MT 26
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DE LA RECHERCHE À L'INDUSTRIE

3D Design of F2D2, the FCC Block-coil Short Model Dipole

F2D2 =
FCC Flared-ends Dipole Demonstrator


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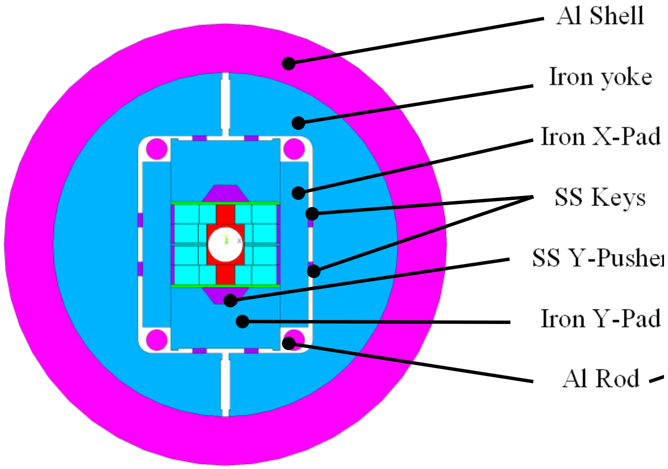
CERN: S. Izquierdo Bermudez, D. Tommasini

24/09/2019

Tue-Mo-Or7-03

F2D2: A MODEL TOWARD FCC HIGH FIELD DIPOLES



- FCC dipoles: high field up to 16 T [1]

- Proposed strategy:

1. Rely on proven technology [2]:
  - State-of-the-art cables
  - Block-coils
  - Bladders and keys

→ Concepts proposed within EuroCirCol [3]

2. Develop grading:
  - Compact, high current density

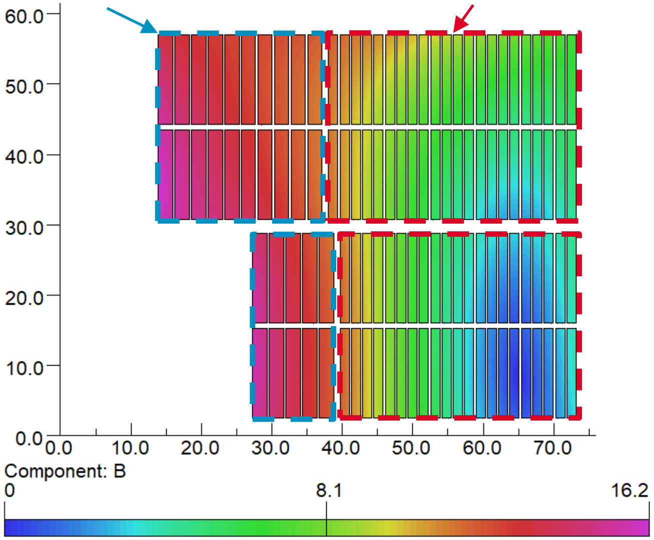
3. Build and test a short model:
  - CERN-CEA collaboration

→ Design/fabrication at CEA

→ Test at CERN

High Field “HF” blocks, low current density

Low Field “LF” blocks, high current density



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[1] D. Schoerling et al., “The 16 T Dipole Development Program for FCC and HE-LHC” , IEEE TAS, 2019

[2] See plenary H. Felice, Tu-Mo-PL2-01: “Advances in Nb3Sn Superconducting Accelerator Magnets”

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

THE F2D2 MAGNET

- F2D2 short model [4]

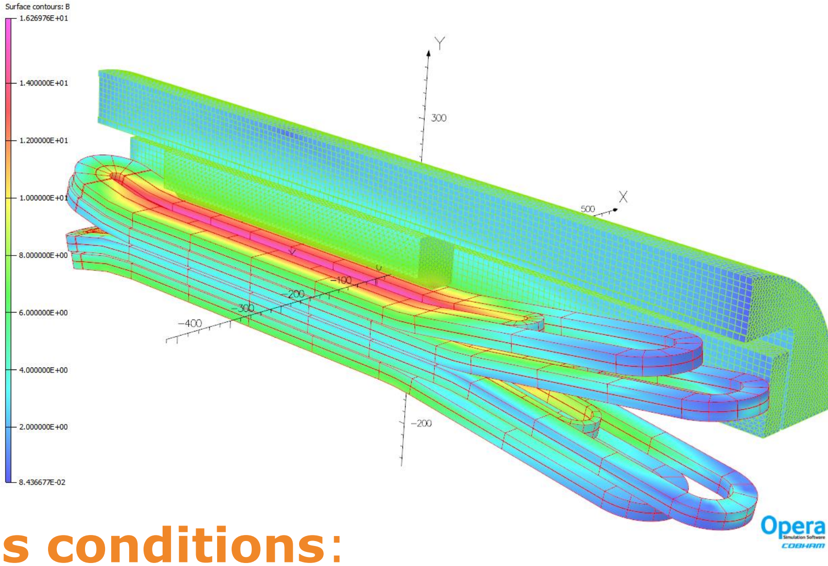
→ Single aperture

→ Same coil design as ECC block-coil [3]

→ Harmonics representative of FCC

→ Protection: QH and CLIC considered

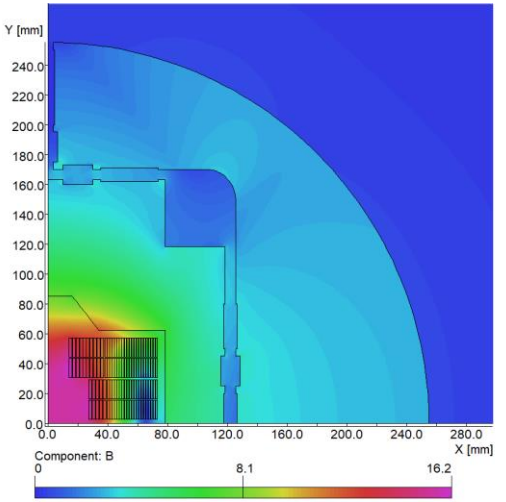
[5] see V. Calvelli et al., Mon-Mo-Po1.04-05



- **Different fields depending on stress conditions**:

→ Pre-load tuned to keep coil-post pressure>0

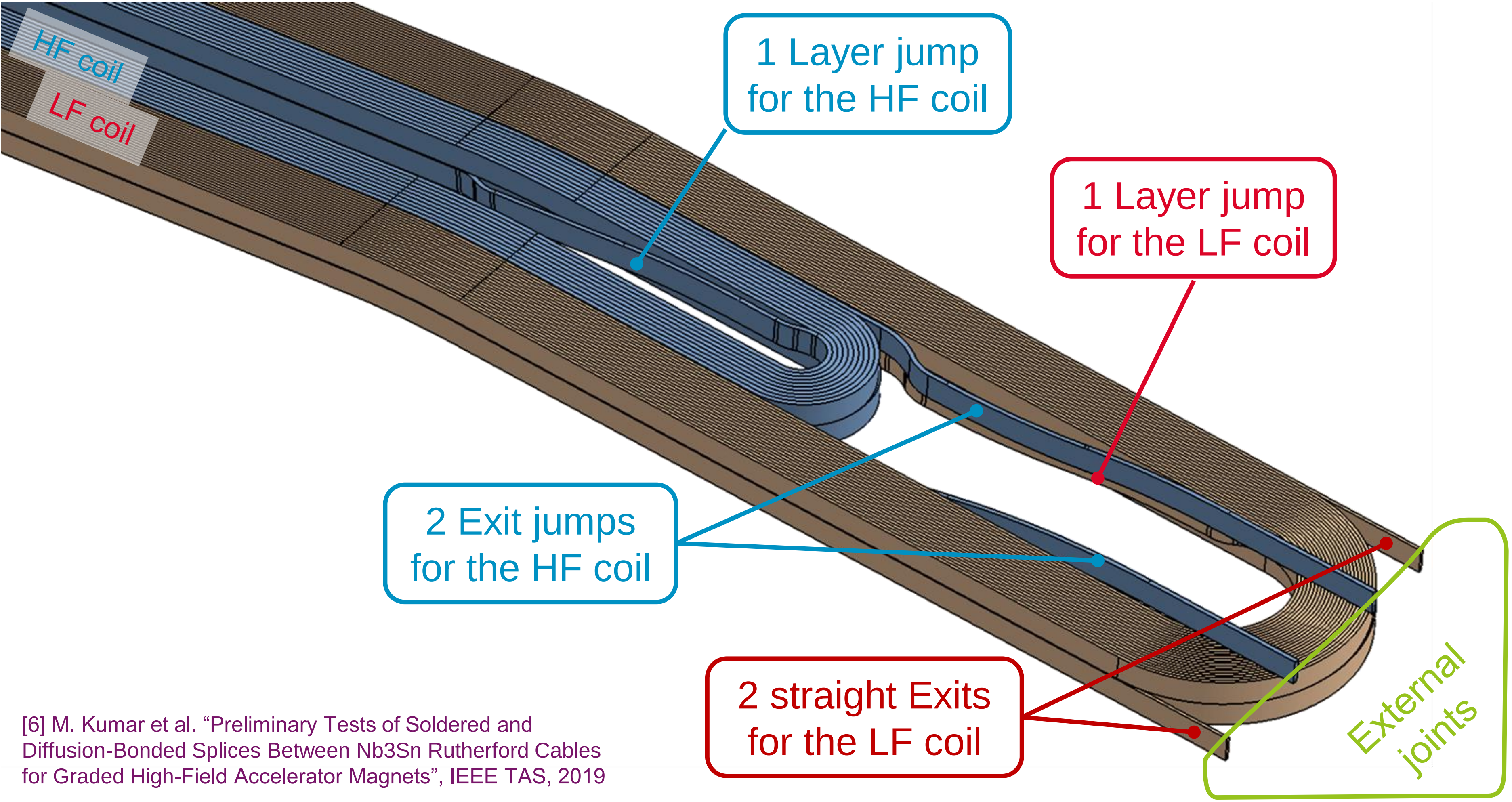
Criterion	Seqv peak [MPa]		Margin @1.9 K [%]	B_0 [T]
	1.9 K	energization		
150 MPa at 1.9 K	**150**	135	24	14.0
150 MPa at energization	171	**150**	18	14.9
Nominal 14% margin	**186**	**162**	**14**	**15.5**
200 MPa at 1.9 K	**200**	173	10	16.1
Short sample	237	202	**0**	17.7



