DE LA RECHERCHE À L'INDUSTRIE

Conceptual Design Review of R2D2 1 - Introduction -

https://indico.cern.ch/event/1003865/

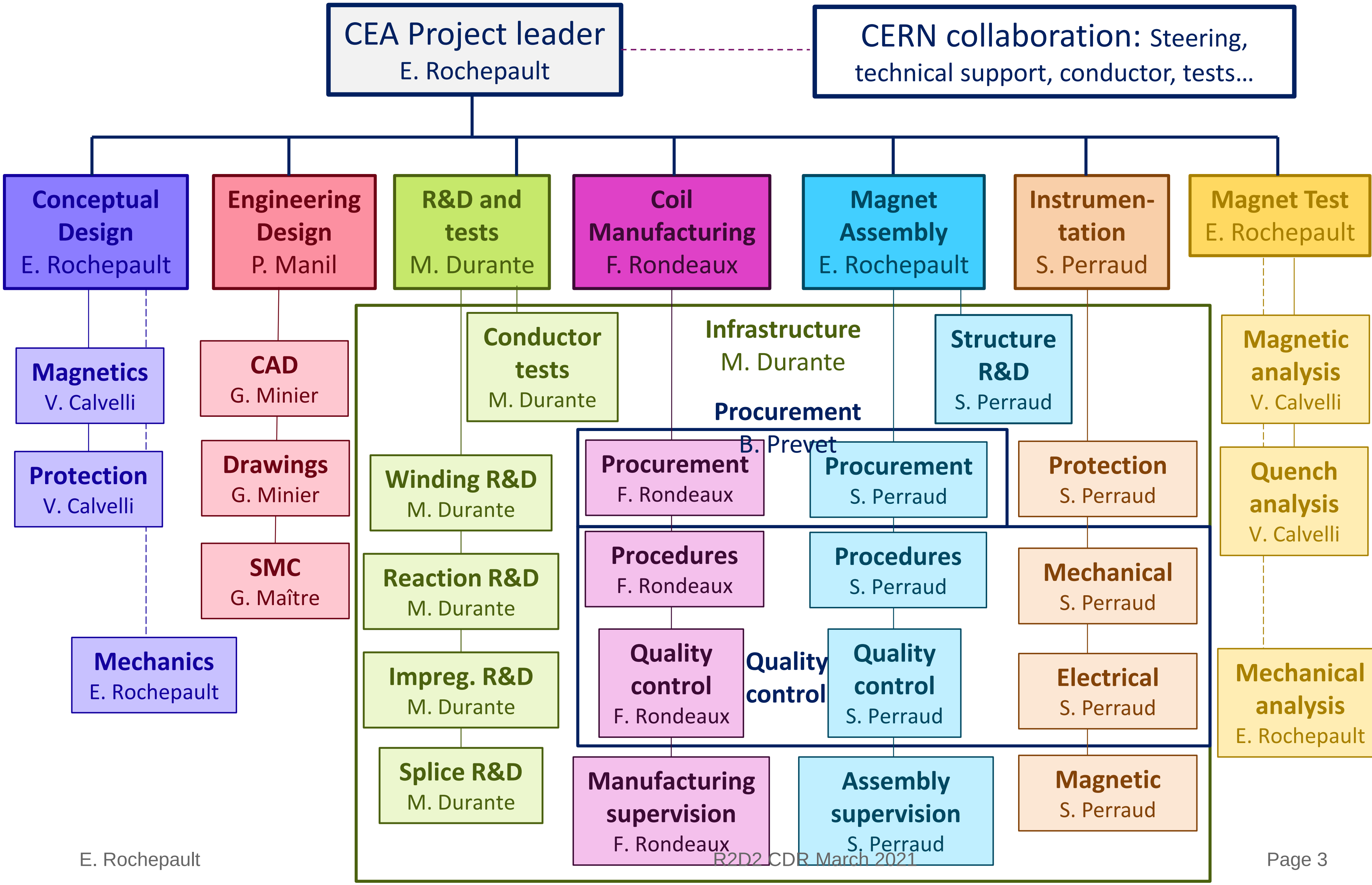
CEA: **E. Rochepault**, V. Calvelli, M. Durante, H. Felice, P. Mallon, P. Manil, G. Minier, G. Maitre, B. Prevet, S. Perraud, F. Rondeaux
CERN: S. Izquierdo Bermudez, J.C. Perez, D. Tommasini, J. Fleiter, H. Felice

08/03/2021

NEW ORGANIZATION

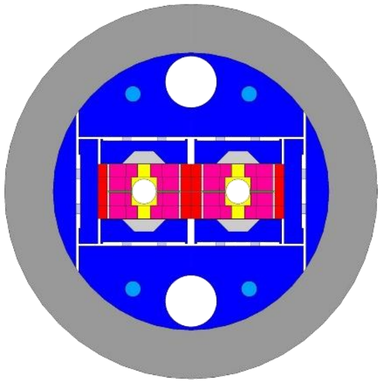
- **CEA Project leader** – E. Rochepault (Former: H. Felice)
  - **Conceptual Design** – E. Rochepault
    - **Magnetics** – V. Calvelli
    - **Protection** – V. Calvelli
    - **Mechanics** – E. Rochepault
  - **Engineering Design** – P. Manil
    - **CAD** – G. Minier
    - **Drawings** – G. Minier
    - **SMC** – G. Maître
  - **R&D and tests** – M. Durante
    - **Conductor tests** – M. Durante
    - **Winding R&D** – M. Durante
    - **Reaction R&D** – M. Durante
    - **Impreg. R&D** – M. Durante
    - **Splice R&D** – M. Durante
  - **Coil Manufacturing** – F. Rondeaux
    - **Procurement** – F. Rondeaux
    - **Procedures** – F. Rondeaux
    - **Quality control** – F. Rondeaux
    - **Manufacturing supervision** – F. Rondeaux
  - **Magnet Assembly** – E. Rochepault (Former: P. Mallon)
    - **Structure R&D** – S. Perraud
    - **Procurement** – S. Perraud
    - **Procedures** – S. Perraud
    - **Quality control** – S. Perraud
    - **Assembly supervision** – S. Perraud
  - **Instrumen-tation** – S. Perraud
    - **Protection** – S. Perraud
    - **Mechanical** – S. Perraud
    - **Electrical** – S. Perraud
    - **Magnetic** – S. Perraud
  - **Magnet Test** – E. Rochepault
    - **Magnetic analysis** – V. Calvelli
    - **Quench analysis** – V. Calvelli
    - **Mechanical analysis** – E. Rochepault

