  - warm: 400 kN = 115 % $F_{z,mag}$
  - Cold: 641 kN **= 183 % $F_{z,mag}$**

→ Small >0 contact in the ends with relatively high pre-load



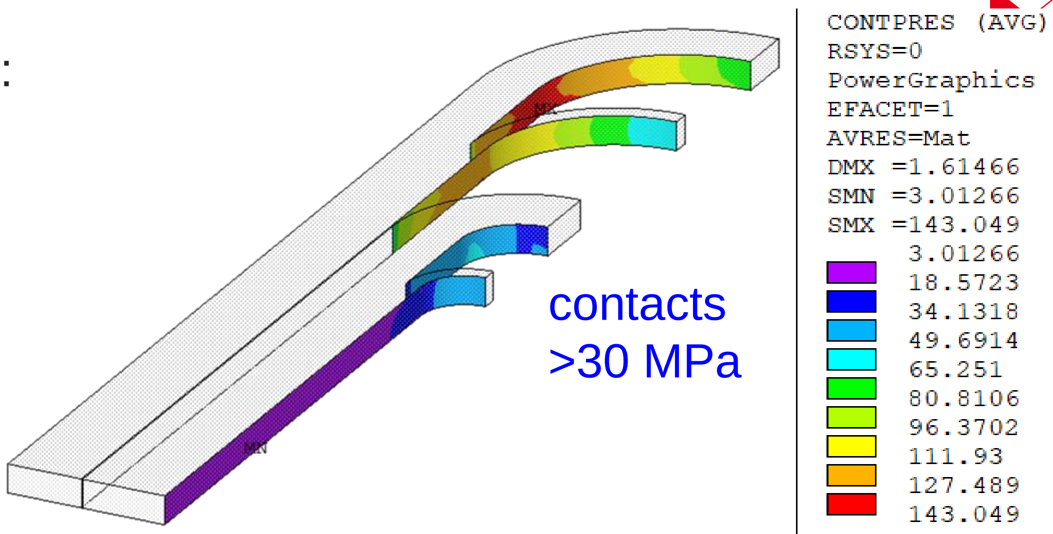


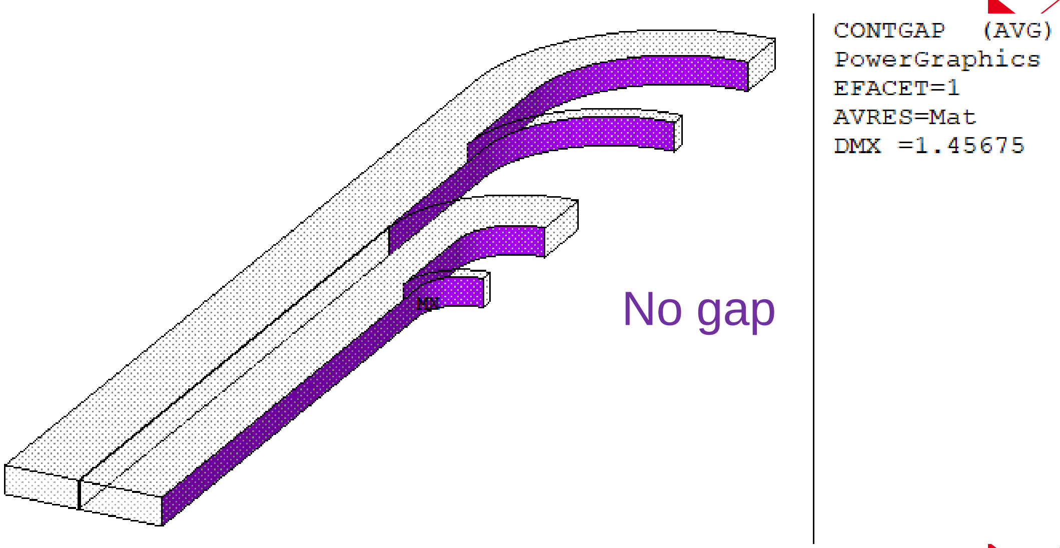
Goals of the longitudinal support:
1. Positive contact pressure
2. Stress < criteria

Pole contact pressure – 3D (+ZPreload)

- Lorentz forces @ **Nominal** current: $F_{z,mag}$ = 350 kN /end
- Xpreload: 0.25 mm interf.
- **Increasing Z Preload +40%**:
  - warm: 529 kN = 151 % $F_{z,mag}$
  - Cold: 783 kN **= 224 % $F_{z,mag}$**

→ contacts >0 in the ends if very high pre-load

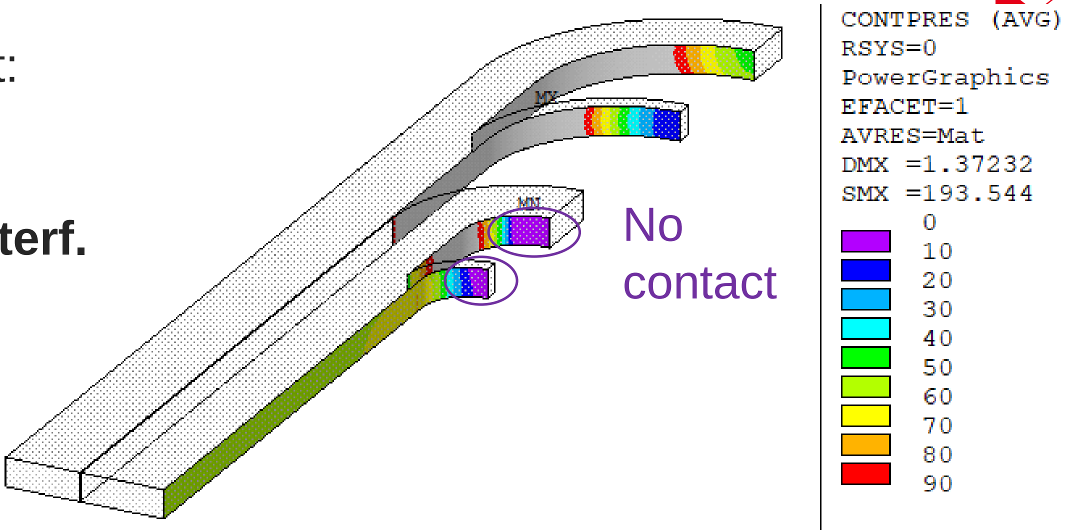


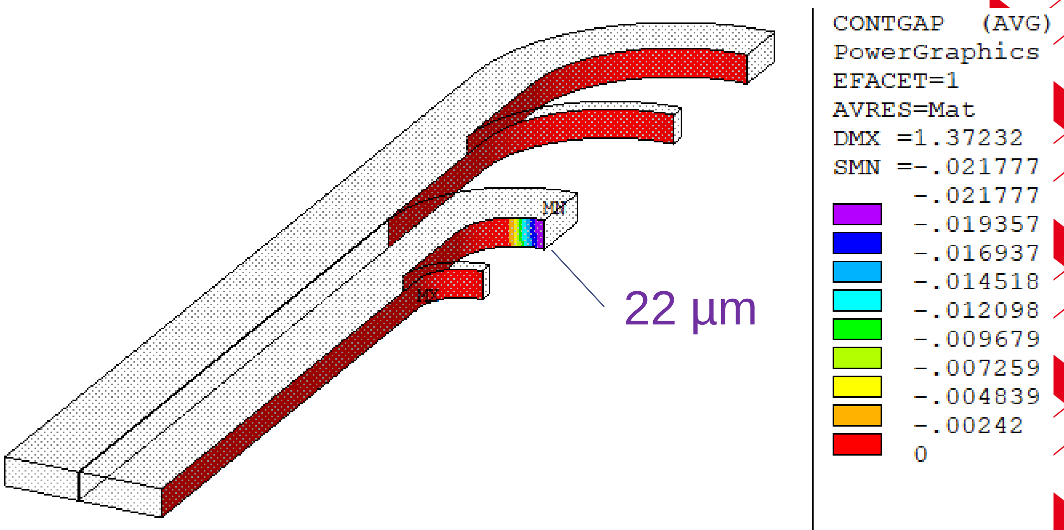


Pole contact pressure – 3D (+X+ZPreload)

- Lorentz forces @ **Nominal** current: $F_{z,mag}$ = 350 kN /end
- **Increasing X preload: 0.6 mm interf.**
- **Increasing Z Preload**:
  - warm: 565 kN = 162 % $F_{z,mag}$
  - Cold: 831 kN **= 238 % $F_{z,mag}$**

→ But: contacts lost if transverse pre-load is too high

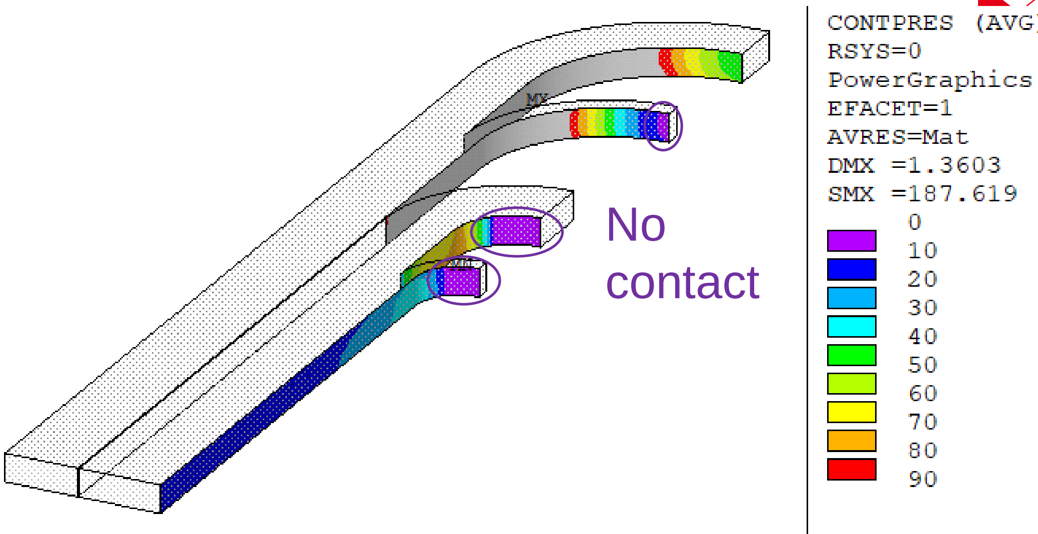


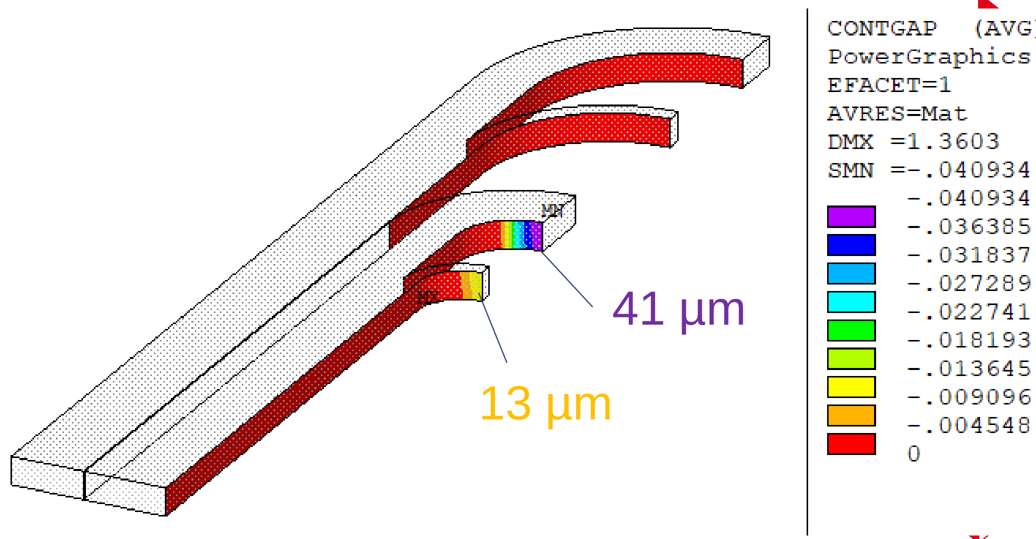


Pole contact pressure – 3D (Ultimate)