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

DEVELOP EXTERNAL JOINTS FOR GRADING

- EPFL-CERN Program: **R&D on internal joints** technology [6]
- **CEA proposal: external joints** to better fit in schedule [4]



1 Layer jump for the HF coil

1 Layer jump for the LF coil

2 Exit jumps for the HF coil

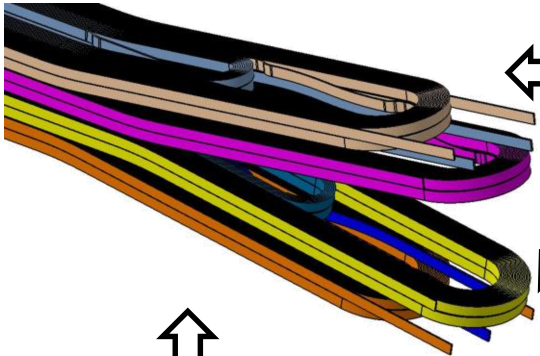
2 straight Exits for the LF coil

[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

INTEGRATED 3D COIL-END DESIGN

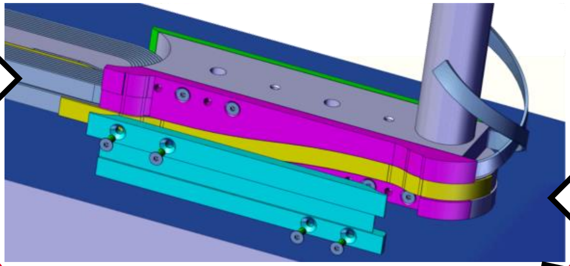
Turn-by-turn coil CAD

→ Define path for cable exits



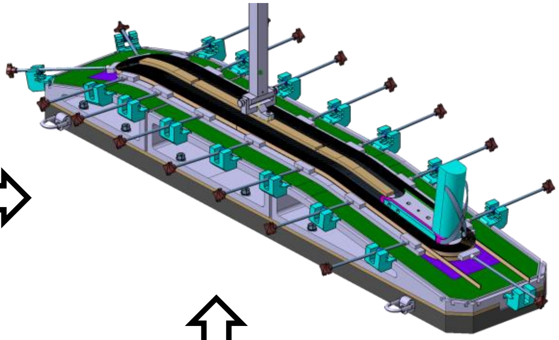
Coil components CAD

→ Study concepts for external joints

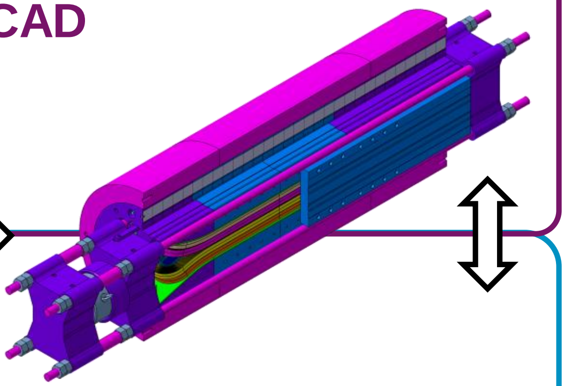


Fabrication tooling CAD

→ Study compatibility with the fabrication process

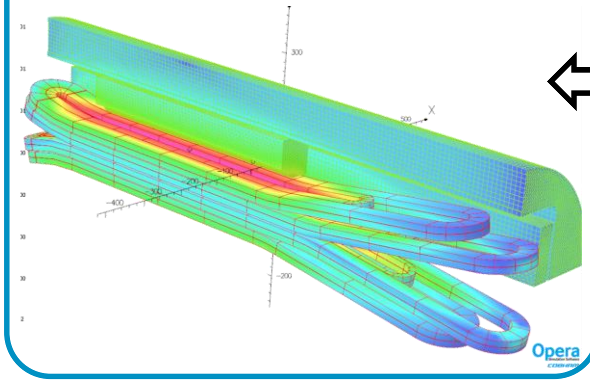


Mechanical Structure CAD



3D Magnetic FEM

→ Margins in coil-ends

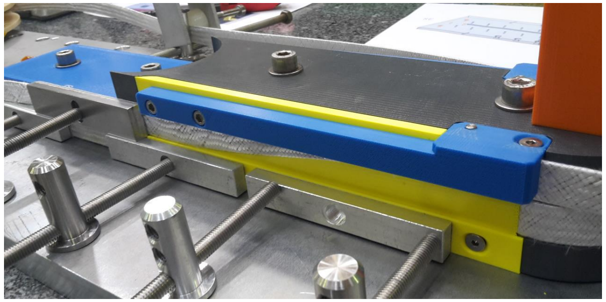


3D Mechanical FEM