New Organization



OUTCOME OF EUROCIRCOL

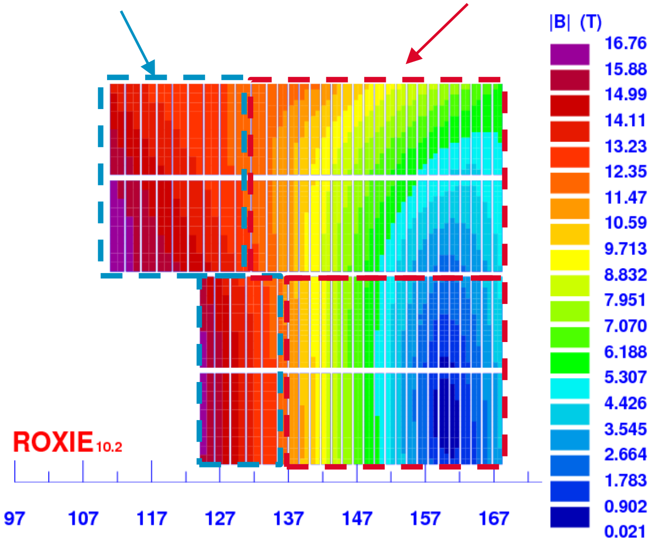
- Starting point: **block-coil option for FCC**
  - 16 T → max. achievable field
  - Graded coils → most compact possible
  - High-Jc cables
  - Double aperture → accelerator type
  - Conceptual design



- CEA-CERN collaboration:
  - Probe the **16 T limit**
  - **Test grading** in block-coils
  - State-of-the-art cables
  - **develop and build** a demonstrator
  - Single aperture
  - Short models

High Field "HF" blocks, low current density

Low Field "LF" blocks, high current density

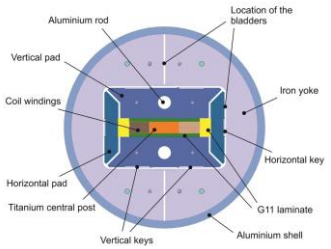


DEVELOPMENT PLAN TOWARD 16 T DIPOLES FOR FCC

1. SMC 11T (=**S**hort **M**odel **C**oil)

Racetrack coils

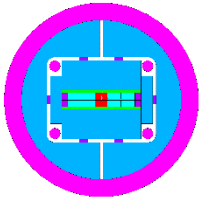
No grading → **Demonstrate field ≥ 12 T**



+Grading

2. R2D2 (=**R**esearch **R**acetrack **D**ipole **D**emonstrator)

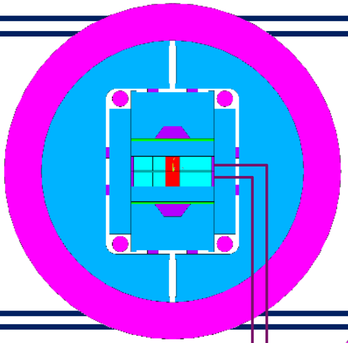
Racetrack + **Grading = 12 T**



+Flared ends

3. FD (=**F**lared **D**ipole)

Grading + **Flared-end coils ≥ 14 T**

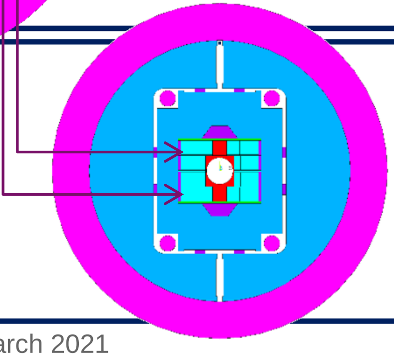


+Aperture

4. F2D2 (=**F**CC **F**lared-ends **D**ipole **D**emonstrator)

Reuse FD coils + structure

Grading + Flared-end coils + **Aperture = 16 T**



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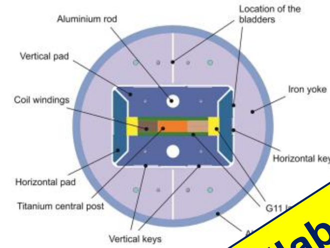

+Grading

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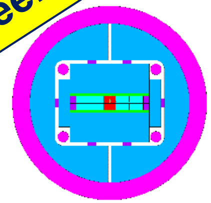
Racetrack + **Grading = 12 T**

Current collaboration agreement



+Flared ends

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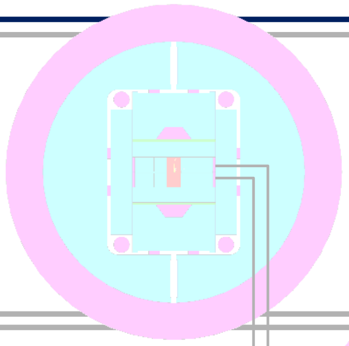

+Aperture

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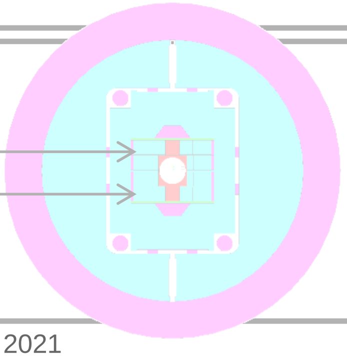
Reuse FD coils + structure

