R2D2 and F2D2 magnet design

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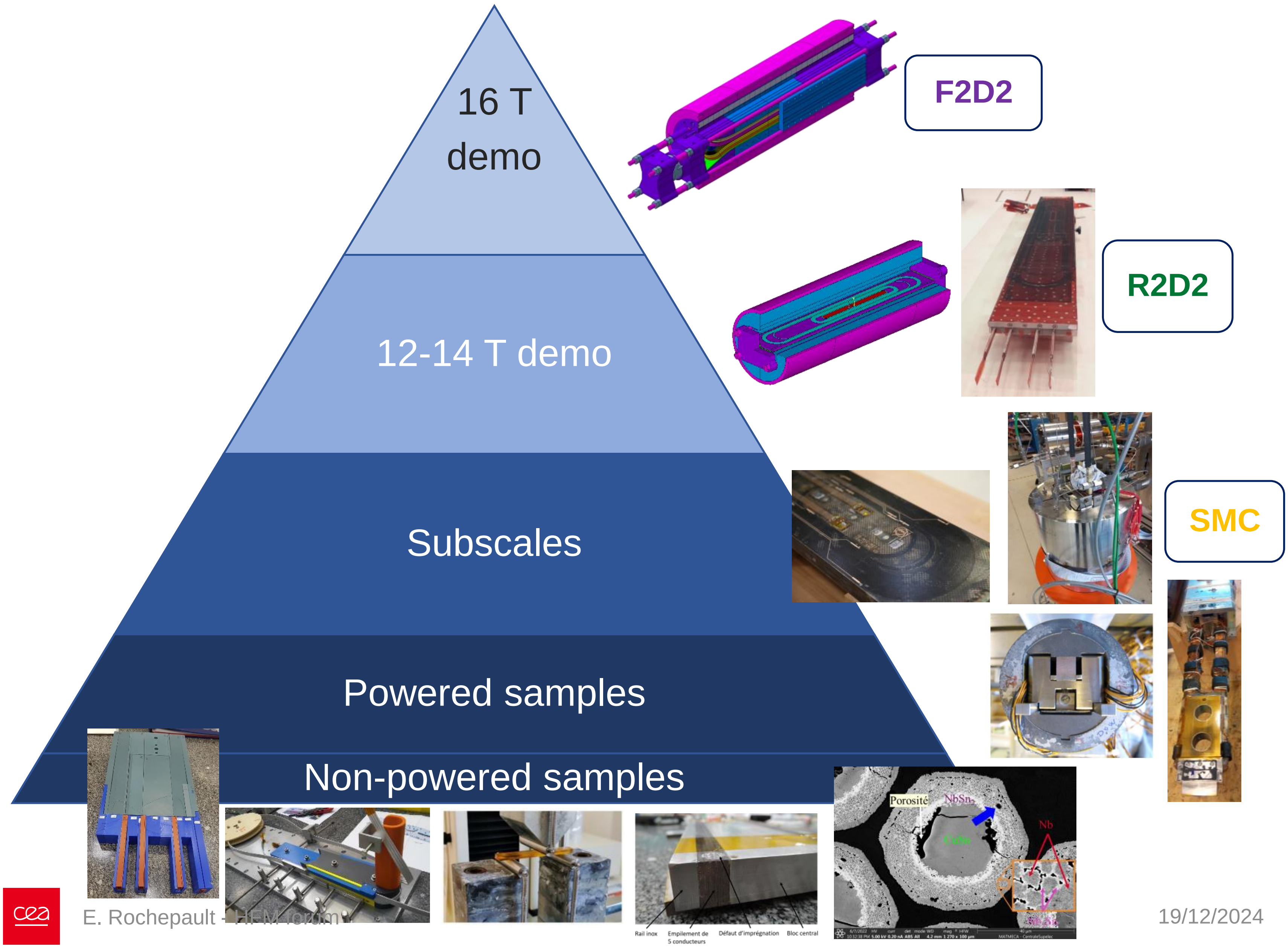
HFM forum – 19/12/2024

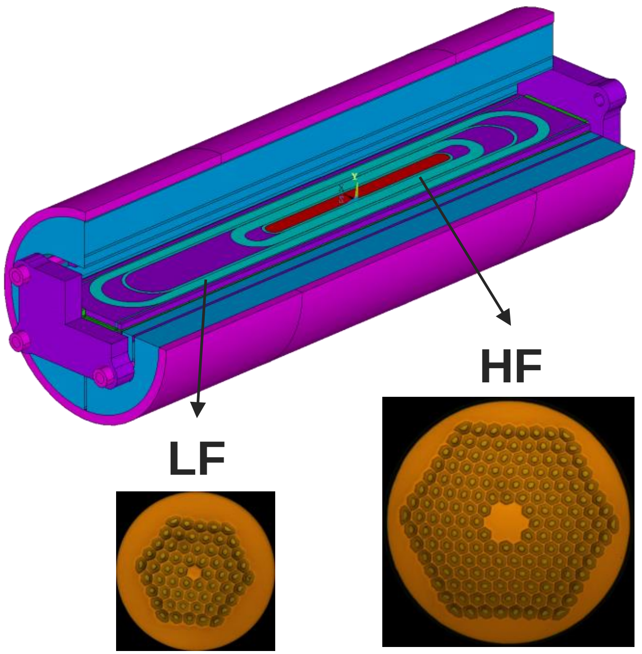
Development Plan towards 16 T Nb_3Sn Dipoles



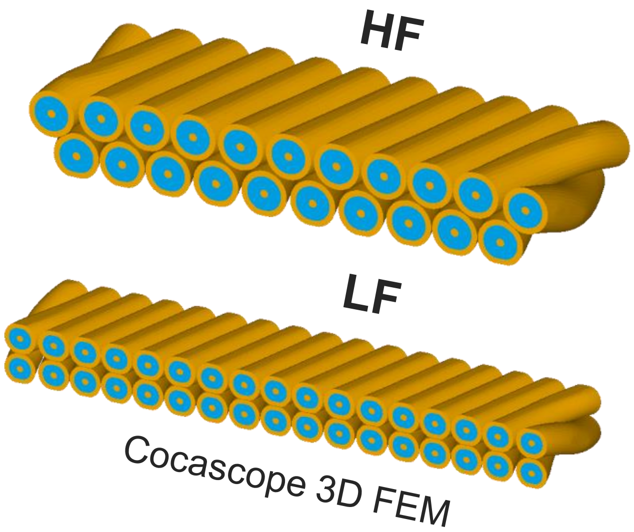
1. R2D2-F2D2 conductors

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



Parameter	Unit	HF cable	LF cable
Strand type		DEM-1.1	DEM-0.7
Strand layout		RRP® 162/169	RRP® 60/91
Strand diameter	mm	1.1	0.7
Number of strands		21	34
Cable mid-thickness	mm	1.969 ± 0.010	1.253 ± 0.010
Cable width	mm	12.579 ± 0.050	12.579 ± 0.050
Pitch	mm	84 ± 3	79 ± 3
Core		No core	No core



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%

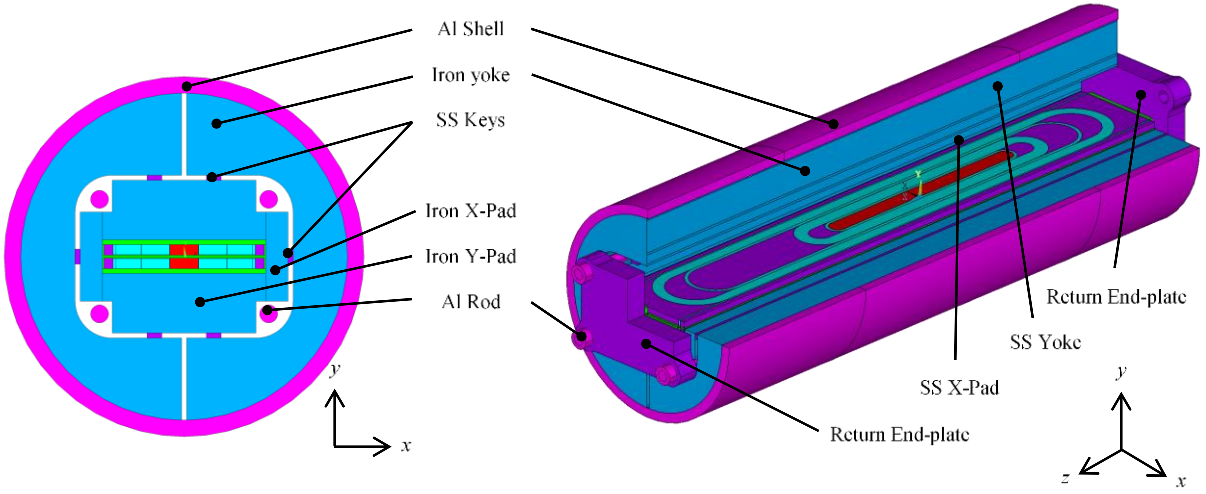
*See for more details: “Performance of Dem-1.1 and Dem-0.7 Wires for R2D2: Heat Treatment Recommendations”, S. Hopkins, internal CERN note

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

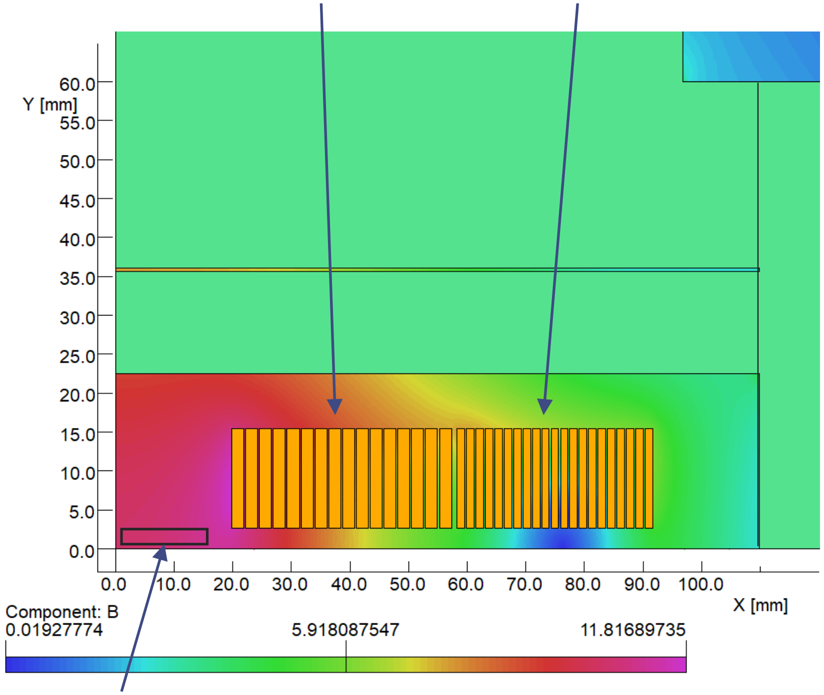


Aperture	None
Outer diameter	480 mm
Structure length	2.0 m
Nominal central field	11.6 T
Ultimate central field	12.1 T

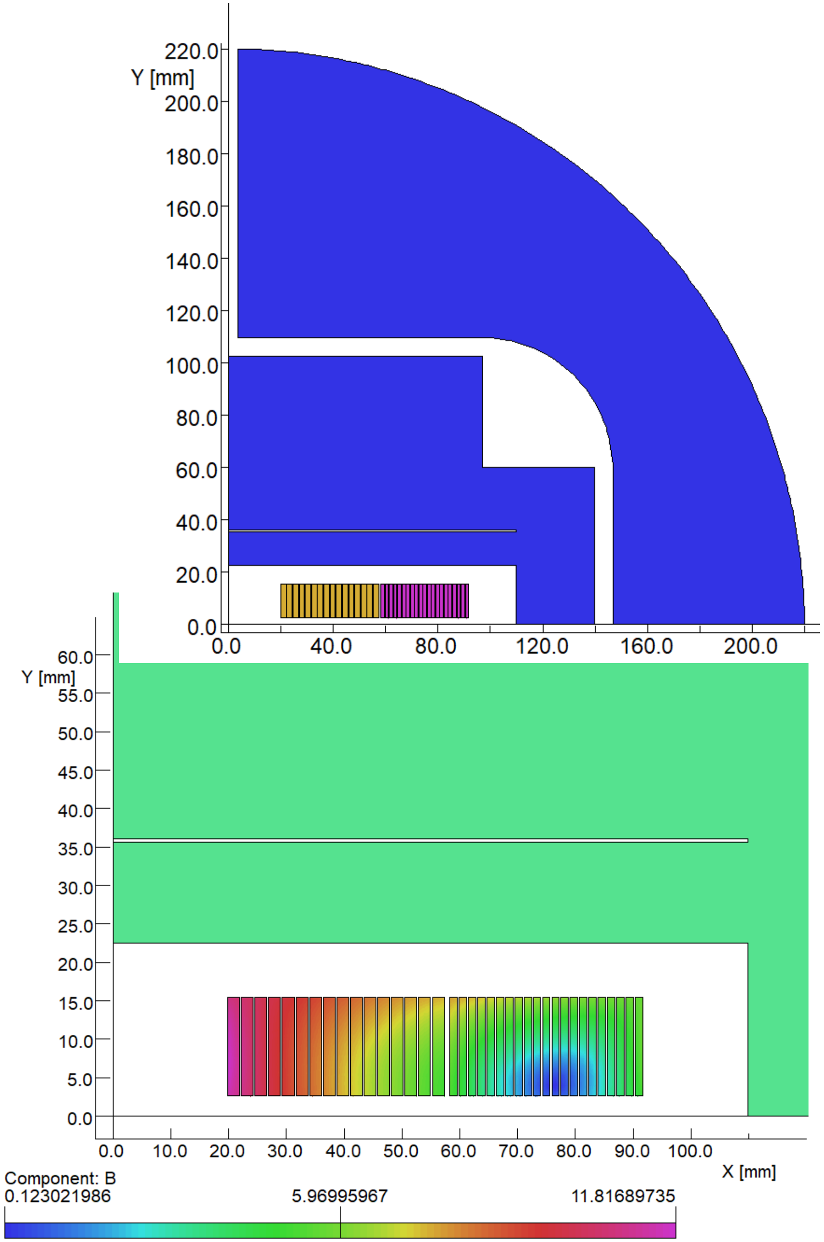
2D Magnetic design

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

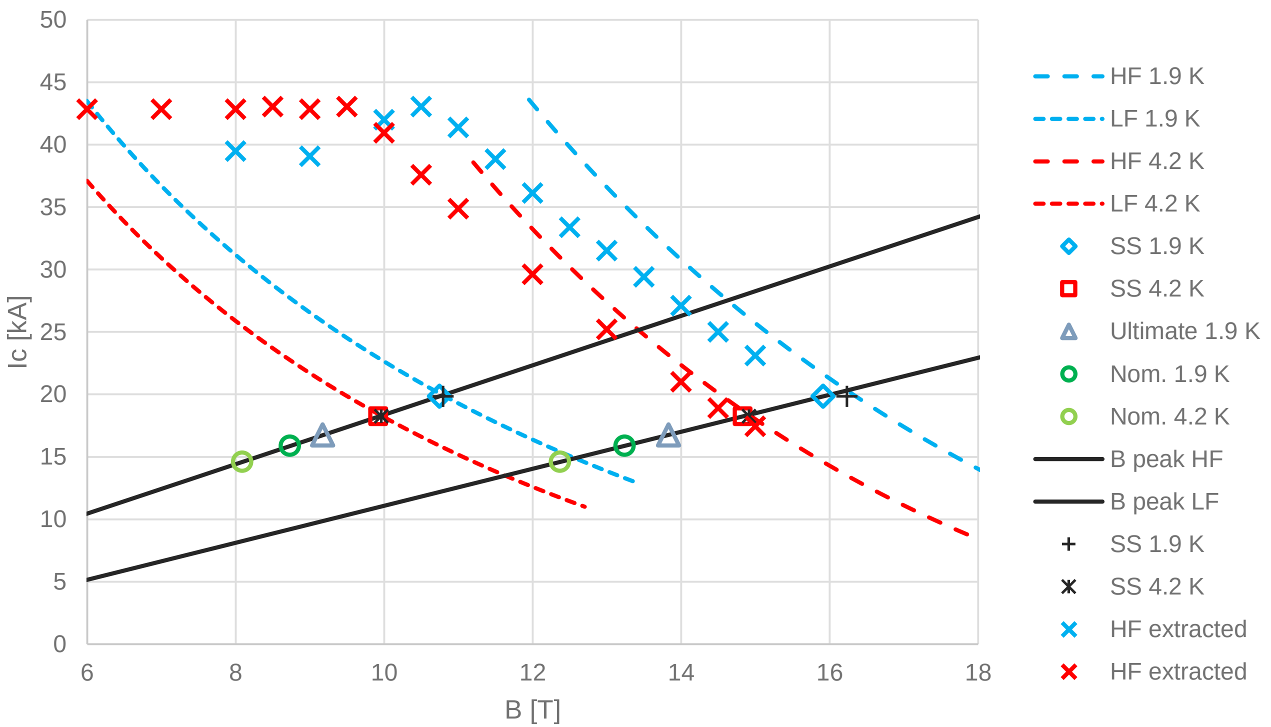
16 HF **21 LF**



Accessible area for measurements (~30 X 5 mm)



R2D2 Load-lines and margins

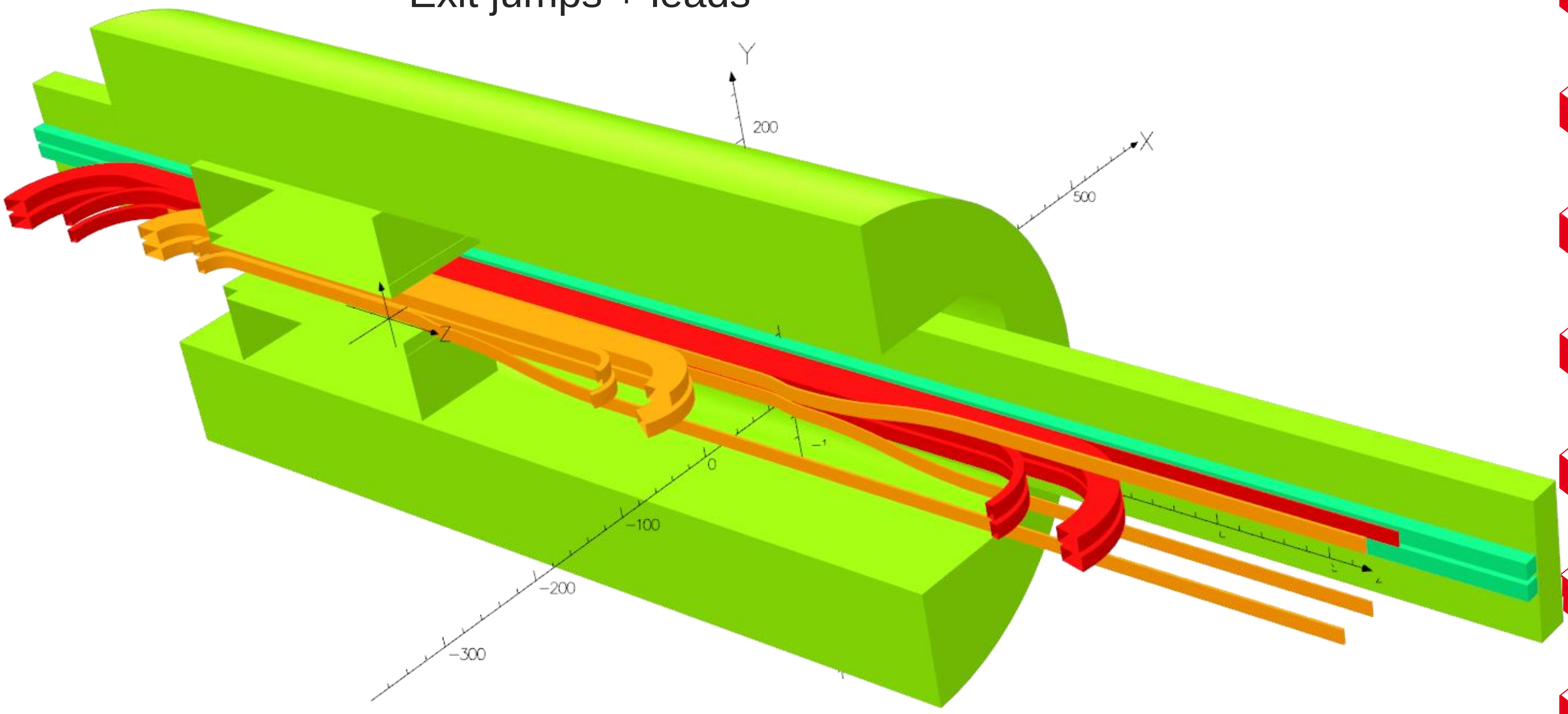


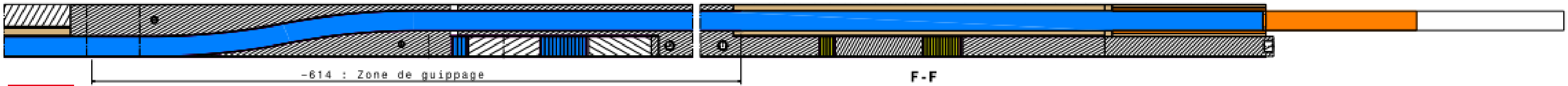
Parameter	Nom. 4.2 K	Nom. 1.9 K	Ultimate* **1.9 K**	SS 4.2 K	SS 1.9 K	Unit
Current [kA]	14.6	15.9	**16.8**	18.2	19.8	kA
LL Margin HF	20.5	21.9	**17.5**	0.7	2.3	%
LL Margin LF	20.3	20.4	**16.0**	0.3	0.5	
B center	10.89	11.62	**12.12**	12.96	13.87	T
B peak HF	12.37	13.24	**13.83**	14.83	15.92	T
B peak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