→ Stress below limits

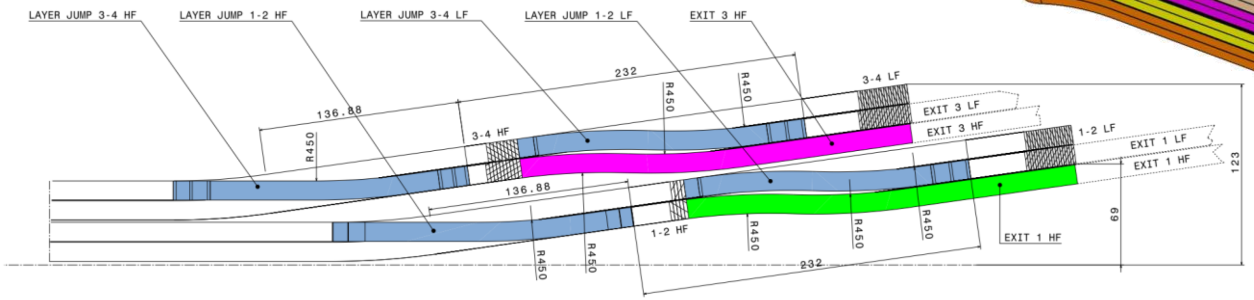
Winding mockups

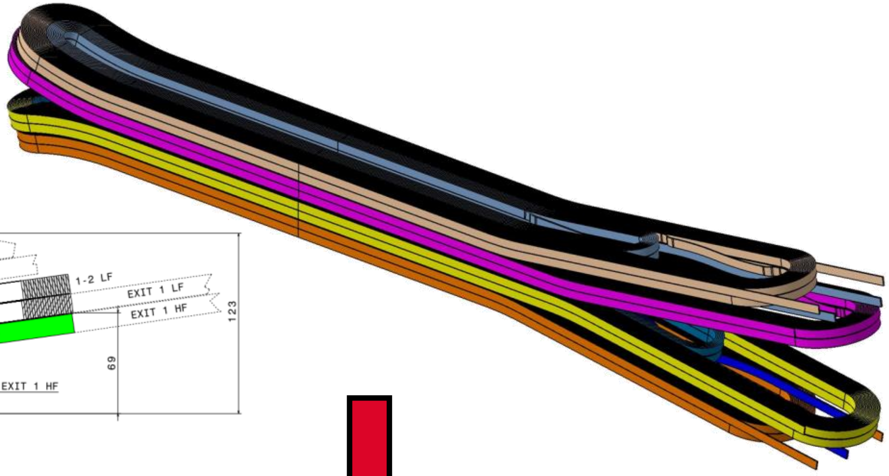
→ Test components and tooling



3D MAGNETIC DESIGN: FIELD IN CRITICAL AREAS

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

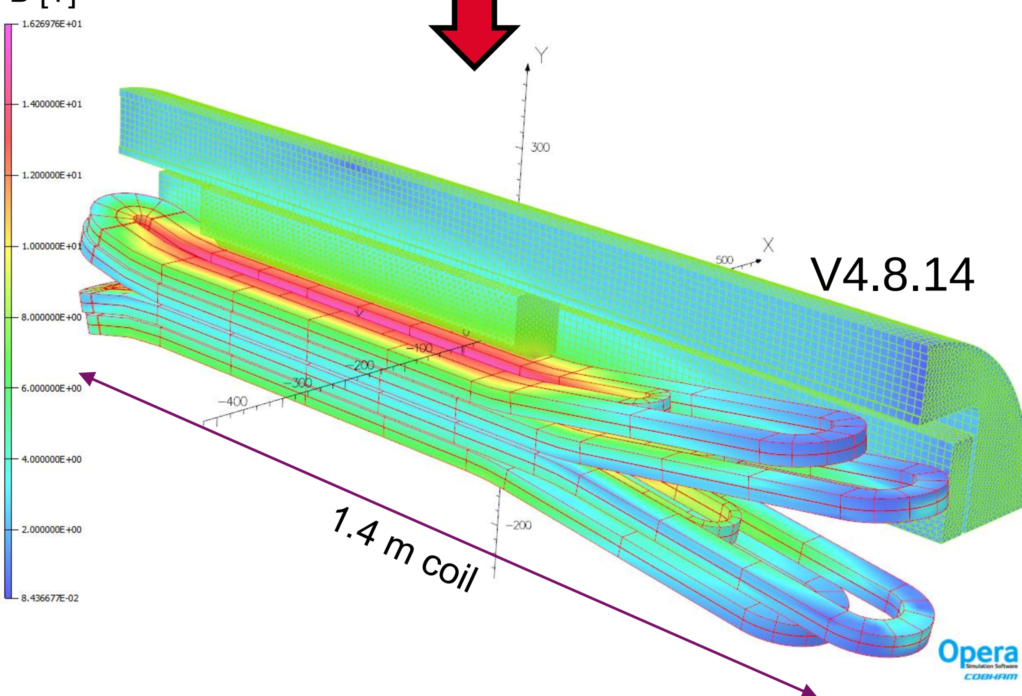




2. **3D simplified Opera FEM**:

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

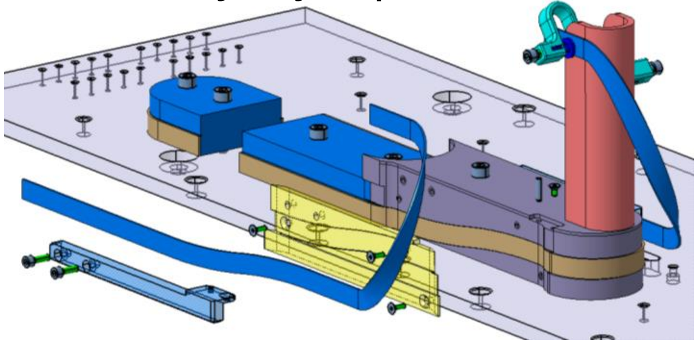
c. Field in critical areas:
- ✓ **Field in the layer jumps < 14 T**
- Advantage of flared ends:
- ✓ **Peak field not in coil-ends**

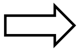


WINDING MOCKUPS TO VALIDATE CONCEPTS

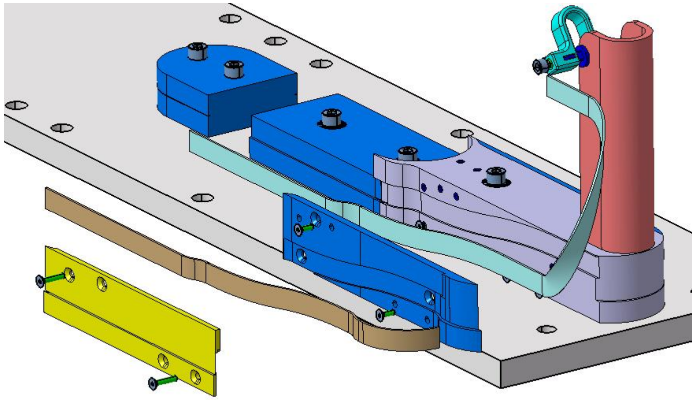
- 2 options for cable exits:

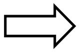
A: → Hard-way only
→ 1 layer jump shim



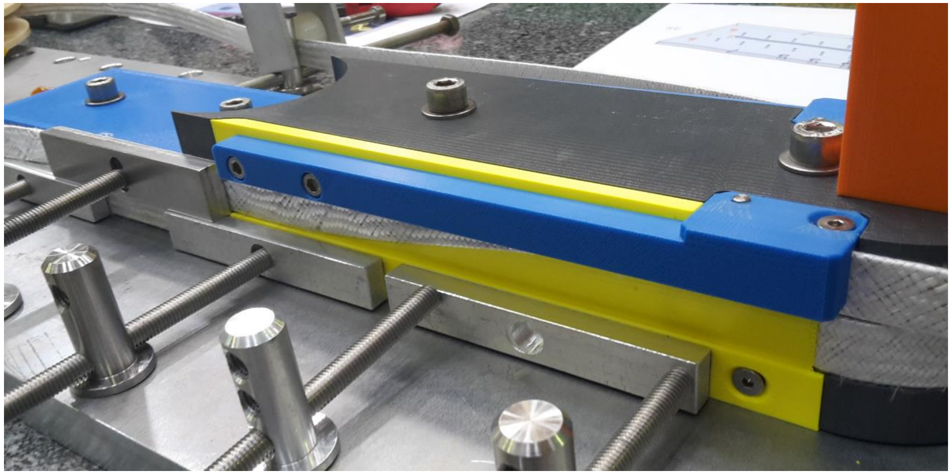


B: → Easy-way + Hard-way
→ 2 layer jump shims

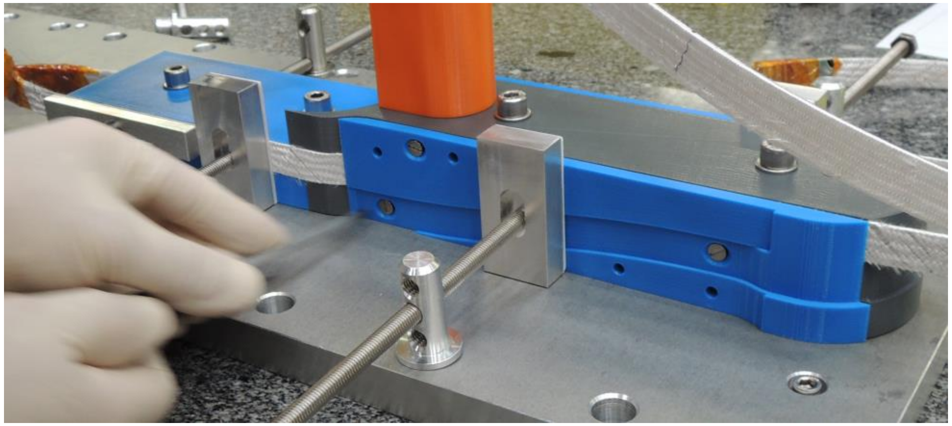




- Winding trials with SMC-11T cable:

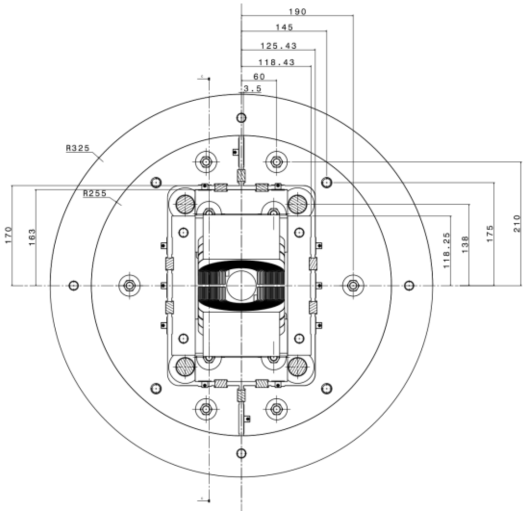


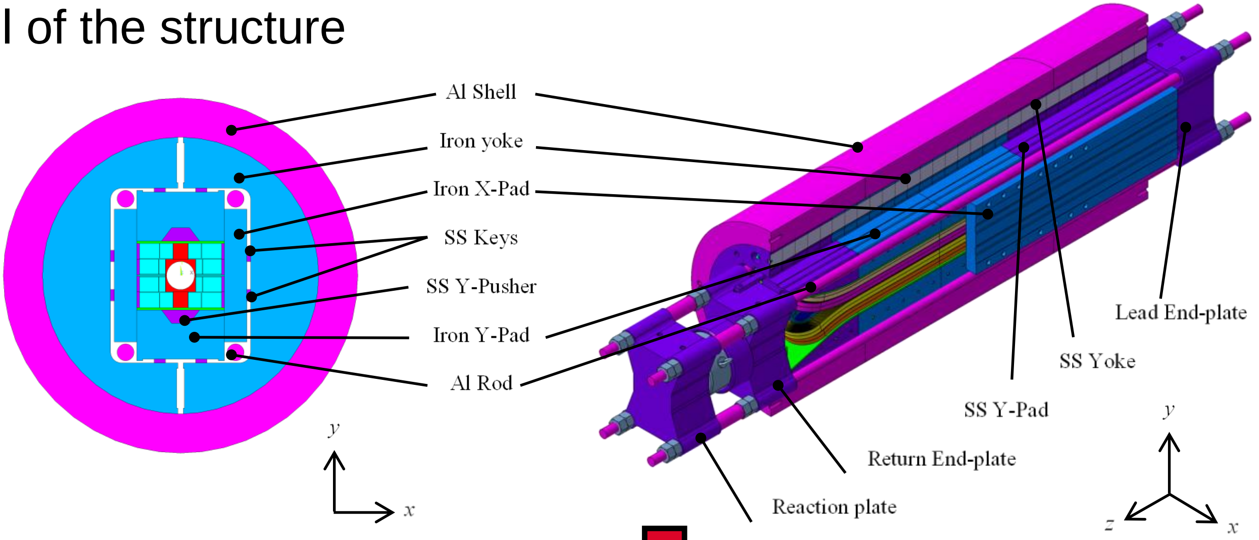
→ Concepts validated with mockups



3D MECHANICAL DESIGN: LONGITUDINAL PRE-LOAD

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

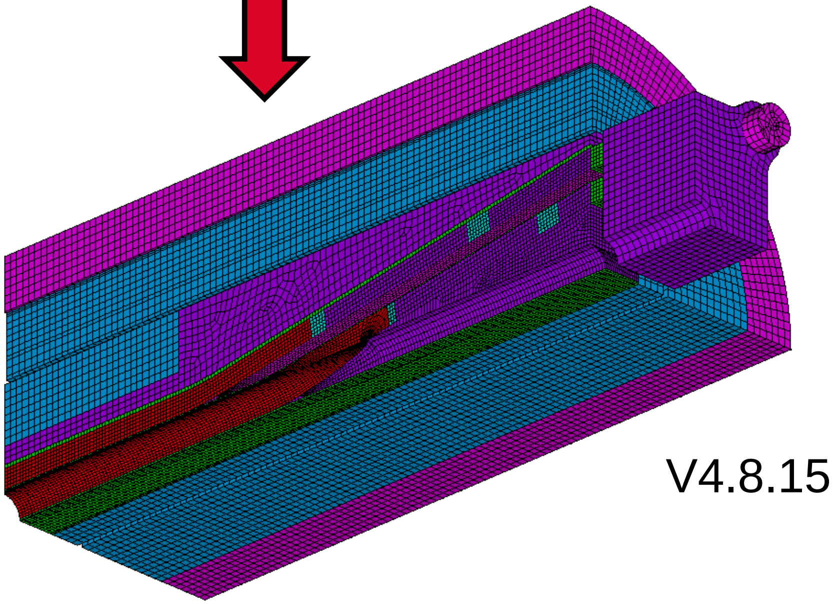




2. **3D simplified Ansys FEM**:

   a. Optimize the longitudinal preload

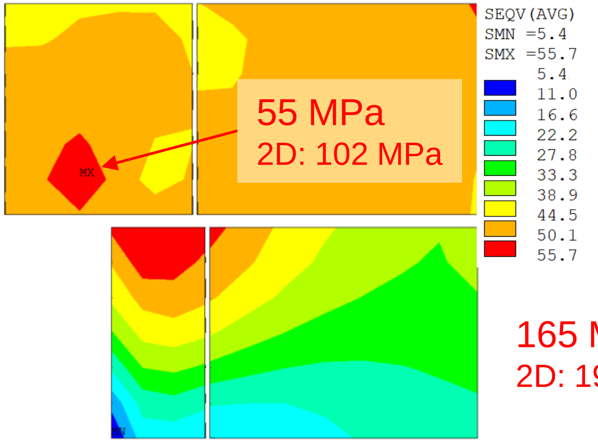
   b. Stay below the stress limits:
      - ✓ **Coil**
      - ✓ **Components**



3D MECHANICAL DESIGN – STRESS AT Z=0

- 0.6 mm interference

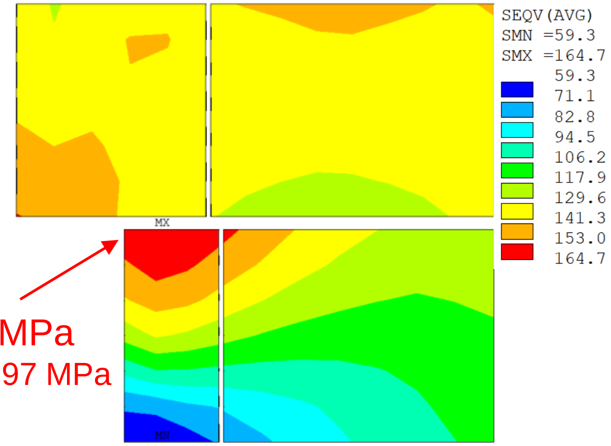
σ Von Mises [MPa]



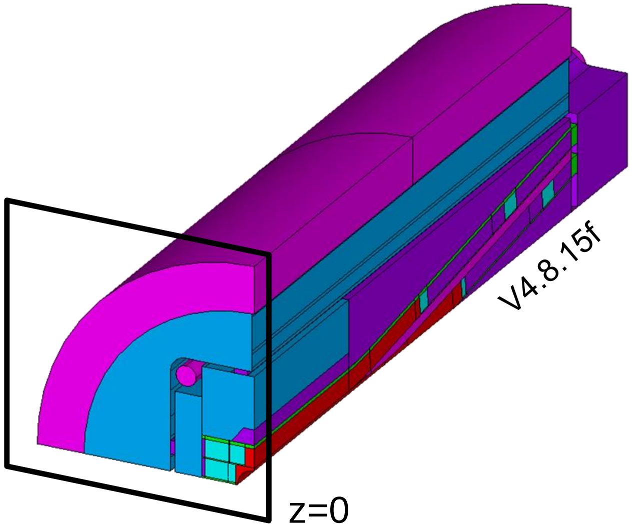
55 MPa
2D: 102 MPa

- 1.9 K

σ Von Mises [MPa]

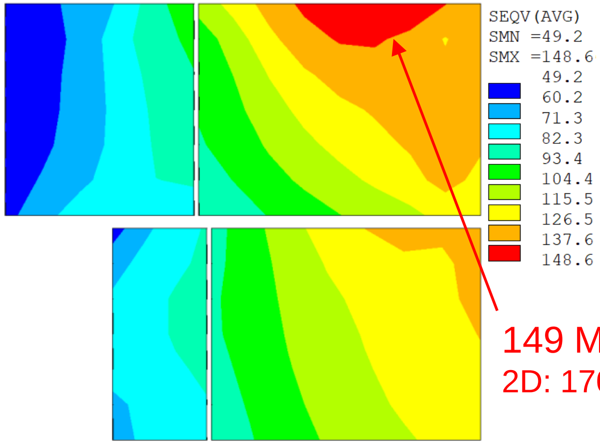


165 MPa
2D: 197 MPa



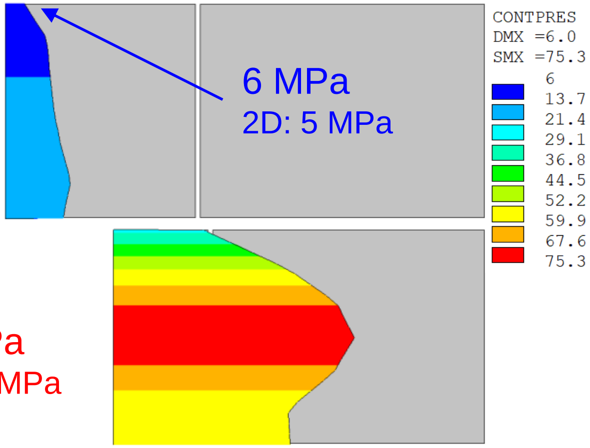
- Nominal operations: 10.4 kA, 14% margin, **15.5 T**

σ Von Mises [MPa]



149 MPa
2D: 170 MPa

Contact pressure [MPa]



6 MPa
2D: 5 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]

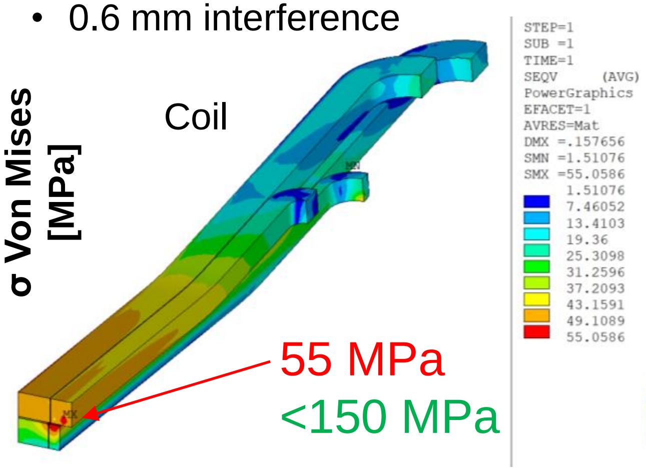
[5] E. Rochepault et al., "Computation of Current Limits in Nb3Sn Superconducting Magnets Using Magnetic Field and Stress" to be published in IEEE TAS.