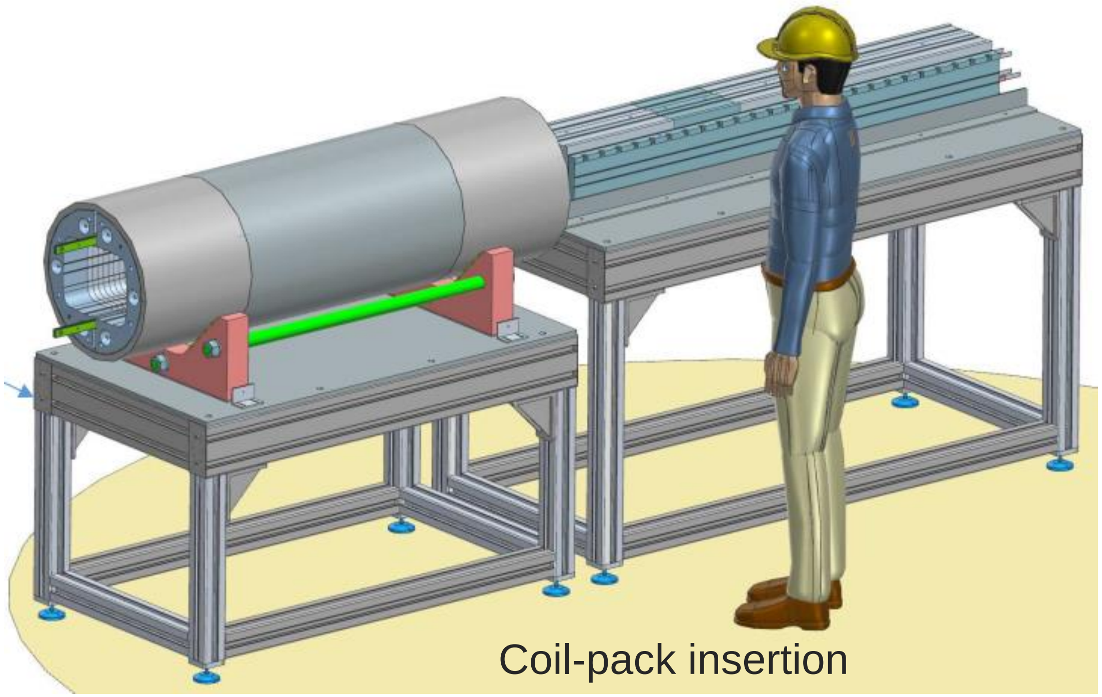
- Lorentz forces @ **Ultimate** current: $F_{z,mag}$ = 477 kN /end
- X preload: 0.6 mm interf.
- Z Preload:
  - warm: 565 kN = 119 % $F_{z,mag}$
  - Cold: 831 kN **= 174 % $F_{z,mag}$**

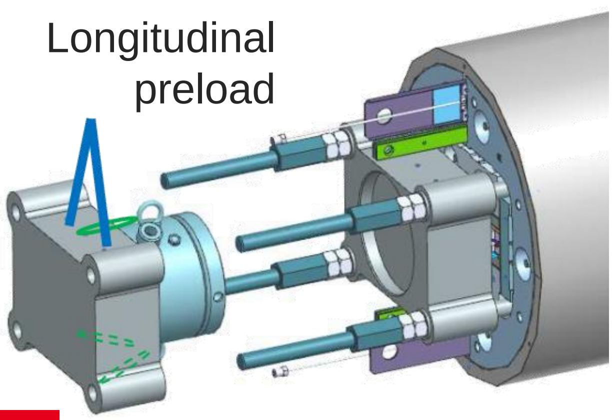
→ Need to considerably increase the pre-load to guarantee full contact in the ends

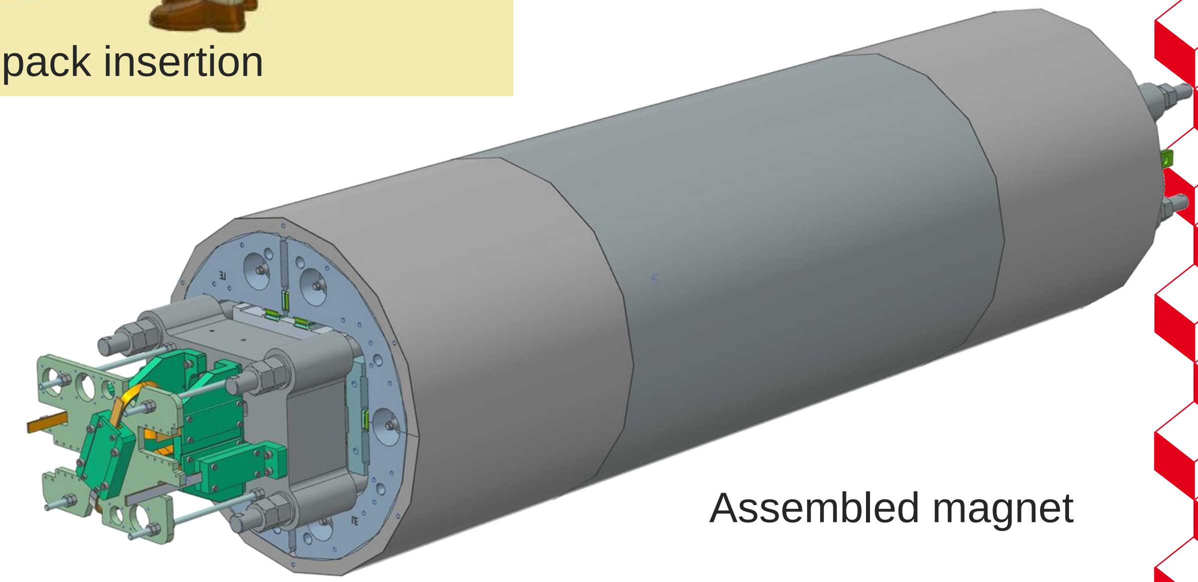




Detailed engineering design





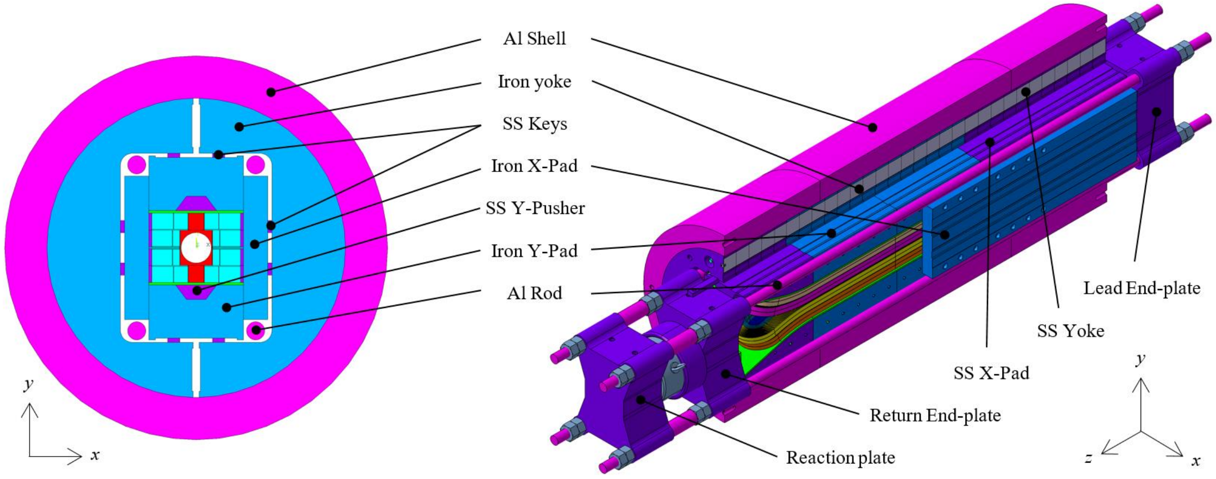


3. FD/F2D2

Overview of the F2D2 design

- **Conceptual design done, detailed engineering started**
- Fabrication, assembly and pre-stress at Saclay
- Tests at cold at CERN
- **Main goal: demonstrate all technologies**
  - Representative of high field magnets: grading, joints, flared-ends, high field and high stress
  - Representative of accelerator magnets: 50 mm bore, field quality

F2D2 = **F**uture **F**lared **D**ipole **D**emonstrator

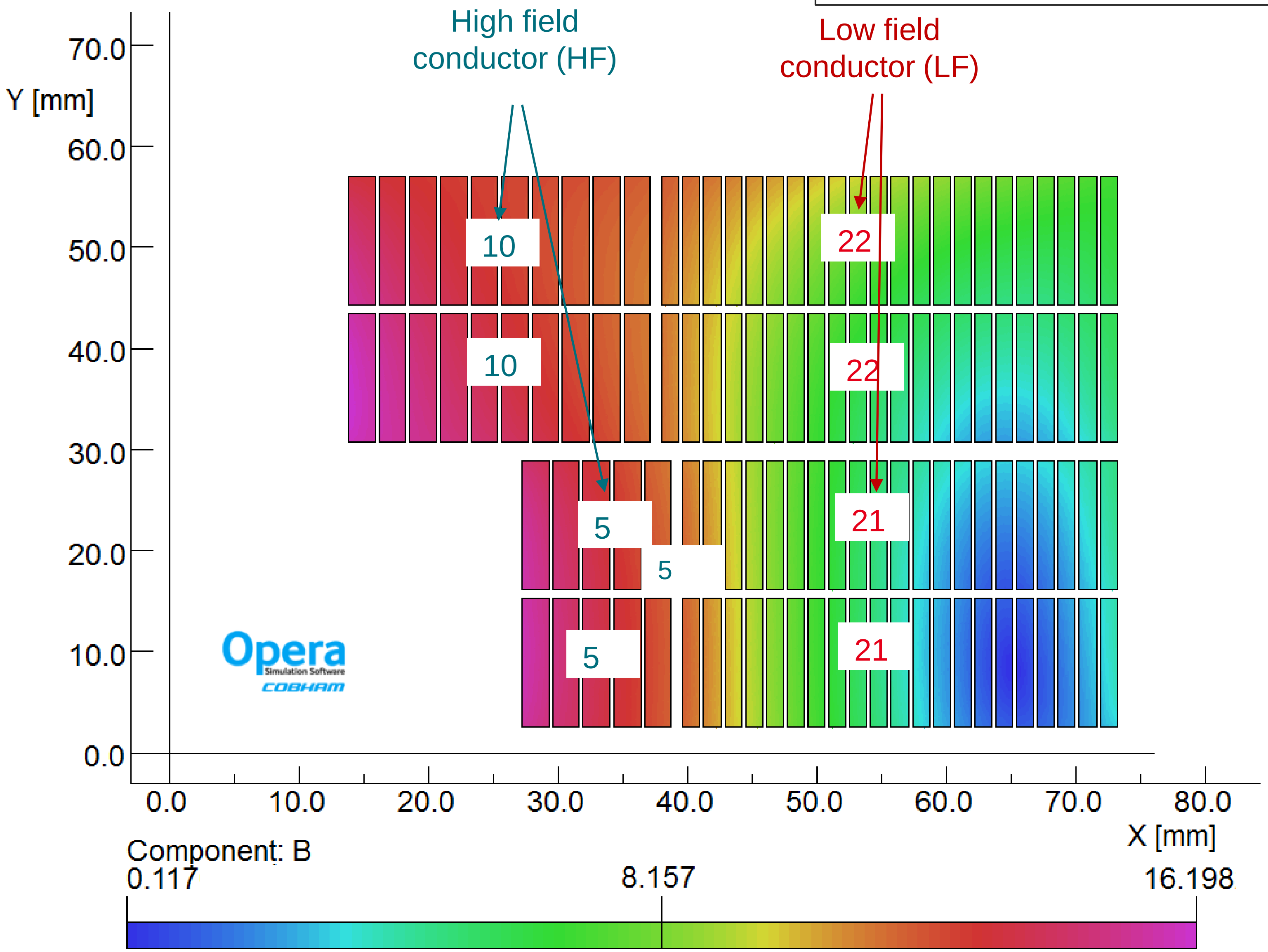


Aperture	50 mm
Outer diameter	650 mm
Structure length	2.0 m
Central field @76% LL	14.0 T
SS central field	17.8 T

