DE LA RECHERCHE À L'INDUSTRIE

F2D2: the CEA Dipole Model for the FCC

F2D2 = FCC Flared-ends Dipole Demonstrator

CEA: **E. Rochepault**, V. Calvelli, M. Durante, H. Felice, P. Mallon, P. Manil, J.F. Millot, G. Minier, J.M. Rifflet, L. Ramos-Vieira
CERN: S. Izquierdo Bermudez, D. Tommasini, J. Fleiter

27/06/2019

STRONG INTERACTION WITH MAGNET PROGRAMS

CEA-CERN Program

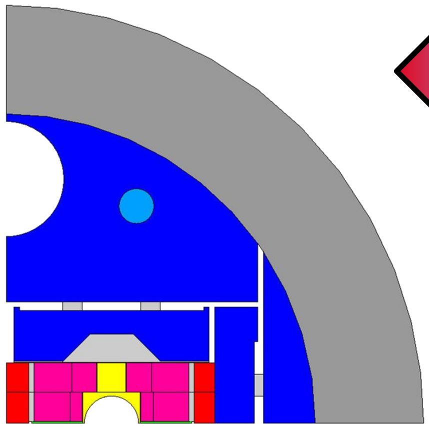
1. ECC block-coil design [1-2]

→ 16T Conceptual design

→ Double aperture

[1] M. Segreti et al., “2D and 3D Design of the Block-coil Dipole Option for the Future Circular Collider”, IEEE TAS, 2019

[2] See “Evolution of the block-coils design”, this conference



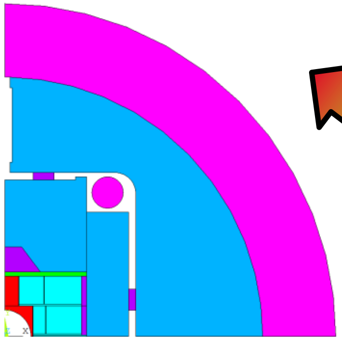
2. F2D2 short model [3]

→ Design/fabrication at CEA

→ Test at CERN

→ Single aperture

→ Same coil design as ECC



[3] H. Felice et al. “F2D2: a Block-coil Short Model Dipole Toward FCC”, IEEE TAS, 2019

CERN Programs

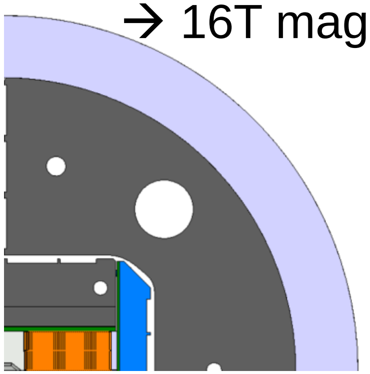
- SMC models

→ Technology development

→ Conductor qualification

- ERMC/RMM models [4,5]

→ 16T magnet R&D



[4] S. Izquierdo et al., “Design of ERMC and RMM, the Base of the Nb3Sn 16 T Magnet Development at CERN”, IEEE TAS, 2017

[5] See “Mechanical validation of the support structure of the eRMC and RMM, the 16-T R&D magnets for the FCC”, this conference

EPFL-CERN Program

- R&D on jonction technology [6-7]

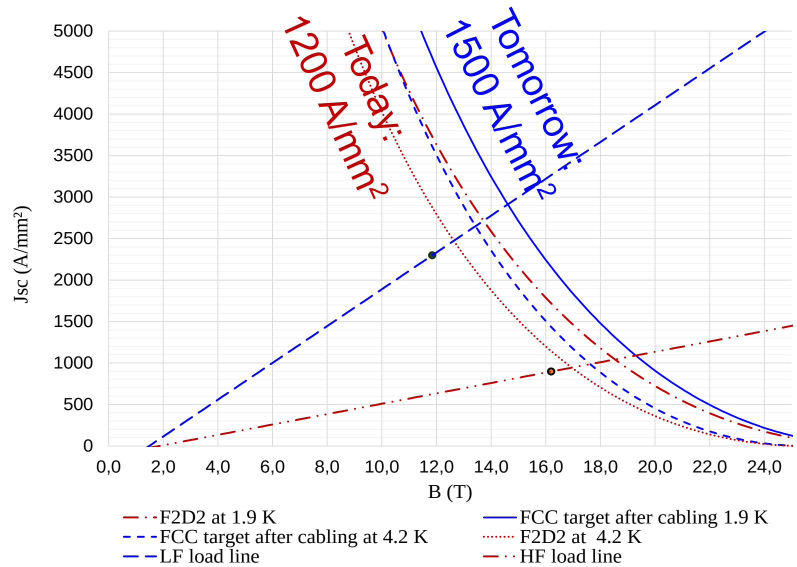
[6] M. Kumar et al. “Preliminary Tests of Soldered and Diffusion-Bonded Splices Between Nb3Sn Rutherford Cables for Graded High-Field Accelerator Magnets”, IEEE TAS, 2019

[7] See “Soldered and diffusion-bonded splices between Nb3Sn Rutherford cables for graded high-field accelerator magnets “”, this conference

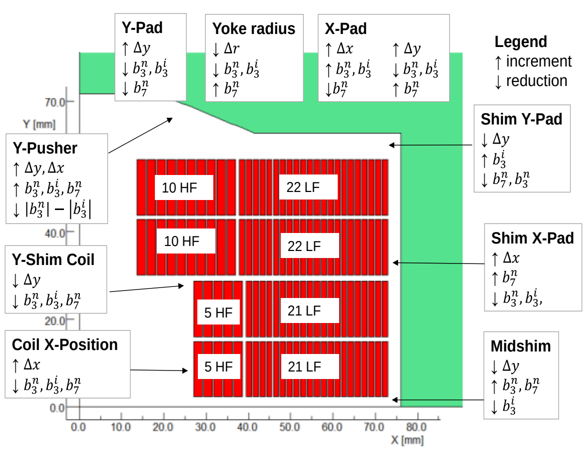
2D Magnetic Design - Finalized

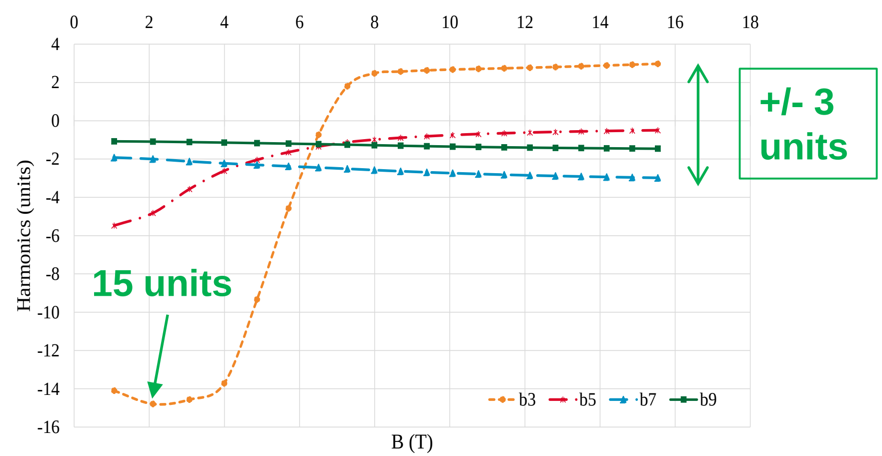
1. Maximize central field with margins:

Nominal Current Inom	10378 A
Short sample current I_{ss}	12118 A
Bore field By_0 at Inom (I_{ss})	**15.54** (17.81) T
Peak Field at Inom (HF/LF)	16.20 / 11.85 T
Peak Field at Iss (HF/LF)	18.58 / 13.62 T
Loadline Margin at Inom (HF/LF)	**14.0** / 15.4 %
Stored Energy Inom	1.4 MJ/m

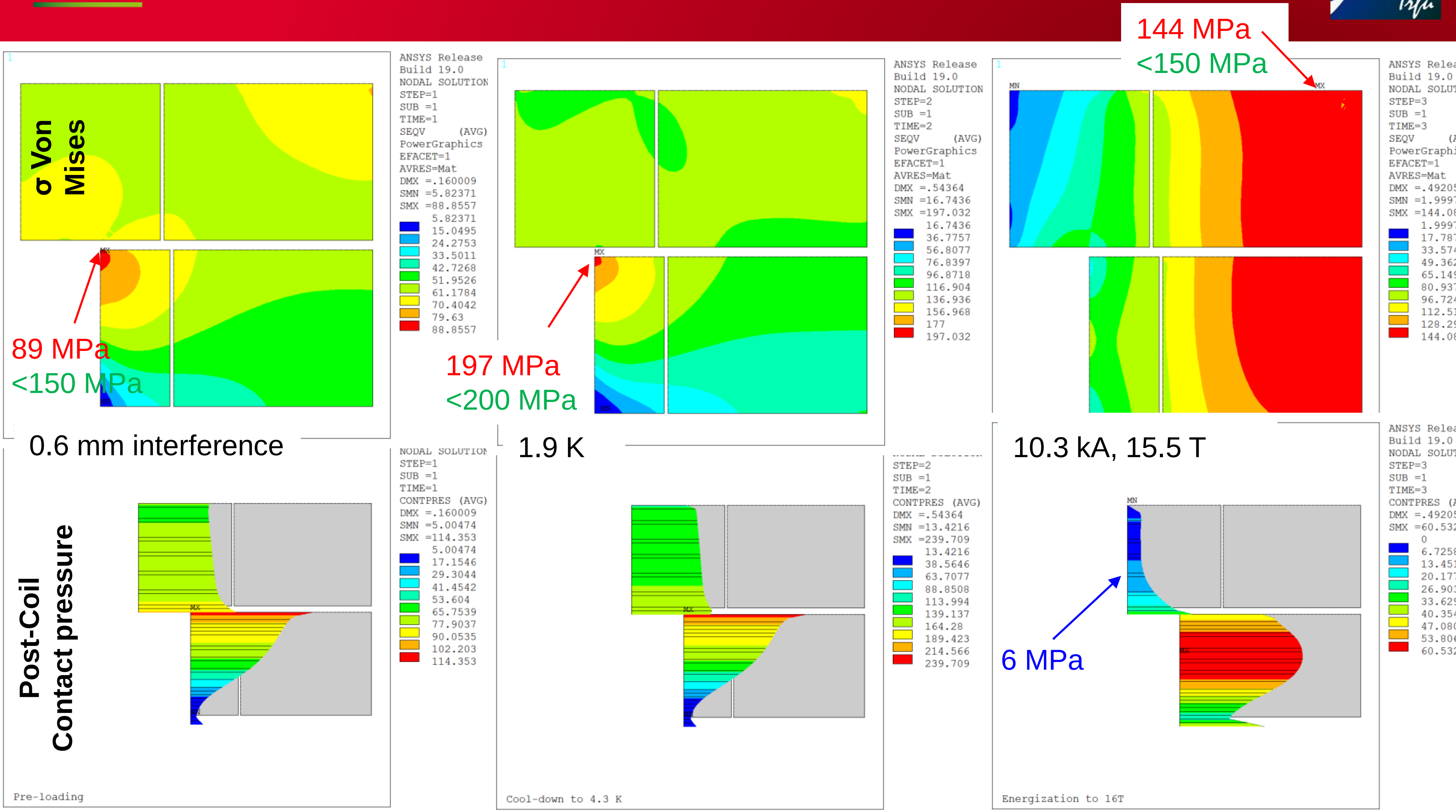


2. Harmonics representative of an accelerator magnet:





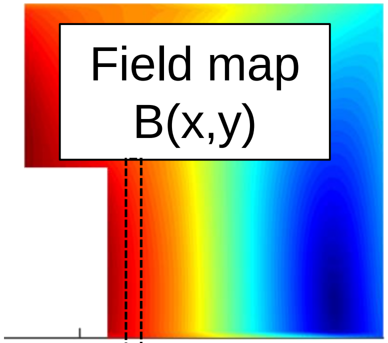
2D Mechanical Design - Finalized

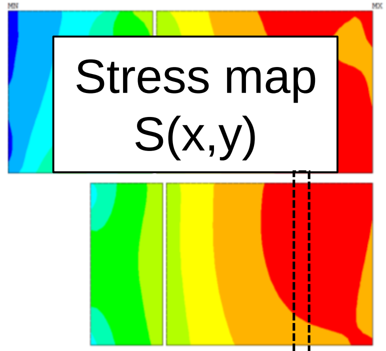


V4.8.14a

1. Provide **coil-pole contact during nominal operation**
2. Keep **peak stress below** (reversible) **degradation limits**