3D MECHANICAL DESIGN - STRESS

σ Von Mises [MPa]

- 0.6 mm interference

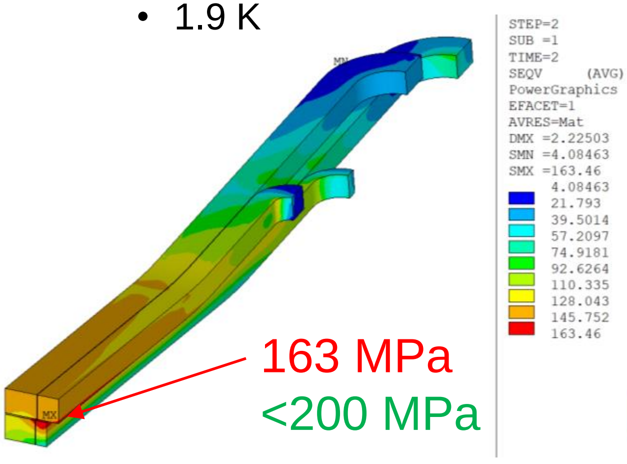
Coil



55 MPa

<150 MPa

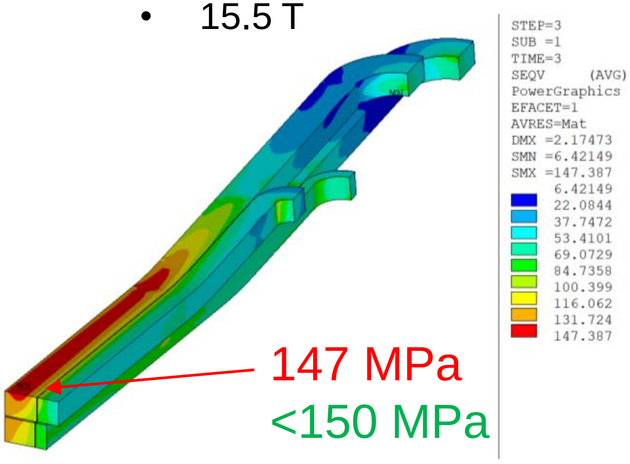
- 1.9 K



163 MPa

<200 MPa

- 15.5 T



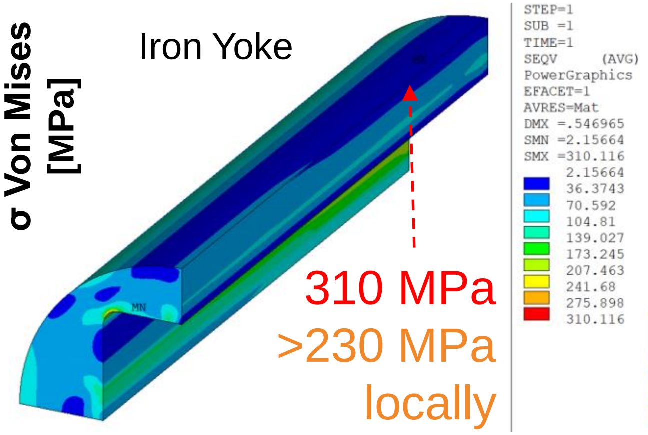
147 MPa

<150 MPa

σ Von Mises [MPa]