Grading + Flared-end coils + **Aperture = 16 T**



DEVELOPMENT PLAN TOWARD 16 T DIPOLE FOR FCC

1. SMC 11T (=Short Model Coil) [10]
Racetrack coils
No grading → **Demonstrate field ≥ 12 T**

+Grading

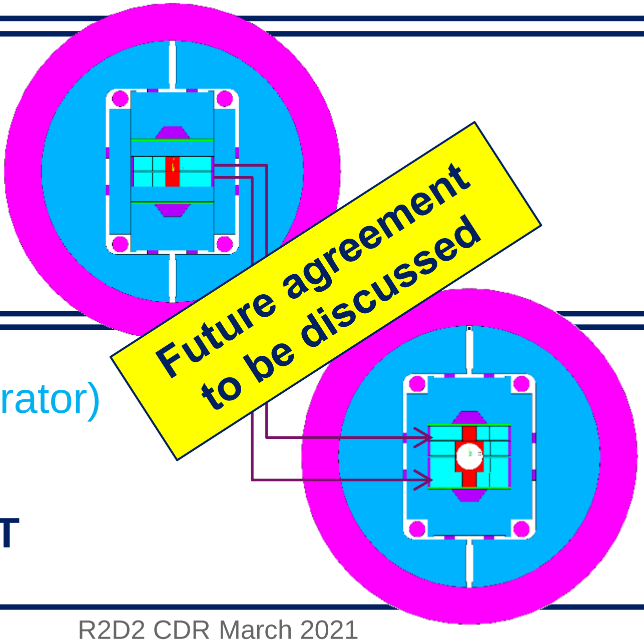
2. R2D2 (=Research Racetrack Dipole Demonstrator)
Racetrack + **Grading = 12 T**

+Flared ends

3. FD (=Flared Dipole)
Grading + **Flared-end coils ≥ 14 T**

+Aperture

4. F2D2 (=FCC Flared-ends Dipole Demonstrator)
Reuse FD coils + structure
Grading + Flared-end coils + **Aperture = 16 T**



DEVELOPMENT PLAN TOWARD 16 T DIPOLES FOR FCC

1. **SMC 11T** (=**S**hort **M**odel **C**oil) [10]

Racetrack coils

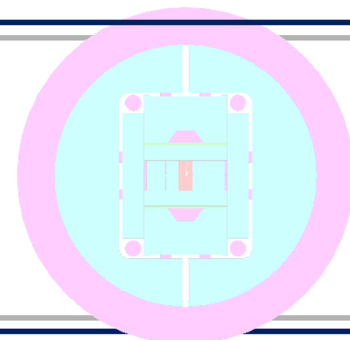
No grading → **Demonstrate field ≥ 12 T**

2. **R2D2** (=**R**esearch **R**acetrack **D**ipole **D**emonstrator)

Racetrack + **Grading = 12 T**

3. **FD** (=**F**lared **D**ipole)

Grading + **Flared-end coils ≥ 14 T**



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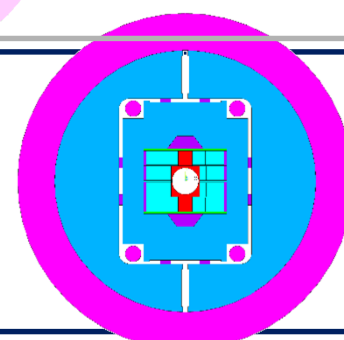
Reuse FD coils + structure

Grading + Flared-end coils + **Aperture = 16 T**



First part of this talk

DEVELOPMENT PLAN TOWARD 16 T DIPOLES FOR FCC

1. **SMC 11T** (=**S**hort **M**odel **C**oil) [10]
Racetrack coils
No grading → **Demonstrate field ≥ 12 T**

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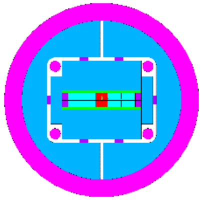
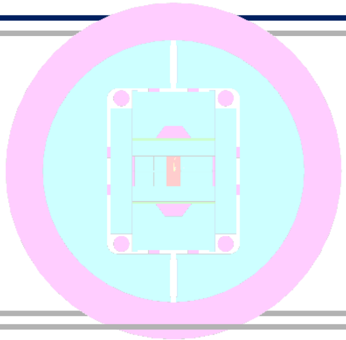
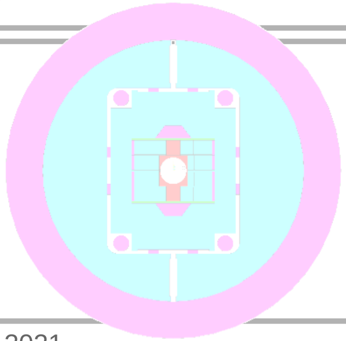