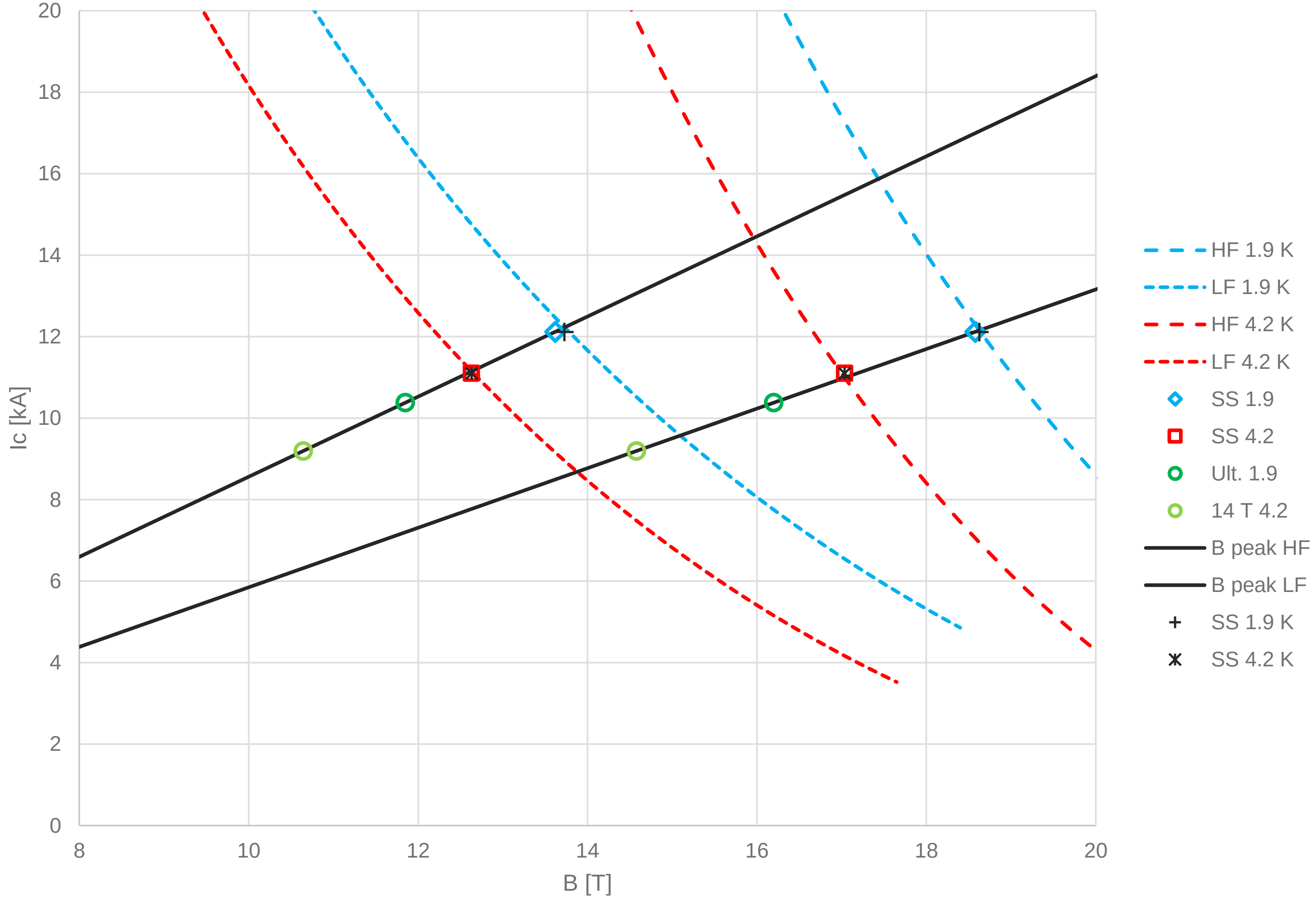
@1.9 K

2D magnetic design

X-section from EuroCirCol, minor adjustments



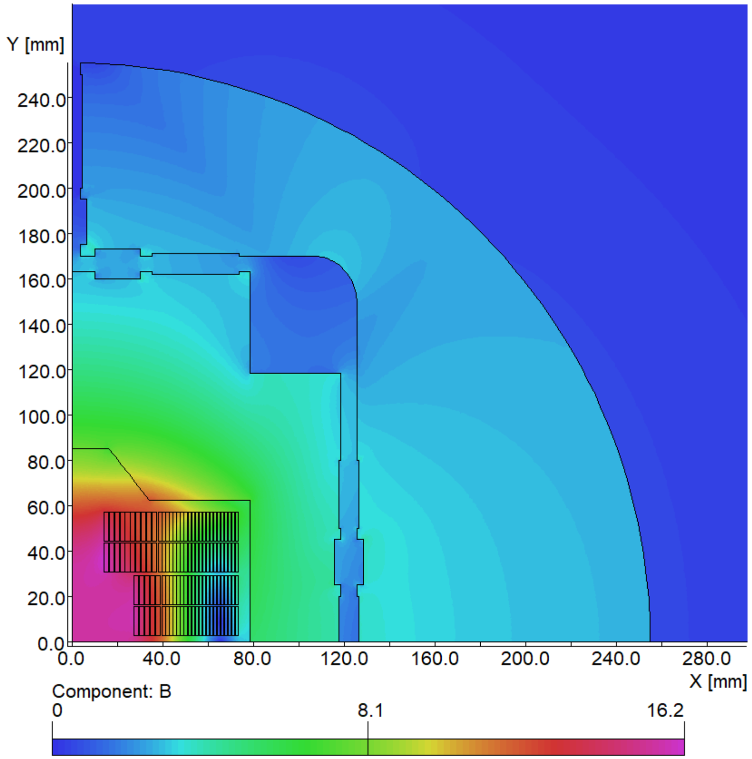
F2D2 Load-lines and margins

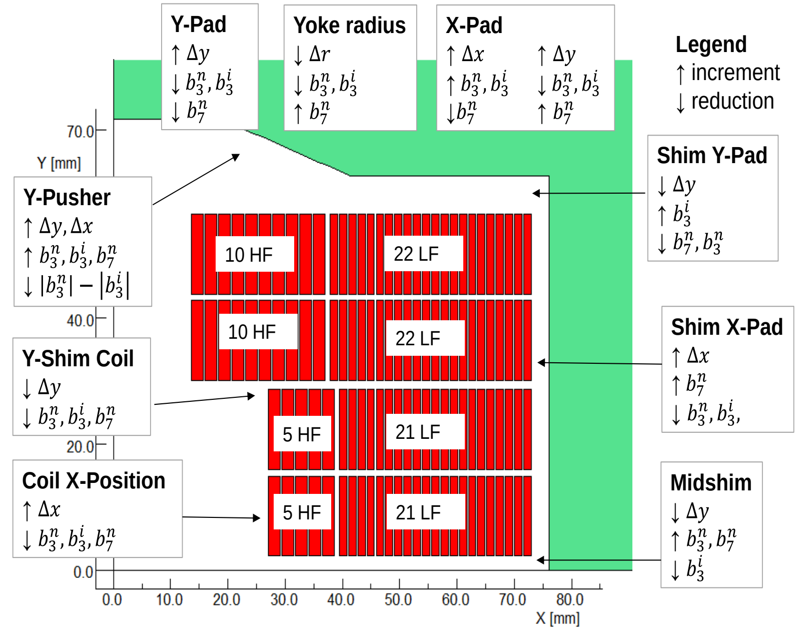


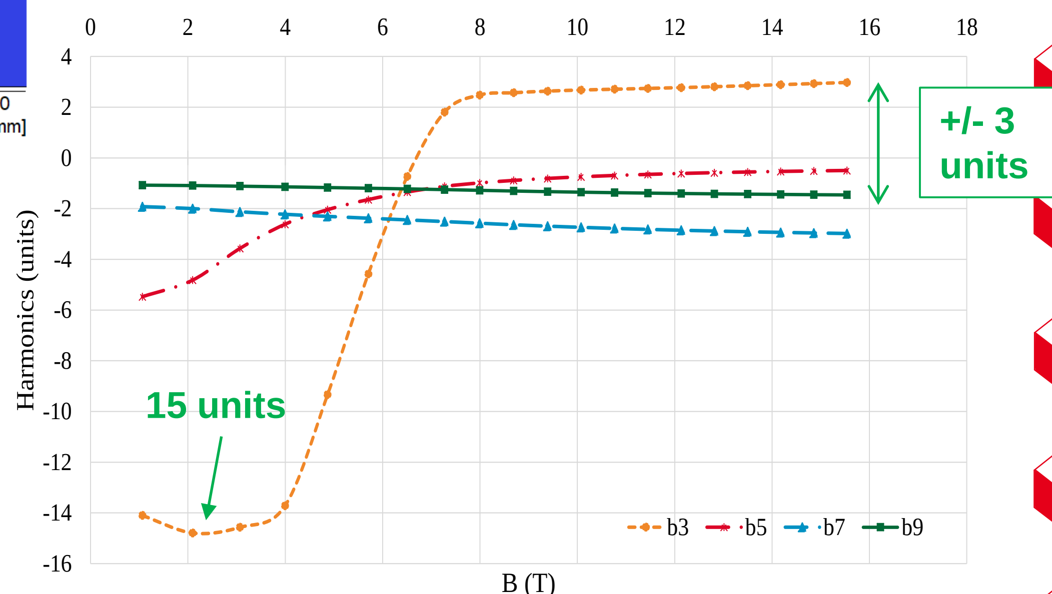
F2D2 Load-lines and margins

Operation	14 T operational	14 T operational	20 % margin	Ultimate	SS	SS	Unit
Temp	4.2	**1.9**	1.9	1.9	4.2	1.9	K
Current [kA]	9.2	**9.2**	9.7	10.4	11.1	12.1	kA
LL Margin HF	16.3	**24.3**	20.0	14.6	-1.0	0.3	%
LL Margin LF	17.5	**24.8**	20.5	15.1	0.4	0.9	%
B center	14.00	**14.00**	14.68	15.54	16.48	17.81	T
B peak HF	14.58	**14.58**	14.58	16.20	17.04	18.58	T
B peak LF	10.65	**10.65**	10.65	11.85	12.63	13.62	T
J block HF	298.8	**298.8**	315.8	337.2	360.7	393.8	A/mm2
J block LF	438.0	**438.0**	463.0	494.3	528.7	577.2	A/mm2
J Sc HF	837	**837**	885	945	1010	1103	A/mm2
J Sc LF	1870	**1870**	1977	2111	2258	2465	A/mm2
J Cu HF	930	**930**	983	1050	1123	1226	A/mm2
J Cu LF	1039	**1039**	1098	1173	1254	1369	A/mm2
Energy	1.1	**1.1**	1.2	1.4	1.6	1.9	MJ/m
Inductance				26.0			mH/m

2D magnetic design



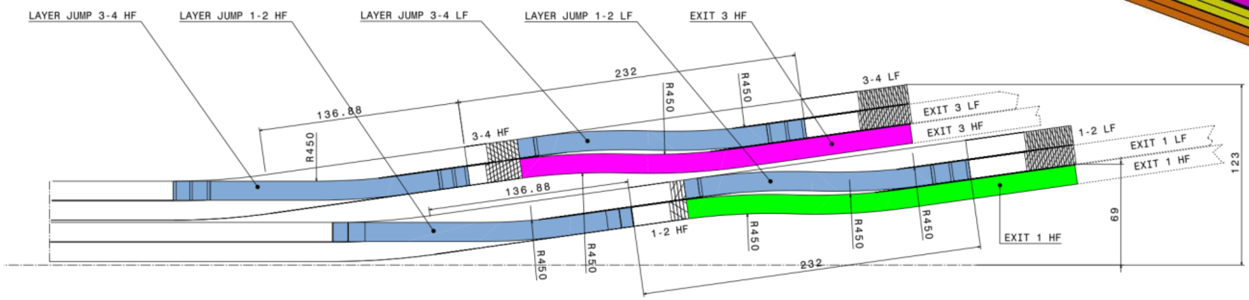


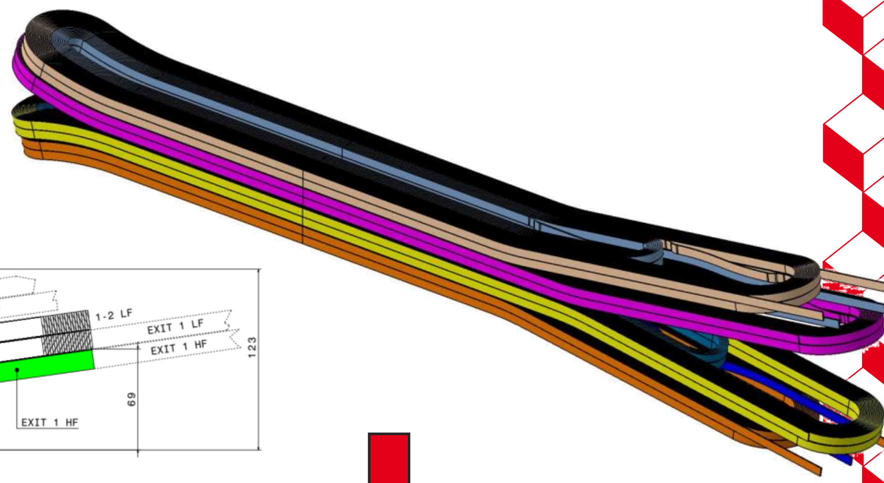


Harmonics representative of an accelerator magnet

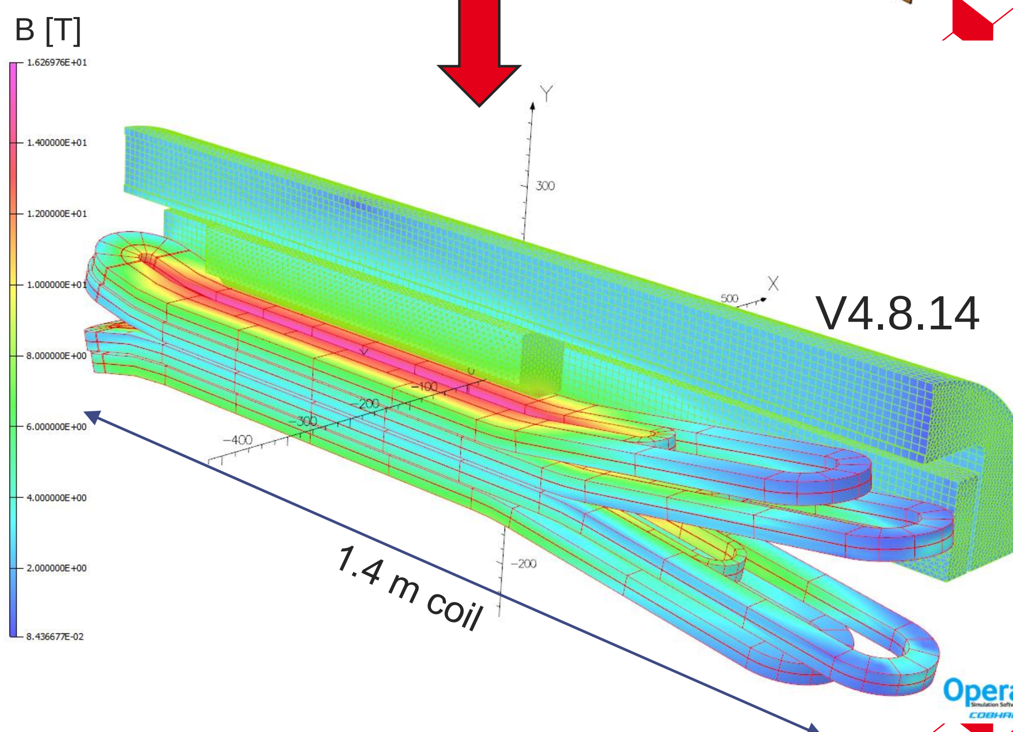
3D magnetic design

1. **Preliminary CAD** model of the coils





2. **3D simplified Opera FEM**:

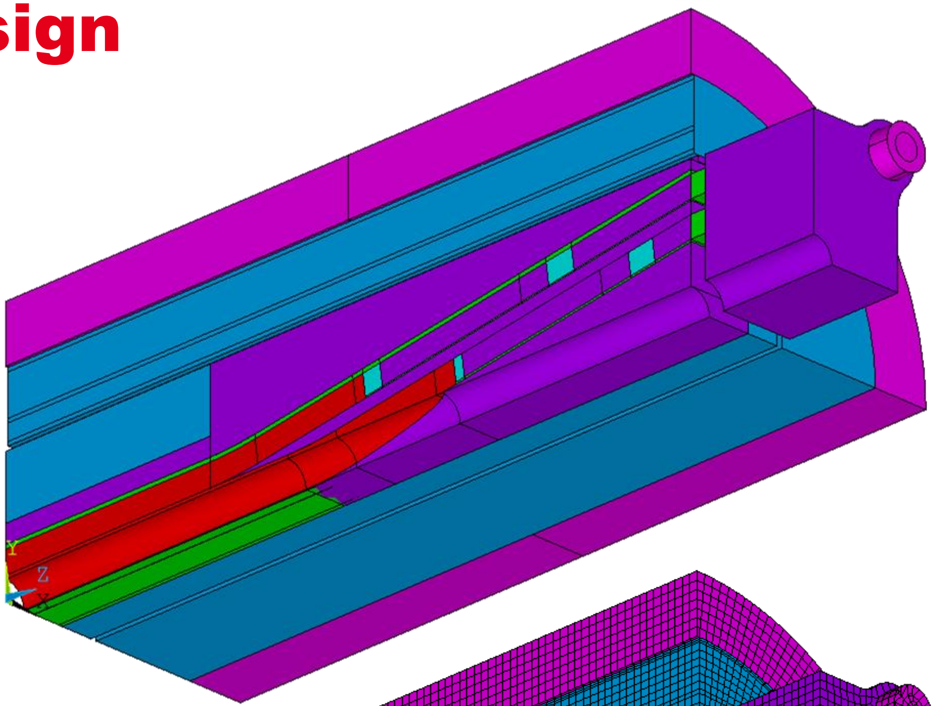


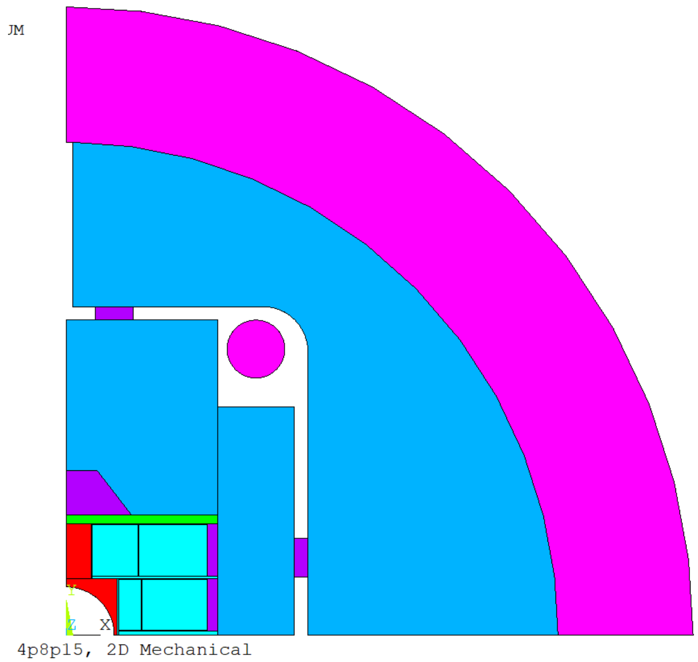
a. Central field:
- Magnetic Length = 1042 mm
- Uniform field (±1%) = 249 mm

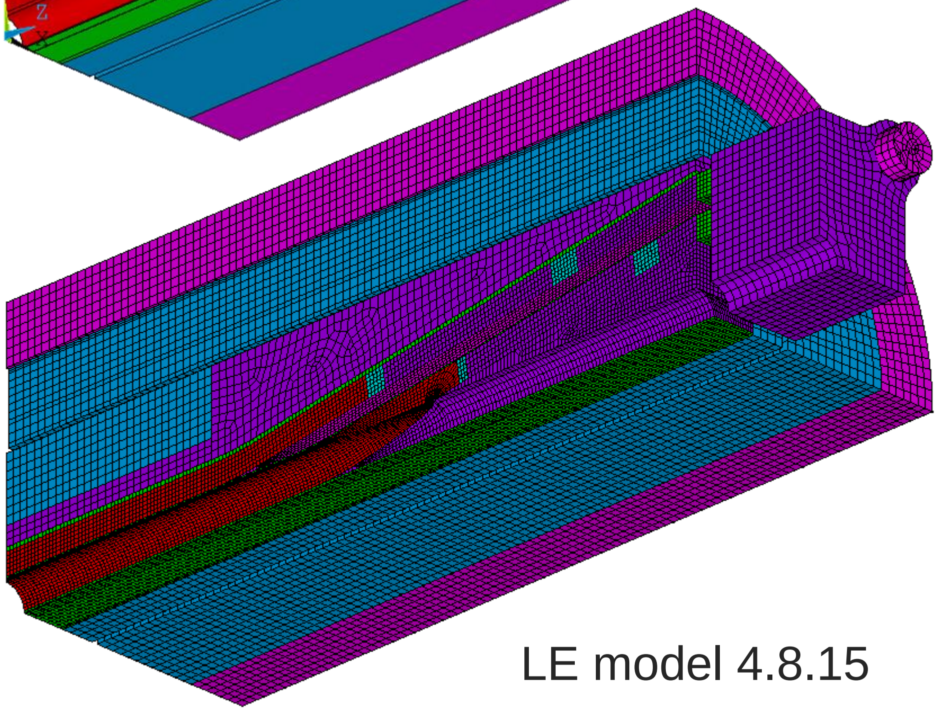
b. Field in critical areas:
- ✓ **Field in the layer jumps < 14 T**
- Advantage of flared ends:
- ✓ **Peak field not in coil-ends**

3D mechanical design

2 models:
- RE model
- LE model





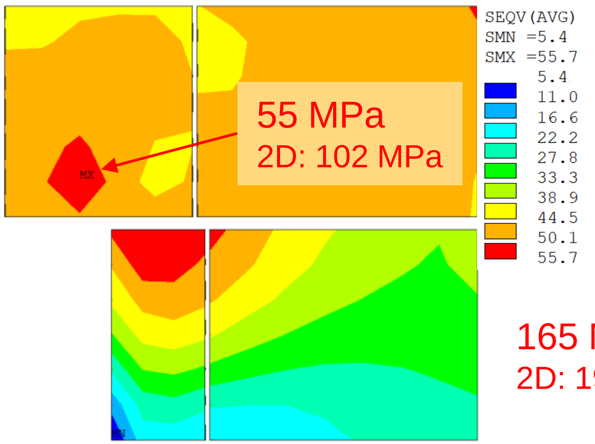


LE model 4.8.15

3D mechanical design – stress at z = 0

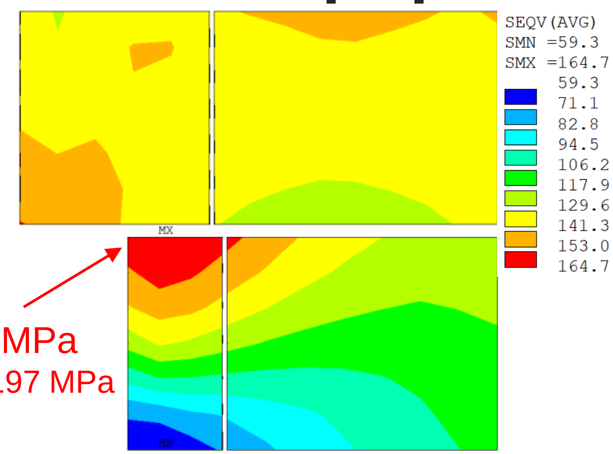
- 0.6 mm interference

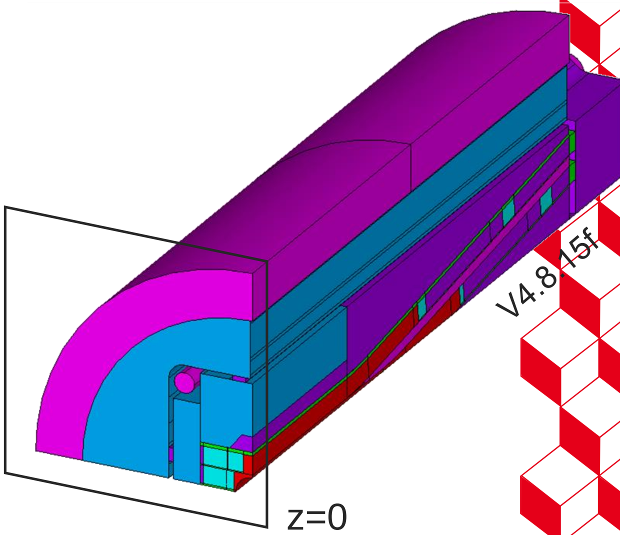
σ Von Mises [MPa]



- 1.9 K

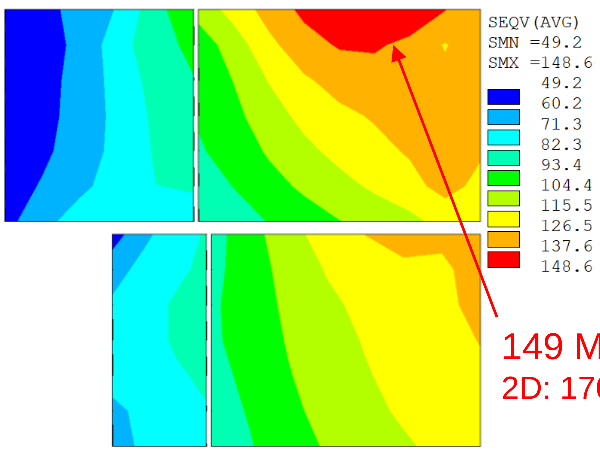
σ Von Mises [MPa]



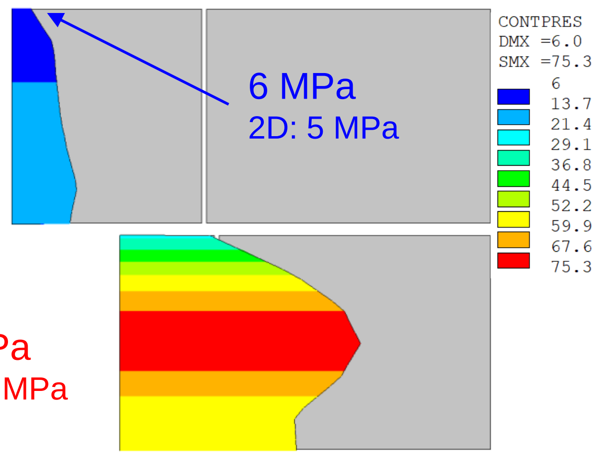


- Ultimate operations: 10.4 kA, 14% margin, **15.5 T**

σ Von Mises [MPa]



Contact pressure [MPa]



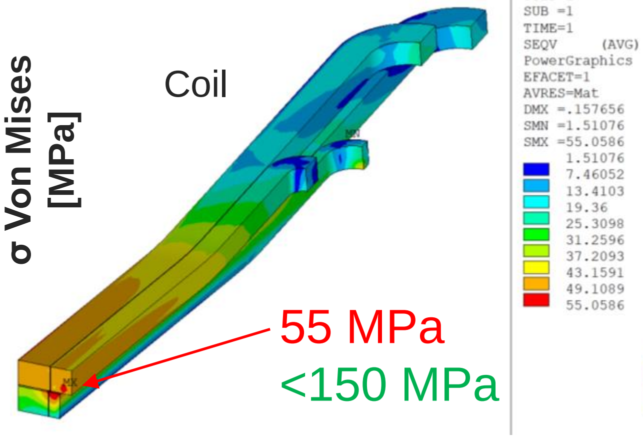
- Verified consistency with 2D model at z=0
- Coil peak stress within targets at z=0
- Next step: estimate stress-induced current limit with 3D stress [5]

[5] E. Rochepault et al., "Computation of Current Limits in Nb3Sn Superconducting Magnets Using Magnetic Field and Stress" to be published in IEEE TAS.