- 0.6 mm interference

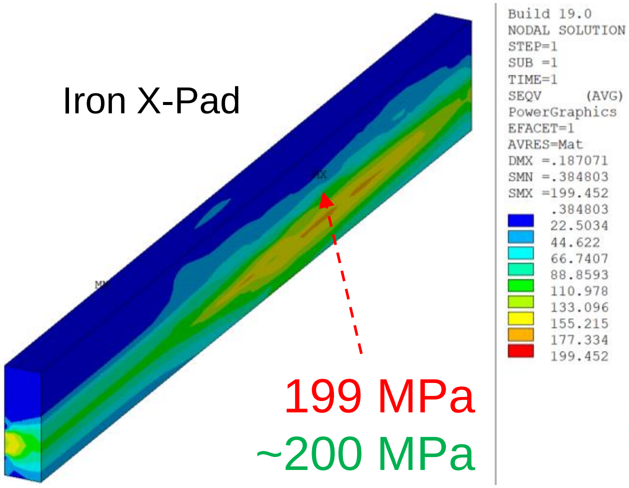
Iron Yoke



310 MPa

>230 MPa locally

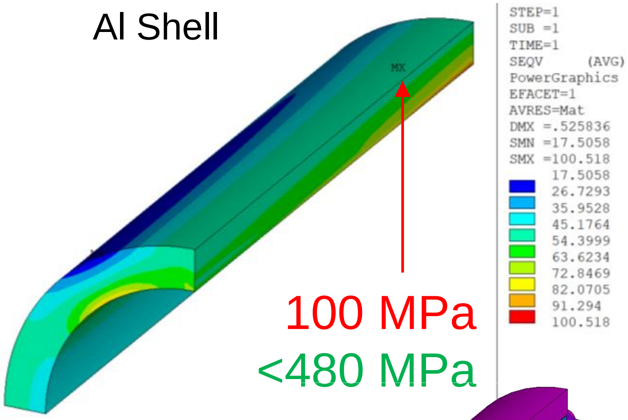
Iron X-Pad



199 MPa

~200 MPa

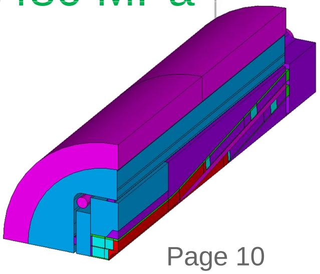
Al Shell



100 MPa

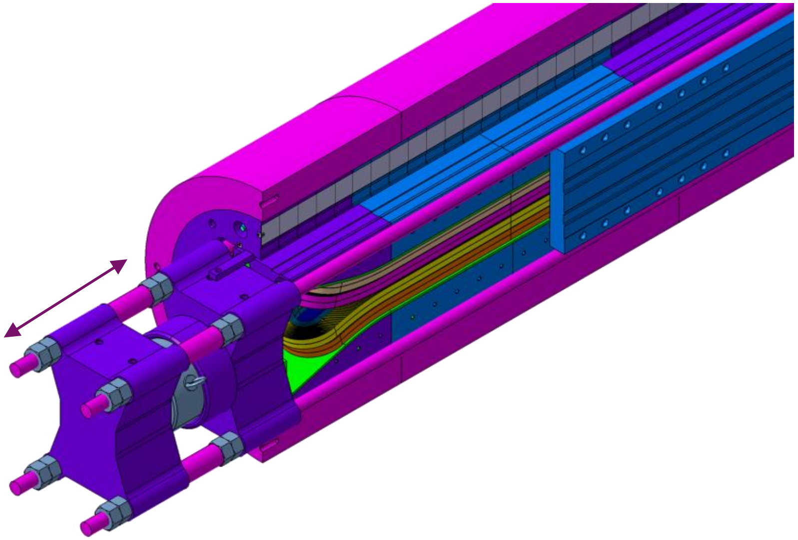
<480 MPa

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

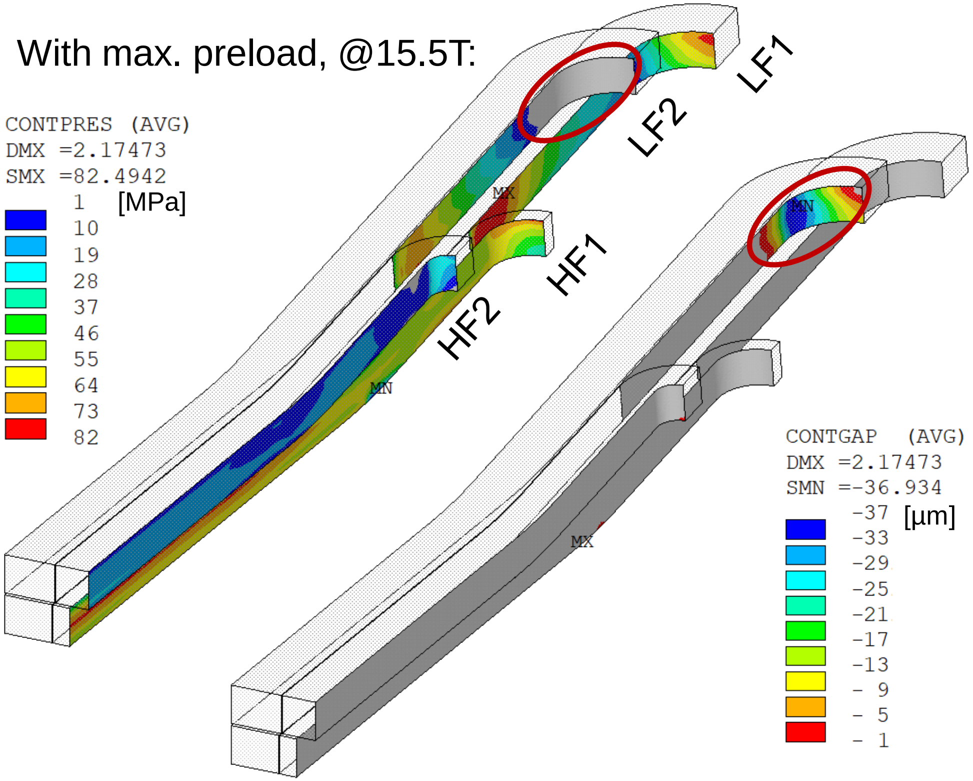


3D MECHANICAL DESIGN – LONGITUDINAL PRELOAD

	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

R2D2: A PROOF-OF-CONCEPT SUB-MODEL

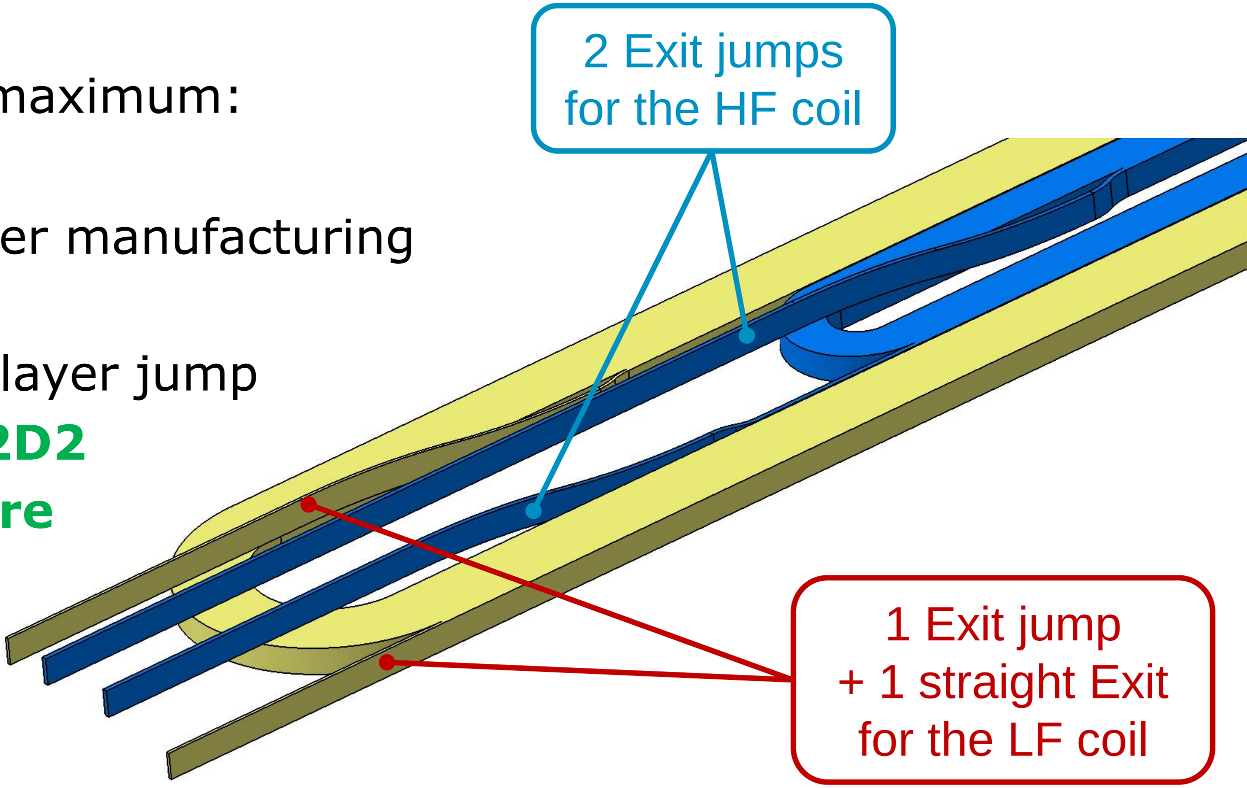
- **R2D2 = <u>R</u>esearch <u>R</u>acetrack <u>D</u>ipole <u>D</u>emonstrator**

- Goals are to demonstrate:
  - **Grading with blocks**
  - **Exit jumps with external joints**

- Design simplified at maximum:
  - **Racetrack**

  → no flared end, easier manufacturing
  - **Single layer**

  → less conductor, no layer jump
  - Assembly in the **F2D2 mechanical structure**



CONCLUSION

- Goal: Demonstrate key concepts for FCC block-coil dipoles:

  → **Grading between blocks**
  → **Joint technology**
- Relying on proven concepts:
  - **Block-coil**
  - **Bladders and keys structure**
  - **External joints**
- Integrated 3D design of coil-ends:

  → CAD to define coil, components, tooling

  → Winding mockups → **concepts validated**

  → Magnetic FEM → **operational margins in coil-ends**

  → Mechanical FEM → **safe stress conditions**
- **Challenging magnet!**

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

   → Demonstrate grading + external joints
2. **2nd stage:** F2D2 **graded flared-end** coils

DE LA RECHERCHE À L'INDUSTRIE

THANK YOU FOR YOUR ATTENTION!

www.cea.fr

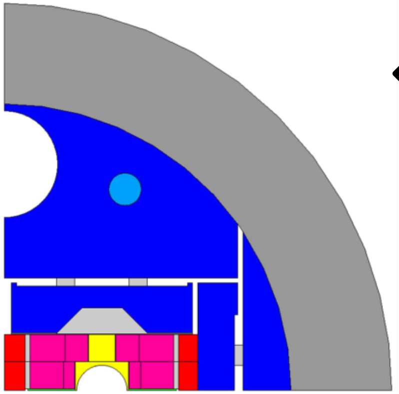
STRONG INTERACTION WITH MAGNET PROGRAMS

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

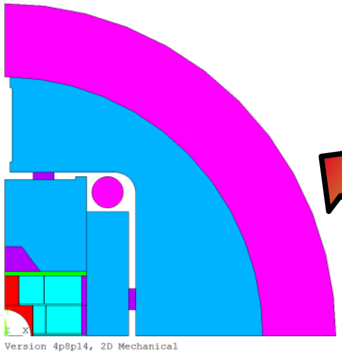
2. F2D2 short model [3]

→ Design/fabrication at CEA

→ Test at CERN

→ Single aperture

→ Same coil design



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

CERN Programs

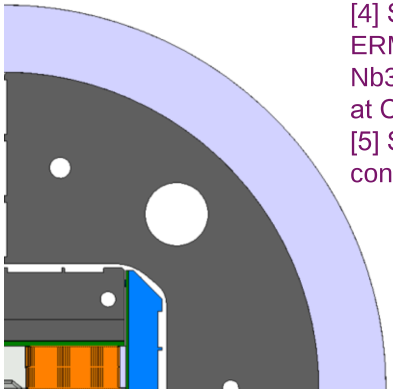
- SMC models

→ 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 “ERMC/RMM”, this conference