Focus of the CDR

3. **FD** (=**F**lared **D**ipole)
Grading + **Flared-end coils ≥ 14 T**

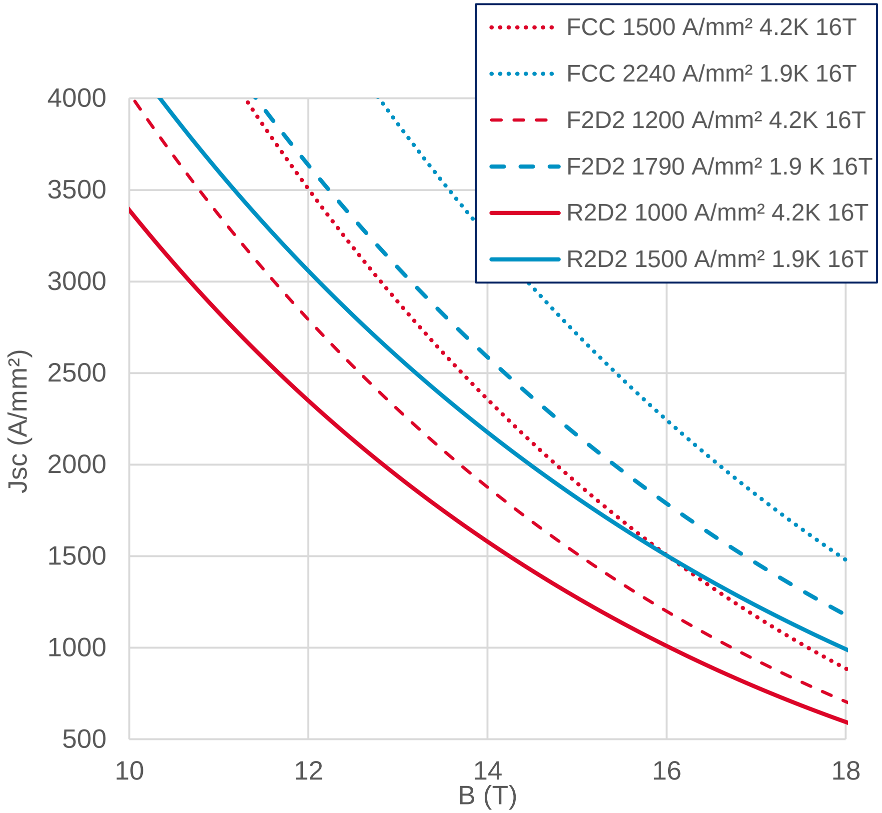


4. **F2D2** (=**F**CC **F**lared-ends **D**ipole **D**emonstrator)
Reuse FD coils + structure
Grading + Flared-end coils + **Aperture = 16 T**



Conductor for F2D2 and R2D2

Expected Parameters	HF	LF
# strands	21	34
∅ strands	1.1 mm	0.7 mm
Pitch angle	16.5 deg	16.5 deg
Transposition pitch	85.0 mm	85.0 mm
Cu/Sc ratio	0.8	2
Insulation	0.15 mm	0.15 mm
Expected Dimensions (reacted & insulated)	2.36 x 13.04 mm	1.61 x 13.04 mm



- Cu cables expected T1 2021
- LF cable very similar to the 11-T cable
- HF cable new, 1.1 mm strand

→ risk of changes in dimensions, mitigated with dimensional margins (see **4**, P. Manil)

- J_c and RRR extrapolated

→ risks of impact on the design, mitigated with design margins (see **2**, V. Calvelli)

F2D2: A Model Toward FCC High Field Dipoles

- 16 T target for FCC [1], proposed strategy:

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

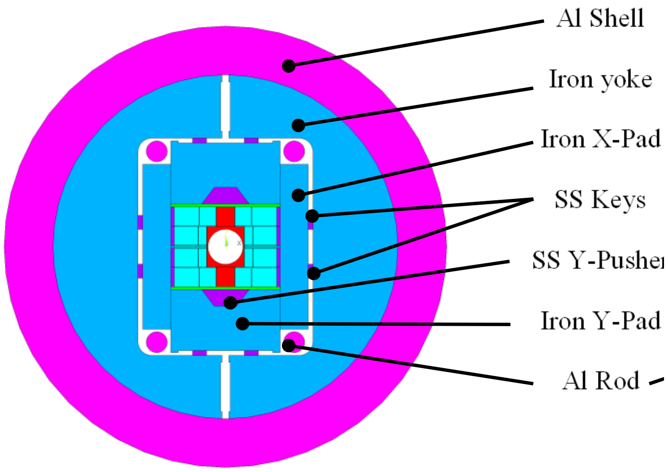
→ Concepts proposed within EuroCirCol [3]

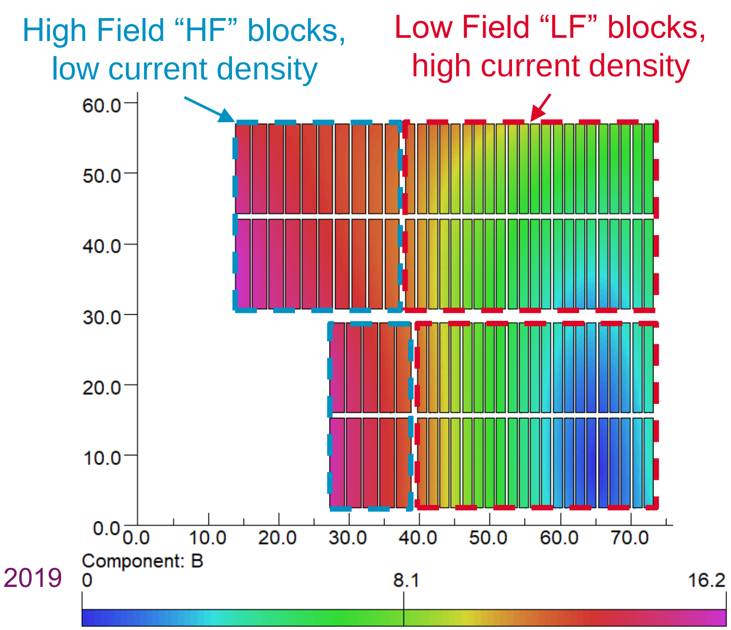
2. **Develop grading**:
   - Compact, high current density