2D Magneto-Mechanical Design - Finalized



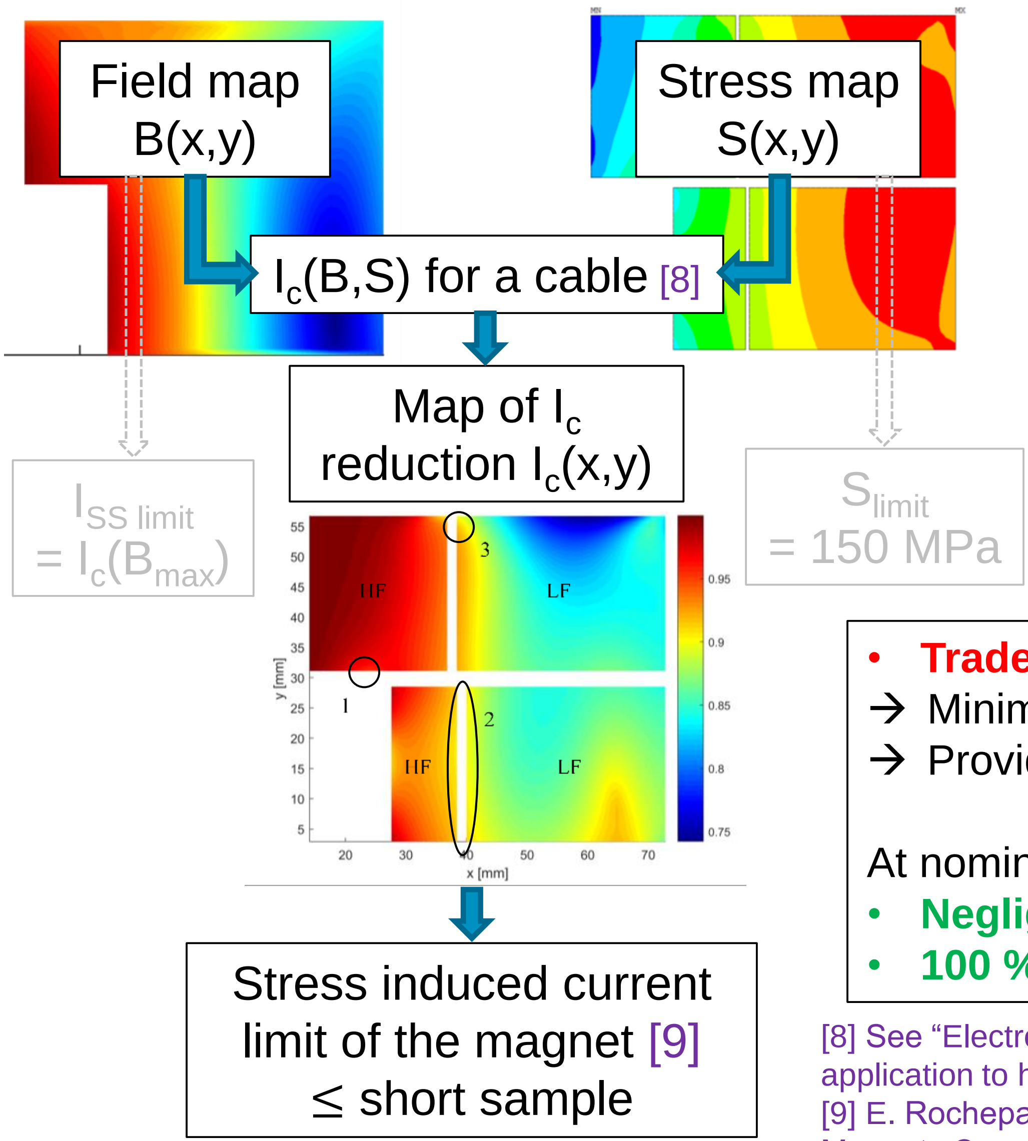


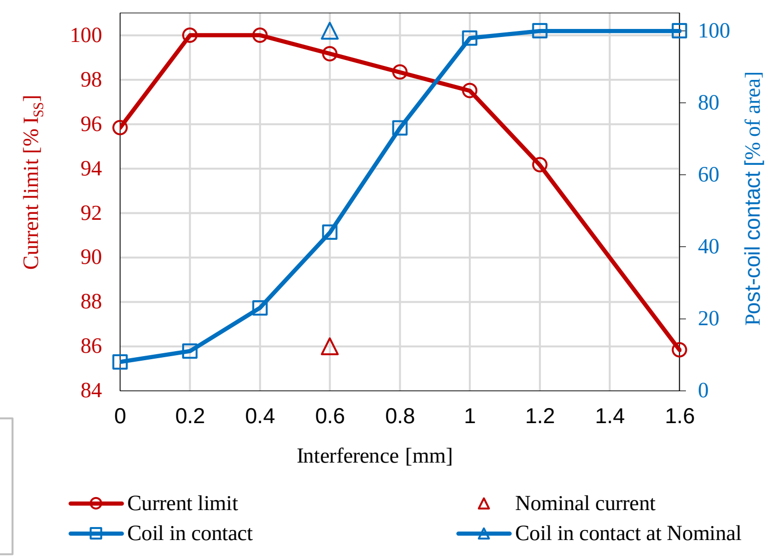
$I_{SS\ limit} = I_c(B_{max})$

Traditional approach

$S_{limit} = 150$ MPa

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**

[8] See "Electro-mechanical properties of Nb3Sn conductors for application to high-field magnets", this conference

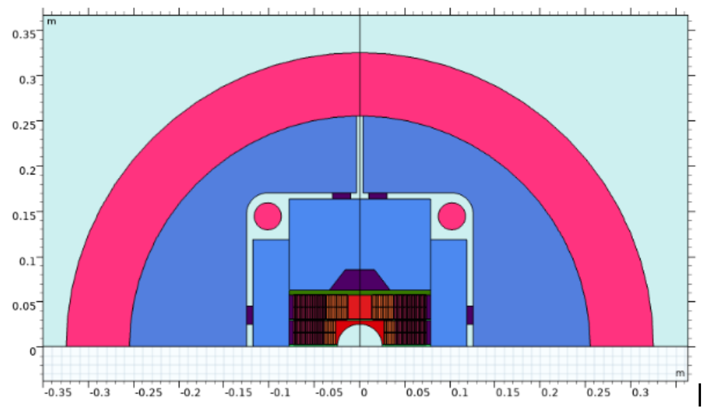
[9] E. Rochepault et al., "Current Limits in Nb3Sn Superconducting Magnets Considering Magnetic Field and Stress", submitted to IEEE TAS

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

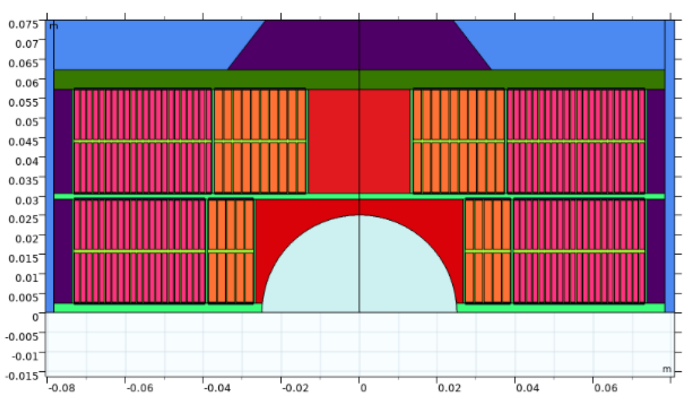
Quench Study using Comsol

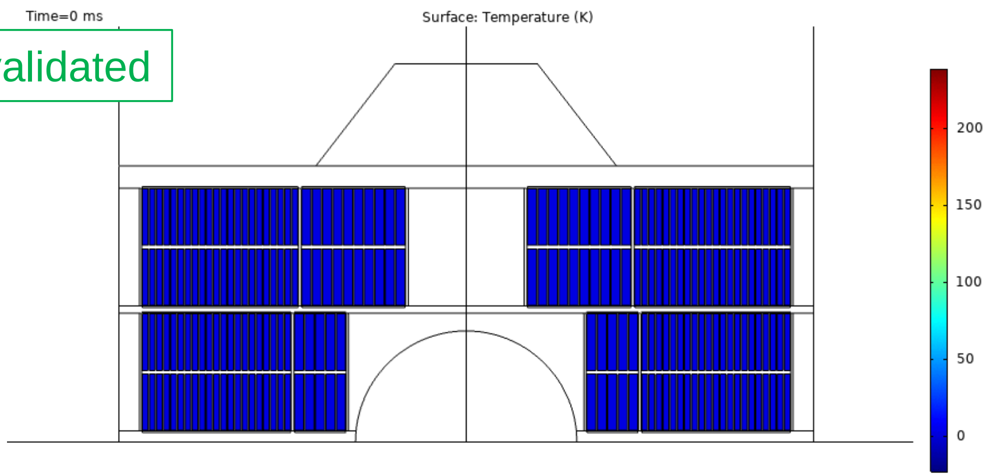


Model Hypotheses:

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

→ Magnetic, electrical, thermal models validated

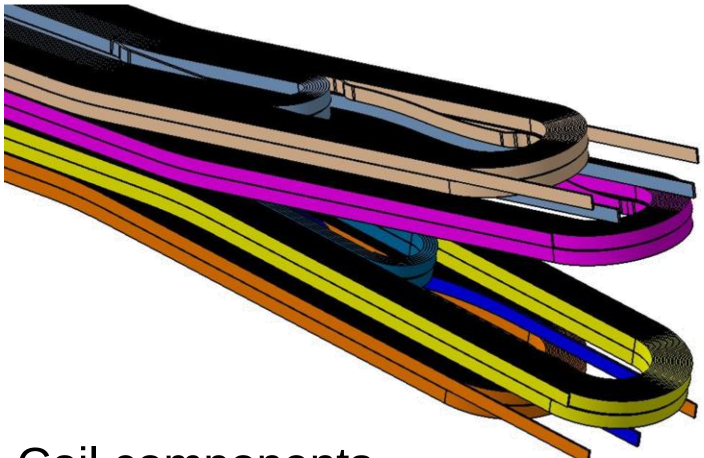




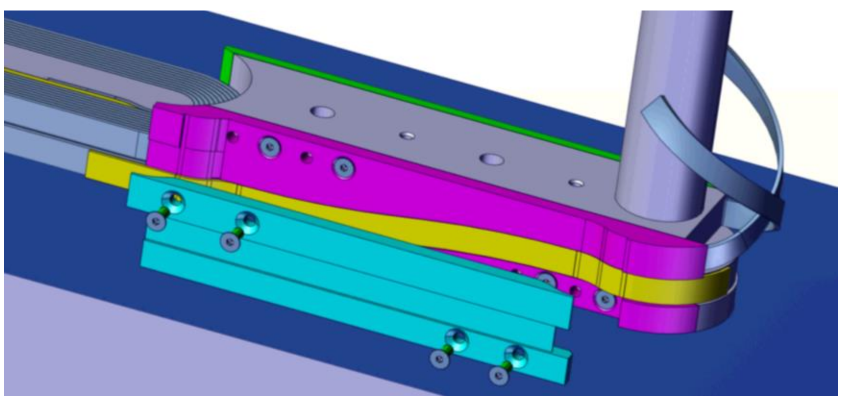
Case study : QH HF1+HF3 off

Preliminary CAD Design - Ongoing

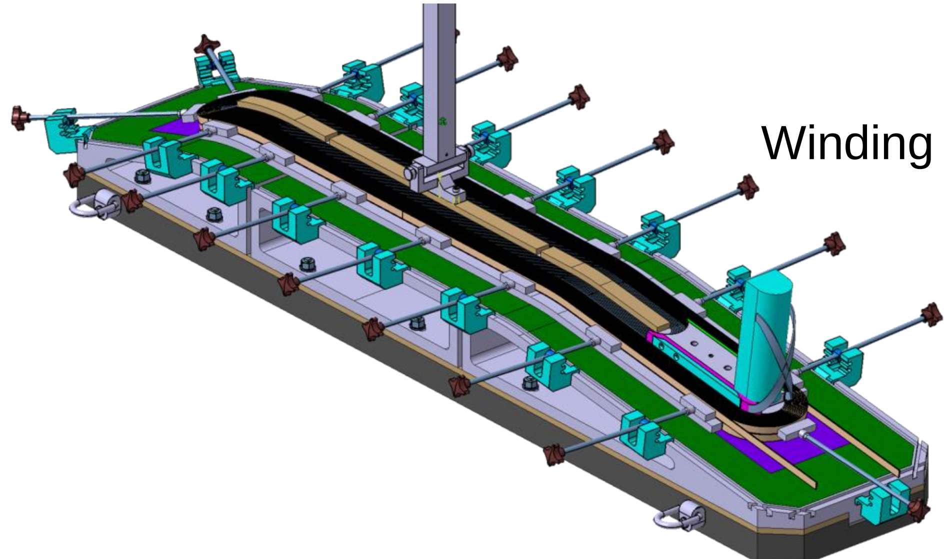
1. Turn-by-turn coil model
→ External joints option
→ Define path for cable exits

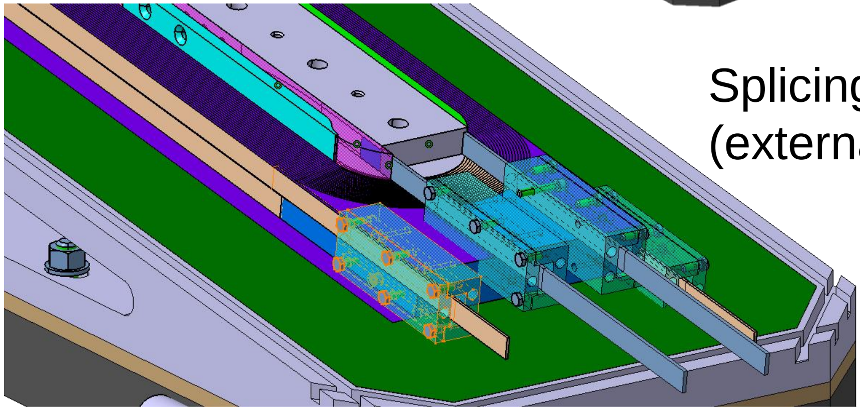


2. Coil components
→ Study concepts for external joints



3. Coil fabrication tooling
→ Winding + reaction + splicing + impregnation
→ Study compatibility with the fabrication process

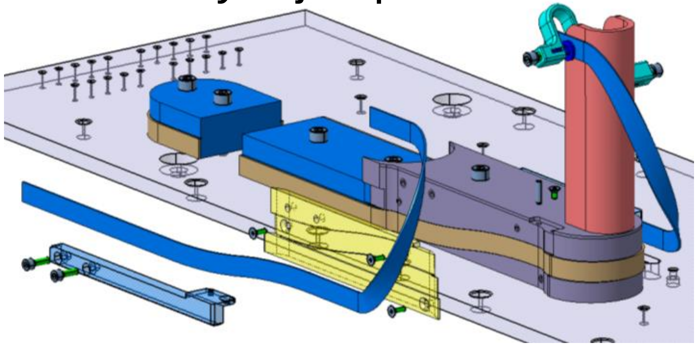




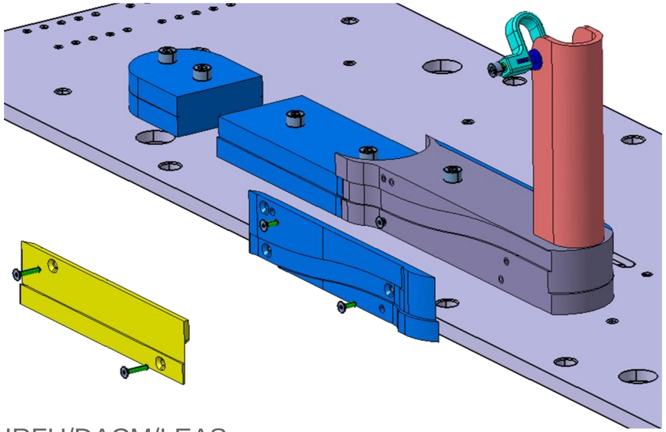
Winding Mockups - Finalized

- 2 options for cable exits:

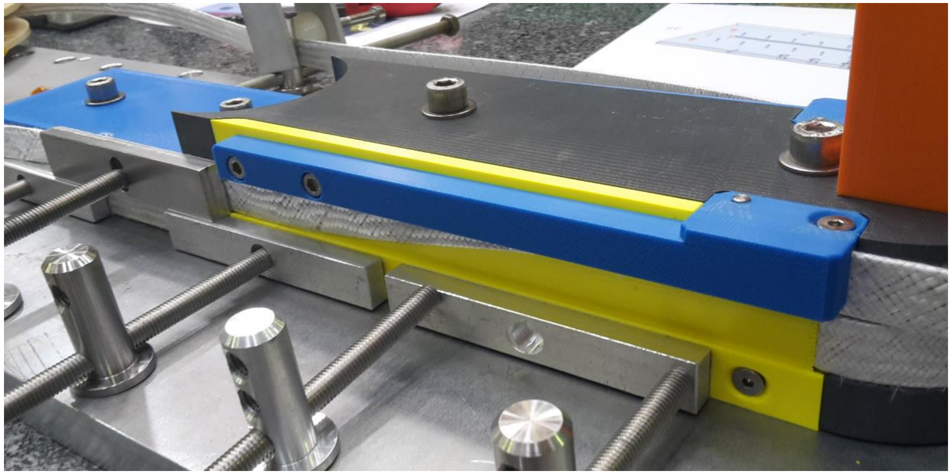
A: → Hard-way only
→ 1 layer jump shim

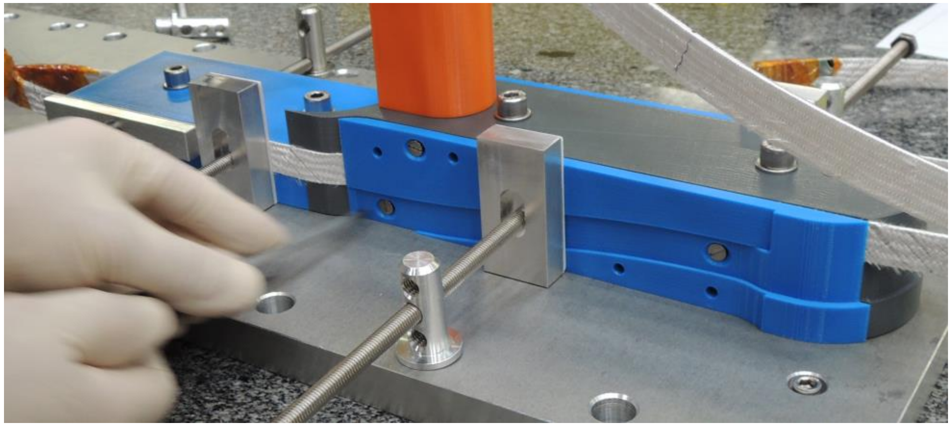


B: → Easy-way + Hard-way
→ 2 layer jump shims



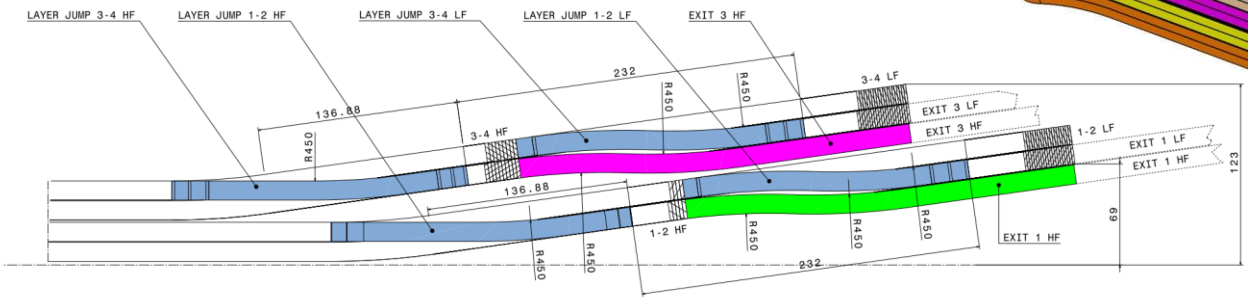
- Winding trials with SMC-11T cable:

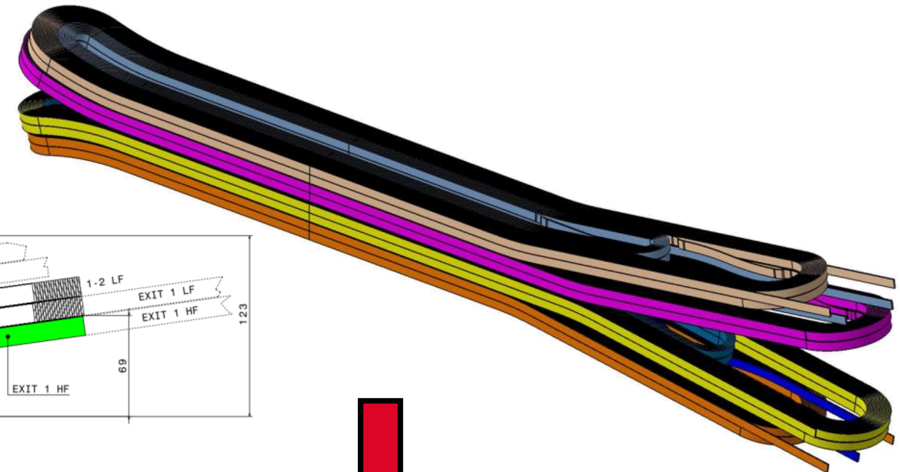




3D MAGNETIC DESIGN - FINALIZED

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

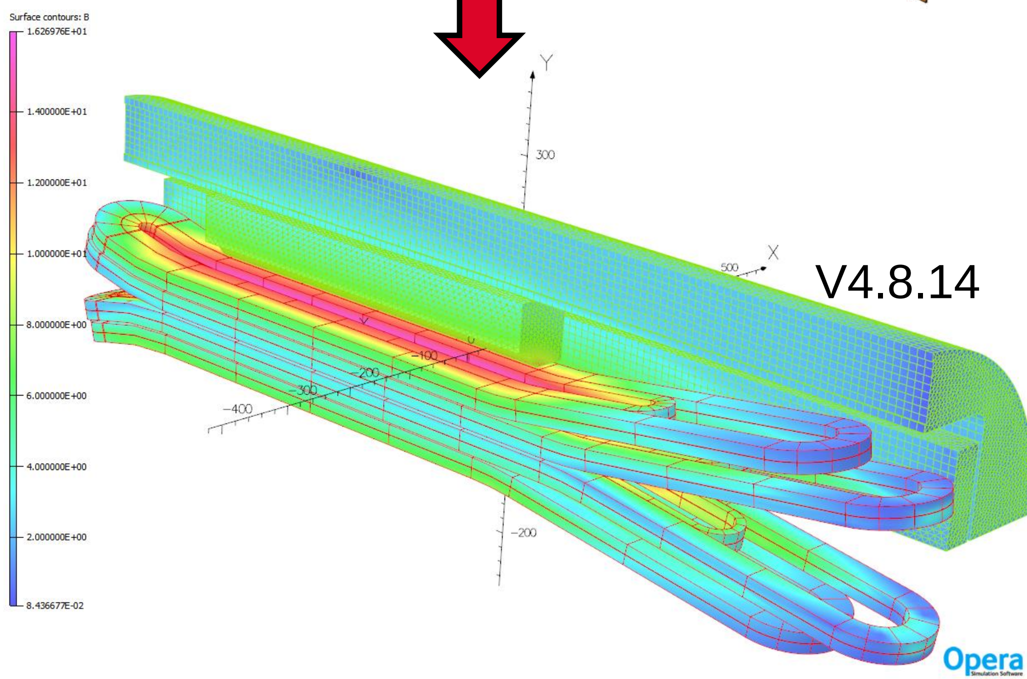




2. **3D simplified Opera FEM**:

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

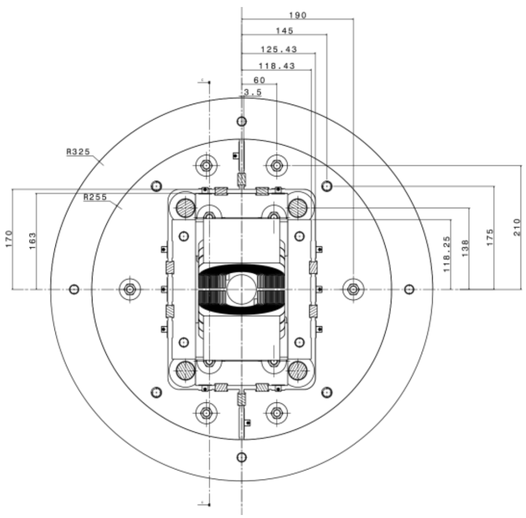
   c. Field in critical areas:
   - **Peak field in straight section**
   - **Field in the layer jumps < 14 T**

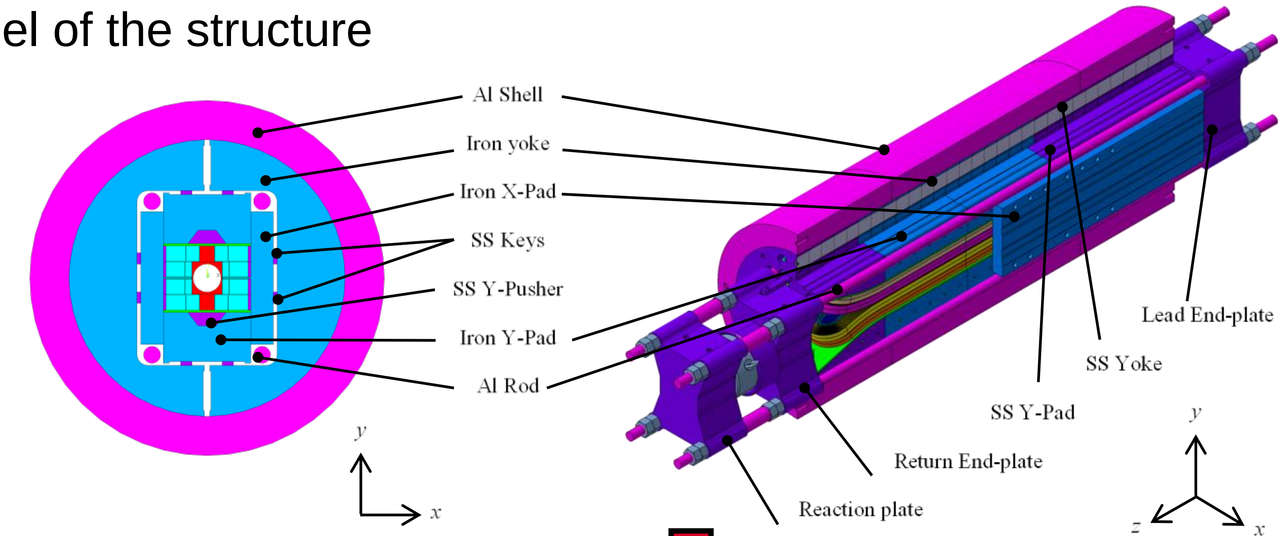


V4.8.14

3D Mechanical Design - Ongoing

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

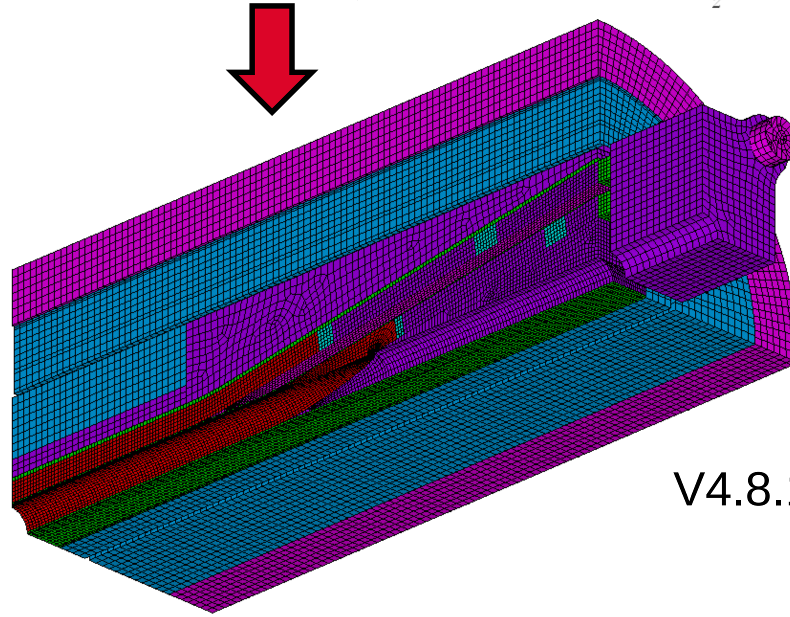




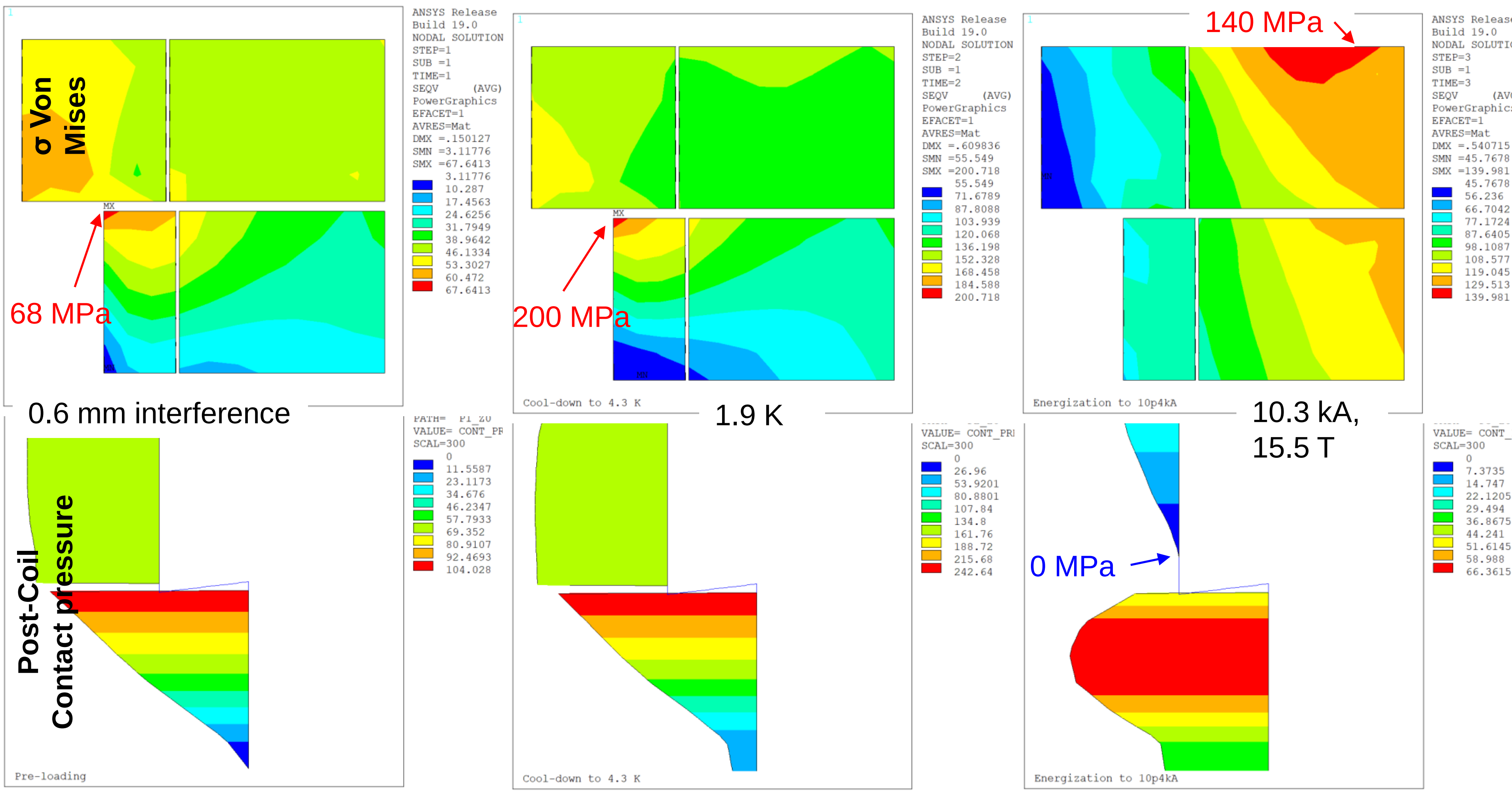
2. **3D simplified Ansys FEM**:

   a. Optimize the transverse preload

   b. Stay below the stress limits:
      - Coil
      - Components



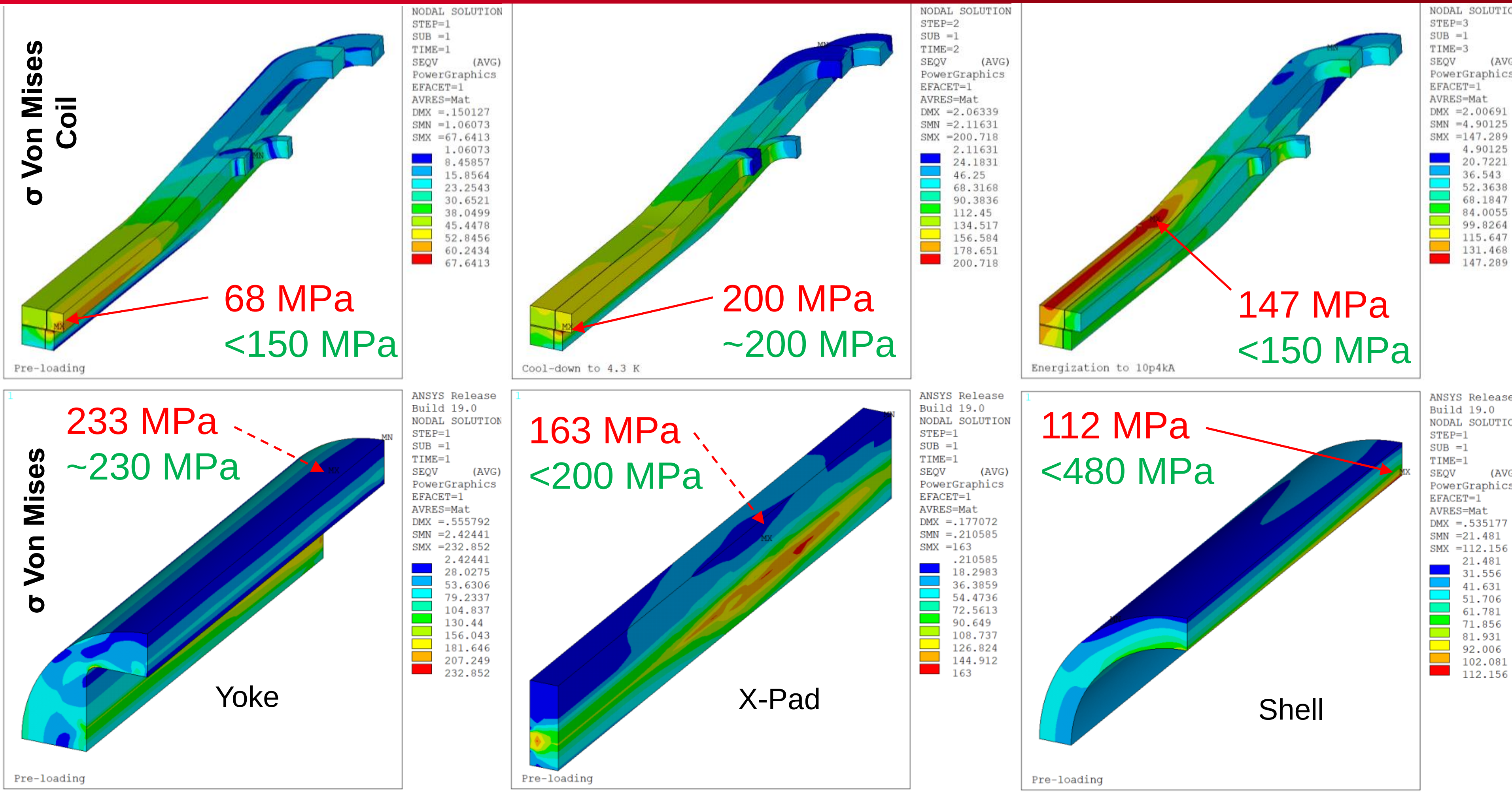
V4.8.15



V4.8.15e

- Verified consistency with 2D model at z=0
- Coil peak stress within targets at z=0

3D Mechanical Design - Ongoing



- Peak stress in coil and critical components within targets
- Next step: optimize longitudinal pre-load

Conclusion 1/2

- Goal: Demonstrate some key concepts for FCC block-coil dipoles:
  - → Grading between blocks
  - → Joint technology

- How?
  - → Relying on **proven technology**:
    - Block-coil
    - Bladders and keys structure
  - → Using **state of the art conductors**
  - → Developing **engineering solutions for joints**
    - 2 proposed solutions: internal and external
    - **External joints** selected to reduce the risks
    - Room to implement internal joints

- With today's state of the art conductors:
  - **15.5 T achievable at 14 % margin**
  - **~18 T at short sample**

CONCLUSION 2/2

- Status:

→ Integrated magnetic and mechanical design:

- **2D magnetic + 2D mechanical completed**
- Protection ongoing
- **3D magnetic completed,** 3D mechanical ongoing

→ Engineering design:

- Conceptual design of the **coil ends and structure finalized**
- Technical solution **validated with mock-ups**

→ **Challenging magnet!**

- Future plans: **preserve complexity and mitigate risks**

1. **1st stage:** Proof-of-concept **graded racetrack** coils

   → Assembly and test in the F2D2 structure

2. **2nd stage:** F2D2 **graded flared-end** coils

   → Assembly and test of the final F2D2 magnet

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Backup Slides

GRADING CONCEPT IN BLOCK-COILS

- 2D: "grading" needed for FCC [3]

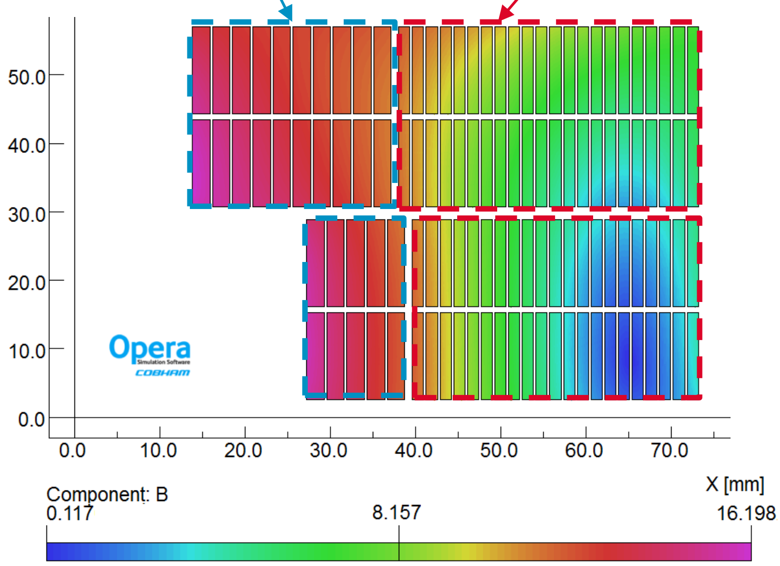
→ 2 cable sizes, same current

→ Optimizing the current density

→ Compact coils = less conductor

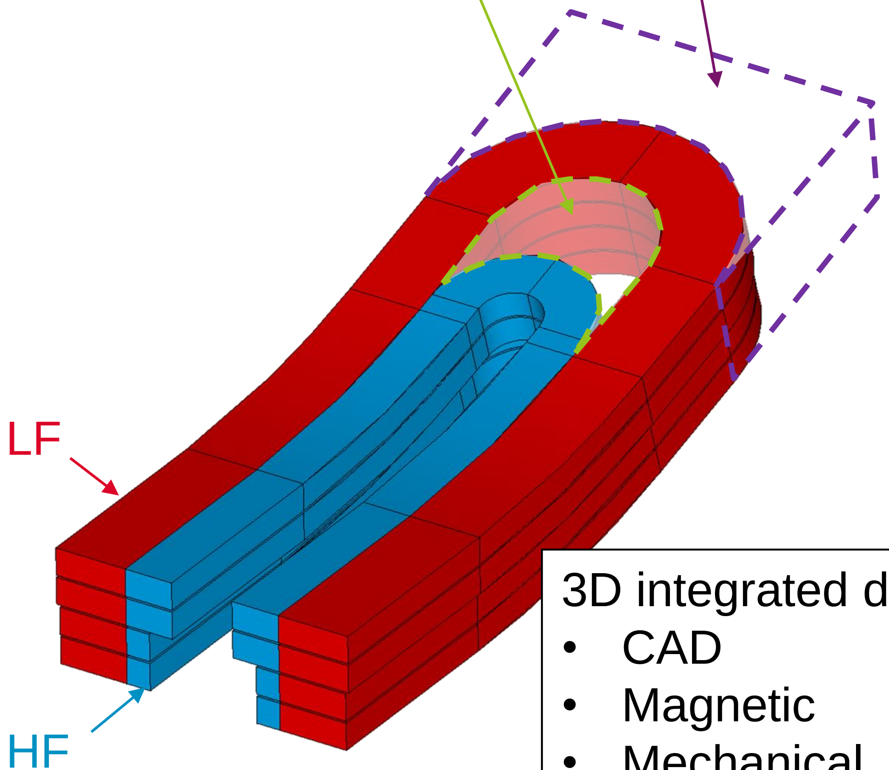
High Field "HF" blocks, low current density

Low Field "LF" blocks, high current density



- **3D: need "joints" between the cable grades**

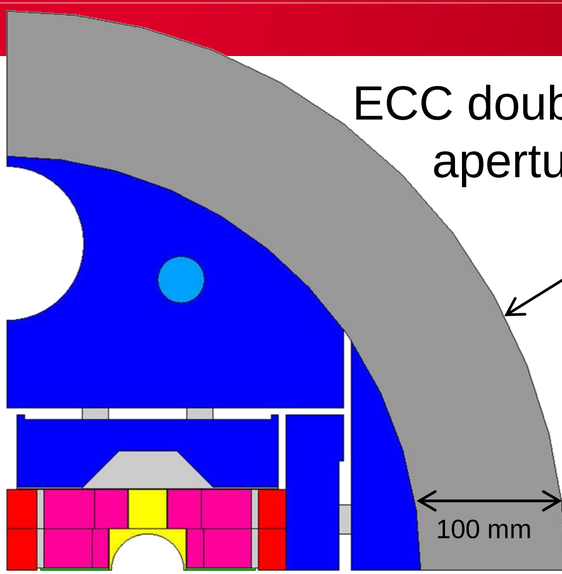
1. Internal joints explored within EPFL-CERN Program
2. External joints explored at CEA