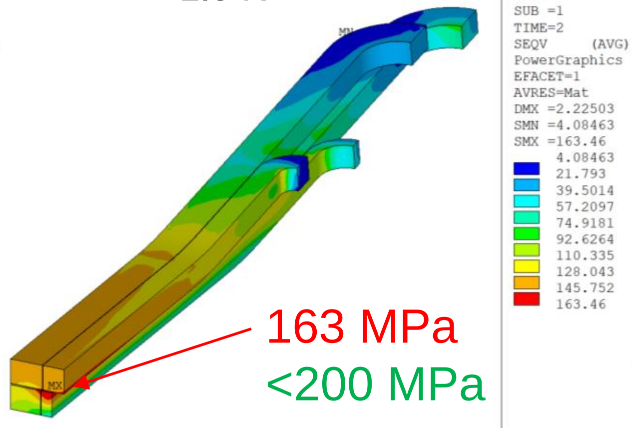
3D Mechanical Design - Stress

σ Von Mises [MPa]

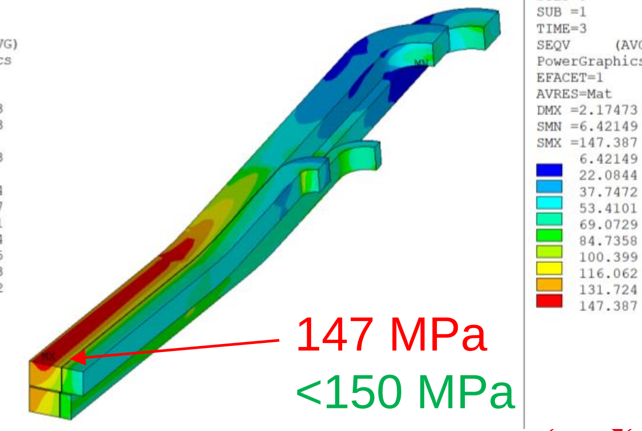
- 0.6 mm interference



- 1.9 K

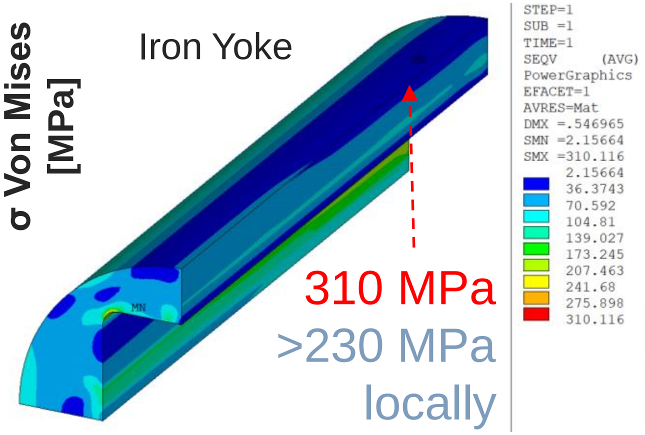


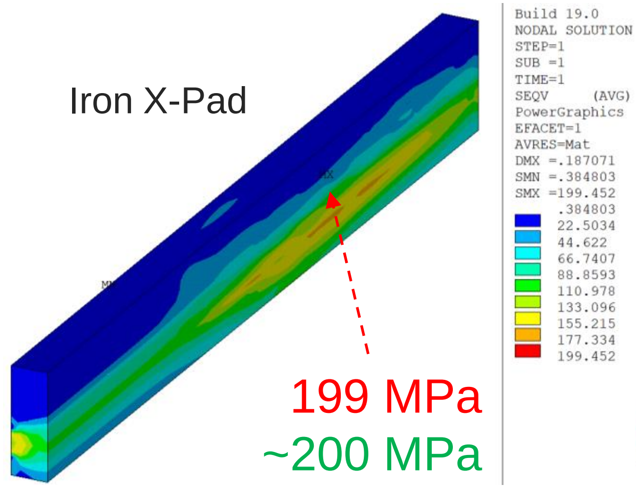
- 15.5 T

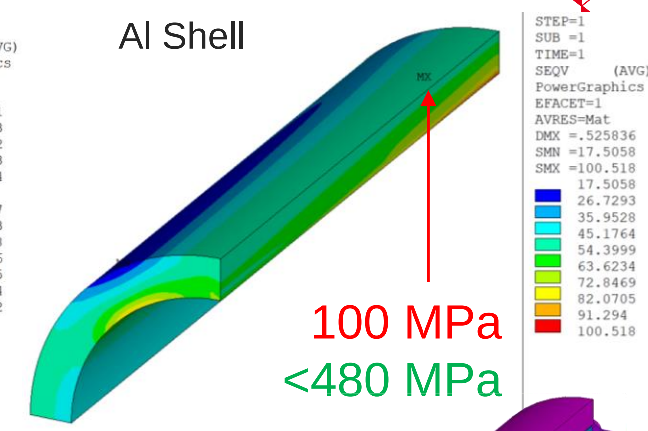


σ Von Mises [MPa]

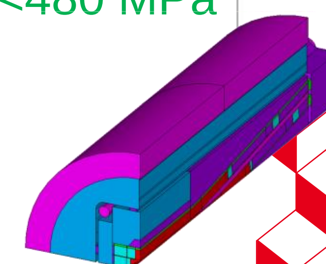
- 0.6 mm interference





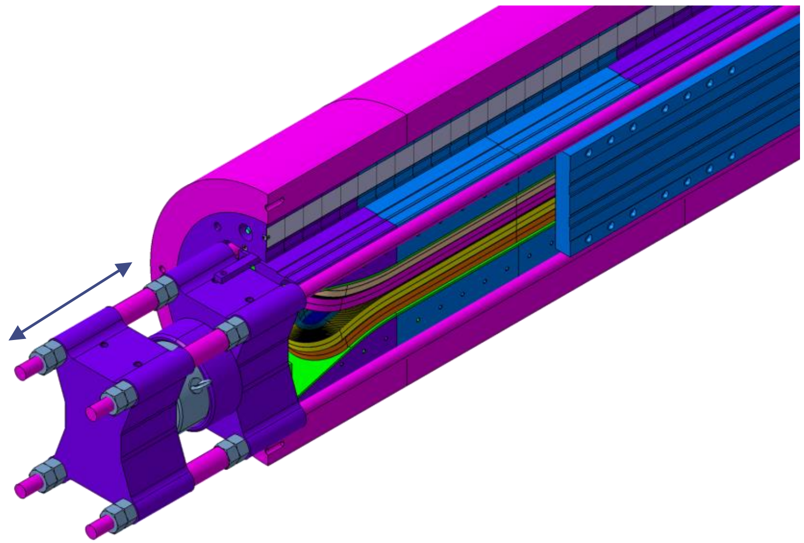


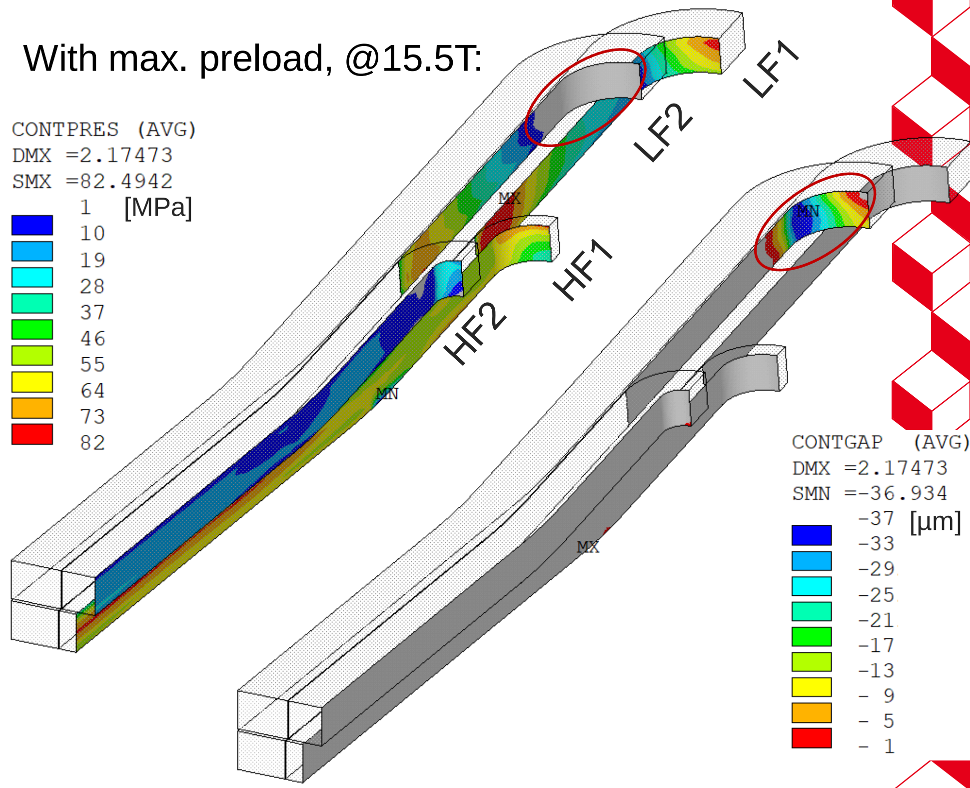
- Peak stress in coil and critical components within targets
- Accepted local plasticization of the iron yoke



3D Mechanical Design – Longitudinal Preload

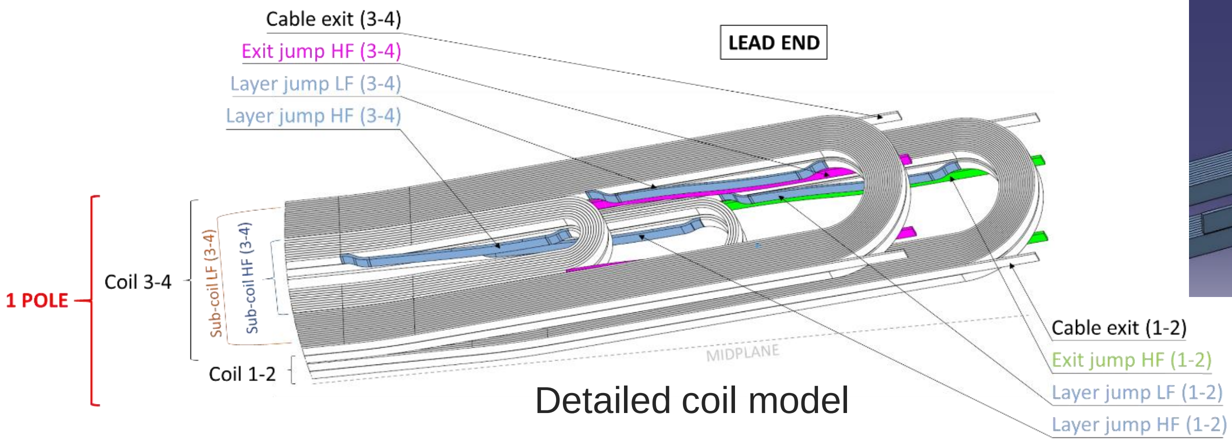
	Rod, Pre-load		Rod, Cool-Down		Contact pressure at 15.5 T [MPa]			
	F_z [%]	S_z [MPa]	F_z [%]	S_z [MPa]	HF1	LF1	HF2	LF2
Criterion	<109	<480	<157	<690	>0	>0	>0	>0
Min. preload	4	15	33	146	9	0 (no gap)	0 (no gap)	0
100% of EM forces	64	281	100	440	29	1	0 (no gap)	0
Max. preload	109	480	151	662	45	4	1	0



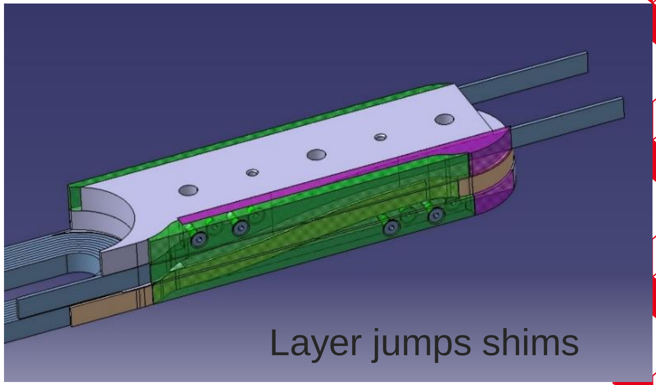


- Longitudinal preload tuned with the tie-rods, up to 150 % if necessary
- Difficult to maintain contact in LF2