3. **Build and test a short model** [4]
   - CERN-CEA collaboration

→ **Design/fabrication at CEA**

→ **Test at CERN**





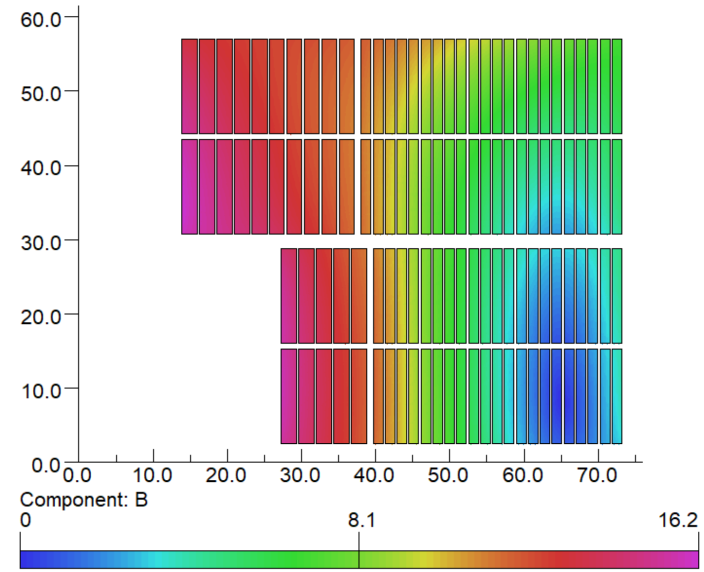
[1] D. Schoerling et al., "The 16 T Dipole Development Program for FCC and HE-LHC" , IEEE TAS, 2019
[2] Plenary H. Felice, MT26: "Advances in Nb3Sn Superconducting Accelerator Magnets"
[3] M. Segreti et al., "2D and 3D Design of the Block-coil Dipole Option for the Future Circular Collider", IEEE TAS, 2019
[4] H. Felice et al. "F2D2: a Block-coil Short Model Dipole Toward FCC", IEEE TAS, 2019

2D Magnetic Design - Finalized

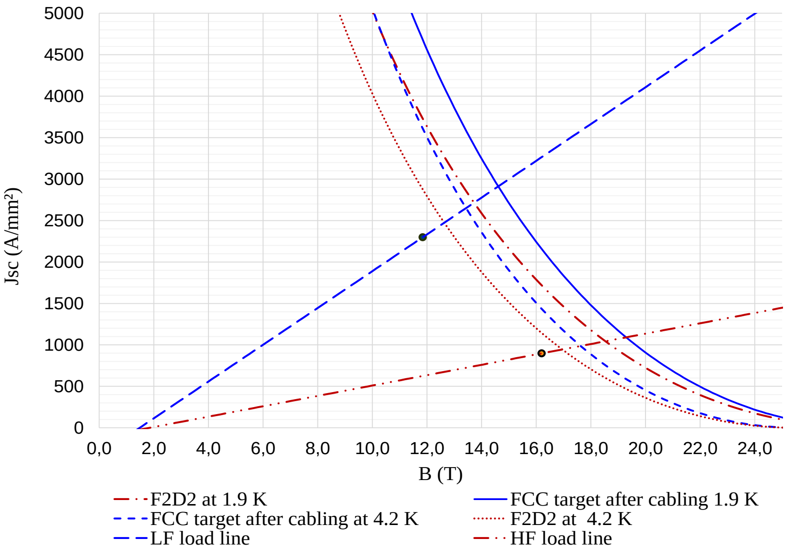
1. Maximize central field with margins:

- 15,5 T with available conductor (1200 A/mm2 @ 16T, 4,2K)
- At least 14 % margin on the load-line
- Margins balanced HF/LF

V. Calvelli



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



DEVELOP EXTERNAL JOINTS FOR GRADING

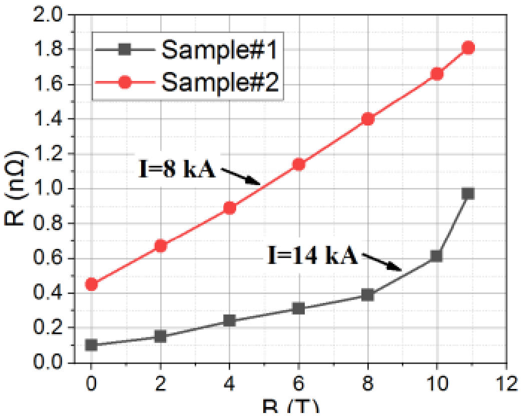
- EPFL-CERN Program: **R&D on internal joint** technologies [6]

→ Ultrasound (US), Soldering (CRS), Diffusion bonding (DB)

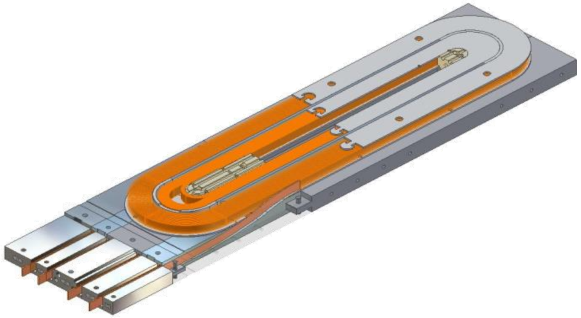
→ DB promising but: pressure required during heat treatment

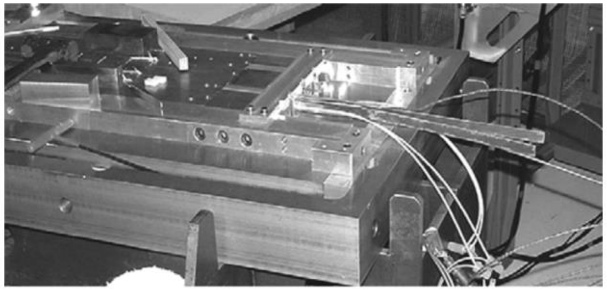
Figure 5. Sample#2 during the disassembly of the heat treatment sample holder and assembly of the test sample holder without manipulation of the components in contact with the splice.