3D integrated design
- CAD
- Magnetic
- Mechanical

V1.1.1: FROM DOUBLE TO SINGLE APERTURE

ECC double aperture



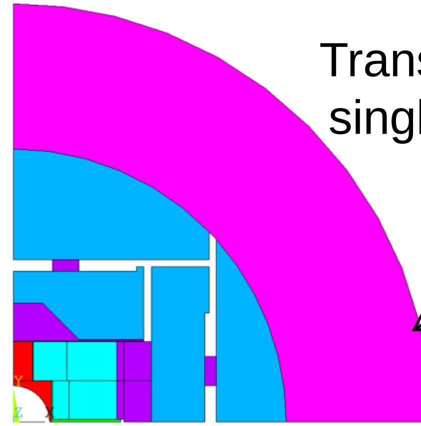
Ø770 mm

100 mm

97 mm interbeam

→ 16,1 T @ 86 %

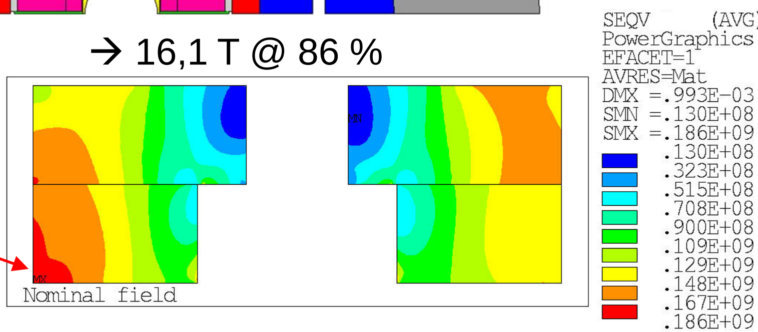
Translation in a single aperture



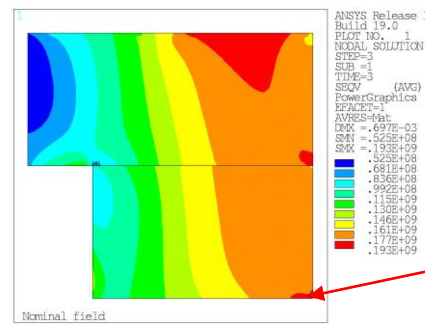
Ø576 mm

0 mm interbeam

→ 15,8 T @ 86 %

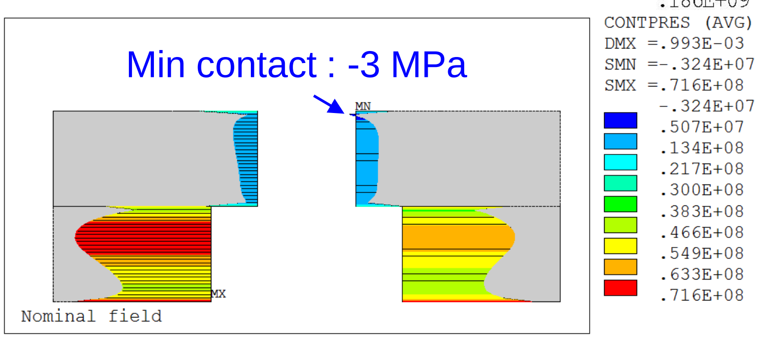


Peak stress: 186 MPa

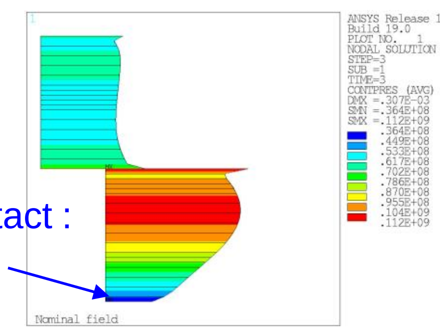


Peak stress: 193 MPa

Min contact : -3 MPa



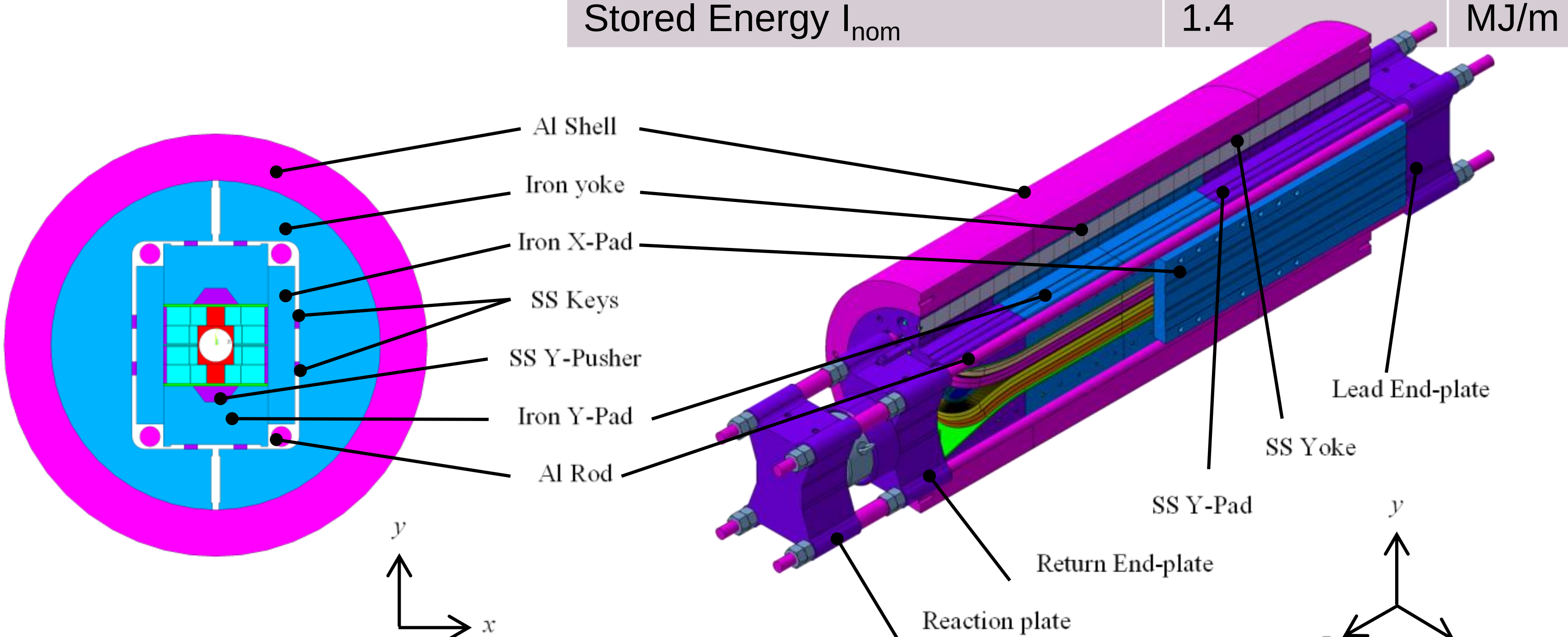
Min contact : 36 MPa



MAIN DESIGN FEATURES

- Rectangular Block-coils
- Shell-based structure with Bladders&Keys
- Conductor with present performances

Nominal Current I_{nom}	10378	A
Short sample current I_{ss}	12118	A
Bore field at I_{nom} (I_{ss})	**15.54** (17.81)	T
Peak Field at I_{nom} (HF/LF)	16.20 / 11.85	T
Peak Field at I_{ss} (HF/LF)	18.58 / 13.62	T
Loadline Margin at I_{nom} (HF/LF)	**14.0 / 15.4**	%
Stored Energy I_{nom}	1.4	MJ/m



Parameter Table

Parameter	Initial (Clément) V1		Updated (Jerôme)		Proposed v4		Unit
	HF	LF	HF	LF	HF	LF	
Strand diameter	1.1	0.7	1.1	0.7	1.1	0.7	mm
Number of strands	21	34	21	34	21	34	-
Unreacted width	12.47	12.47	12.310	12.579	12.579	12.579	mm
Unreacted thickness	1.94	1.23	1.969	1.253	1.969	1.253	mm
Reacted width	12.6	12.6	12.433	12.705	**12.74**	**12.74**	mm
Reacted thickness	2.00	1.27	2.028	1.291	**2.06**	**1.31**	mm
Copper/non-Copper ratio	0.8	2.0	0.8	2.0	0.8	2.0	-
Insulation thickness	0.15	0.15	0.15	0.15	0.15	0.15	mm
Bare cable compaction	11.8	12.0	10.5	10.5	10.5	10.5	%
Packing factor	85.4	88.2	85.9	86.6	84.9	87.5	%
Pitch angle	15	15	16.5	16.5	16.5	16.5	°
Transposition pitch	93	93	83.1	84.9	84.0	84.0	mm

$$Th_{target} = 2d(1 - comp)$$

$$W_{target} = \frac{Nd}{2\cos(PA)} + 0{,}24d$$

$$Packing = \frac{A_{strands}}{A_{bare\ cable}} = \frac{N\pi d^2}{4\cos(PA)Th_{bare}W_{bare}}$$

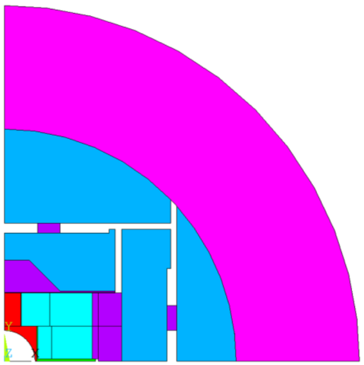
CABLE DIMENSIONS V4

- Cable does not exist, baseline defined as:
  1. Thickness compaction after cabling: 9 to 12 % → **baseline 10.5 %**
  2. Expansion during reaction → ECC baseline: **+3 % thickness / +1 % width**
  3. Insulation → ECC baseline: **150 µm**
- Strategy: **fixed insulated reacted cable dimensions** for the CAD design
  - **Baseline cable with increased room for expansion**
    → compensation of thicker cables
  - Insulation used to compensate thinner cables

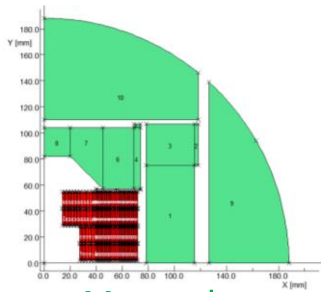
Parameter	Unit	HF: 1.1mmx21 strands		LF: 0.7mmx34 strands		Source
		Thick.	Width	Thick.	Width	
Bare Virgin	**µm**	**1969**	**12579**	**1253**	**12579**	Cabling formulas
Insulation thick.	µm	150	150	150	150	ECC spec
Room for expansion during reaction	**%**	4.6	1.3	4.5	1.3	Bare reacted/ virgin
Insulated Reacted	**mm**	**2.36**	**13.04**	**1.61**	**13.04**	Rounded values

INTEGRATED 2D MAGNETIC AND MECHANICAL OPTIMIZATION

V1.1.1
ECC 2017 design single aperture



Mechanical

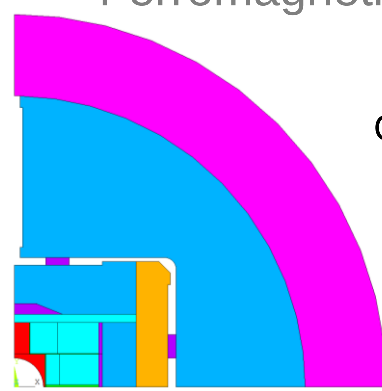


Magnetic

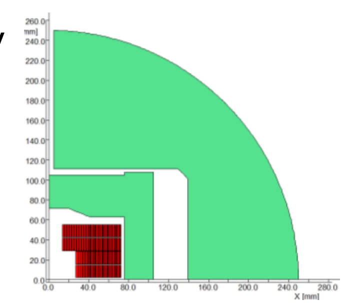
V4.1.1
+ F2D2 Cable V4

V4.4.1
+ Coil position from ECC 2018

V4.4.2
Structure optimized for harmonics
- Non ferromagnetic pad
- Ferromagnetic filler