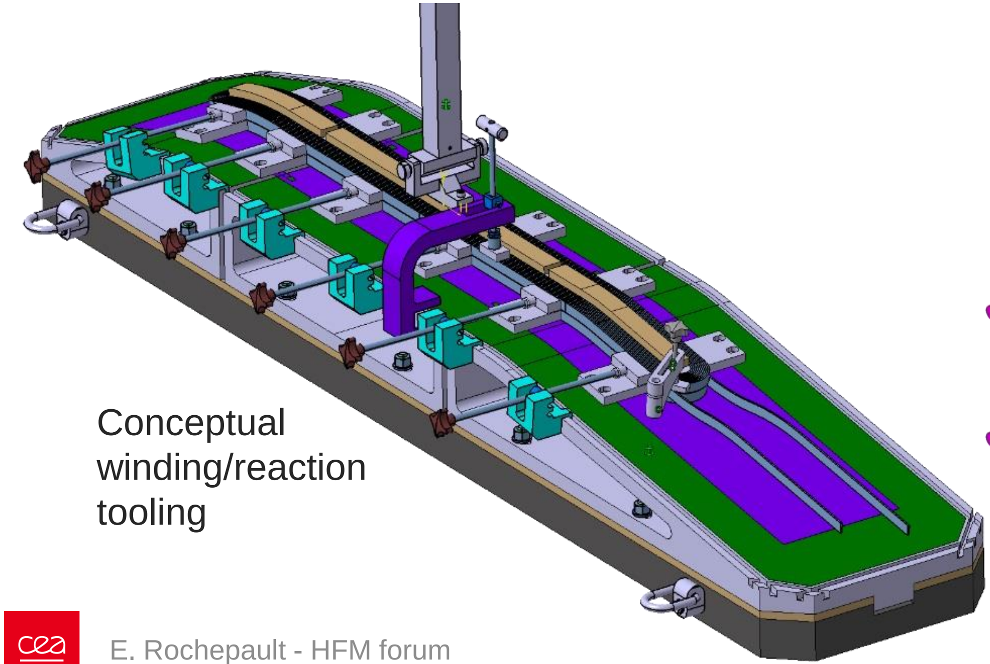
Conceptual engineering design



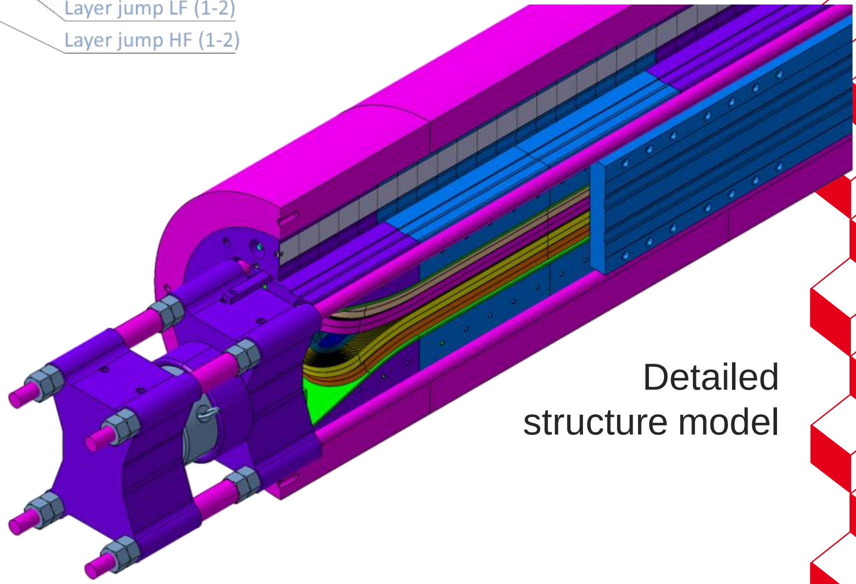
Detailed coil model



Layer jumps shims



Conceptual winding/reaction tooling

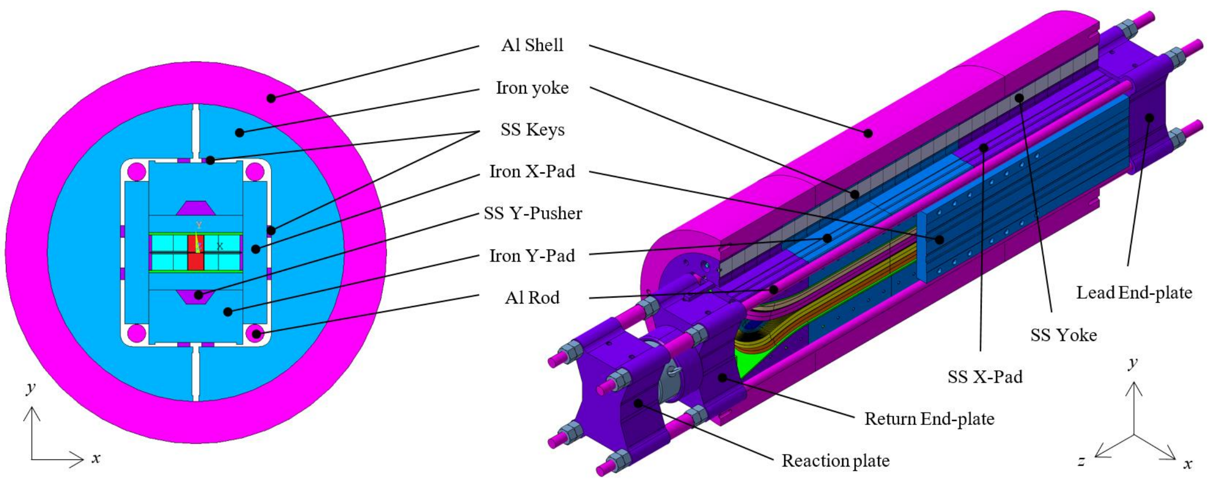


Detailed structure model

Overview of the FD design

- **FD = Intermediate assembly of F2D2, only layers 3-4**
- Fabrication, assembly and pre-stress at Saclay
- Tests at cold at CERN
- **Main goal: demonstrate key technologies**
  - Representative of high field magnets: grading, joints, flared-ends, high field and high stress
  - Some simplifications: 1 type of coils, no bore

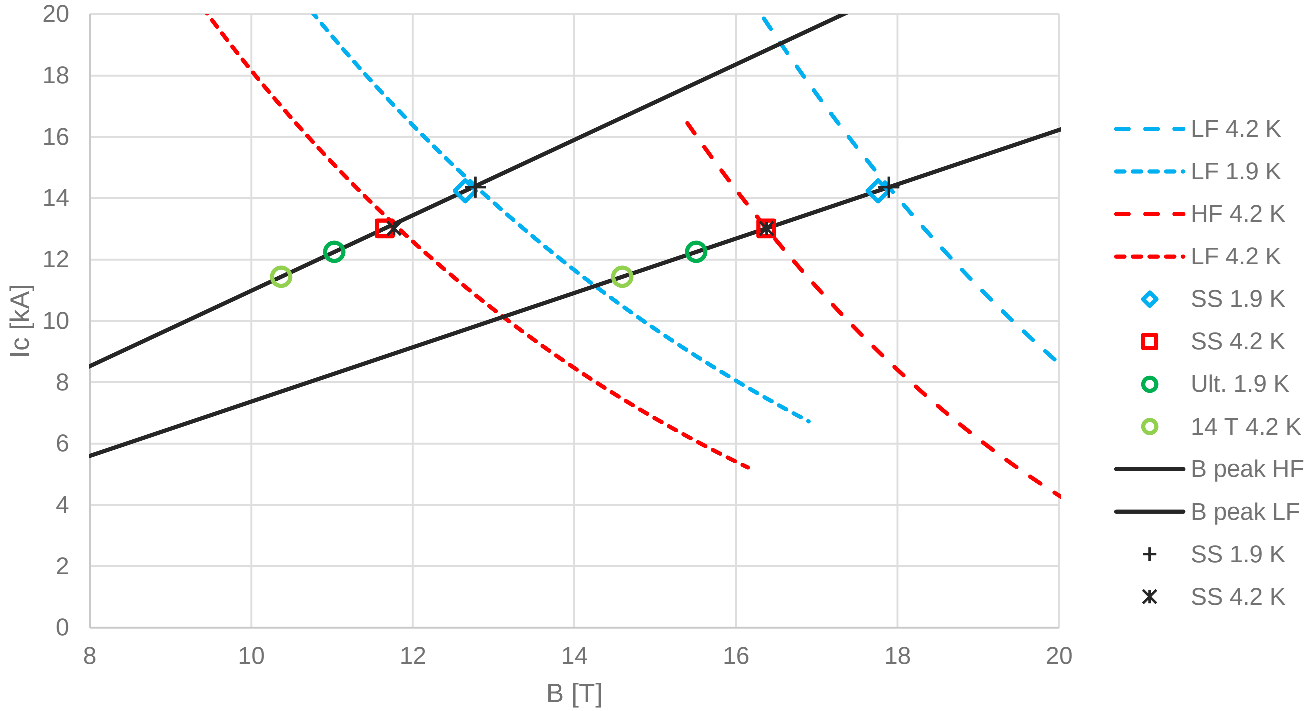
FD = **Fl**ared **D**ipole



Aperture	None
Outer diameter	650 mm
Structure length	2.0 m
Central field @84% LL	14.0 T
SS central field	16.6 T

@1.9 K

FD Load-lines and margins



Operation	14 T operational	14 T operational	Ultimate	SS	SS	Unit
Temp	4.2	**1.9**	1.9	4.2	1.9	K
Current [kA]	11.4	**11.4**	12.2	13.0	14.4	kA
LL Margin HF	12.1	**20.3**	14.7	0.0	0.0	%
LL Margin LF	13.0	**20.5**	14.9	1.0	0.2	%
B center	14.00	**14.00**	14.87	15.70	17.14	T
B peak HF	14.60	**14.60**	15.51	16.38	17.89	T
B peak LF	10.37	**10.37**	11.03	11.66	12.75	T
J block HF	371.7	**371.7**	398.0	423.0	466.7	A/mm2
J block LF	544.9	**544.9**	583.4	620.1	684.1	A/mm2

Conclusion: plan towards ultimate-field Nb_3Sn

1. R2D2 as a 1st demonstrator
   - Demonstrator for **grading in block-coils**
   - Simplified design → **single-layer, flat racetracks, no bore**
   - ~12 T @1.9 K with 20 % margin on the load-line
   - **Fabrication of the coils ongoing**

2. FD as an intermediate assembly
   - Demonstrator for **grading with flared-ends**
   - Only coils layers 3-4 → **double-layer coils with layer jumps, no bore**
   - 14 T @1.9 K with 20 % margin on the load-line
   - **Detailed engineering design started**

3. F2D2: the final goal
   - Demonstrator for **accelerator magnets**
   - **double-layers coils with layer jumps, grading, 50 mm bore, field quality**
   - 14 T @1.9 K with 25 % margin on the load-line
   - 15.5 T @1.9 K with 15 % margin on the load-line
   - **Conceptual engineering design finalized**

Merci !
Thank you !

▪ Backup slides

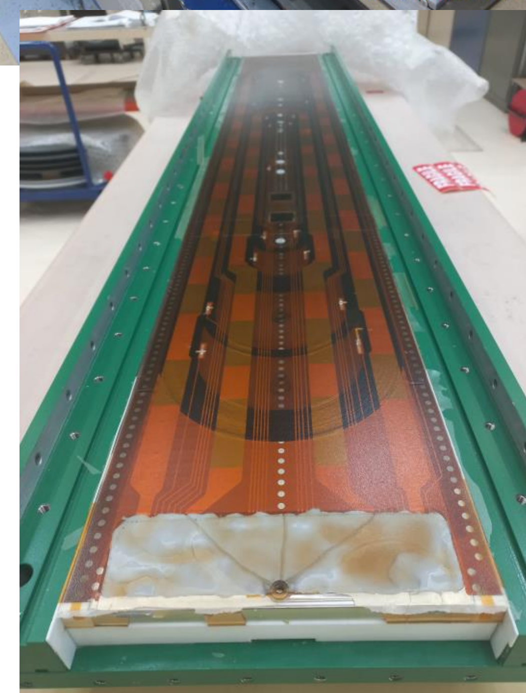
Fabrication of R2D2 coils ongoing

CR01:

- ✓ Winding
- ✓ Heat treatment
- ✓ Junctions
- ✓ Impregnation
- × Electrical shortcuts: cause identified and solved

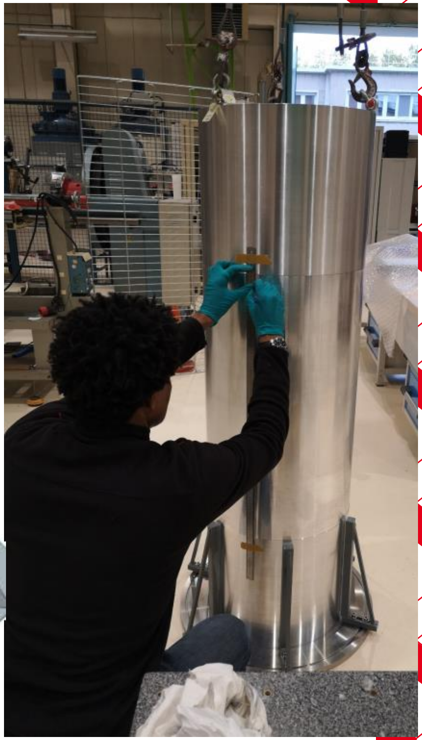
CR02:

- ➢ 1st winding
- ✓ Unwound, solution implemented
- ✓ Rewinding ongoing

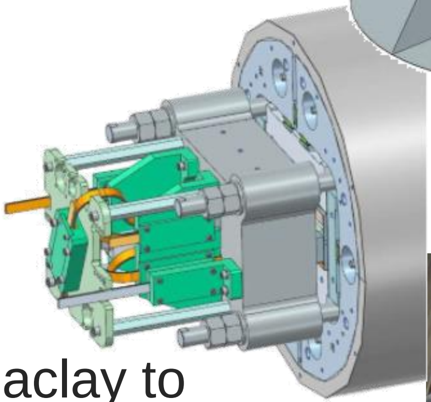


R2D2 structure procurement

- ✓ Shell segments received at CERN
- Structure components:
  - ➢ Delivery of final components today