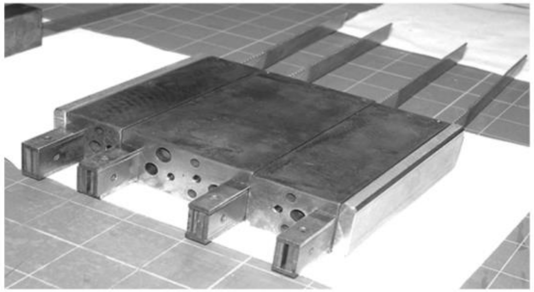
Courtesy V. D'Auria



- TAMU magnets: grading with external splices







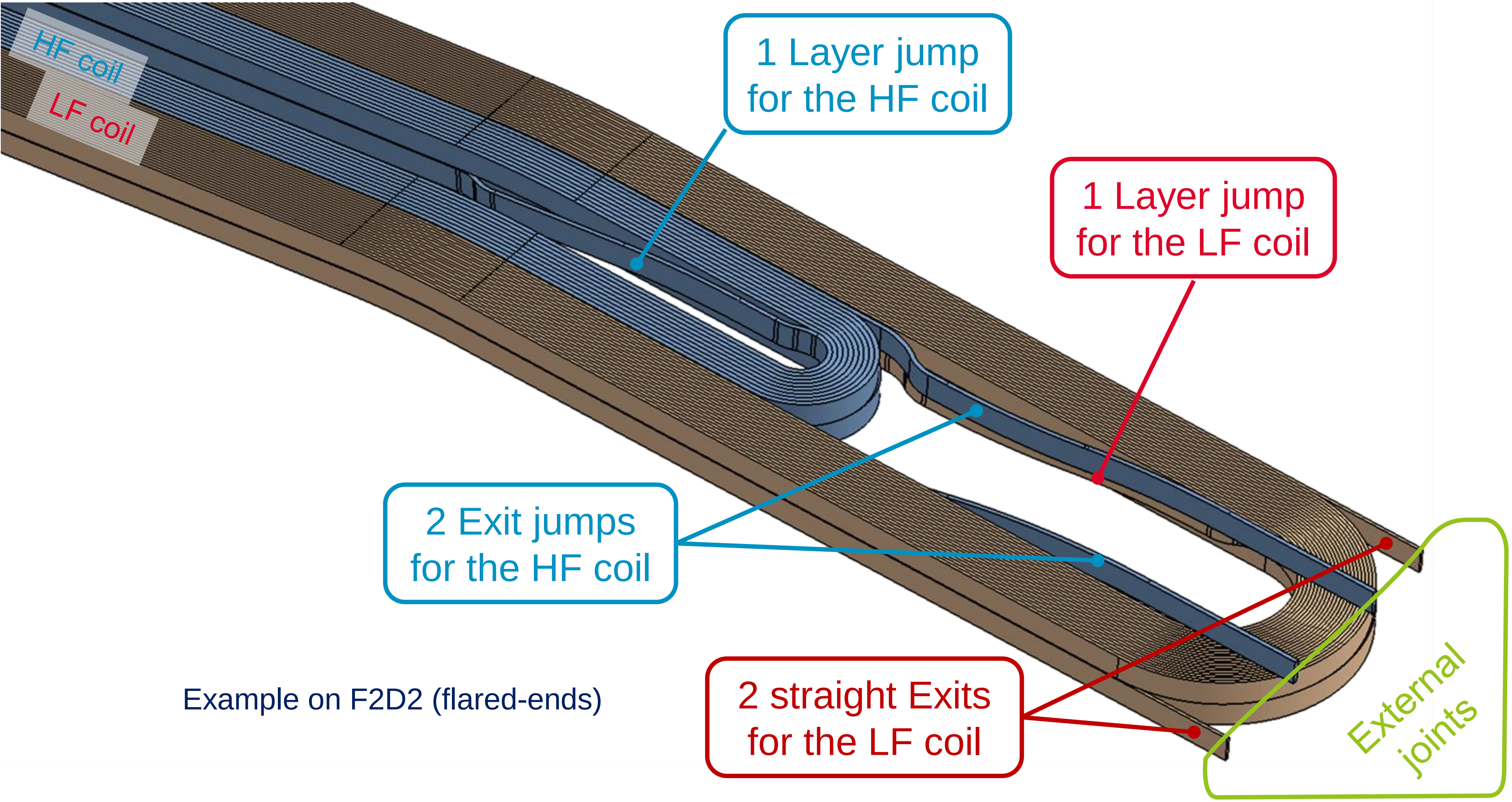
[6] V. D'Auria et al. "Progress on Tests on Splices between Nb3Sn Rutherford Cables for Graded High-Field Accelerator Magnets", submitted to IEEE TAS`

[7] P. Noyes et al.,"Construction of a Mirror-Configuration Stress-Managed Nb3Sn Block-Coil Dipole", IEEE TAS 2006

Develop External Joints for Grading

- **CEA proposal: external joints** to better fit in schedule [4]

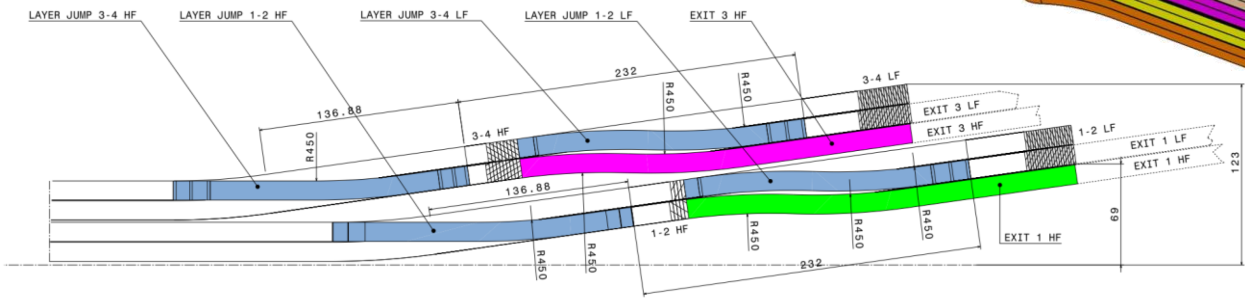
→ Possibility to implement internal joints in a second phase