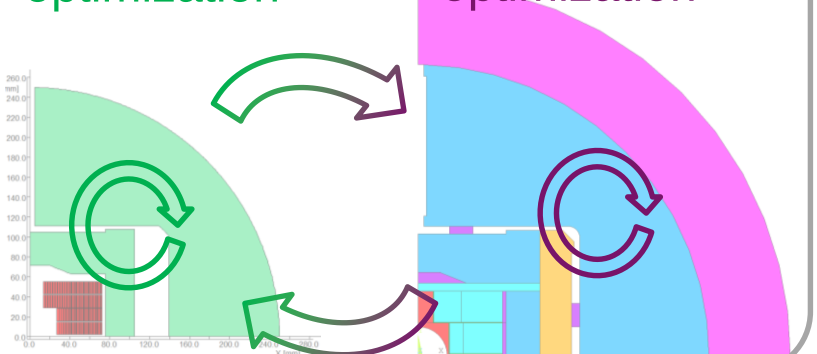


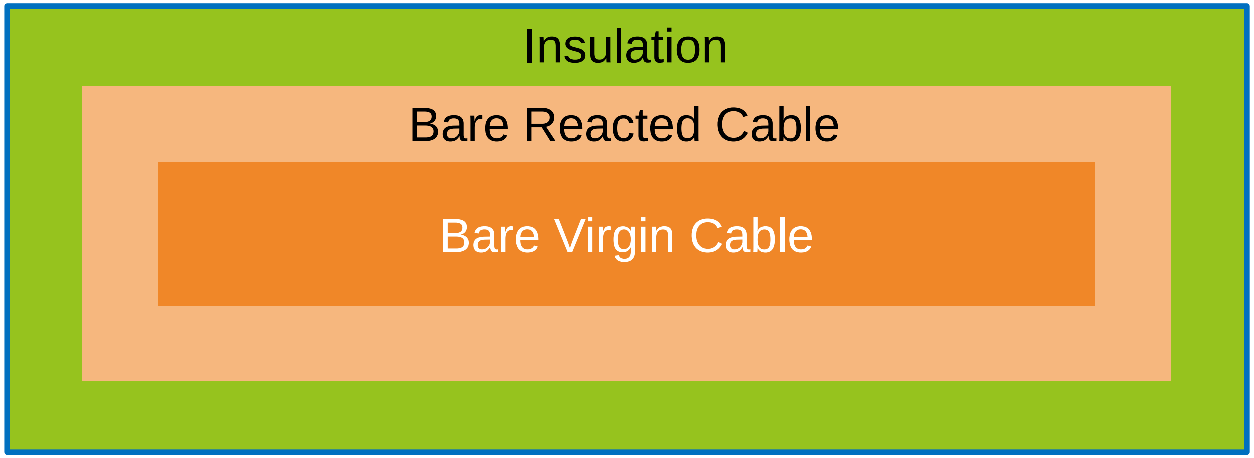
Geometry transfer



V4.4.n
Magnetic optimization

V4.4.3
Mechanical optimization





1st margin to compensate the bare cable

Uncertainty due to cabling R&D

Nominal 150 µm,
2nd possible margin

Fixed Ins. React. Th. for the CAD design

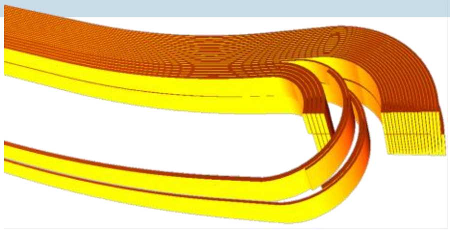
$$Ins\ Reacted\ Th = Max\ Bare\ Virg\ Th \times (1 + Nom\ Exp) + 2 \times Nom\ Ins\ Th$$

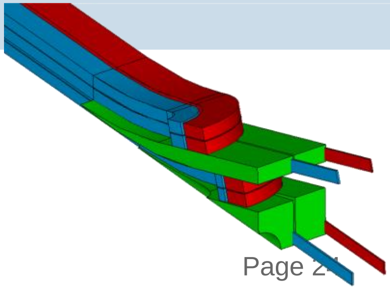
$$= 1.1 \times 2 \times (1 - 9\%) \times (1 + 3\%) + 2 \times 150 = 2362\ \mu m \approx \mathbf{2.36\ mm}$$

3rd margin: variable shims (insulated fiberglass)
→ Fixed value in the nominal drawings
→ Free value in the **as-built drawings**

Internal Vs External

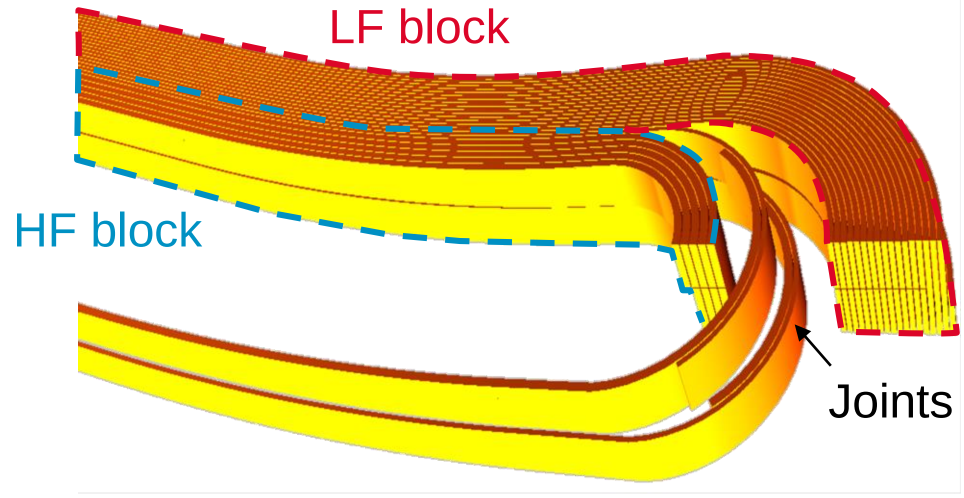
	Internal joints	External joints
Potential show-stoppers	• margin at high field • room for operations • (placing parts, splicing)	• room for support • room for operations (placing parts, splicing)
Clues that it can work	Low joint resistances in FRESCA samples and for EPFL joints	Concept similar to FRESCA2 endshoes
End harmonics	• Compact ends possible	• Ends longer • « naturally » more homogeneous
Axial loads	Behavior under Lorentz forces ? (detachment, motions…)	Impact of pre-load ? (sharp wedges, relative motion…)
Layer jumps	No LF layer jump	• Need additional room for LF layer jump





1ST SOLUTION FOR F2D2: INTERNAL JOINTS

- Ideal solution for FCC
- Concepts:
  - Nb_3Sn-HF to Nb_3Sn-LF joint
  - Performed in an end-spacer
- Winding layout:
  - HF Double-layer pancakes + layer jump
  - LF single layer pancakes



Courtesy C. Lorin

- Status:
  - Joints under development by EPFL-SPC (See presentation “R&D on Nb_3Sn cable splices”, P. Bruzzone and Poster “Preliminary investigations of Rutherford cable splicing techniques for high field accelerator magnets”, M. Kumar)
    - Several explored technical solutions
    - Test on joints in Sultan
- Engineering implementation in coils remains an open question

→ High technical risk for F2D2
→ High risk for the schedule

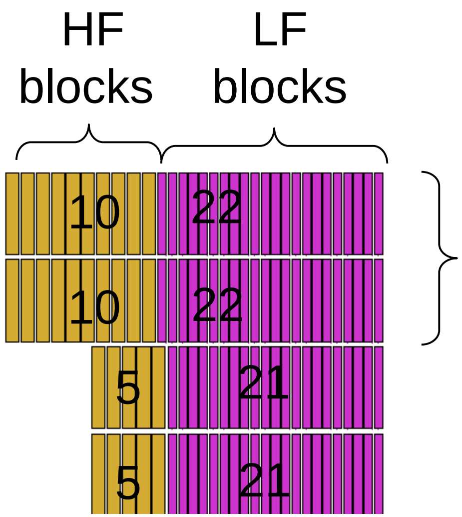
ALTERNATIVE SOLUTION FOR F2D2: EXTERNAL JOINTS

- Decoupling grading and joints for the demonstrator
- Goal:
  - **Minimize risks in coil fabrication**

  → Each coil heat-treated and impregnated individually

  → Use a known joint technique outside of the coil

- CAD Geometric investigation ongoing:
  - **Large footprint outside of the coil**
  - **Routing and supporting the cable**

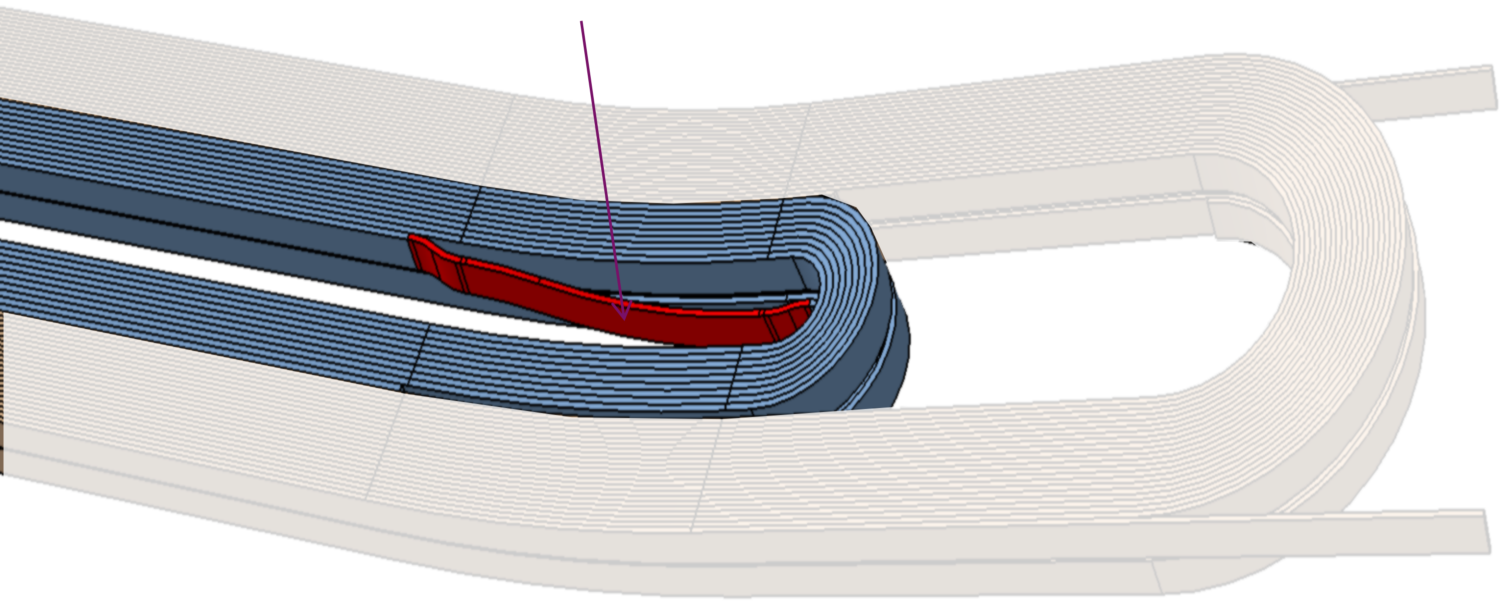


1 coil = 1 HF double pancake
+ 1 LF double pancake

1 pole = 2 coils

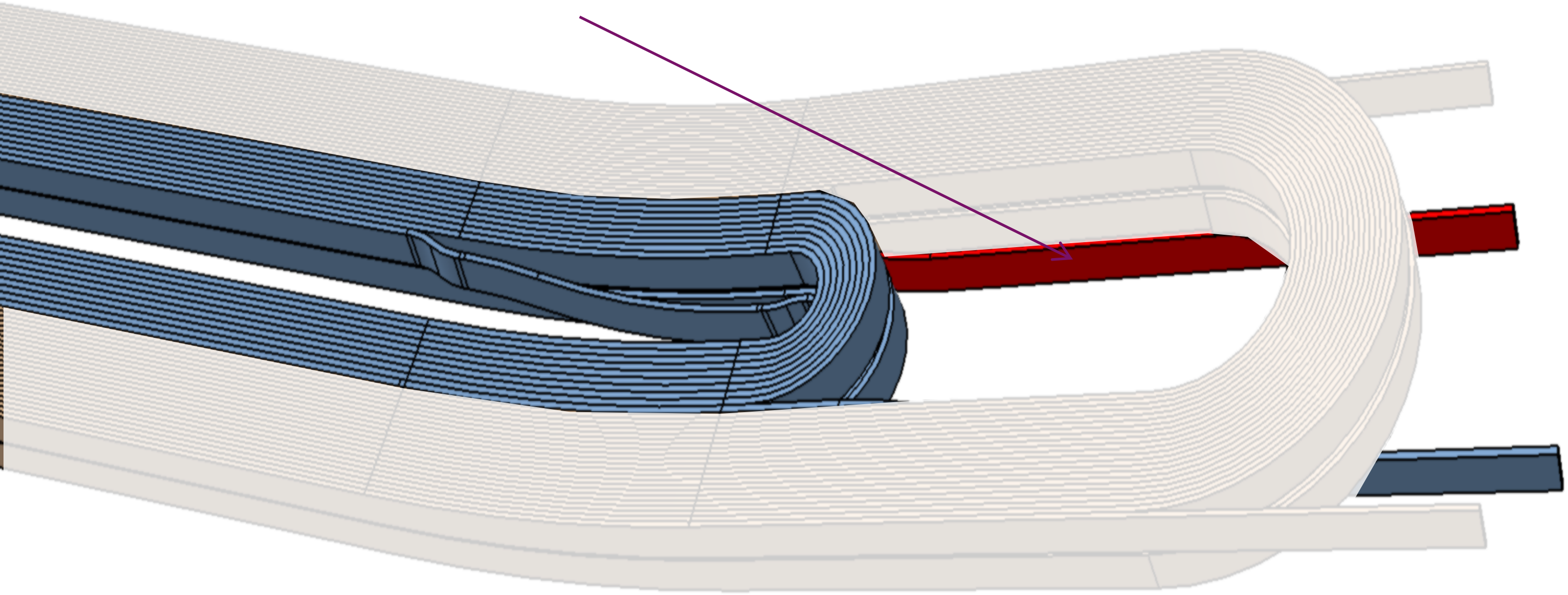
Alternative solution for F2D2: External Joints