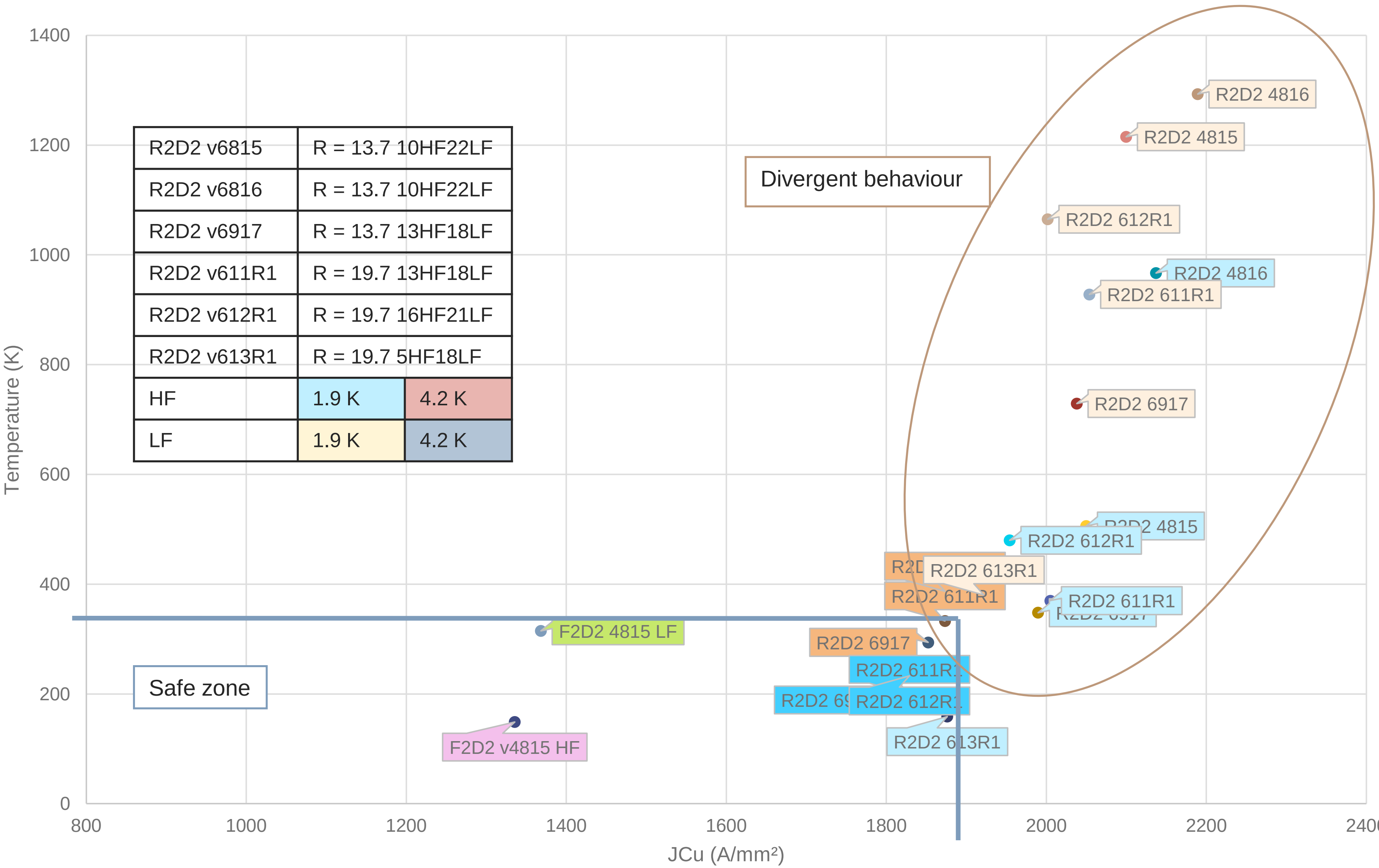


- Connection box:
  - ➢ Mockups ongoing



- Magnet schedule :
  - ➢ Dummy assembly at Saclay to validate the mechanical behavior of the structure
  - ➢ Selection of the 2 best coils for assembly
  - ➢ Delivery at CERN for cold tests

R2D2 – Hot Spot vs J_{Cu}



R2D2 v6815	R = 13.7 10HF22LF	
R2D2 v6816	R = 13.7 10HF22LF	
R2D2 v6917	R = 13.7 13HF18LF	
R2D2 v611R1	R = 19.7 13HF18LF	
R2D2 v612R1	R = 19.7 16HF21LF	
R2D2 v613R1	R = 19.7 5HF18LF	
HF	1.9 K	4.2 K
LF	1.9 K	4.2 K

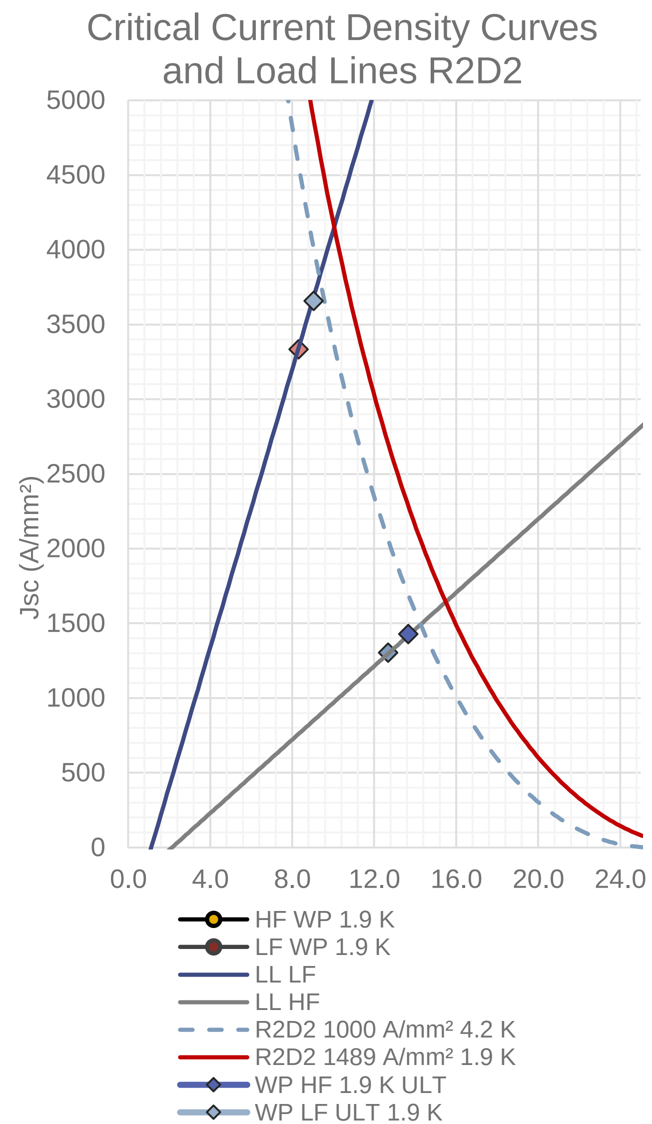
R2D2 v 6.14.R2 – Performances @4.2 K & Ultimate WP

	Nominal	SS	Ultimate WP
I_0	13772 A	17215 A	16500 A
LL margin HF / LF	20.0% / 20.45%	0.0 % / 0.72%	4.15 % / 4.50 %
B @ (0,0)	**10.42 T**	**12.46 T**	**11.98 T**
B peak HF	11.82 T	14.27 T	13.67 T
B peak LF	7.68 T	9.49 T	9.05 T
Energy density $\varepsilon_{4.2K}$	474 KJ/m	725 KJ/m	649 KJ/m
Energy mass density	15.9 KJ/kg	23.8 KJ/kg	21.3 KJ/kg
Magnetic length	785 mm	785 mm	785 mm
Inductance @ I_0	4.79 mH	4.55 mH	4.63 mH
Fx HF / LF	1698 / 112 kN/m	2497 / 61 kN/m	2321 / 74 kN/m
Fy HF / LF	-469 / -752 kN/m	-744 / -1101 kN/m	-683 / 1101 kN/m
E/L HF / LF	41 / 77 kJ/m	61 / 114 kJ/m	56 / 106 kJ/m
J_{Cu} HF / LF	1472 / 1508 A/mm²	1853 / 1886 A/mm²	1783 / 1827 A/mm²
Hotspot HF / LF	**104 K / 141 K**	**260 K / 450 K**	**210 / 350 K**

The Ultimate Working Point is the one where the magnet can operate safely

R2D2 v 6.14.R2 – Performances @1.9 K & Ultimate WP

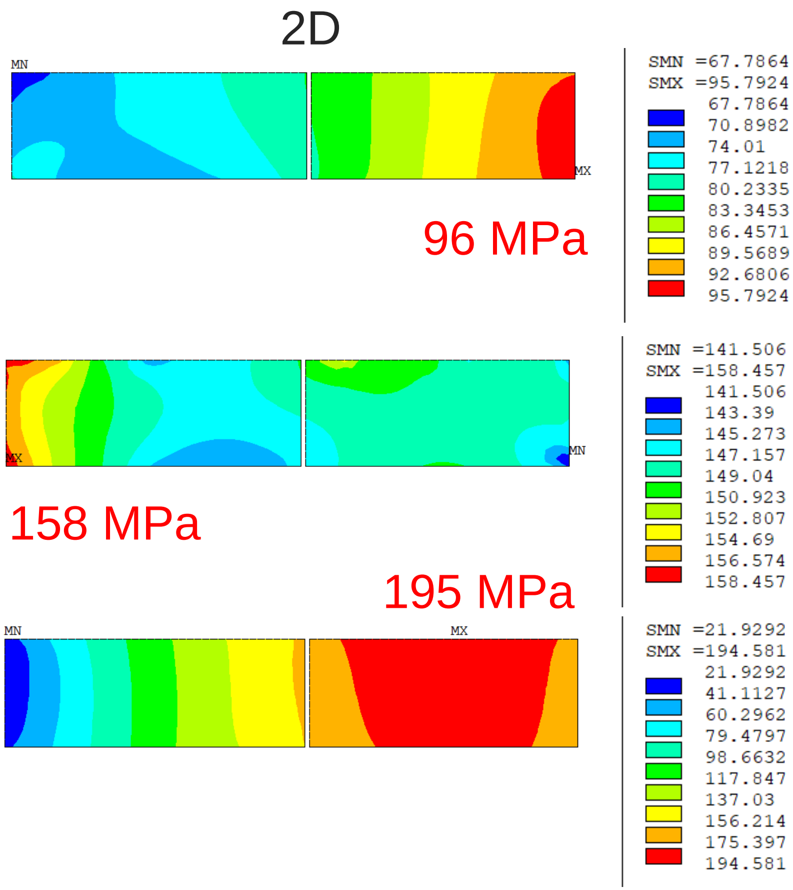
	Nominal	SS	Ultimate WP
I	15055 A	18819 A	16500 A
LL margin HF / LF	20.9% / 20.0%	0.9 % / 0.0%	12.85 % / 11.3 %
B @ (0,0)	**11.15 T**	**13.29 T**	**11.98 T**
B peak HF	12.69 T	15.23 T	13.67 T
B peak LF	8.32 T	10.21 T	9.05 T
Energy density	553 KJ/m	818 KJ/m	649 KJ/m
Magnetic length	785 mm	785 mm	785 mm
Fx HF / LF (kN/m)	1978 / 97	2920 / 25	2321 / 74
Fy HF / LF (kN/m)	-683 / -1101	-894 / -1447	-683 / 1101
E/L HF / LF (kJ/m)	56 / 106	71 / 133	56 / 106
Inductance	4.69 mH	4.32 mH	4.63 mH
J_{cu} HF / LF (A/mm²)	1627 / 1667	2034 / 2084	1827 / 1783
Hotspot HF / LF	**135 K / 203 K**	**580 K / 1192 K**	**233 K / 350 K**



Not possible to go to SS

Lorentz Forces impact in presentation 3

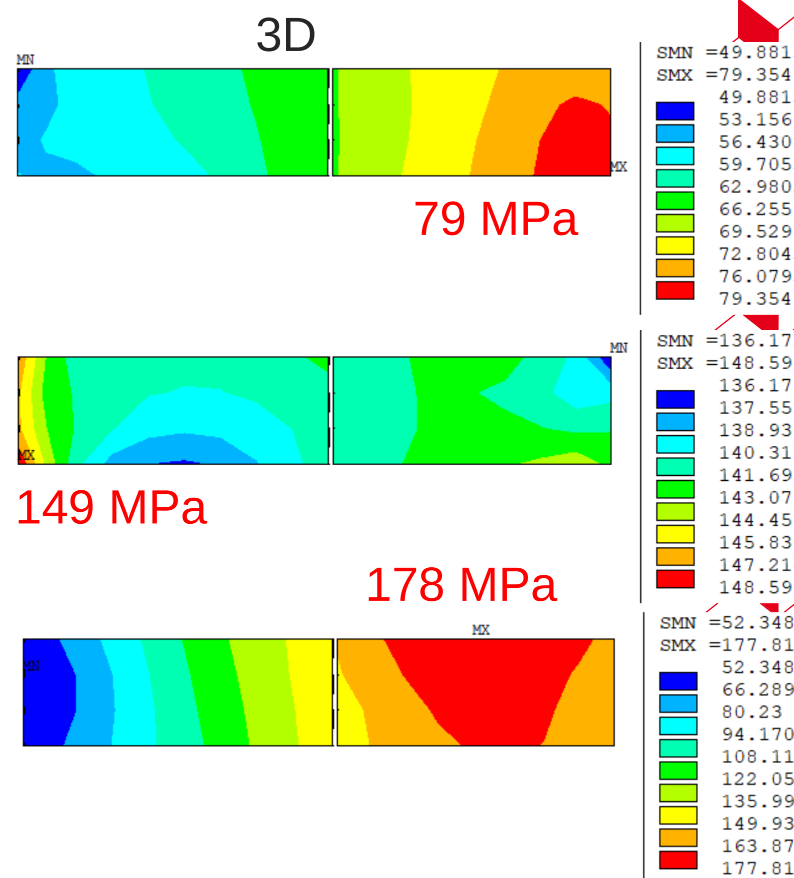
VM Stress – 2D vs 3D (Ultimate)



0.60 mm Xinterf
0.05 mm Yinterf

Cool-down

16.5 kA
Ultimate
current



- **Profile and range very similar between 2D/3D**
- Difference 10-20 MPa in max. VM Stress attributed to 2D plane stress Vs 3D stress, 2D more pessimistic (conservative)
- **Difference <5 MPa in X Stress**

Pole Contact Pressure – 2D vs 3D (Ultimate)