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

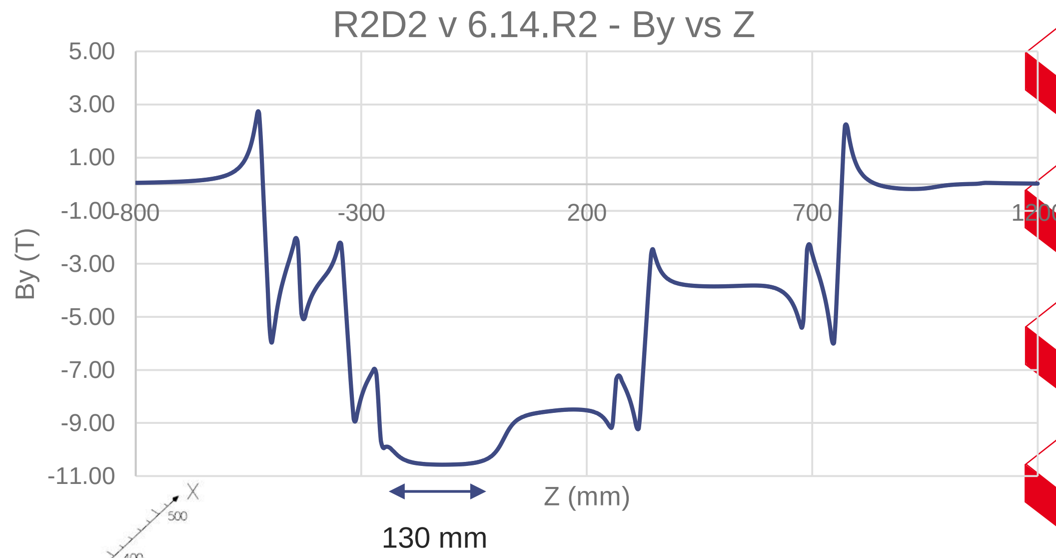
3D Magnetic design

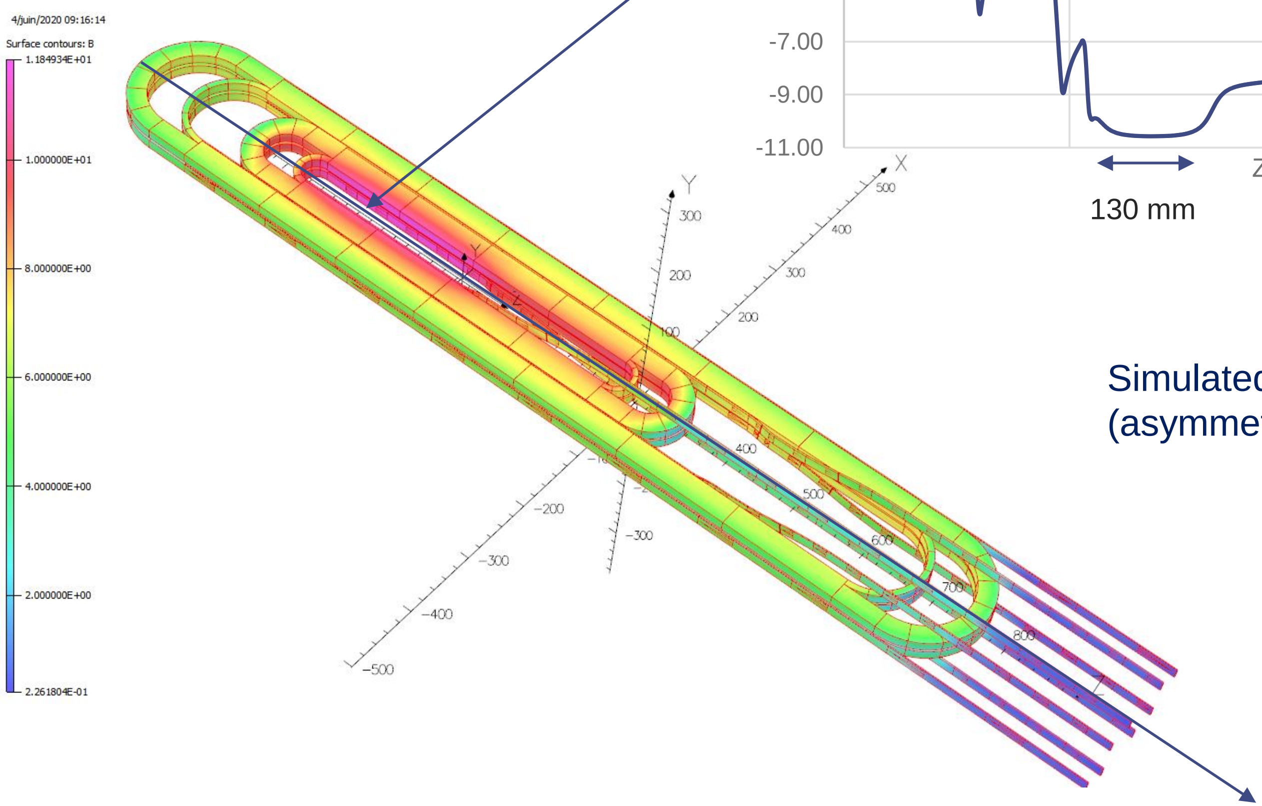
- R2D2 magnet = single-layer coils x2
- 2 coils modelled
- 2 sides RE+LE
- Exit jumps + leads





3D Magnetic design



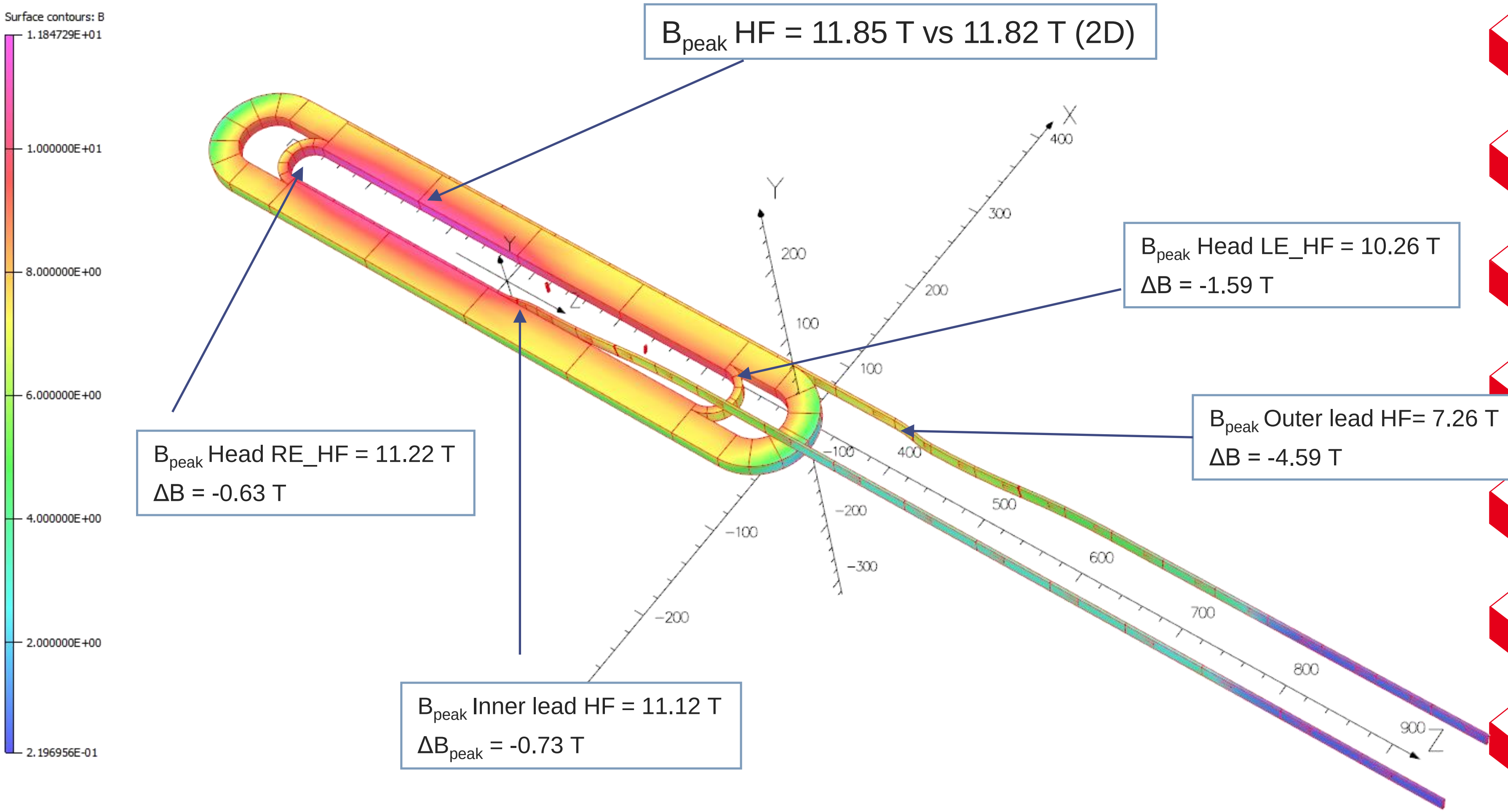


Simulated considering both poles (asymmetric due to the exit leads)

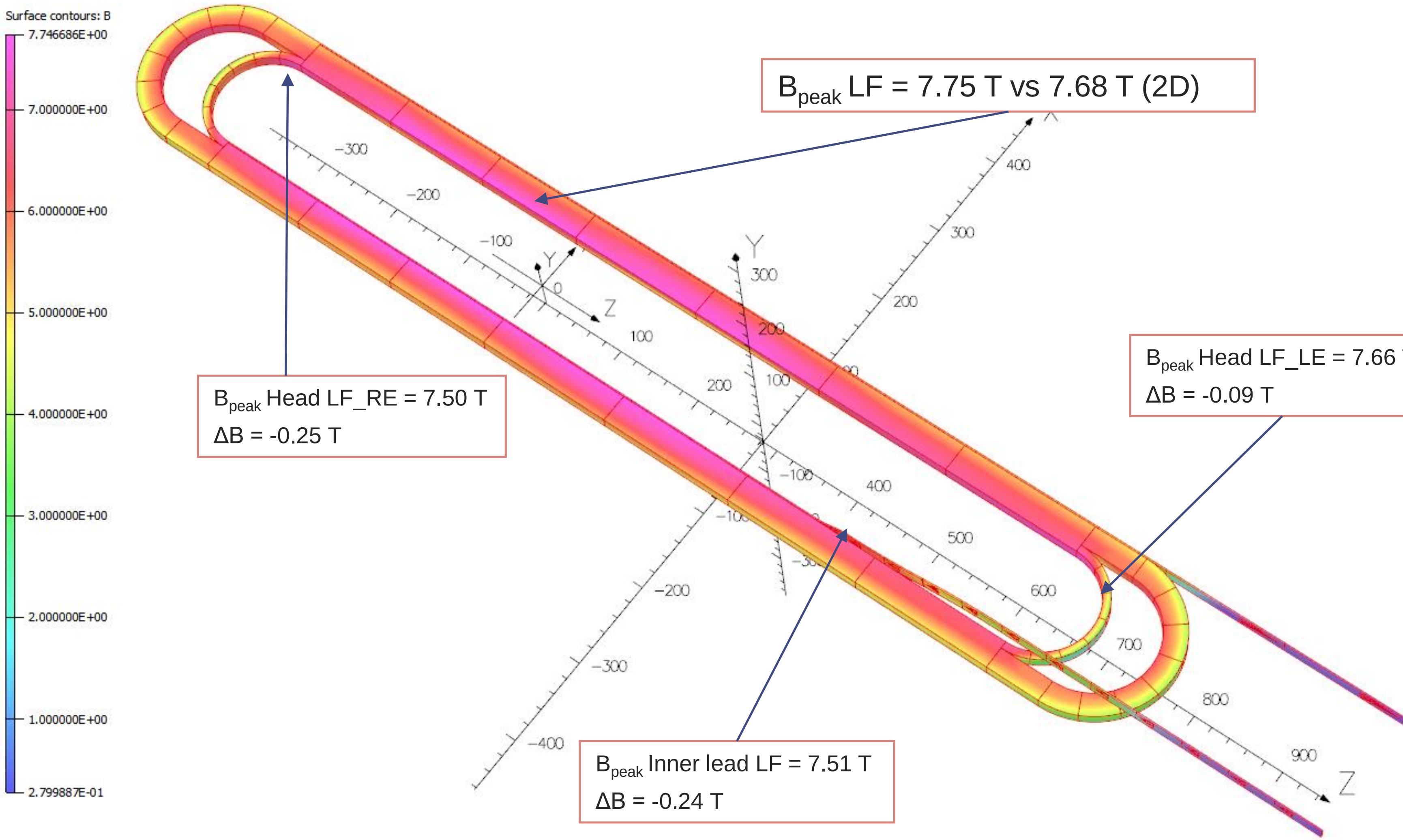
3D Magnetic design

Design optimized to lower the peak fields in critical areas :

→ Coil ends, Leads, and exit jumps



3D Magnetic design

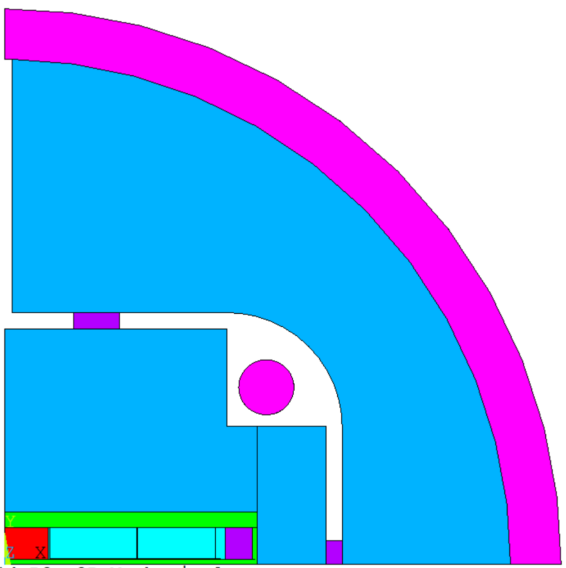


3D Mechanical design

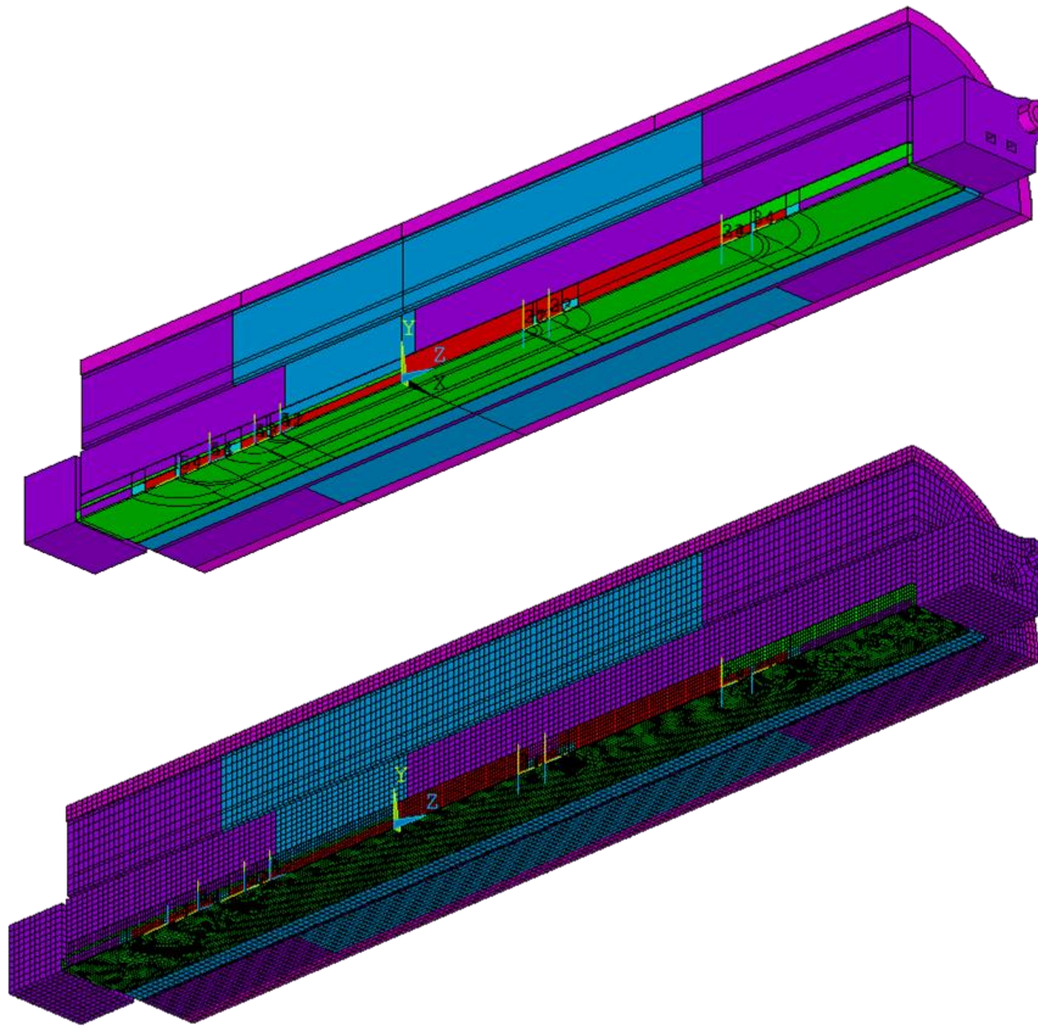
Several models:

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

→ All models consistent

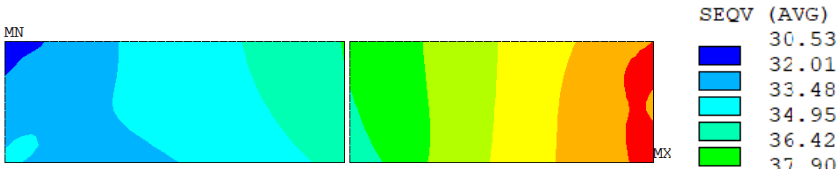


6p14pR2, 2D Mechanical



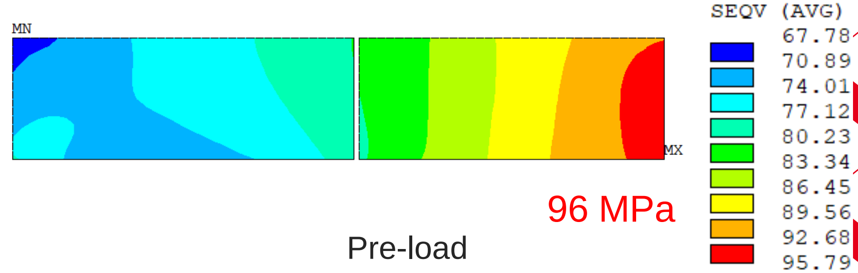
Version 6p14_R2, 3D Mechanical

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



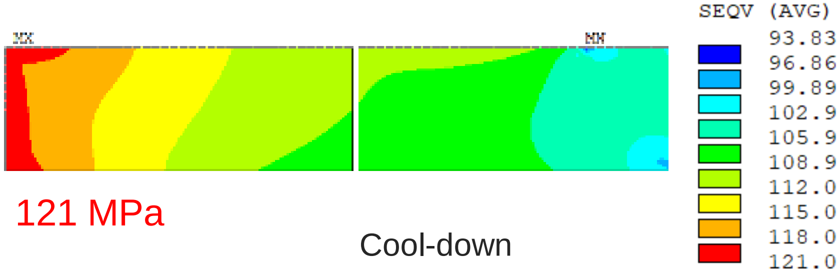
44 MPa

Pre-load



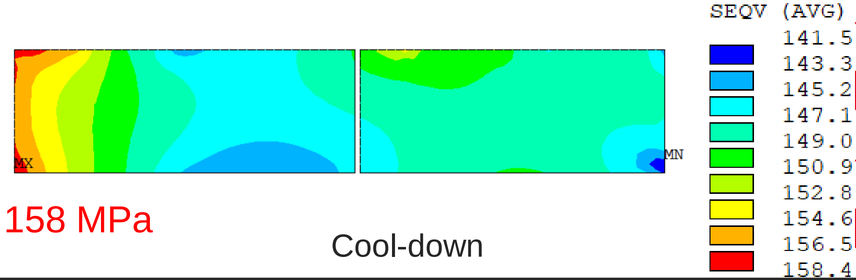
96 MPa

Pre-load



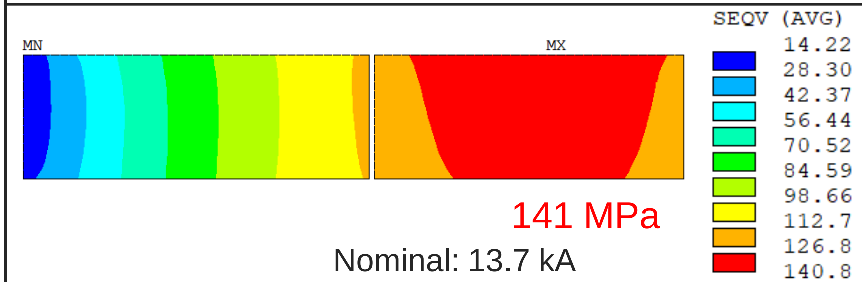
121 MPa

Cool-down



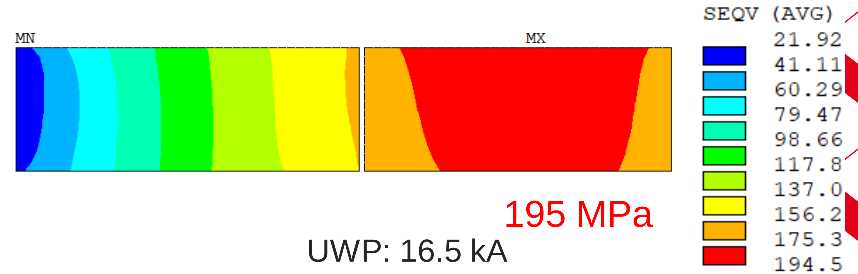
158 MPa

Cool-down



141 MPa

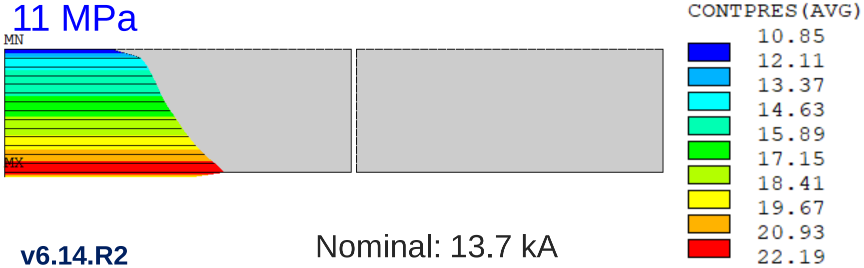
Nominal: 13.7 kA



195 MPa

UWP: 16.5 kA

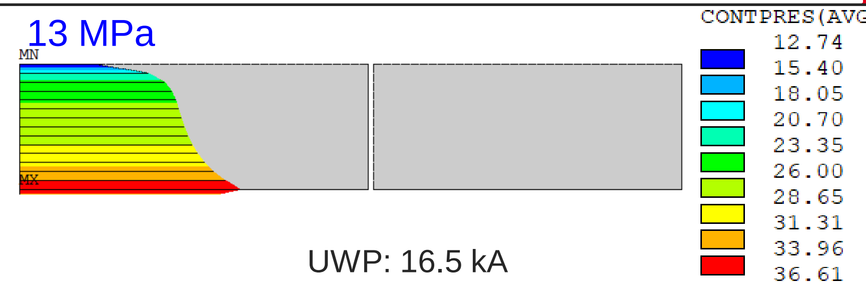
11 MPa



v6.14.R2

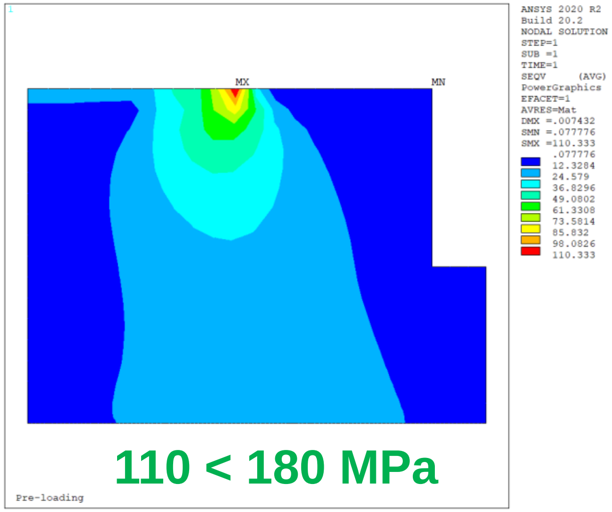
Nominal: 13.7 kA

13 MPa

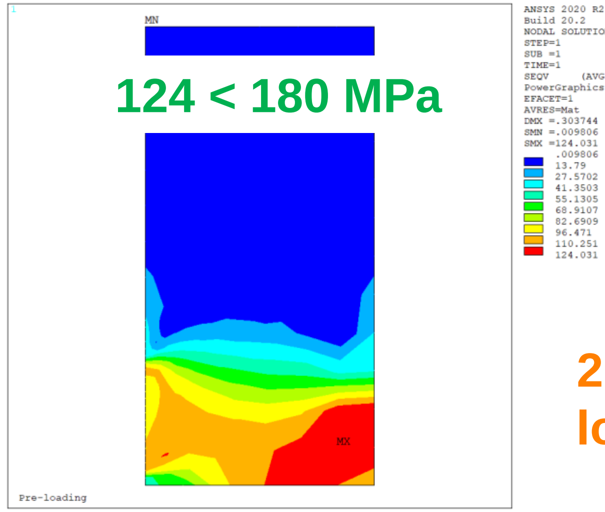


UWP: 16.5 kA

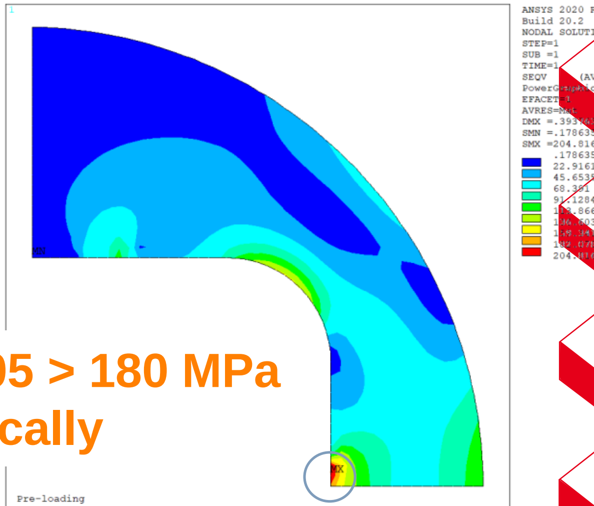
Peak stresses in structure (SS 1.9 K)



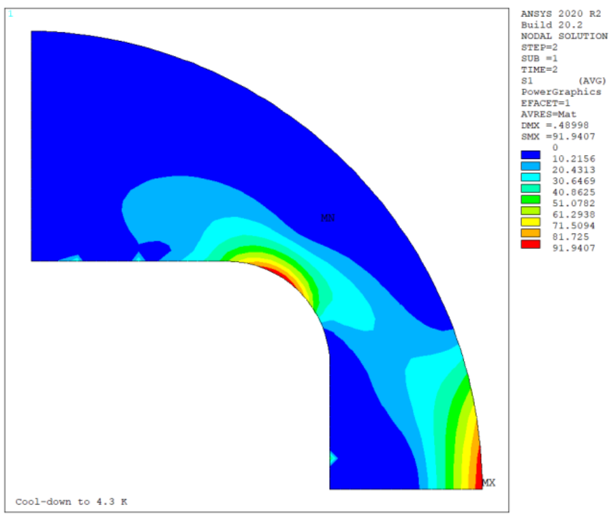
110 < 180 MPa



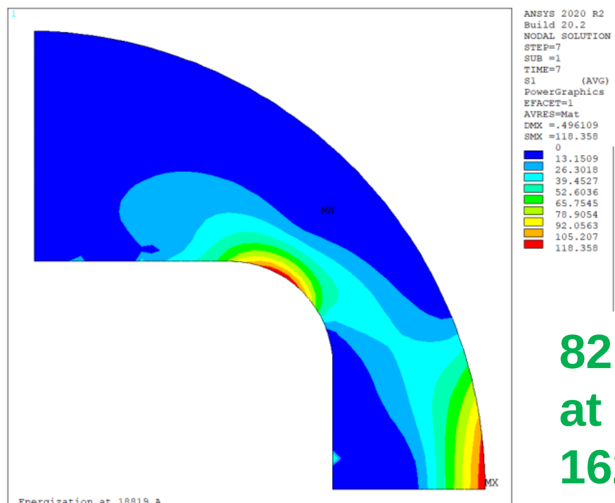
124 < 180 MPa



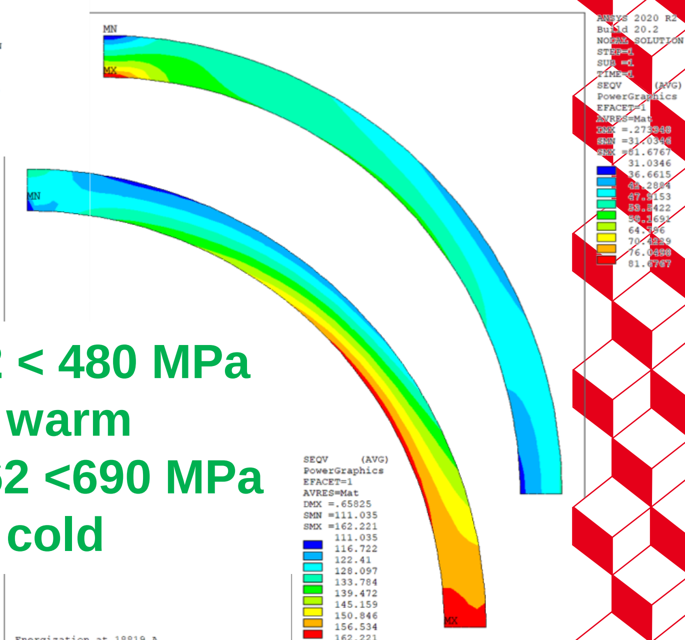
205 > 180 MPa locally



S1 = 92 < 200 MPa at cold



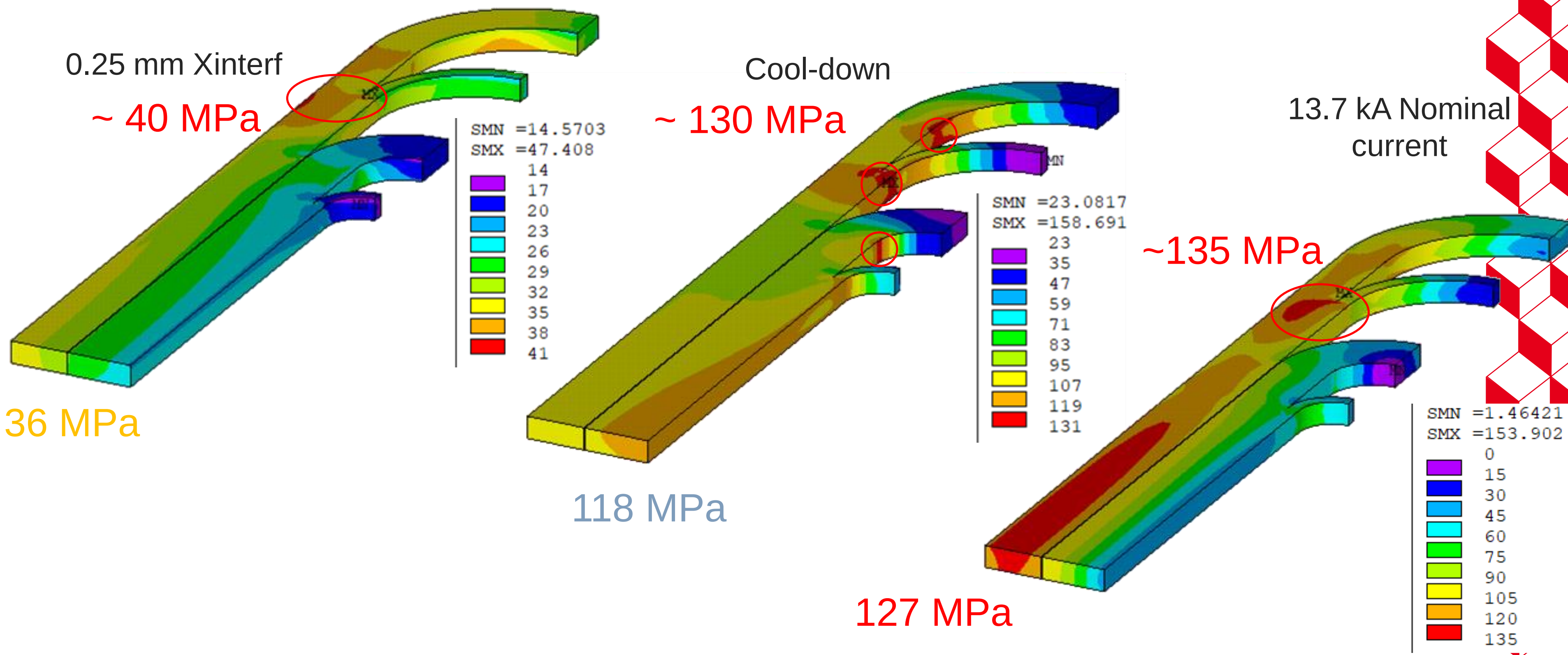
S1 = 118 < 200 MPa at SS



82 < 480 MPa at warm

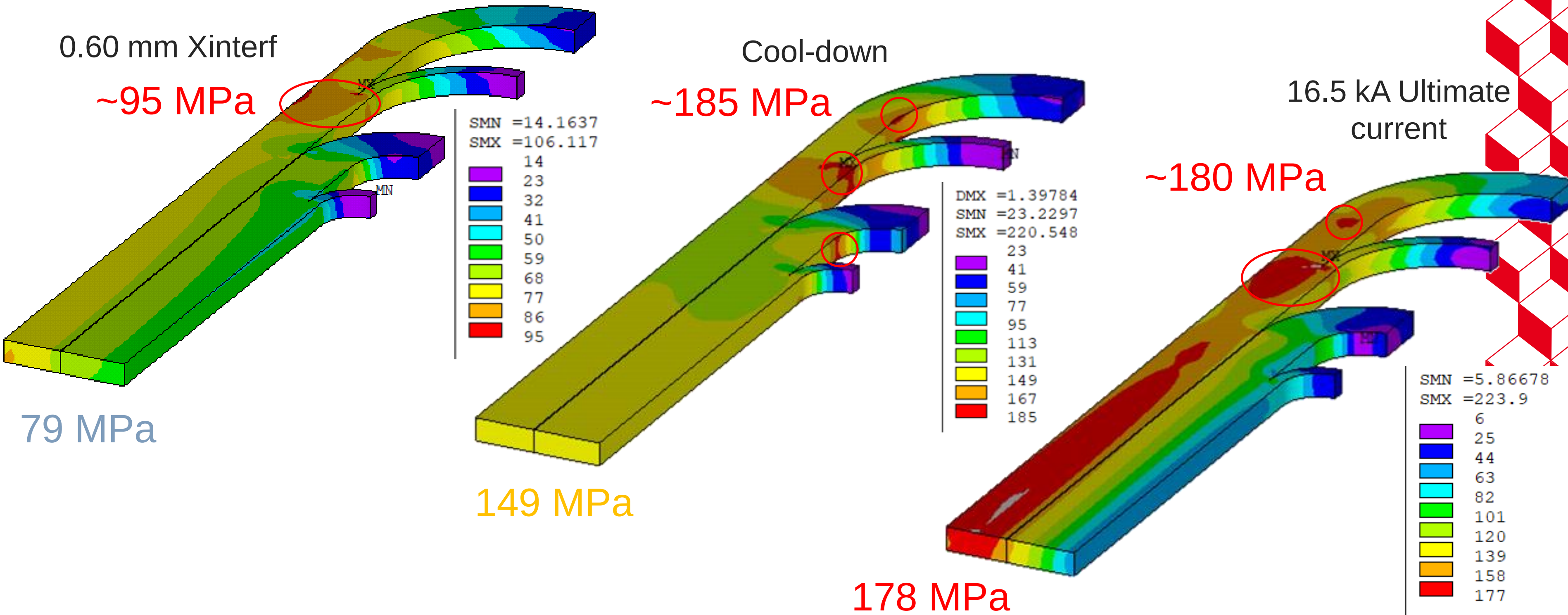
162 <690 MPa at cold

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

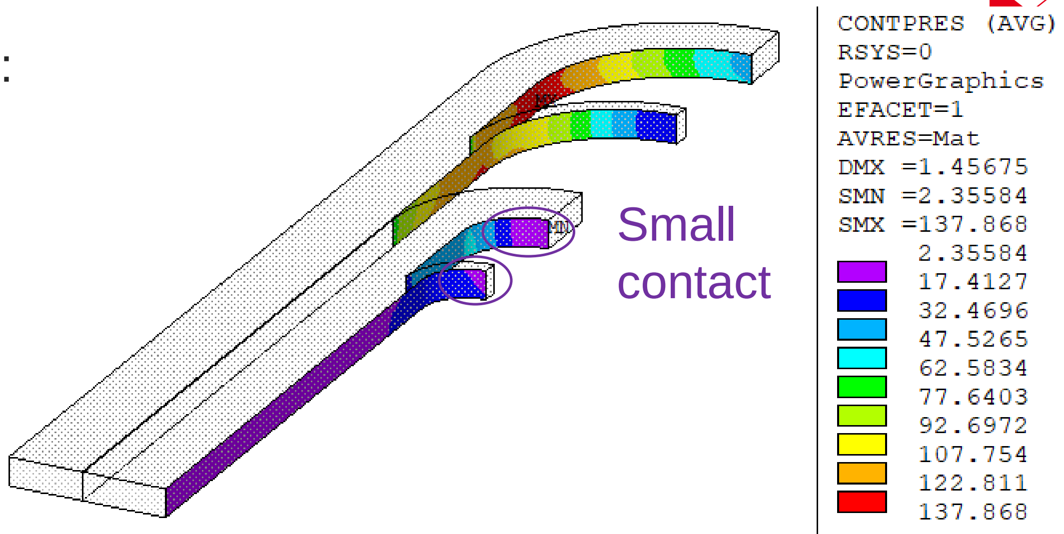
Pole contact pressure – 3D (Nominal)