1. HF double-layer pancake with layer jump in the pole



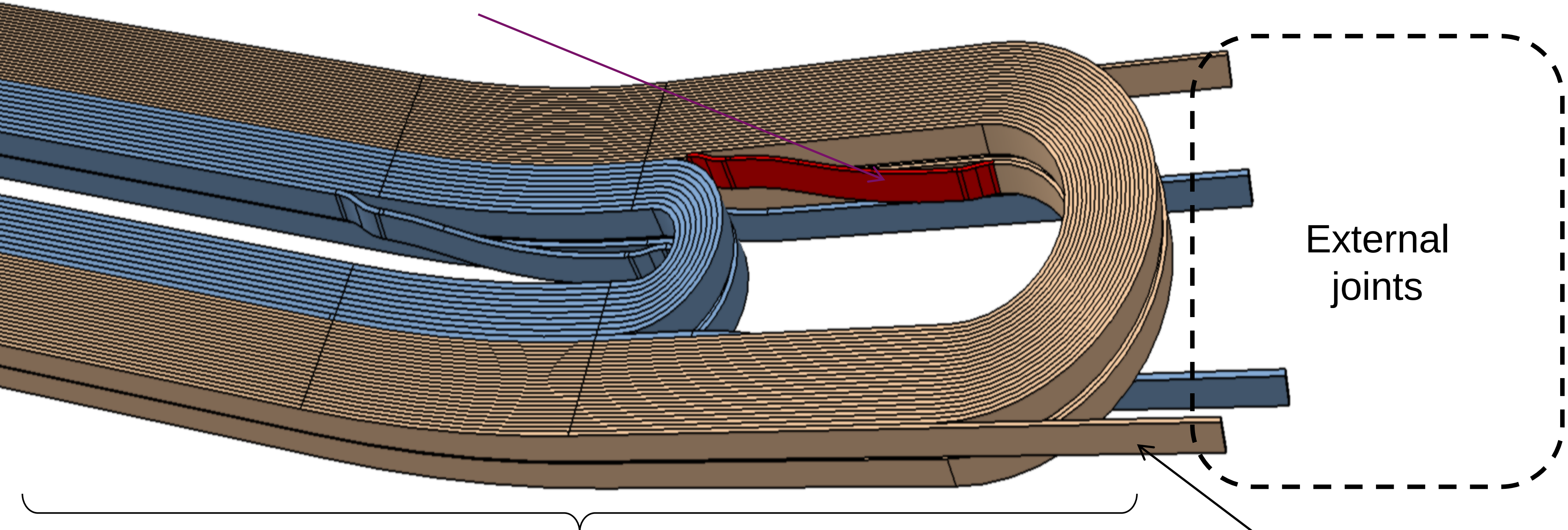
Alternative solution for F2D2: External Joints

2. Routing of the HF leads in an “inter-coil wedge” → take advantage of flared ends



ALTERNATIVE SOLUTION FOR F2D2: EXTERNAL JOINTS

3. LF double-layer pancake with layer jump in the end-spacer



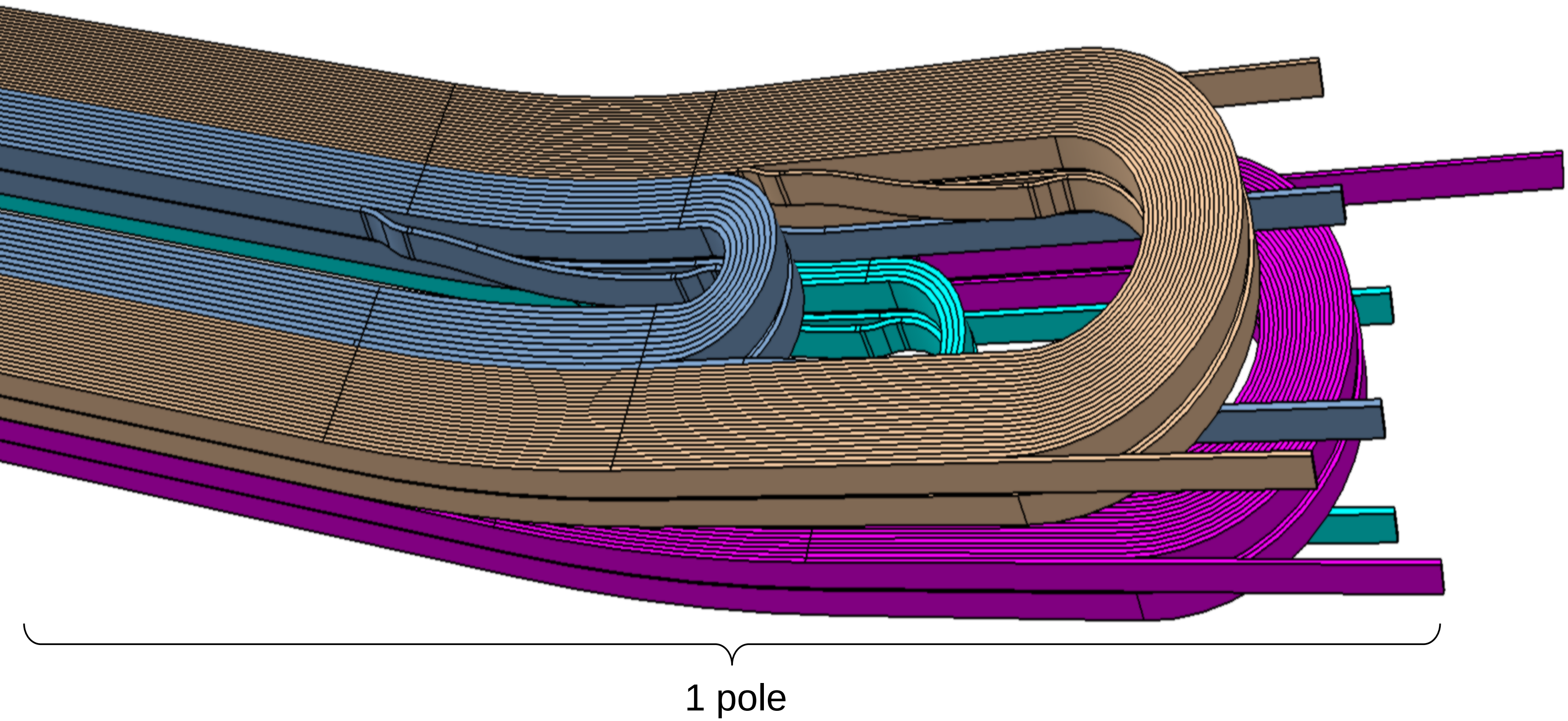
4. LF leads in the end-shoe

5. Heat treatment and impregnation of the coil

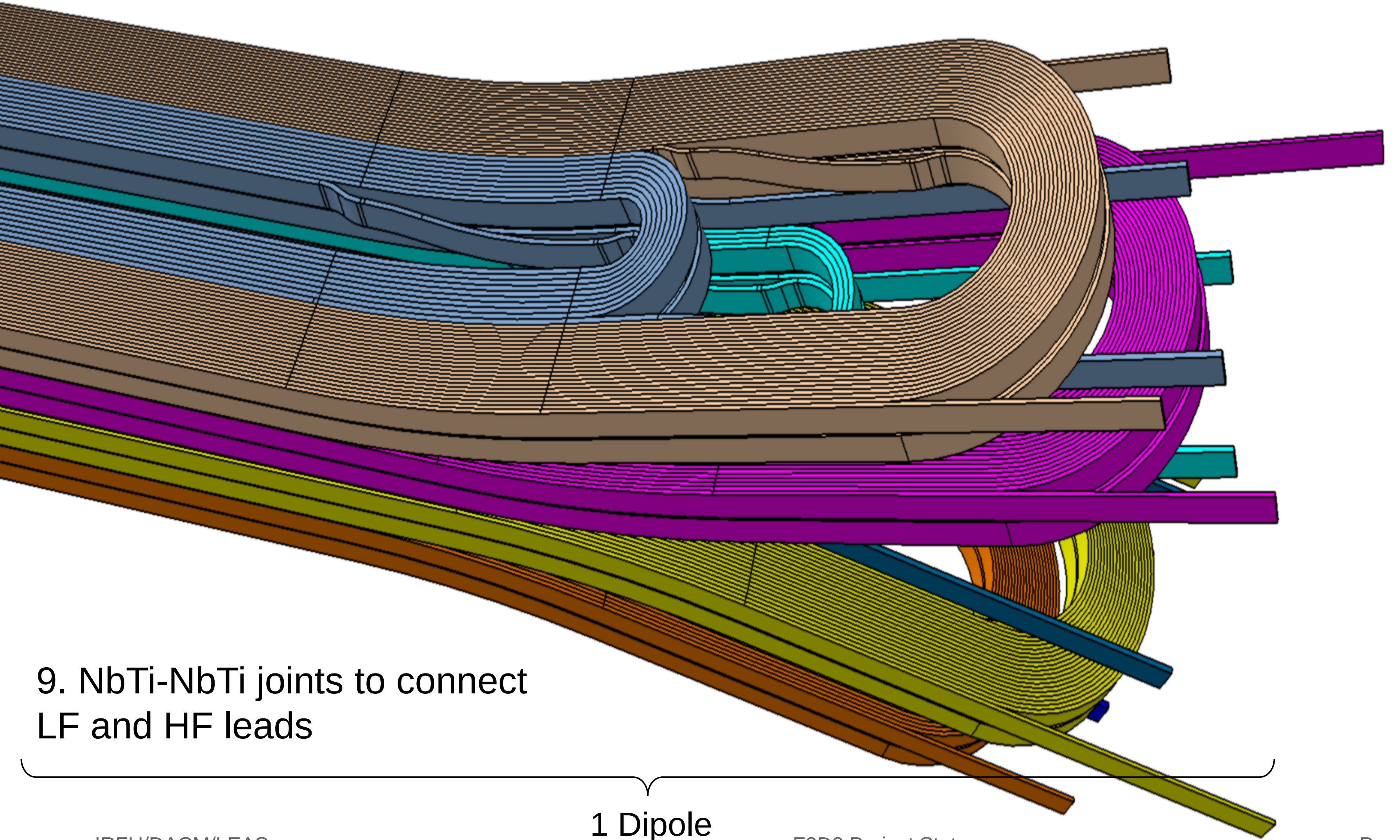
6. Joints Nb3Sn-NbTi outside the coil in the inter-coil wedges

Alternative solution for F2D2: External Joints

7. Same concept for the other coils



8. Assembly of the coils



9. NbTi-NbTi joints to connect
LF and HF leads

1 Dipole