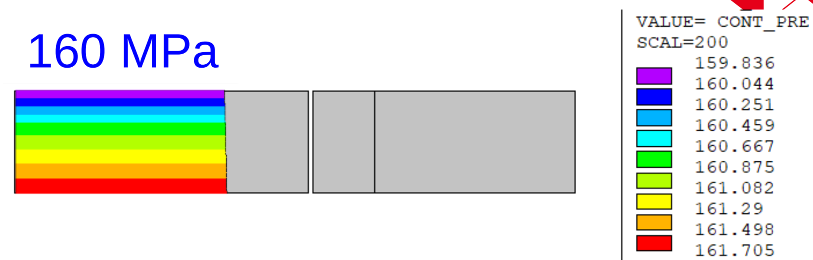
2D

3D

Cool-down

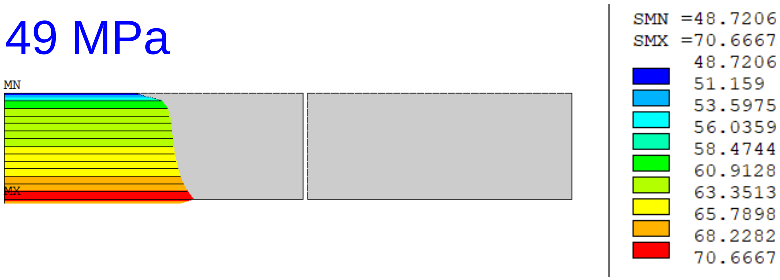
162 MPa

160 MPa

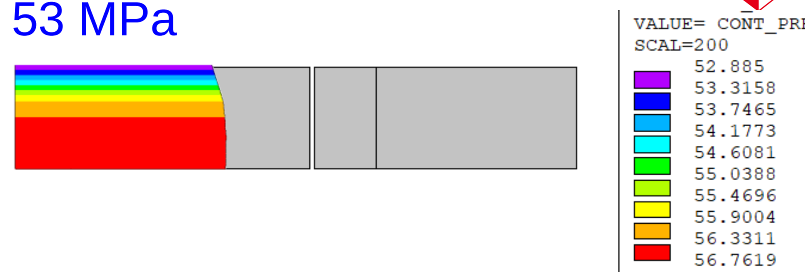


13.7 kA
Nominal
current

49 MPa

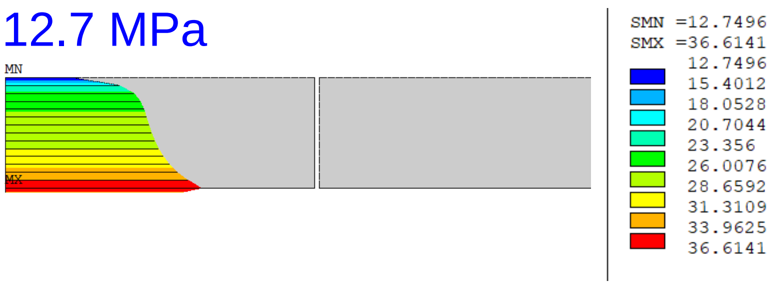


53 MPa

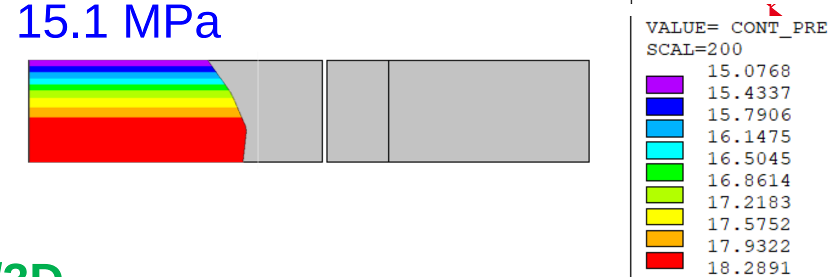


16.5 kA
Ultimate
current

12.7 MPa



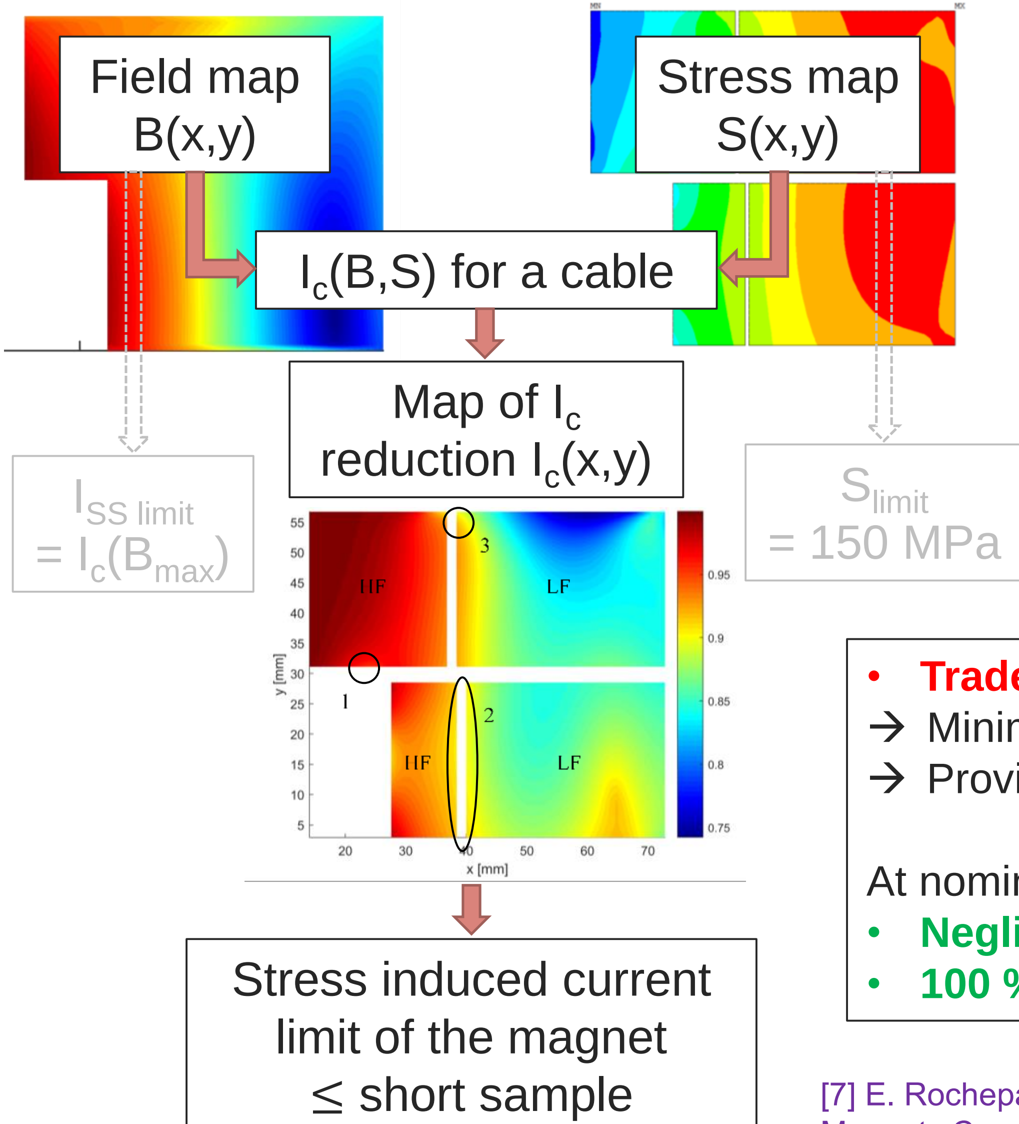
15.1 MPa

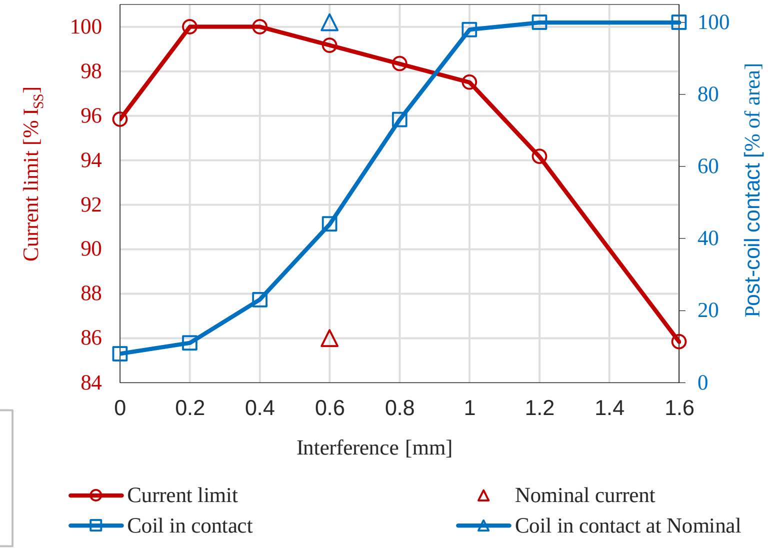


- **Profile and range very similar between 2D/3D**
- Difference <5 MPa in min. contact pressure

→ pre-load to be slightly corrected → +/-5 MPa on coil stress

2D MAGNETO-MECHANICAL DESIGN - FINALIZED





- **Trade-off on the pre-stress** (interference):

→ Minimize I_c reduction

→ Provide sufficient pre-stress

At nominal current :

- **Negligible I_c reduction → I_{limit} = 99% I_{ss}**
- **100 % coil in contact with the post**

[7] E. Rochepault et al., “Current Limits in Nb3Sn Superconducting Magnets Considering Magnetic Field and Stress”, submitted to IEEE TAS

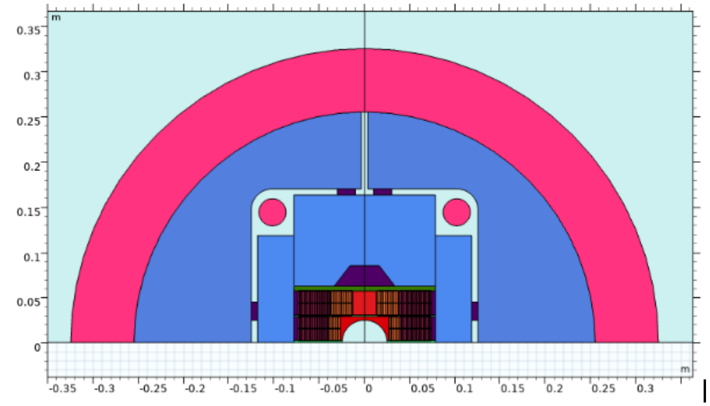
2D Quench Protection - Ongoing

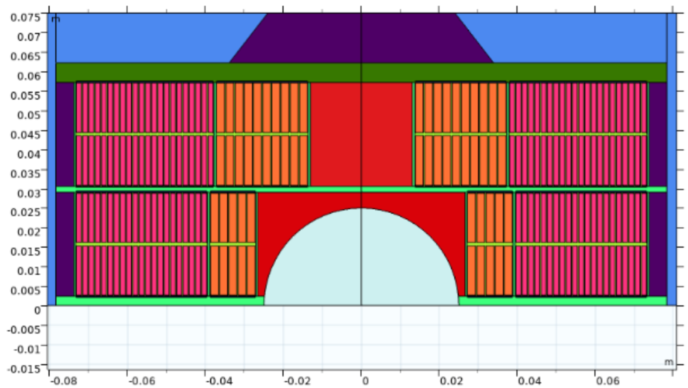
Protection Criteria (same as ECC):
- Every coil has a quench heater
- Detection delay = 20 ms
- Detection voltage = 5 mV
- Heater activation delay = 20 ms
- Max hot spot temperature = 350 K
- Max ΔV to ground = 1200 V

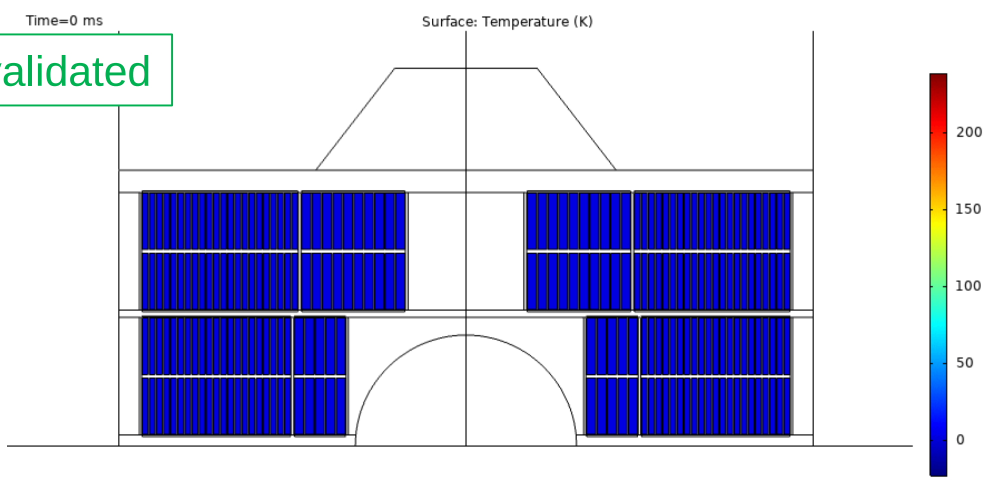
Model Hypotheses:
- Adiabatic Regime
- Cryocomp material database
- Magnetoresistivity included
- Transverse+longitudinal propagations considered

→ Magnetic, electrical, thermal models validated

Quench Study using Comsol







Case study : QH HF1+HF3 off