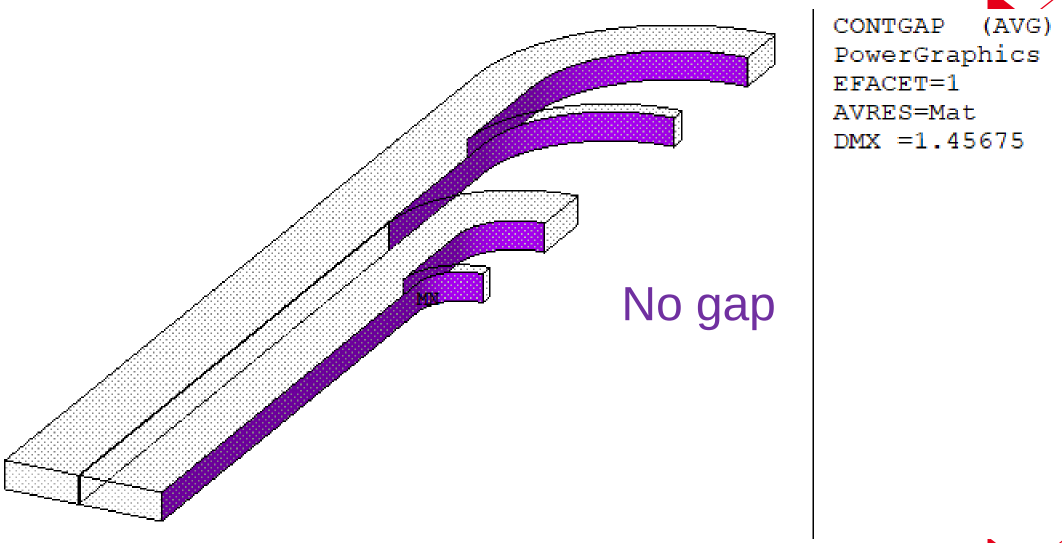
- Lorentz forces @ **Nominal** current:
  $F_{z,mag}$ = 350 kN /end
- Xpreload: 0.25 mm interf.
- Z Preload:
  - warm: 400 kN = 115 % $F_{z,mag}$
  - Cold: 641 kN **= 183 % $F_{z,mag}$**

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

Goals of the longitudinal support:

1. Positive contact pressure
2. Stress < criteria

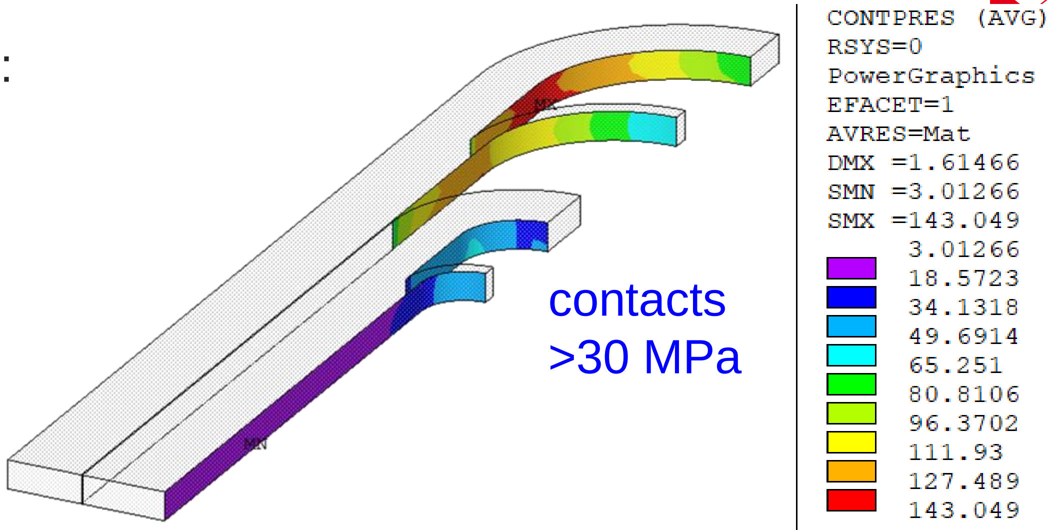


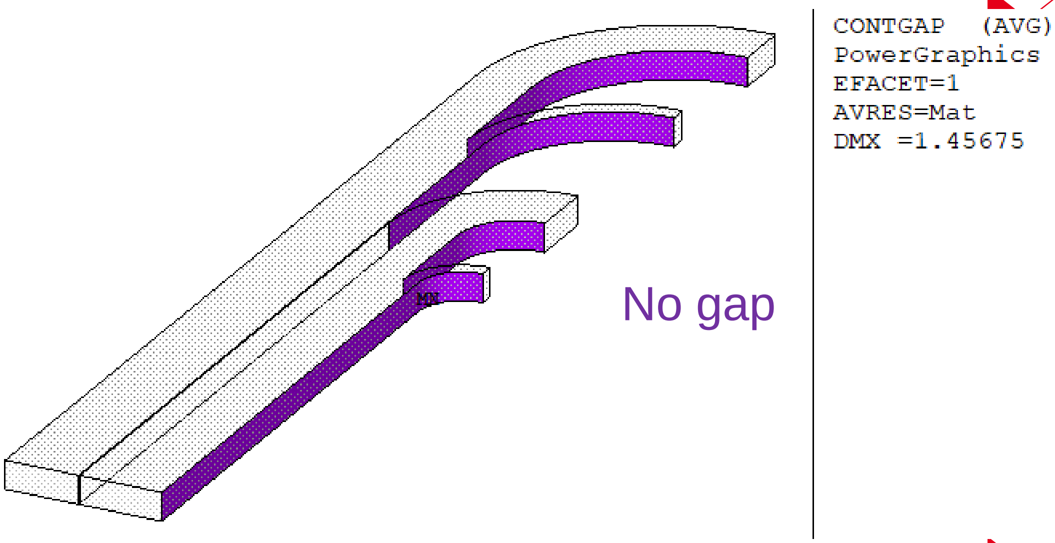


Pole contact pressure – 3D (+ZPreload)

- 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

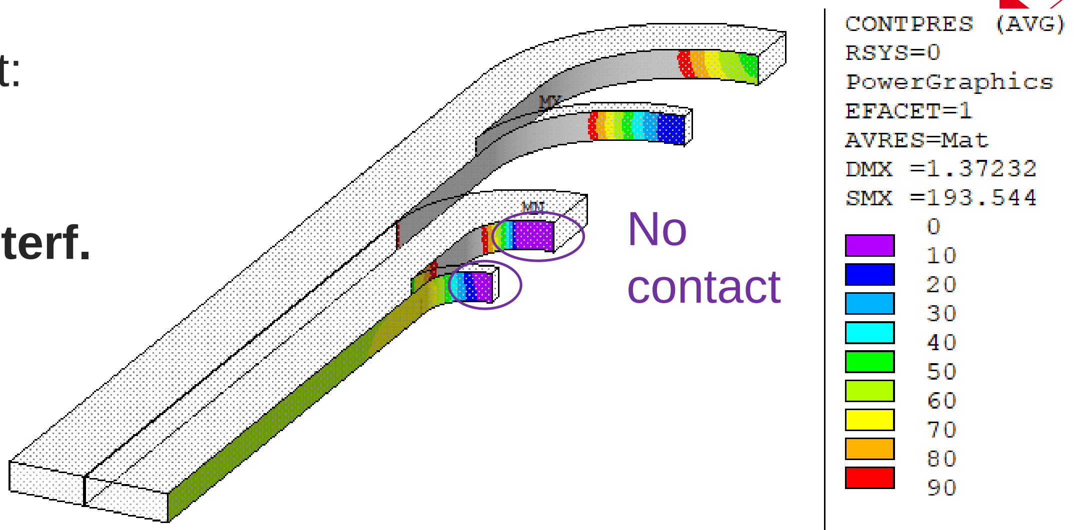


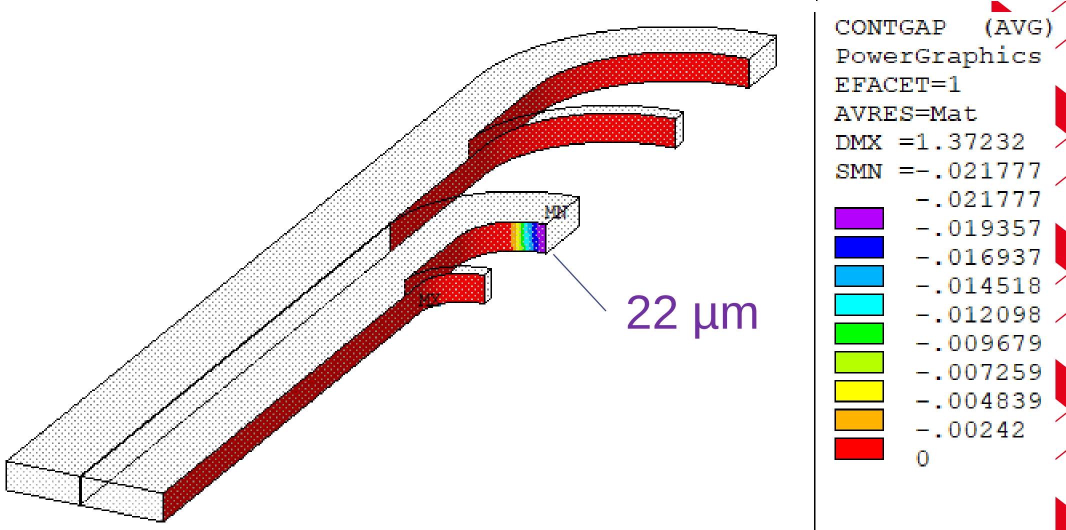


Pole contact pressure – 3D (+X+ZPreload)

- 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

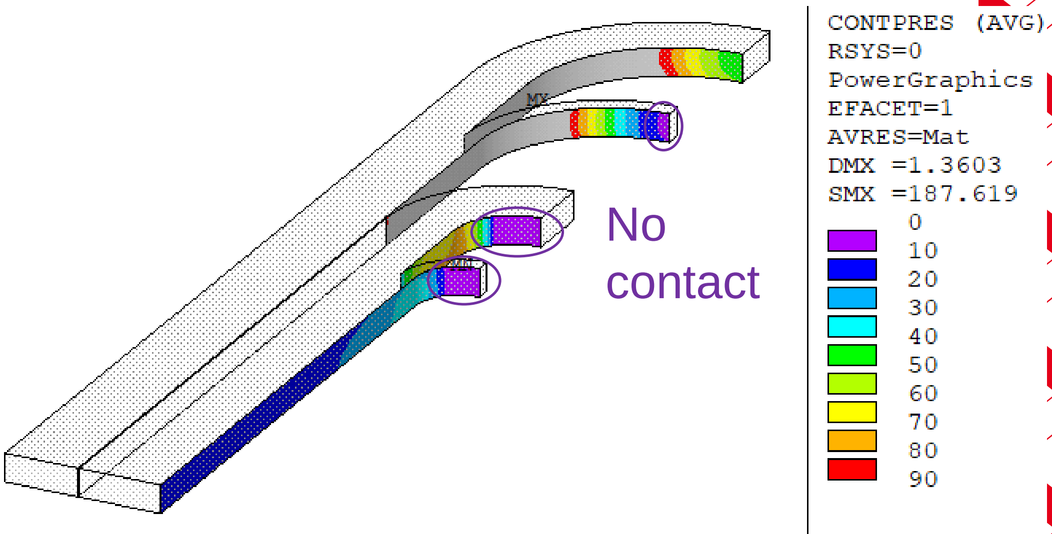


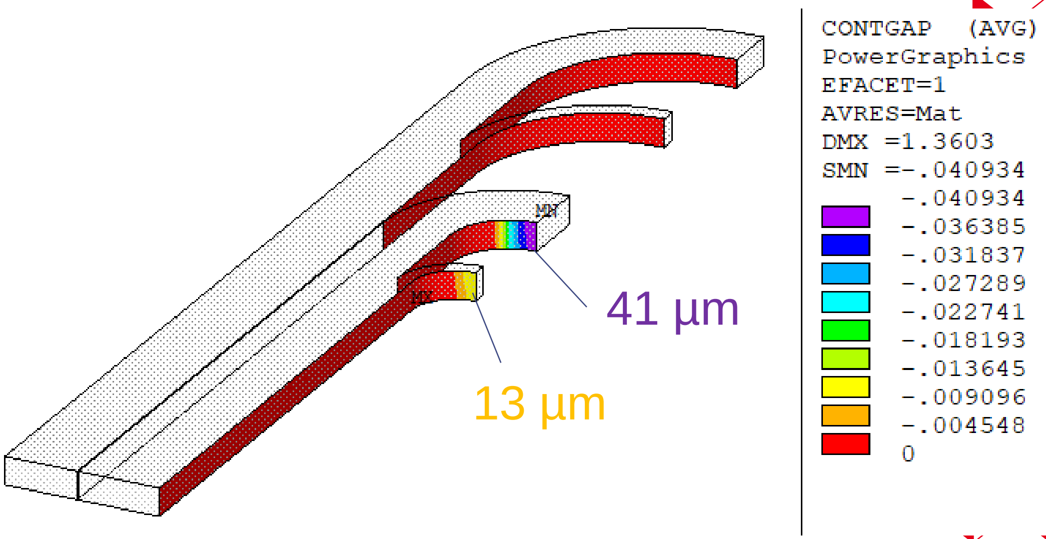


Pole contact pressure – 3D (Ultimate)

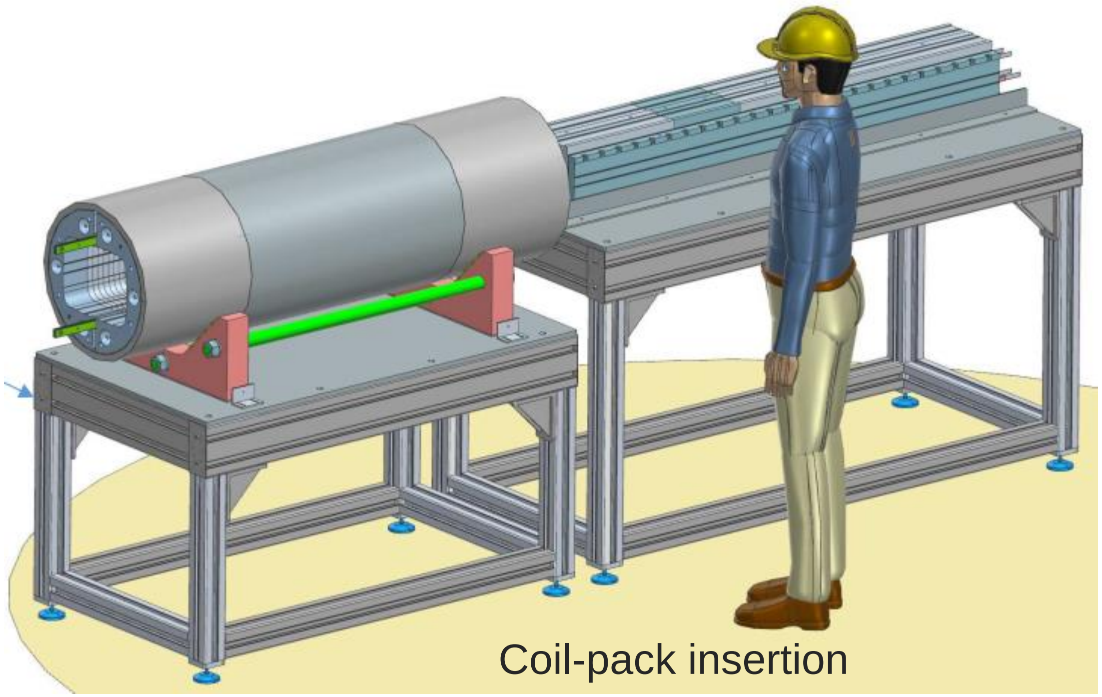
- Lorentz forces @ **Ultimate** current: $F_{z,mag}$ = 477 kN /end
- X preload: 0.6 mm interf.
- Z Preload:
  - warm: 565 kN = 119 % $F_{z,mag}$
  - Cold: 831 kN **= 174 % $F_{z,mag}$**

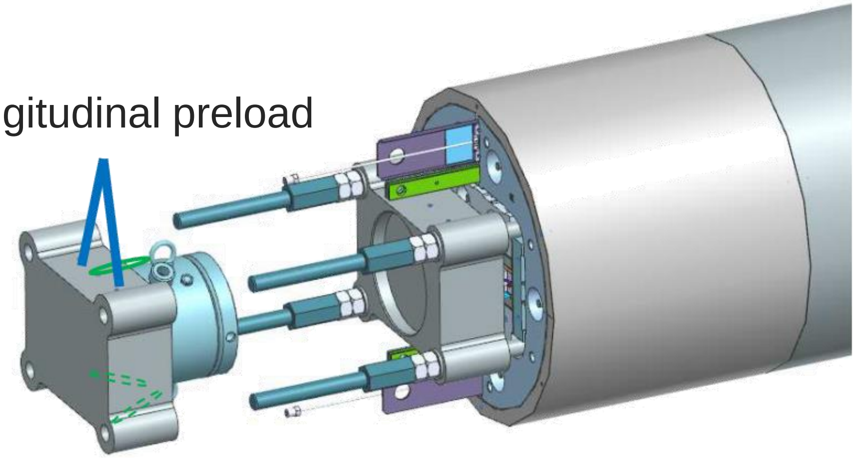
→ Need to considerably increase the pre-load to guarantee full contact in the ends