EPFL-CERN Program

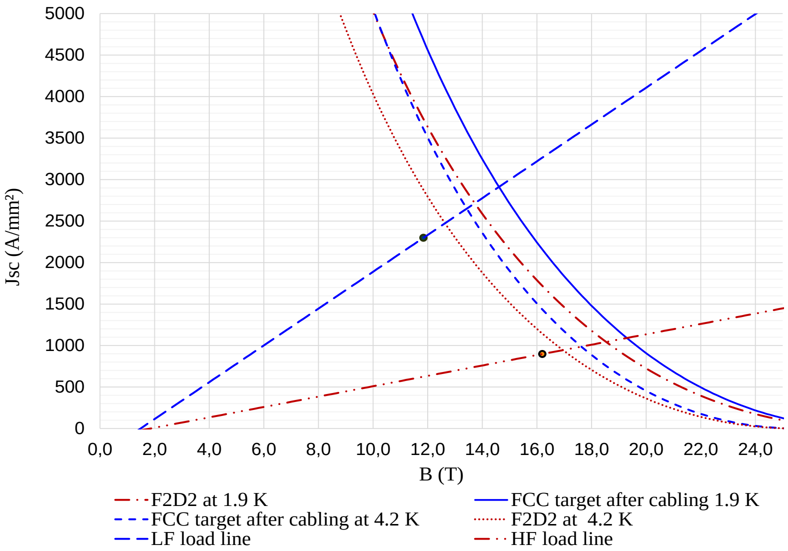
- R&D on jonction technology [6]

[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

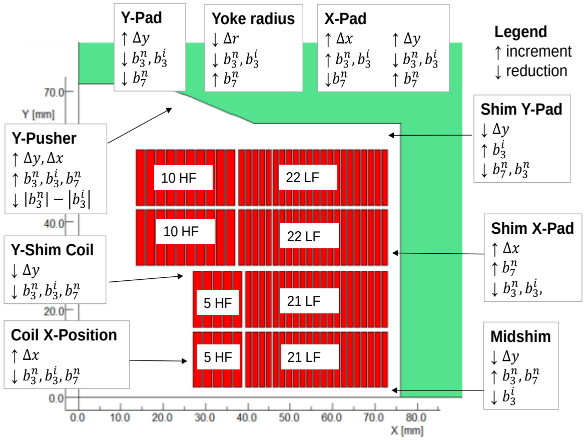
2D MAGNETIC DESIGN - FINALIZED

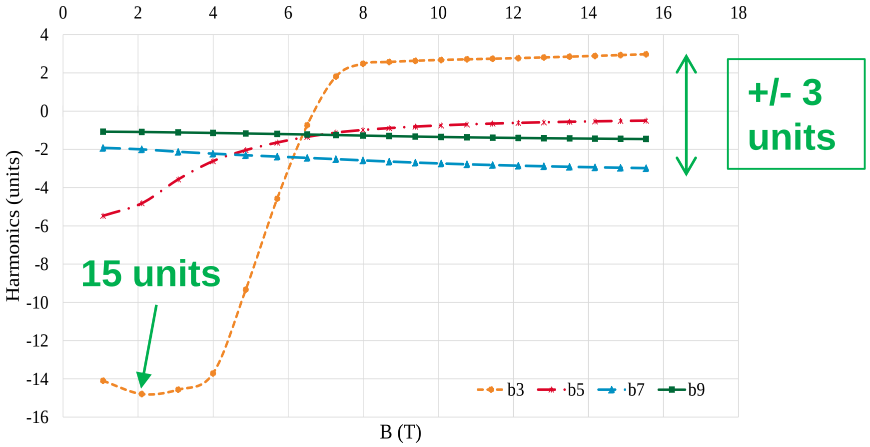
1. Maximize central field with margins:

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

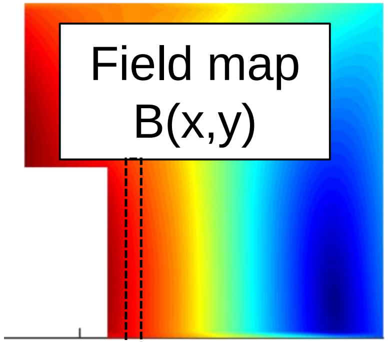


2. Harmonics representative of an accelerator magnet:





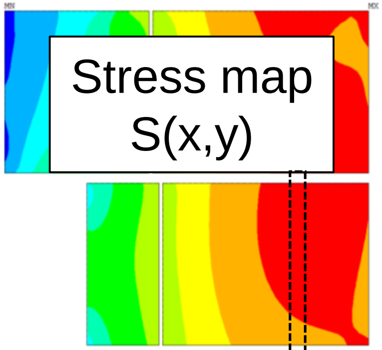
2D MAGNETO-MECHANICAL DESIGN - FINALIZED



Field map
B(x,y)

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

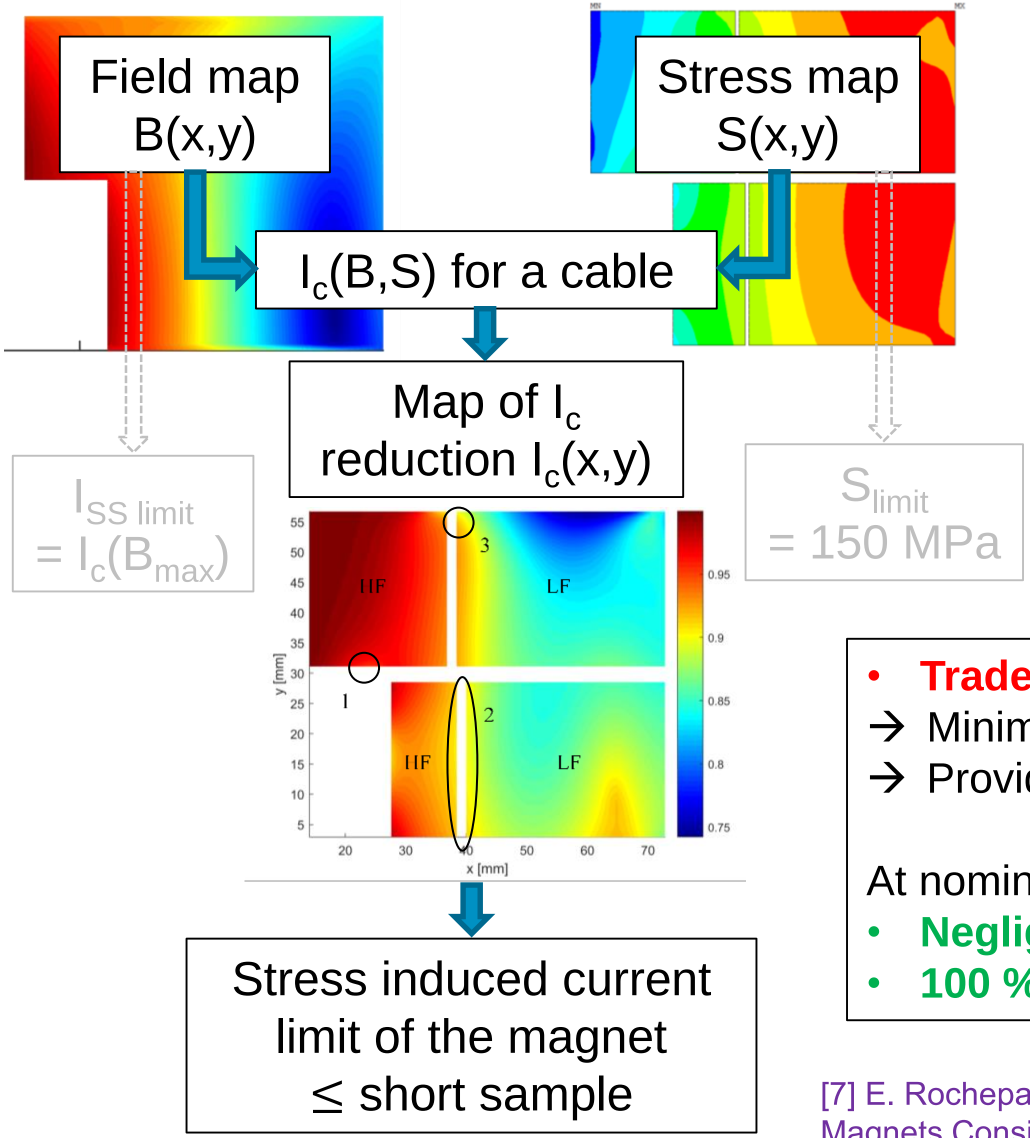
Traditional
approach



Stress map
S(x,y)

S_{limit}
$= 150$ MPa

2D MAGNETO-MECHANICAL DESIGN - FINALIZED



Field map B(x,y)

Stress map S(x,y)

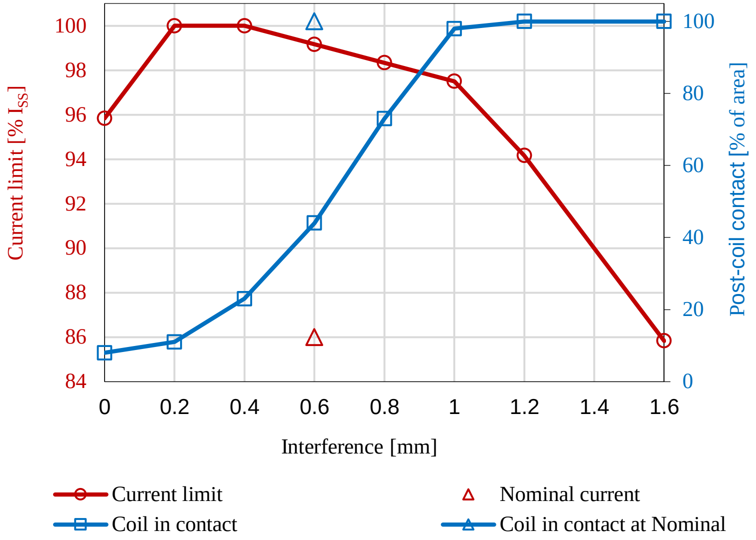
$I_c(B,S)$ for a cable

Map of I_c reduction $I_c(x,y)$

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

S_{limit} = 150 MPa

Stress induced current limit of the magnet ≤ short sample



- **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):