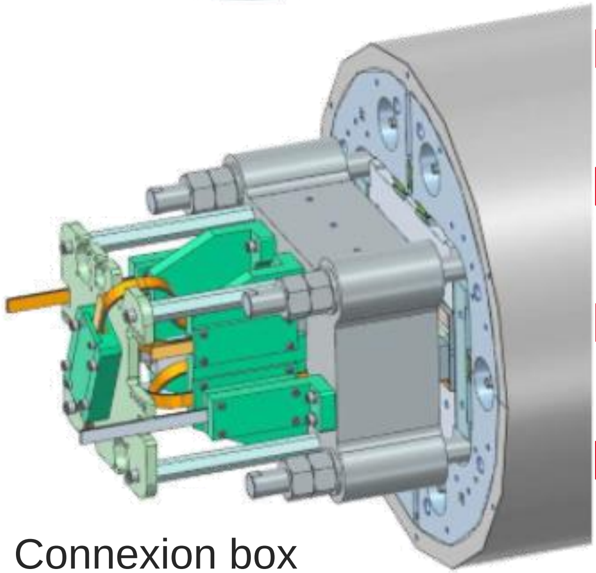




Detailed engineering design





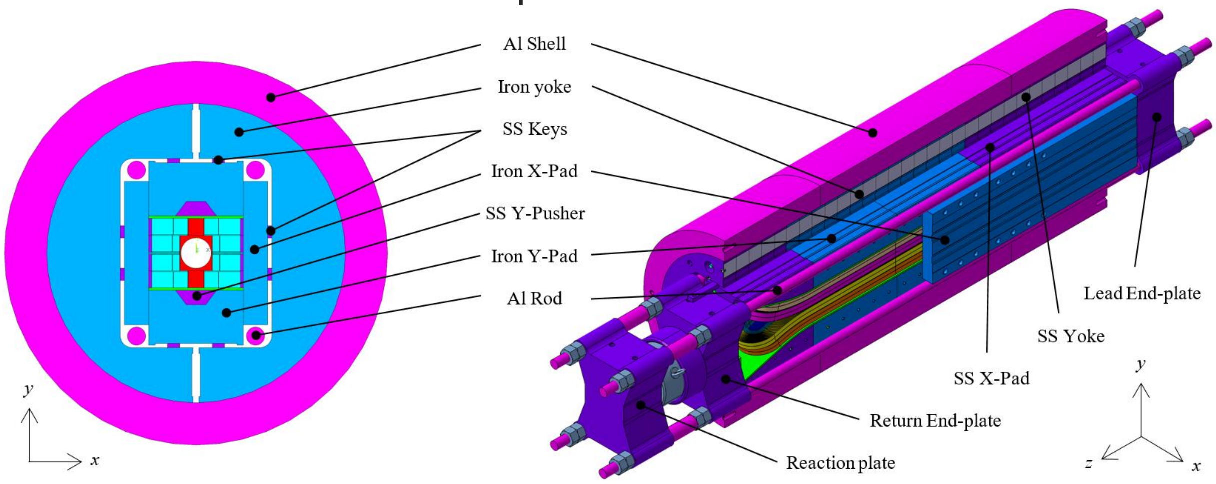


3. FD/F2D2

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

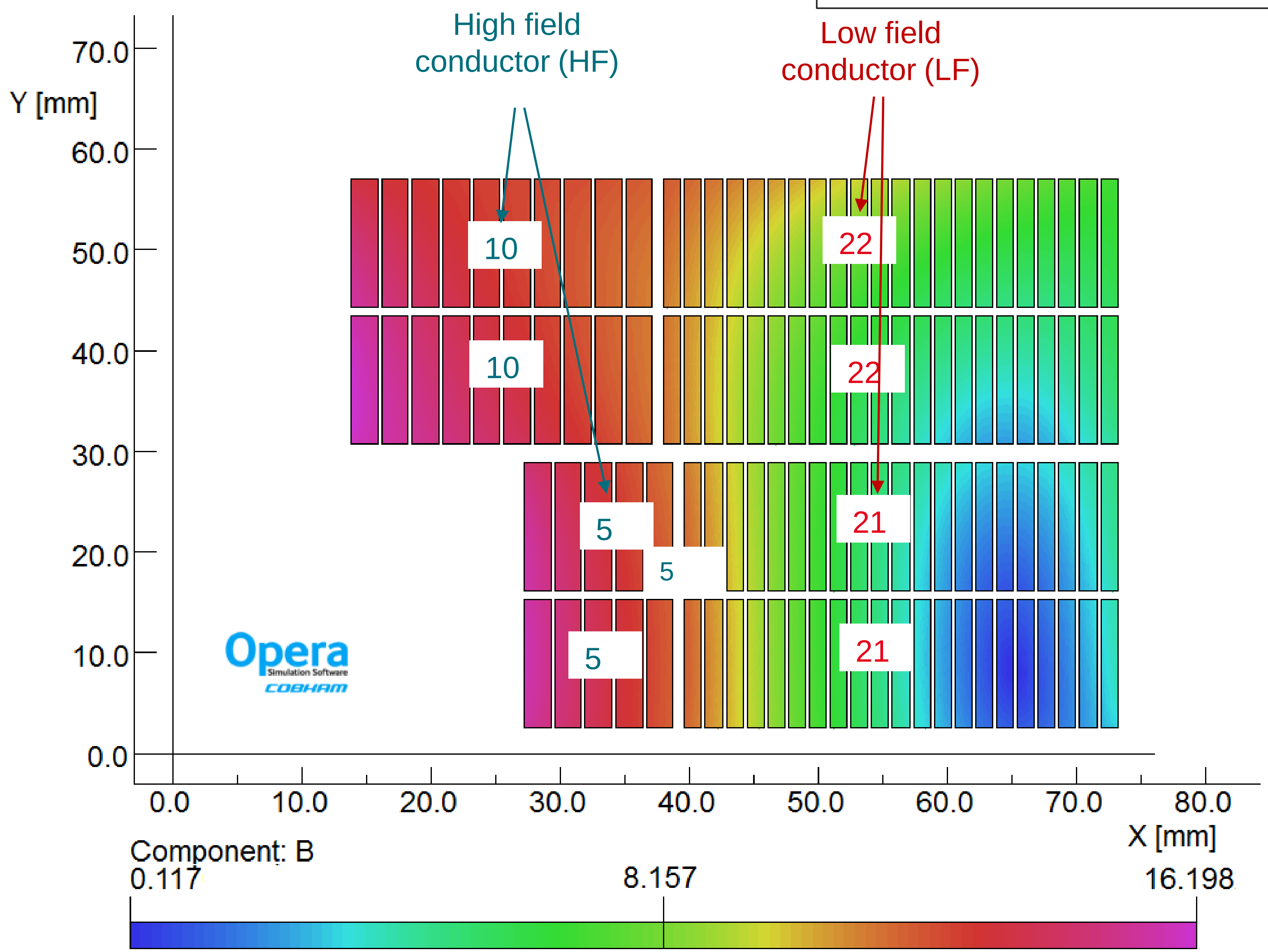


Aperture	50 mm
Outer diameter	650 mm
Structure length	2.0 m
Central field @76% LL	14.0 T
SS central field	17.8 T

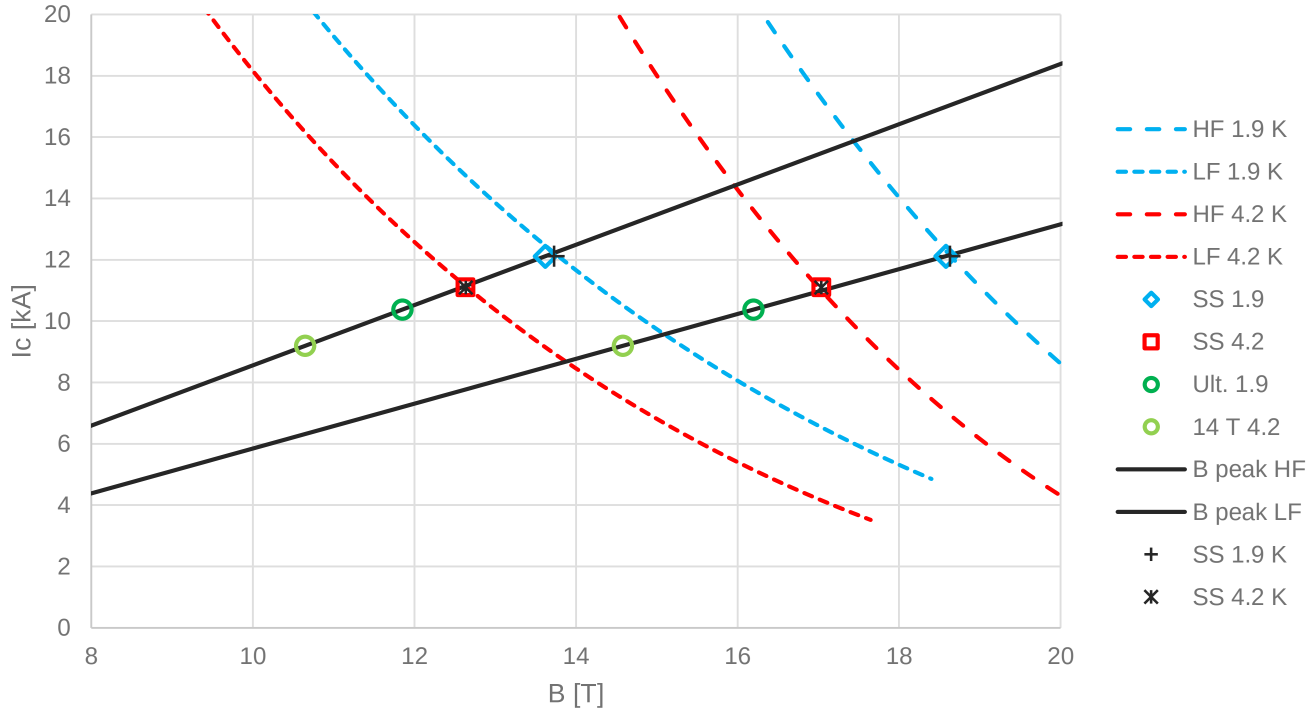
@1.9 K

2D magnetic design

X-section from EuroCirCol, minor adjustments

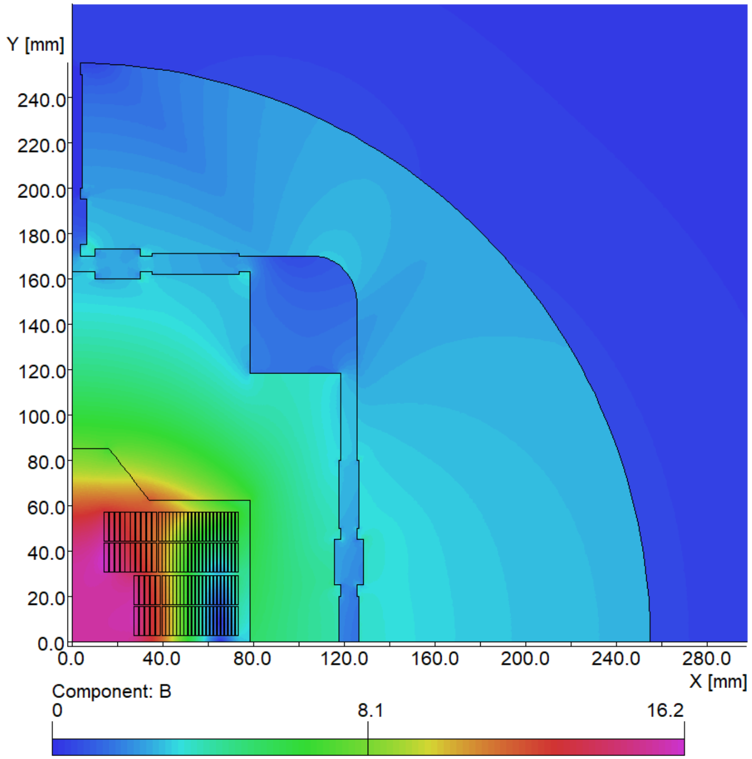


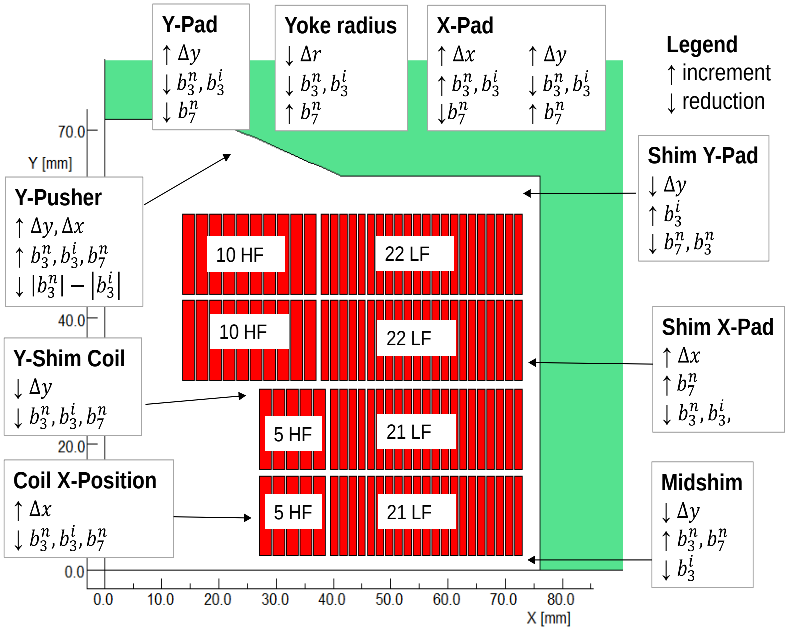
F2D2 Load-lines and margins



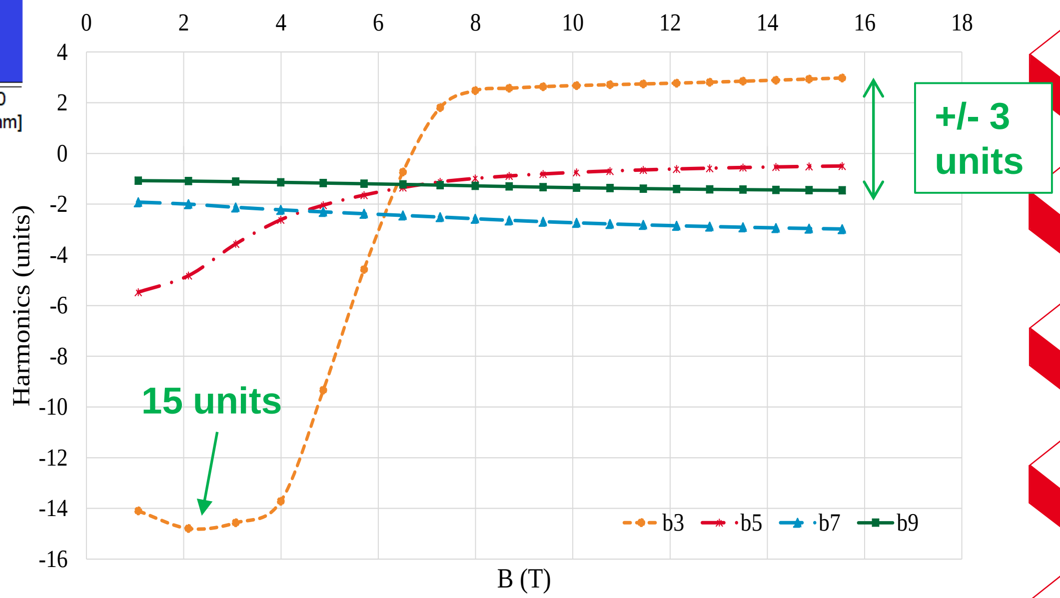
Operation	14 T operational	14 T operational	20 % margin	Ultimate	SS	SS	Unit
Temp	4.2	**1.9**	1.9	1.9	4.2	1.9	K
Current [kA]	9.2	**9.2**	9.7	10.4	11.1	12.1	kA
LL Margin HF	16.3	**24.3**	20.0	14.6	-1.0	0.3	%
LL Margin LF	17.5	**24.8**	20.5	15.1	0.4	0.9	%
B center	14.00	**14.00**	14.68	15.54	16.48	17.81	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

2D magnetic design



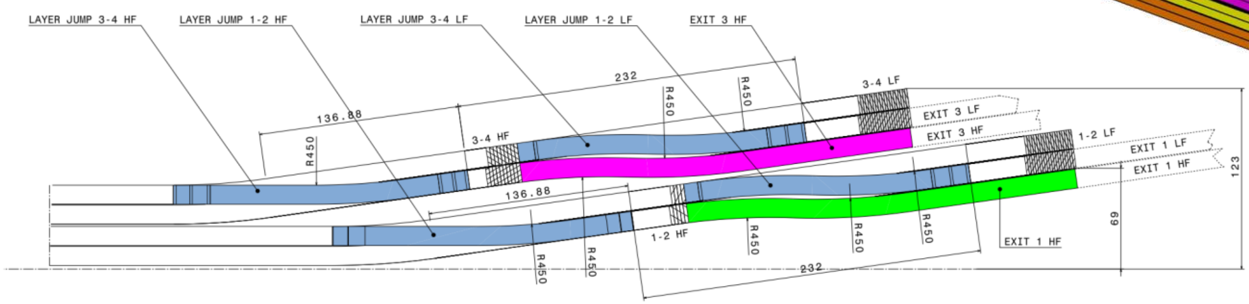


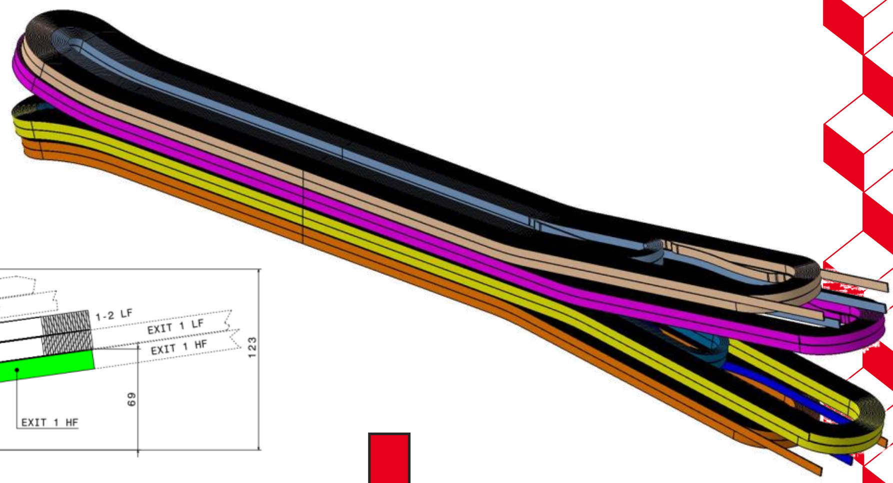
Harmonics representative of an accelerator magnet



3D magnetic design

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

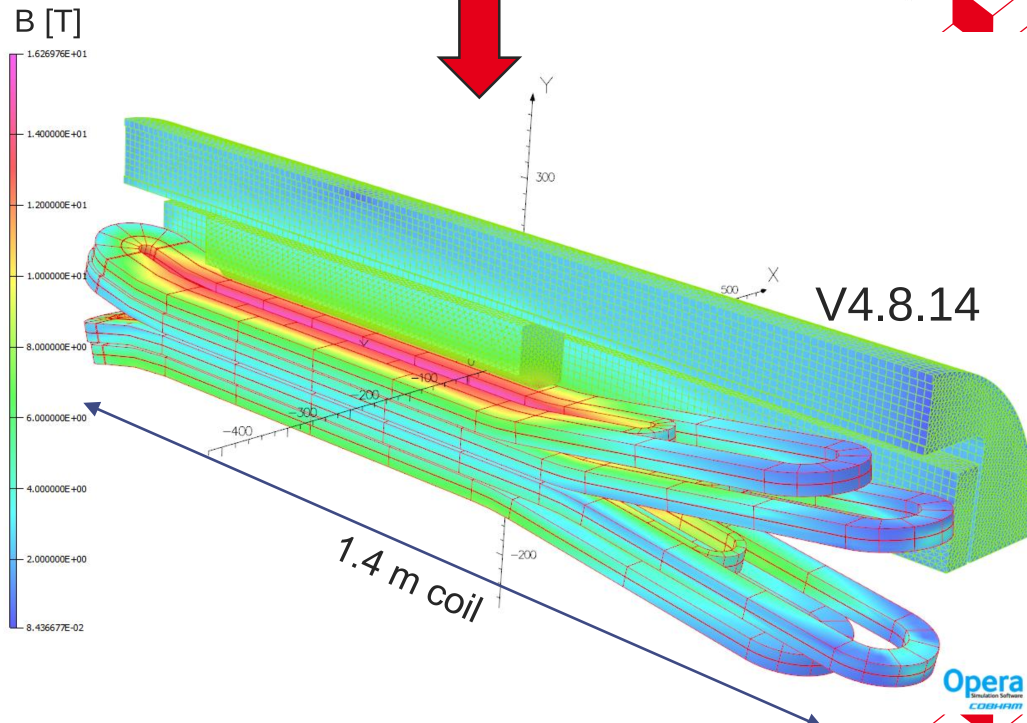




2. **3D simplified Opera FEM**:

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

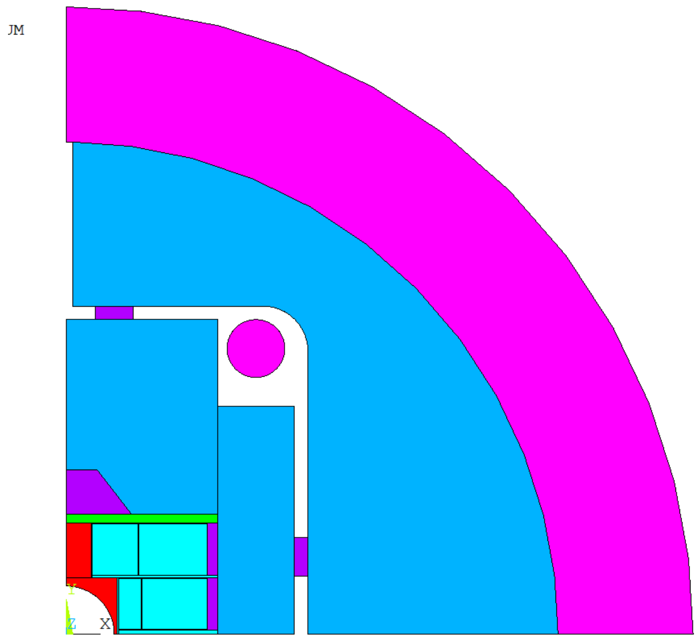
b. Field in critical areas:
- ✓ **Field in the layer jumps < 14 T**
- Advantage of flared ends:
- ✓ **Peak field not in coil-ends**

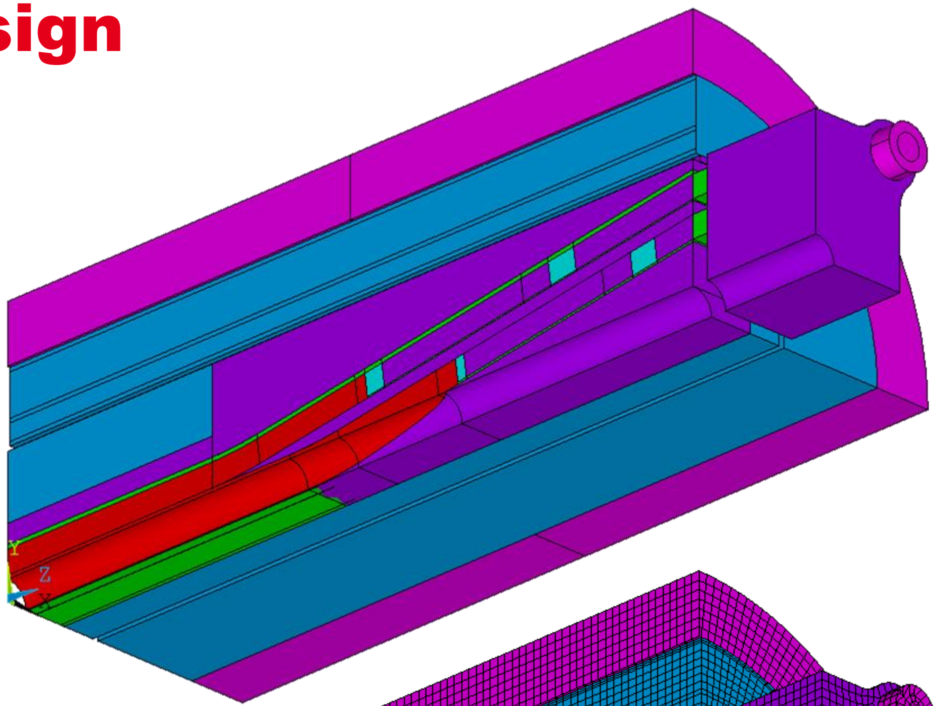


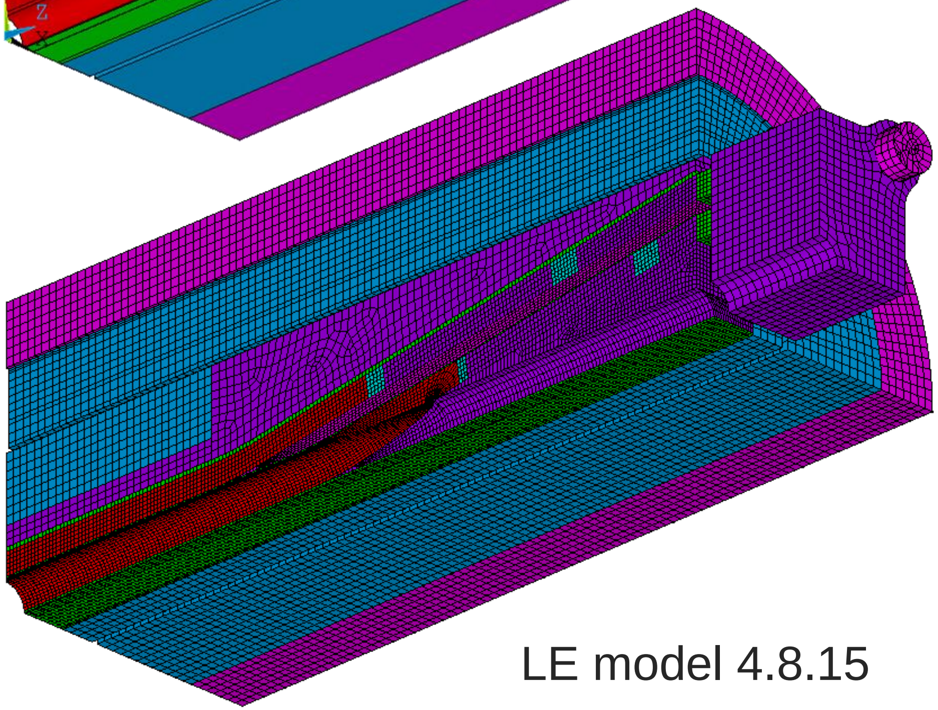
3D mechanical design

2 models:

- RE model
- LE model





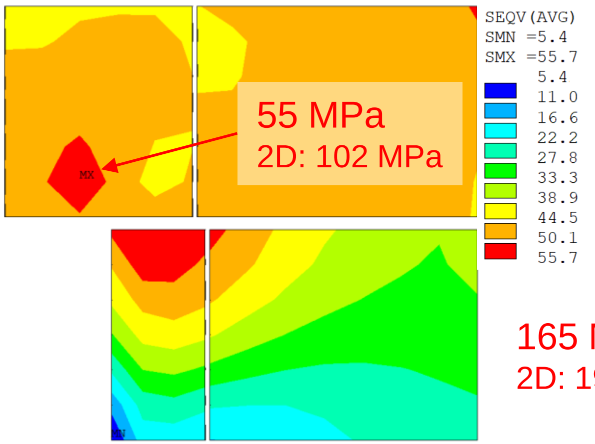


LE model 4.8.15

3D mechanical design – stress at z = 0

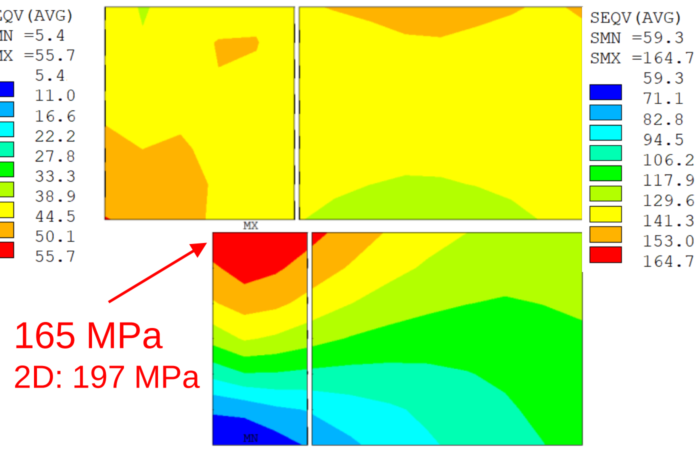
- 0.6 mm interference

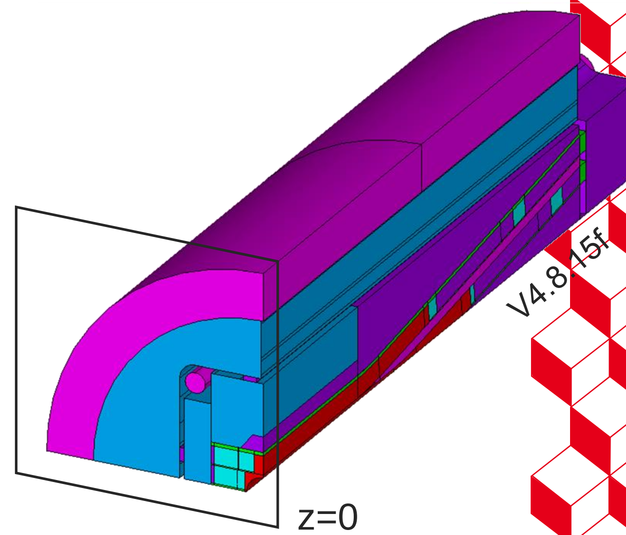
σ Von Mises [MPa]



- 1.9 K

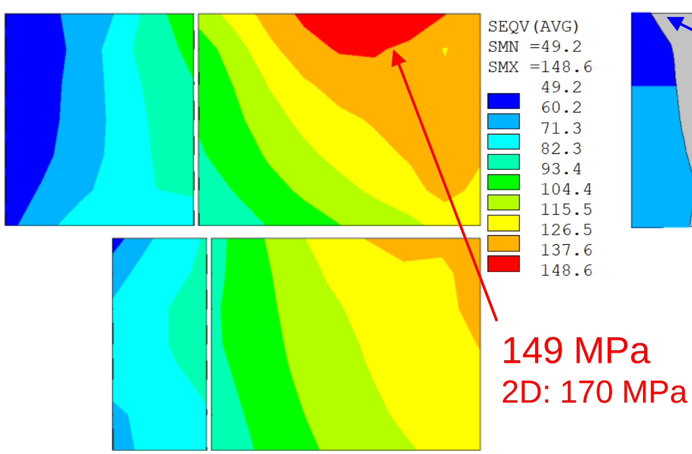
σ Von Mises [MPa]



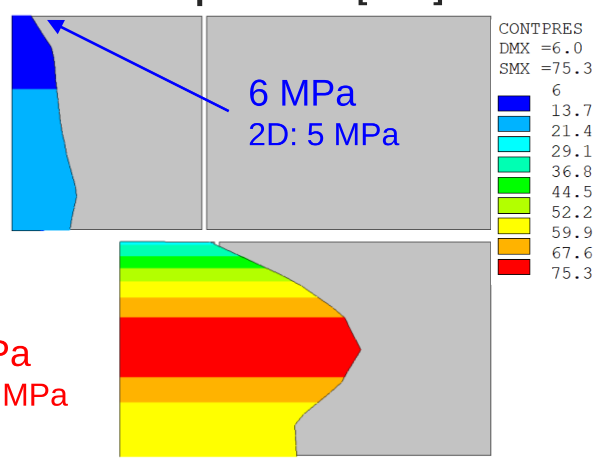


- Ultimate operations: 10.4 kA, 14% margin, **15.5 T**

σ Von Mises [MPa]



Contact pressure [MPa]



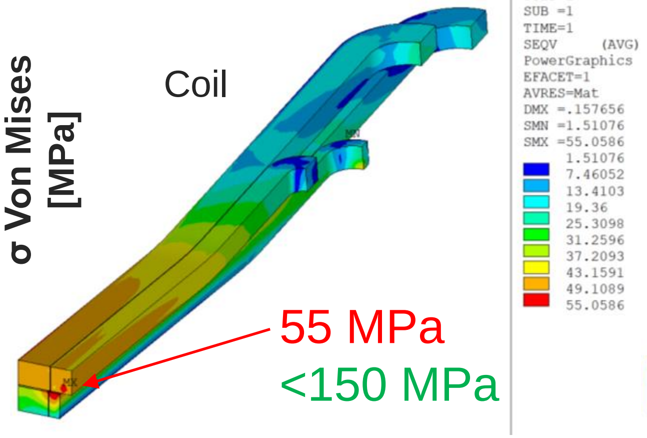
- Verified consistency with 2D model at z=0
- Coil peak stress within targets at z=0
- Next step: estimate stress-induced current limit with 3D stress [5]

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

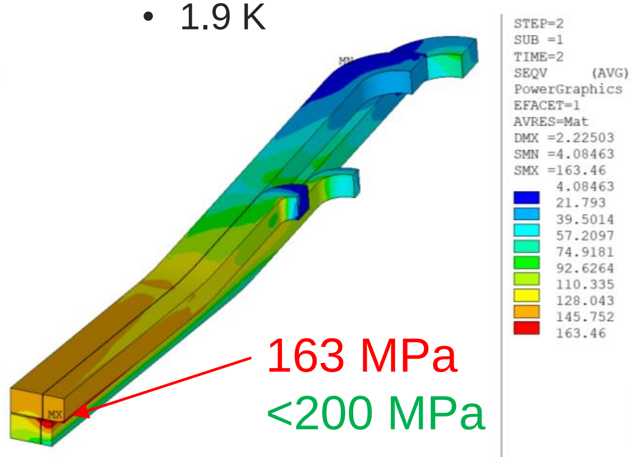
3D Mechanical Design - Stress

σ Von Mises [MPa]

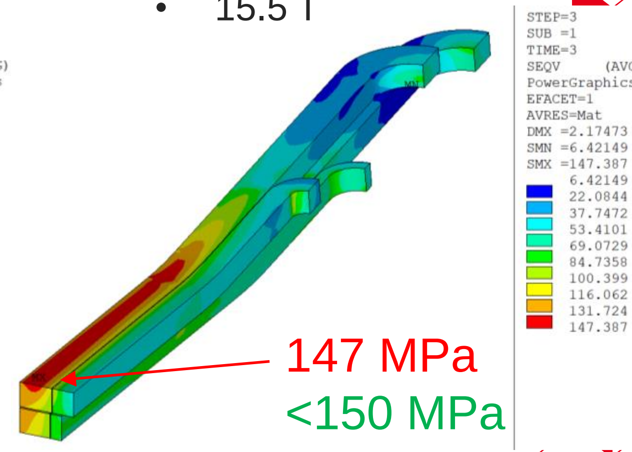
- 0.6 mm interference



- 1.9 K

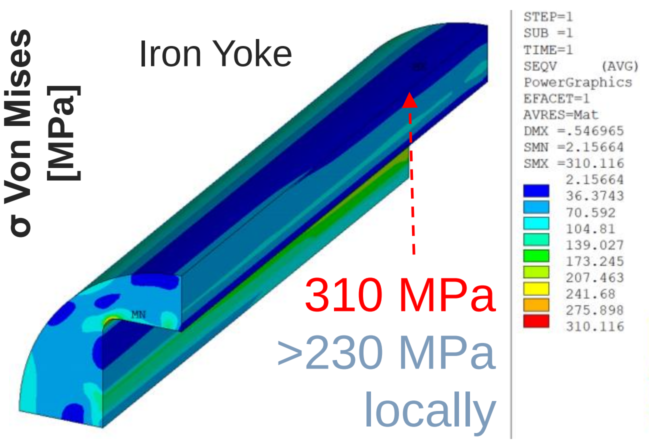


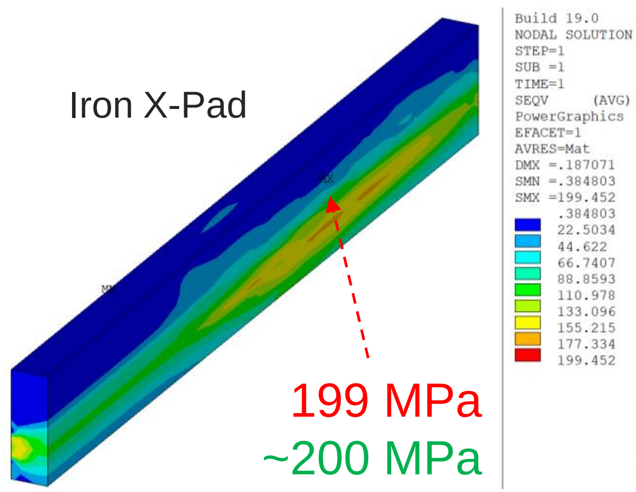
- 15.5 T

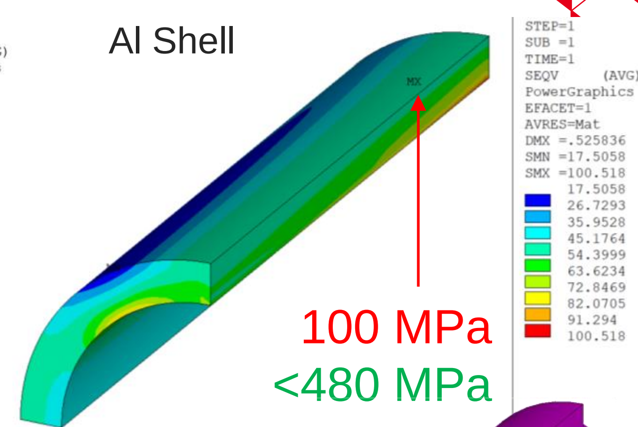


σ Von Mises [MPa]

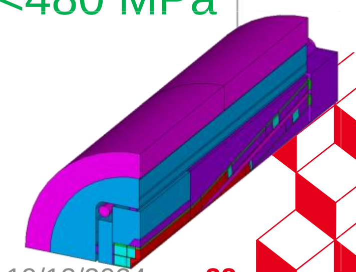
- 0.6 mm interference





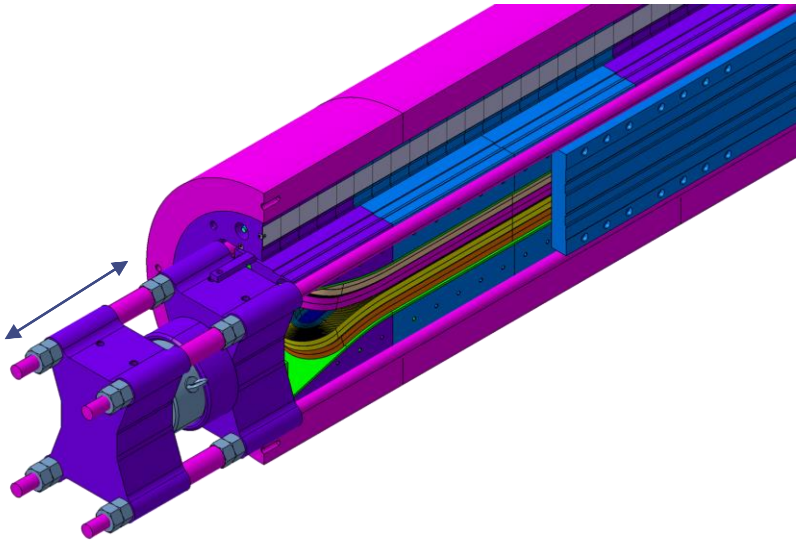


- Peak stress in coil and critical components within targets
- Accepted local plasticization of the iron yoke

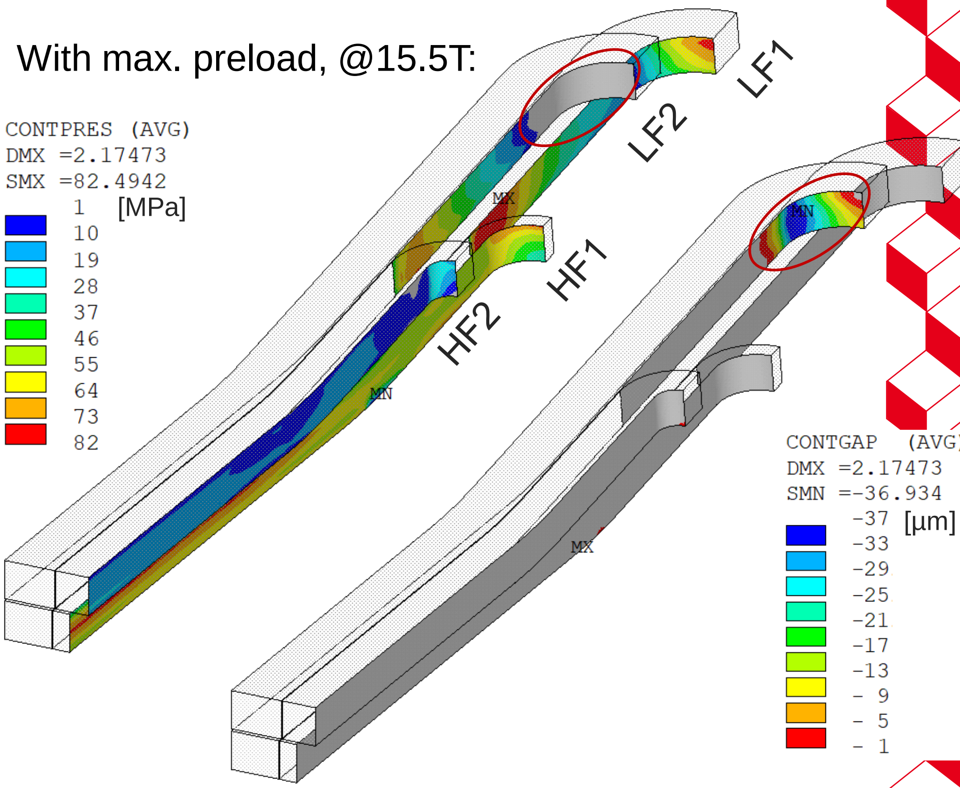


3D Mechanical Design – Longitudinal Preload

	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**

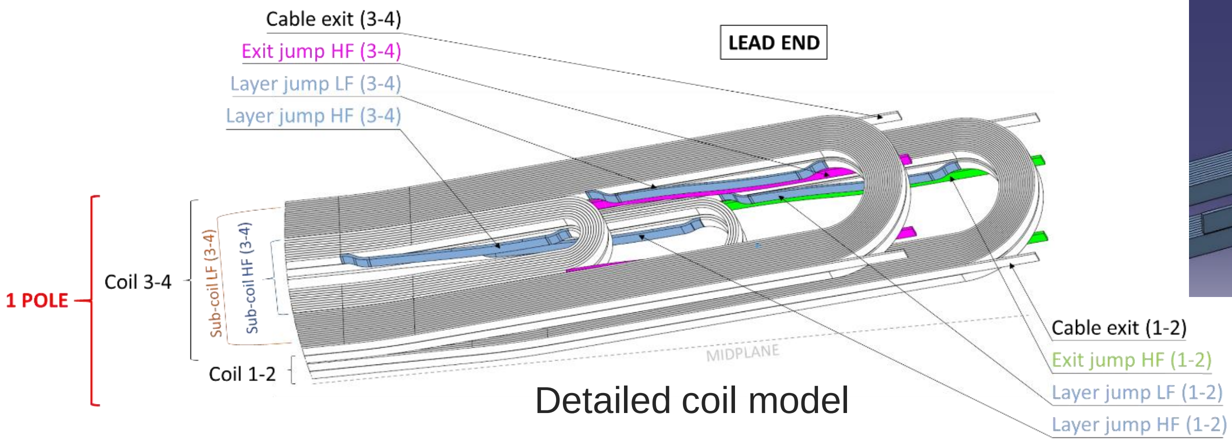


With max. preload, @15.5T:

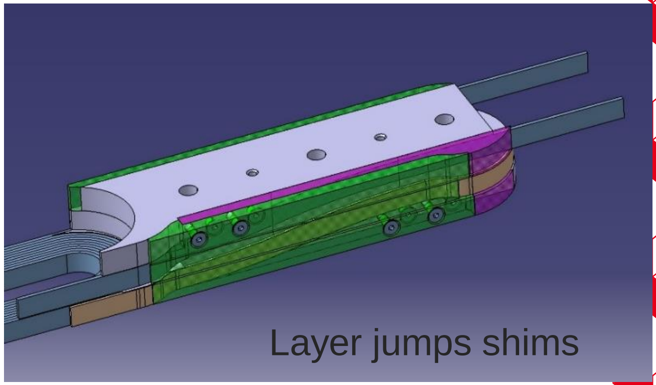


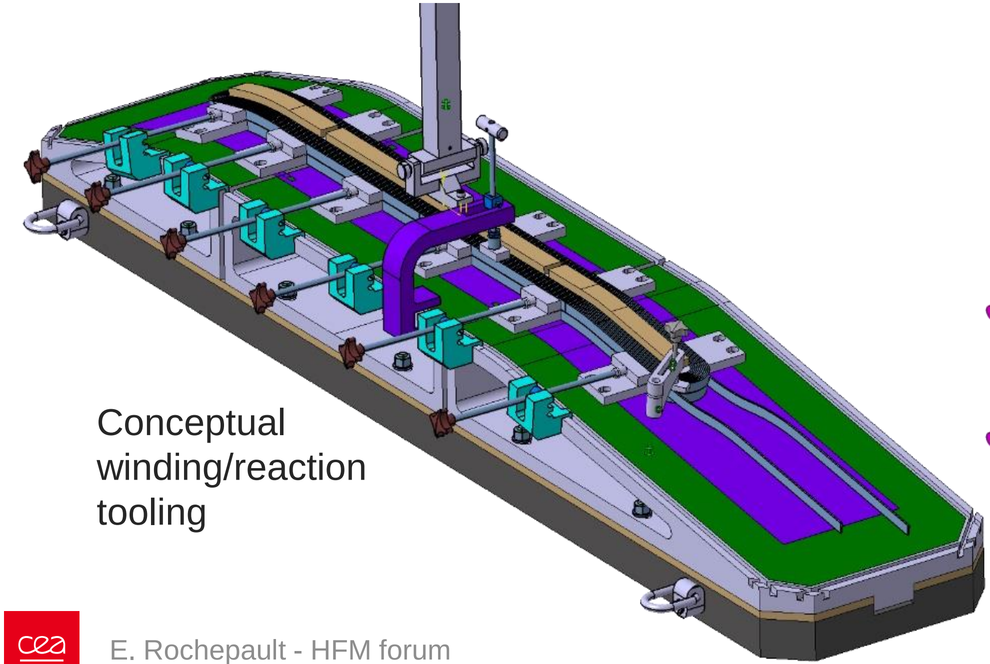
- Longitudinal preload tuned with the tie-rods, up to 150 % if necessary
- Difficult to maintain contact in LF2

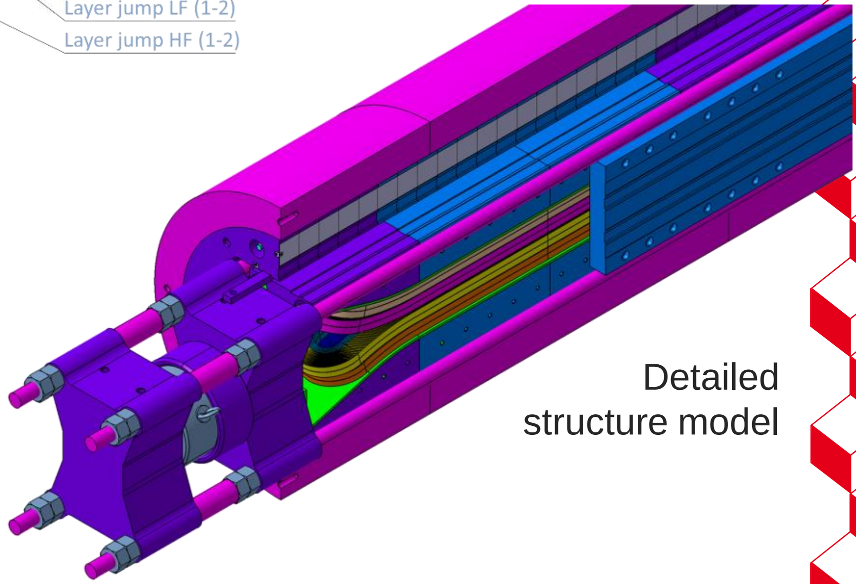
Conceptual engineering design



Detailed coil model


Layer jumps shims

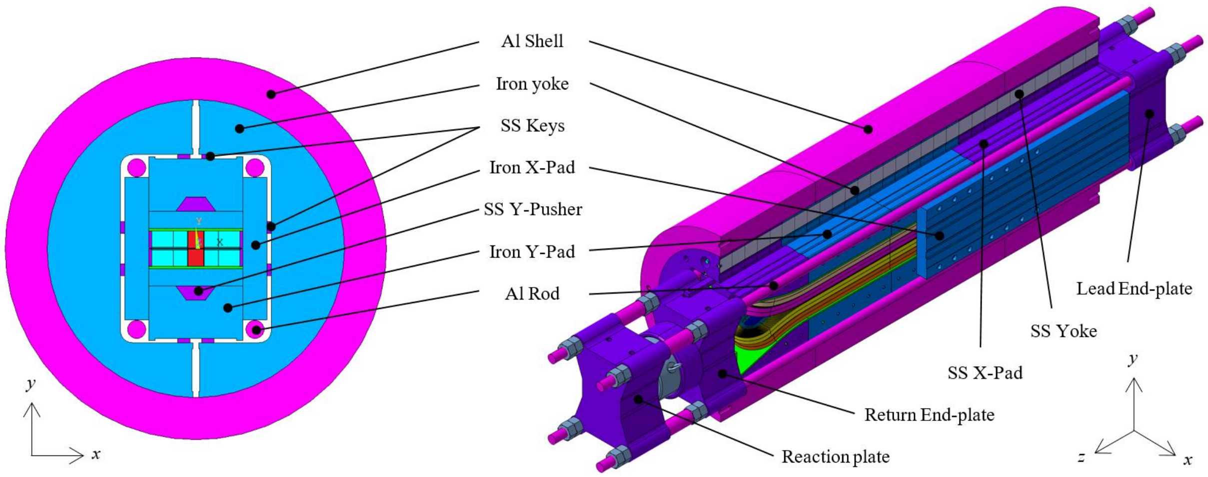

Conceptual winding/reaction tooling


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

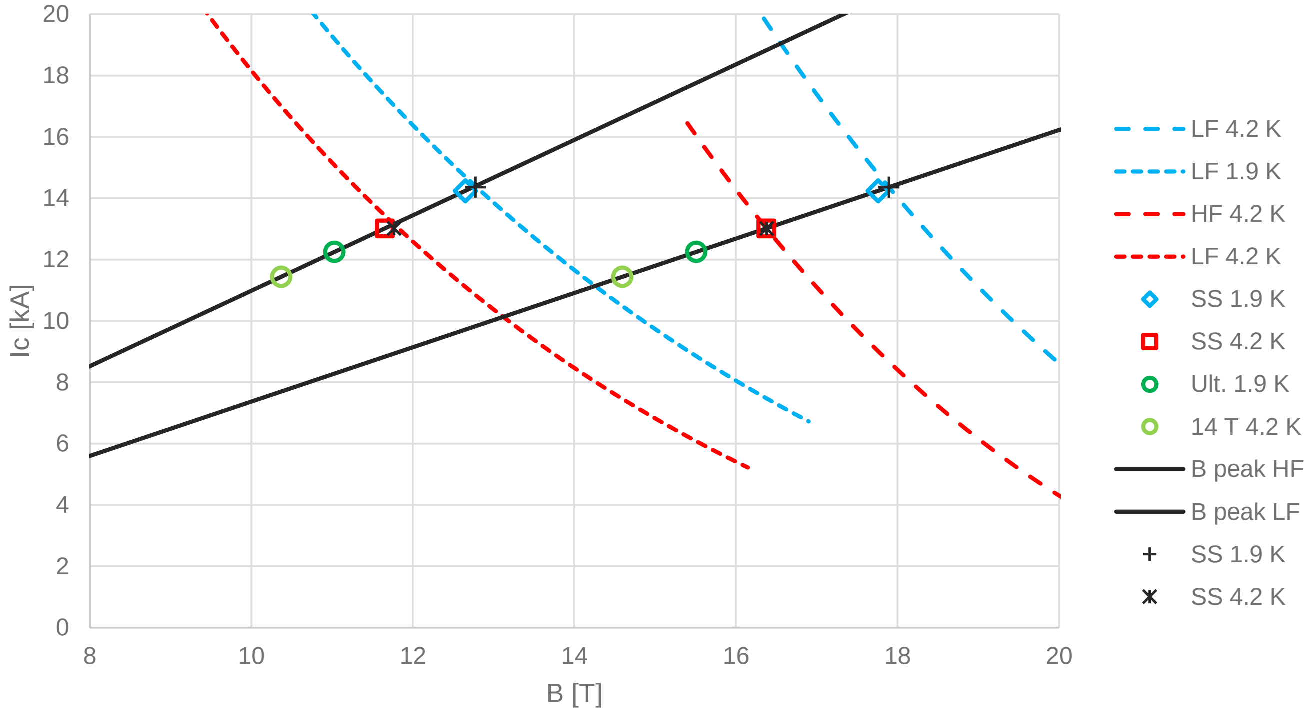
FD = **Fl**ared **D**ipole



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**

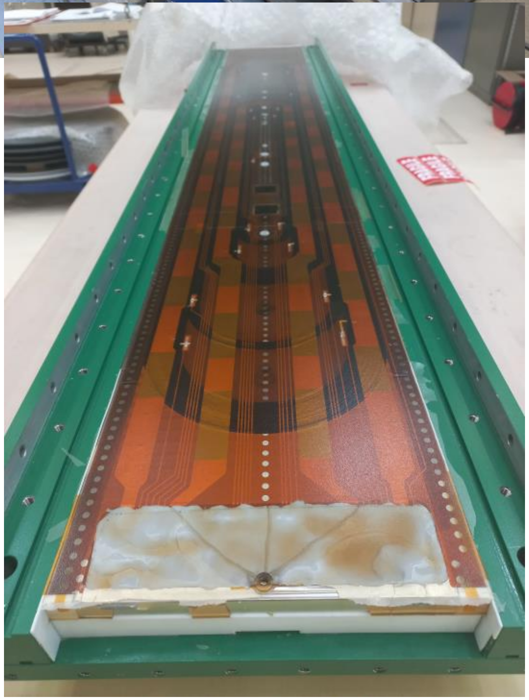
3. F2D2: the final goal
   - Demonstrator for **accelerator magnets**
   - **double-layers coils with layer jumps, grading, 50 mm bore, field quality**
   - 14 T @1.9 K with 25 % margin on the load-line
   - 15.5 T @1.9 K with 15 % margin on the load-line
   - **Conceptual engineering design finalized**

irfu

Merci !
Thank you !

Backup slides

Fabrication of R2D2 coils ongoing



CR01:

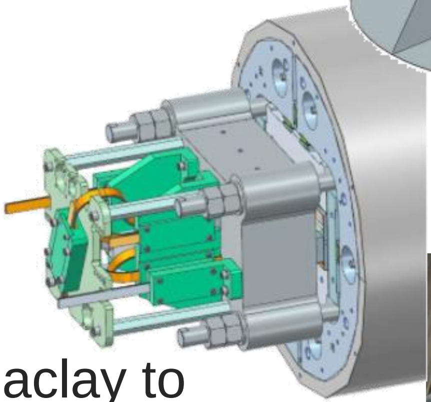
- ✓ Winding
- ✓ Heat treatment
- ✓ Junctions
- ✓ Impregnation
- × Electrical shortcuts: cause identified and solved

CR02:

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

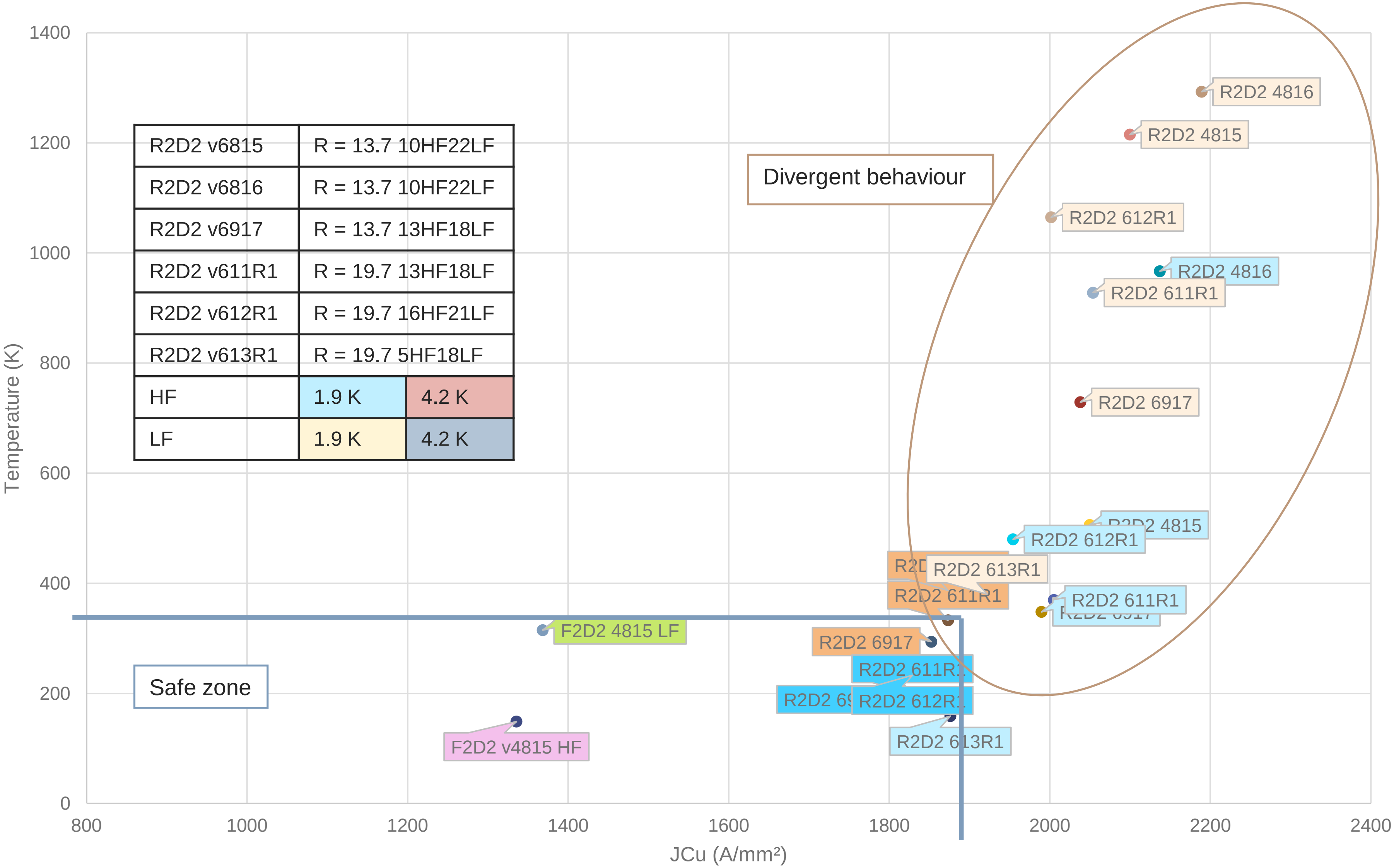
R2D2 structure procurement

- ✓ 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**

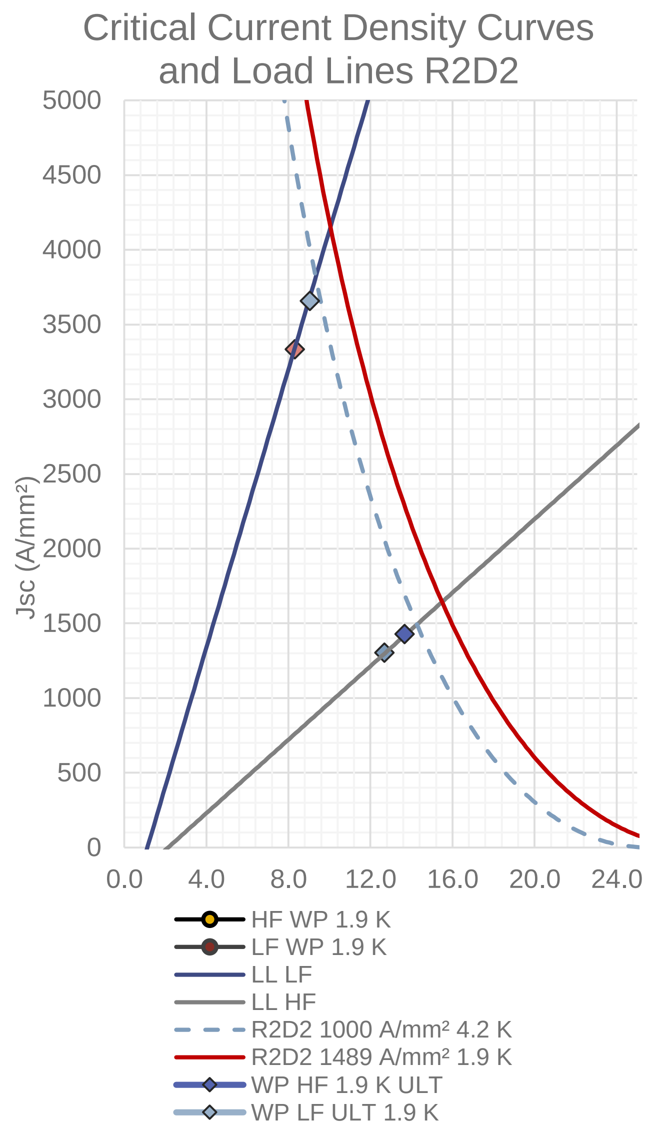
The Ultimate Working Point is the one where the magnet can operate safely