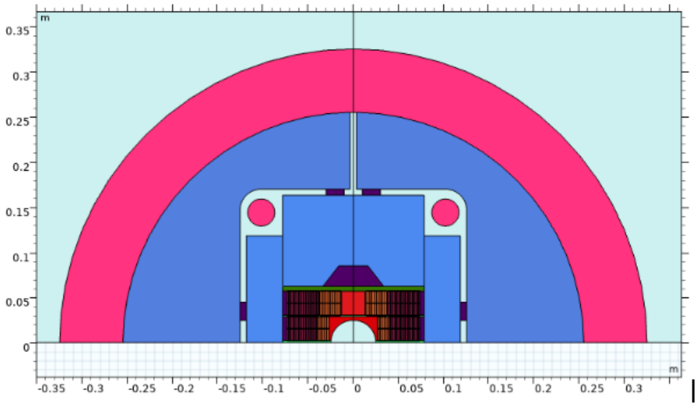
- Every coil has a quench heater
- Detection delay = 20 ms
- Detection voltage = 5 mV
- Heater activation delay = 20 ms
- Max hot spot temperature = 350 K
- Max ΔV to ground = 1200 V

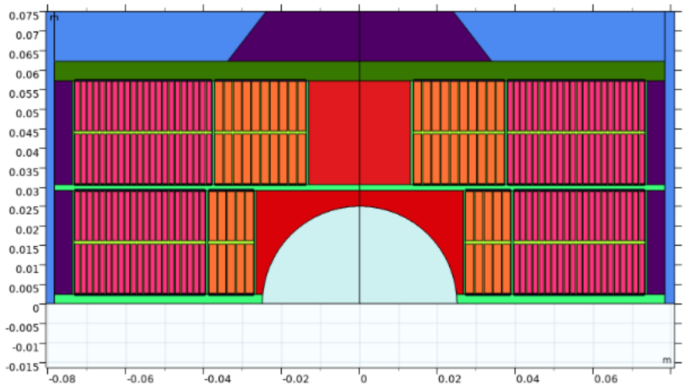
Model Hypotheses:

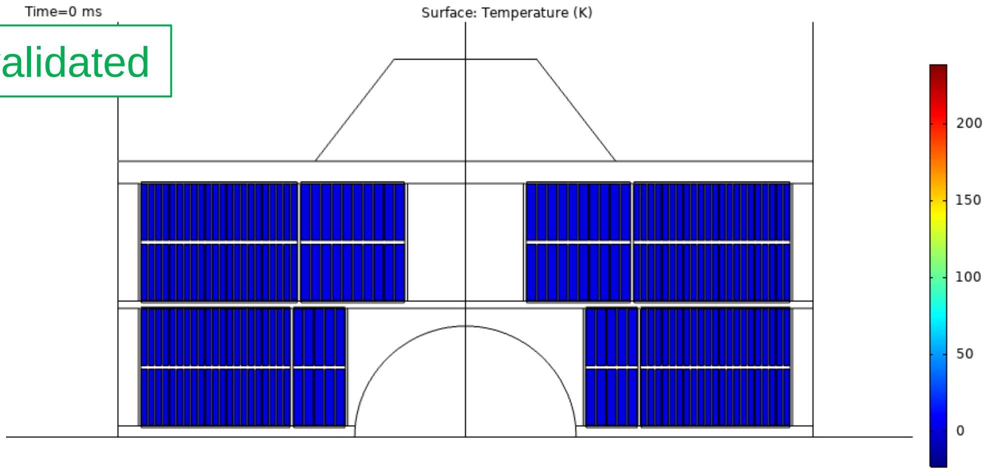
- Adiabatic Regime
- Cryocomp material database
- Magnetoresistivity included
- Transverse+longitudinal propagations considered

→ Magnetic, electrical, thermal models validated

Quench Study using Comsol







Case study : QH HF1+HF3 off

GRADING CONCEPT IN BLOCK-COILS

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

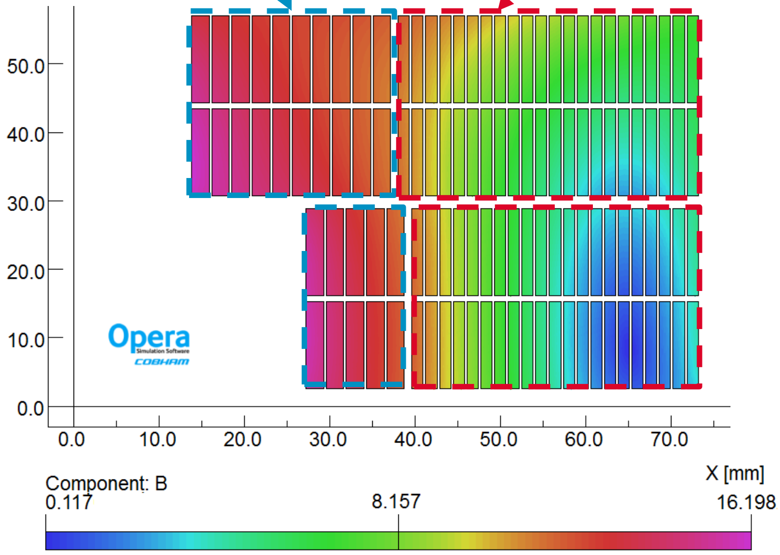
→ 2 cable sizes, same current

→ Optimizing the current density

→ Compact coils = less conductor

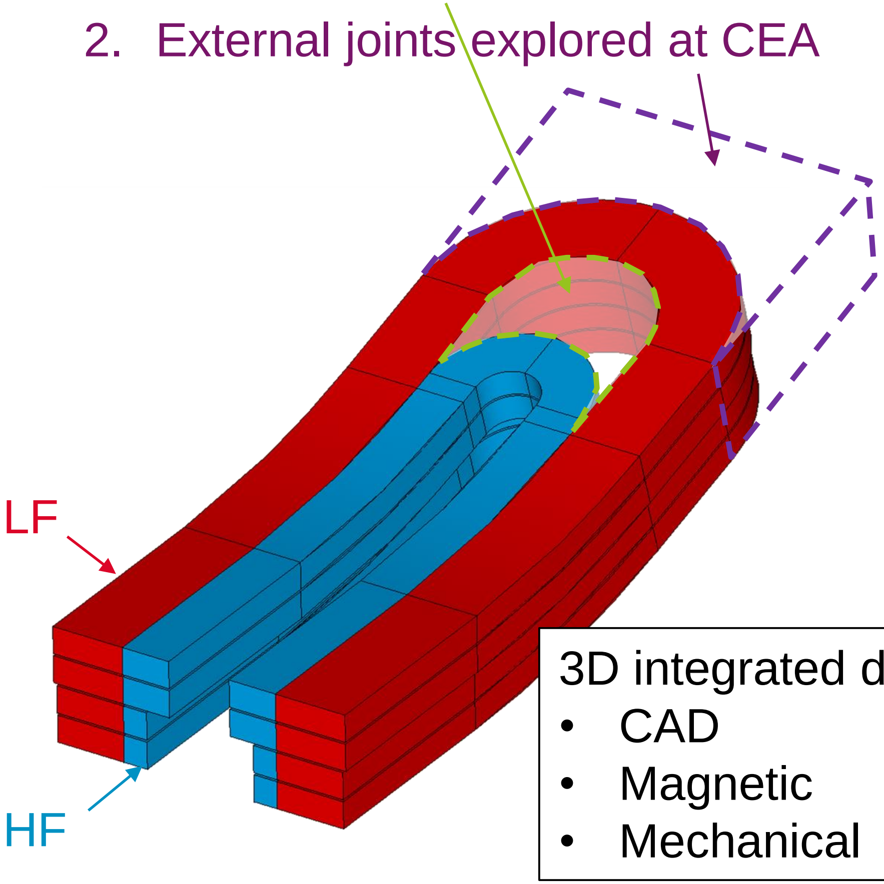
High Field "HF" blocks, low current density

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

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

		HF: 1.1mmx21 strands		**LF: 0.7mmx34 strands**		
Parameter	**Unit**	**Thick.**	**Width**	**Thick.**	**Width**	**Source**
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