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

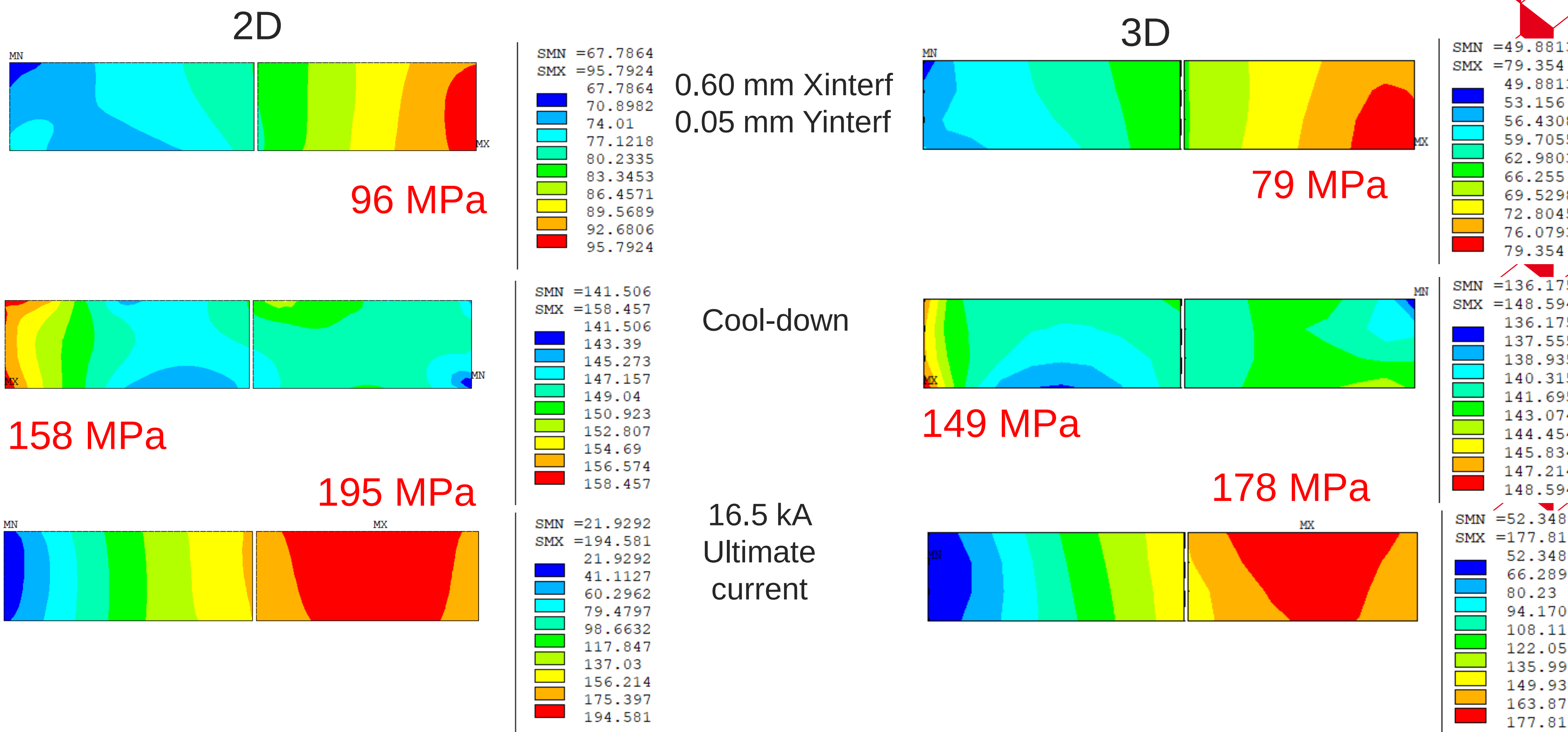
	Nominal	SS	Ultimate WP
I	15055 A	18819 A	16500 A
LL margin HF / LF	20.9% / 20.0%	0.9 % / 0.0%	12.85 % / 11.3 %
B @ (0,0)	**11.15 T**	**13.29 T**	**11.98 T**
B peak HF	12.69 T	15.23 T	13.67 T
B peak LF	8.32 T	10.21 T	9.05 T
Energy density	553 KJ/m	818 KJ/m	649 KJ/m
Magnetic length	785 mm	785 mm	785 mm
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



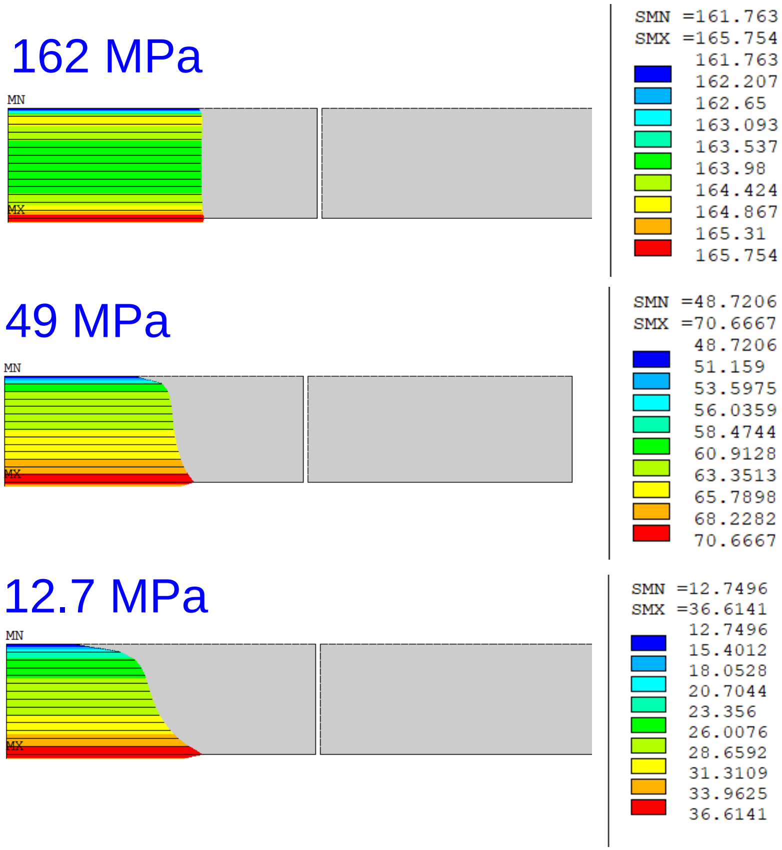
VM Stress – 2D vs 3D (Ultimate)



- **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

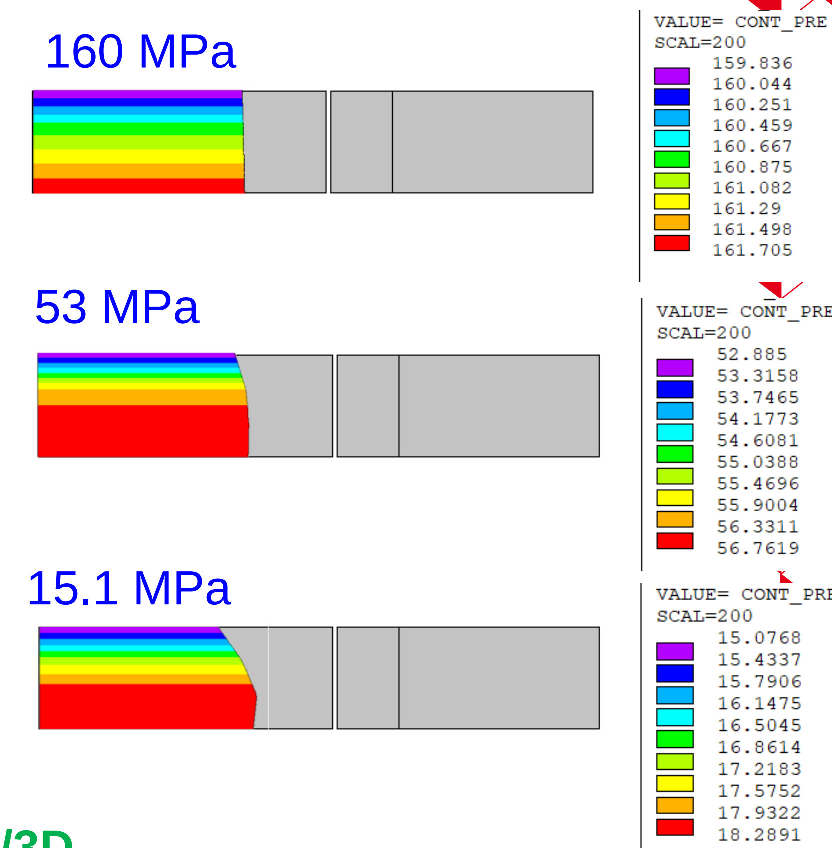


Cool-down

13.7 kA Nominal current

16.5 kA Ultimate current

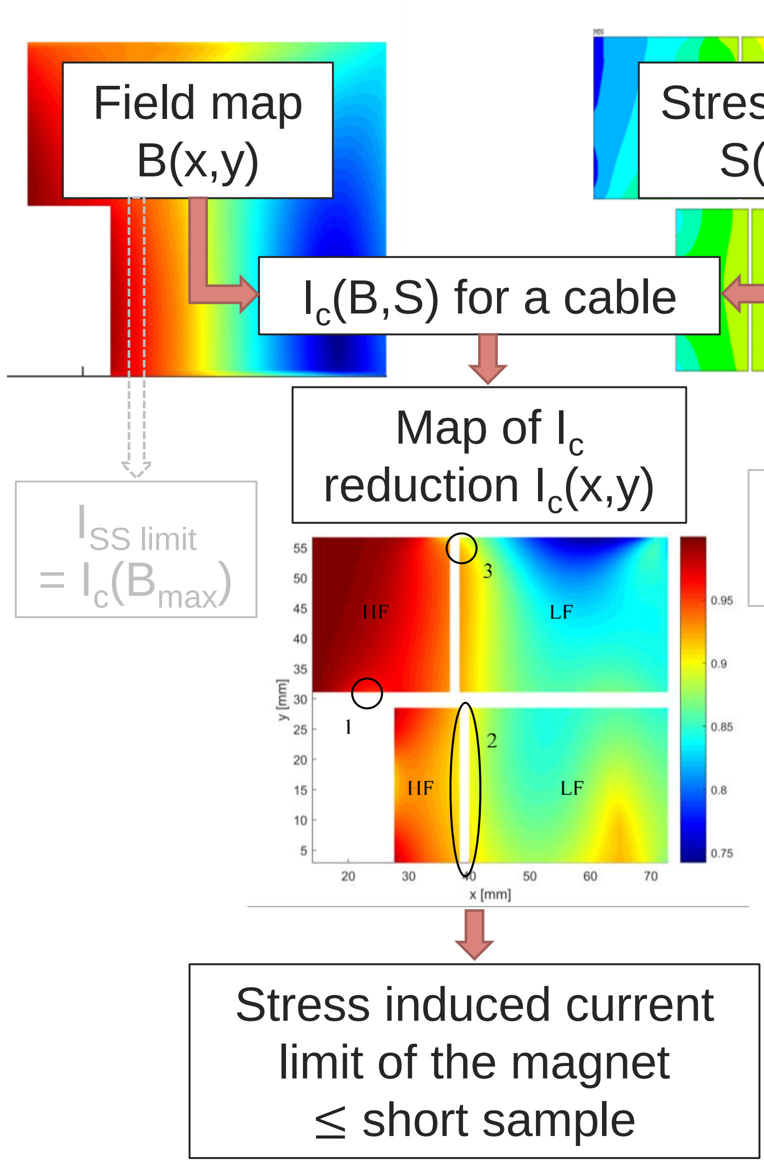
3D

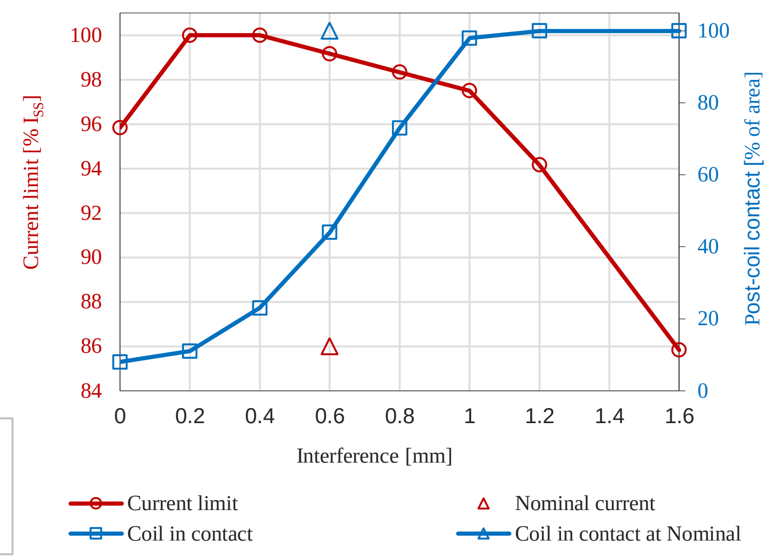


- **Profile and range very similar between 2D/3D**
- Difference <5 MPa in min. contact pressure

→ 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

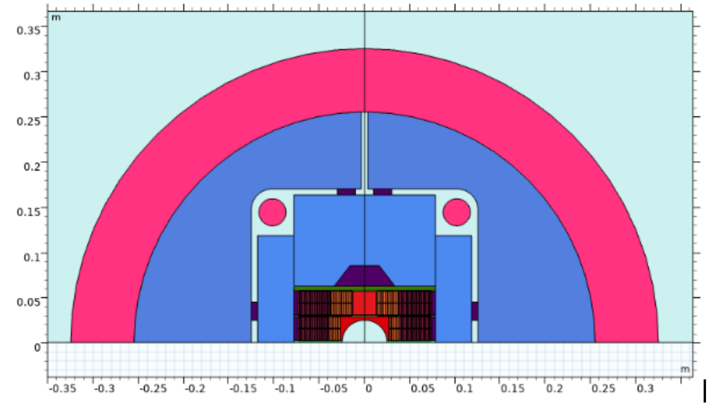
2D Quench Protection - Ongoing

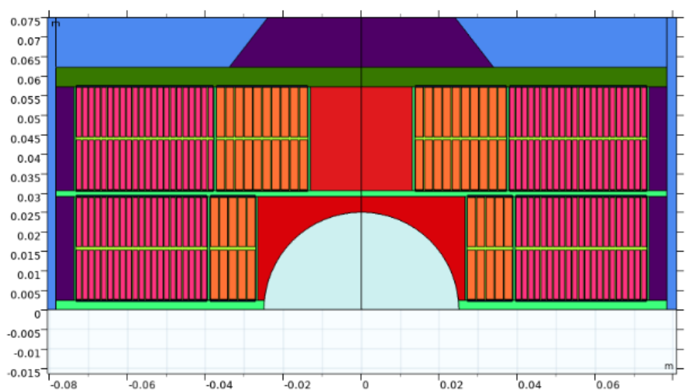
Protection Criteria (same as ECC):
- Every coil has a quench heater
- Detection delay = 20 ms
- Detection voltage = 5 mV
- Heater activation delay = 20 ms
- Max hot spot temperature = 350 K
- Max ΔV to ground = 1200 V

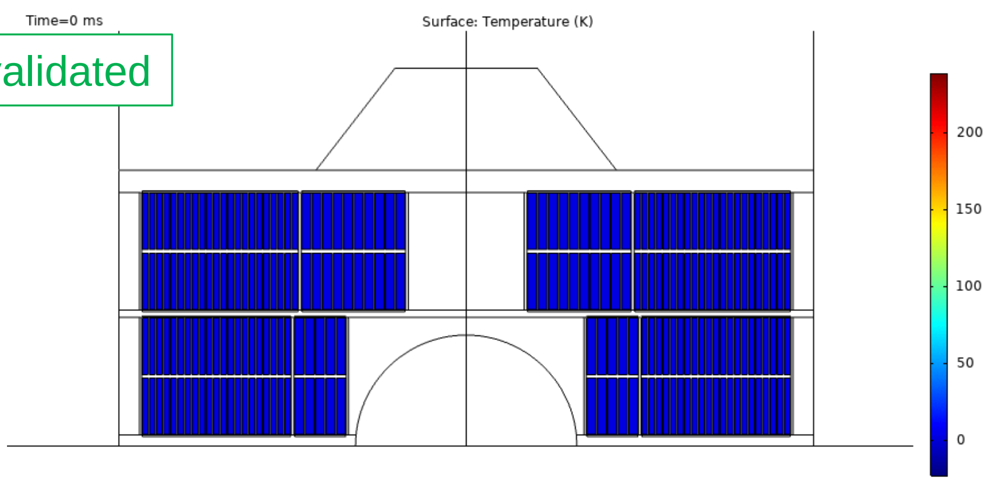
Model Hypotheses:
- Adiabatic Regime
- Cryocomp material database
- Magnetoresistivity included
- Transverse+longitudinal propagations considered

→ Magnetic, electrical, thermal models validated

Quench Study using Comsol







Case study : QH HF1+HF3 off