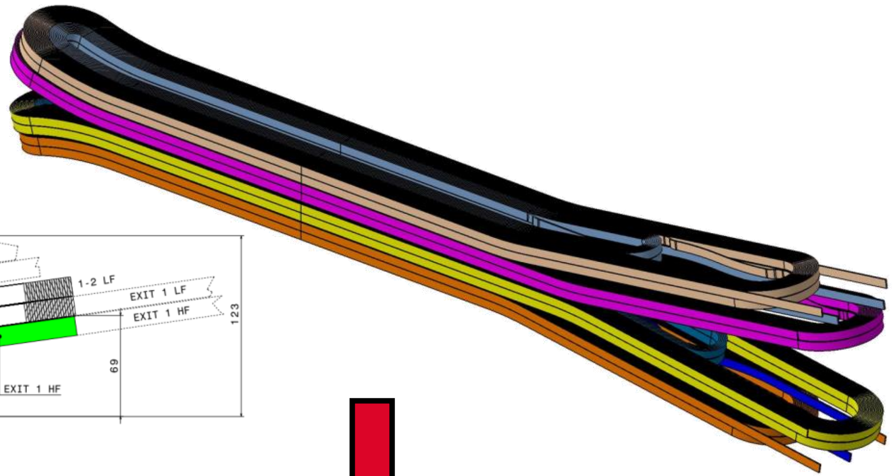


Example on F2D2 (flared-ends)

3D Magnetic design: Field in Critical Areas

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

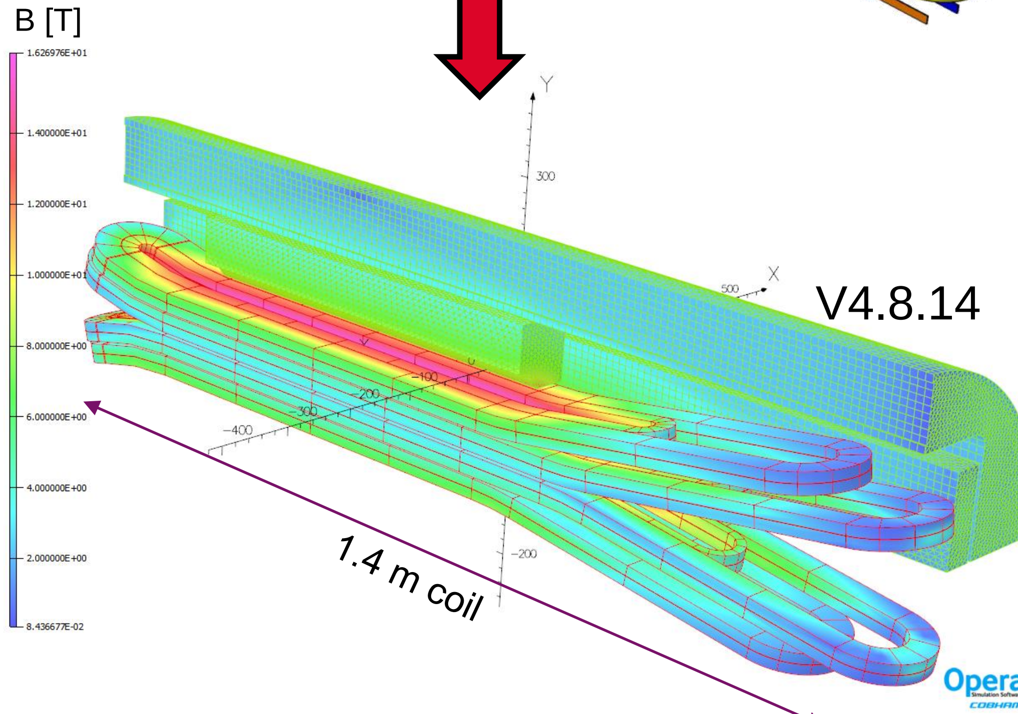




2. **3D simplified Opera FEM**:

a. Central field:

- Magnetic Length = 1042 mm
- Uniform field (±1%) = 249 mm



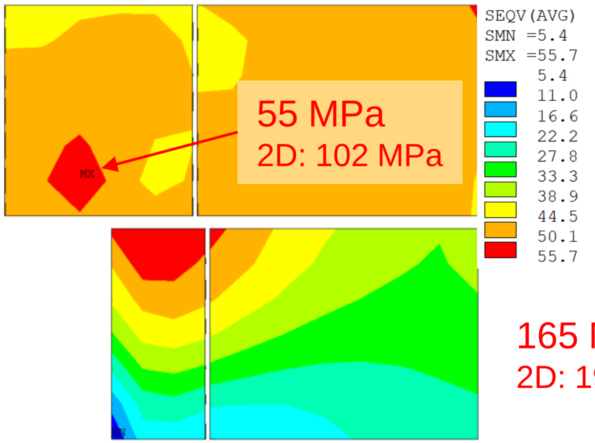
b. Field in critical areas:

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

3D Mechanical Design – Stress at z=0

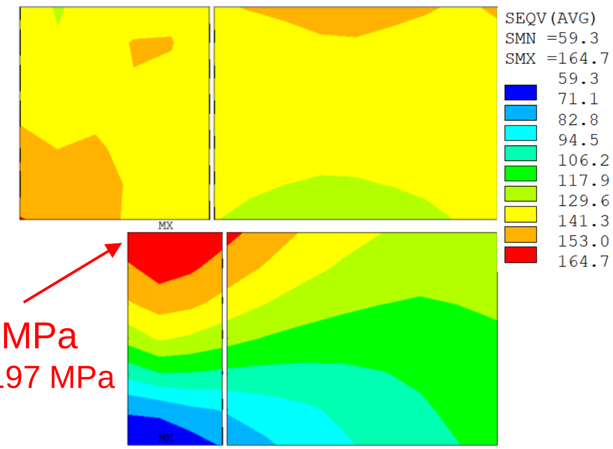
- 0.6 mm interference

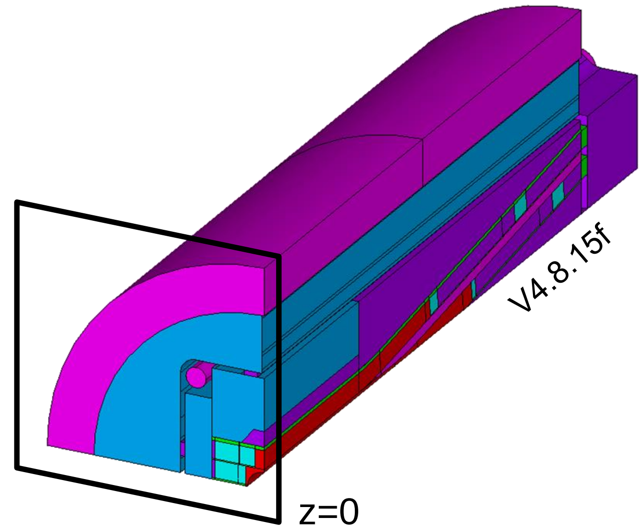
σ Von Mises [MPa]



- 1.9 K

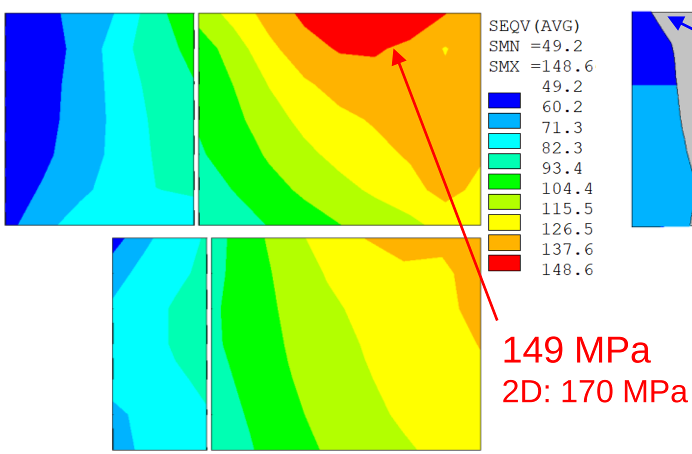
σ Von Mises [MPa]



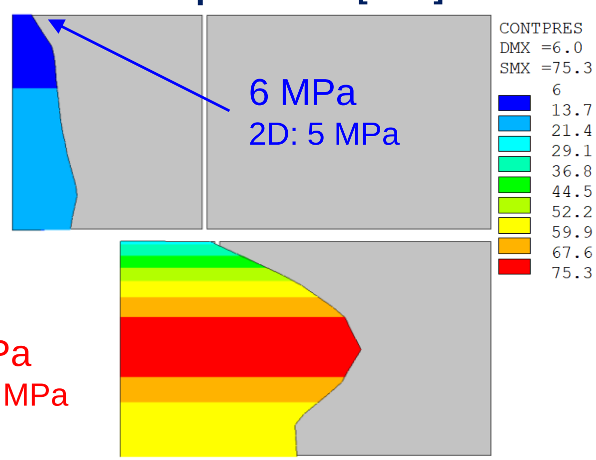


- Nominal operations: 10.4 kA, 14% margin, **15.5 T**

σ Von Mises [MPa]



Contact pressure [MPa]



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

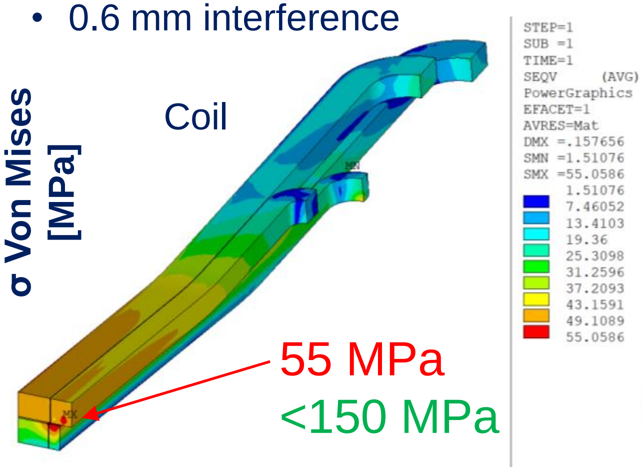
- Next step: estimate stress-induced current limit with 3D stress [5]

3D Mechanical Design - Stress

σ Von Mises [MPa]

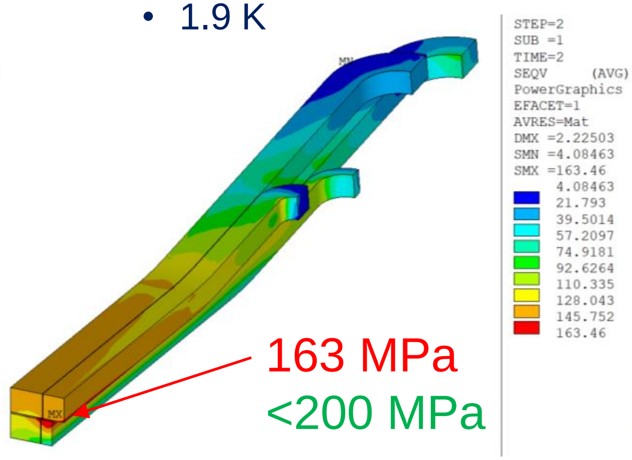
- 0.6 mm interference

Coil



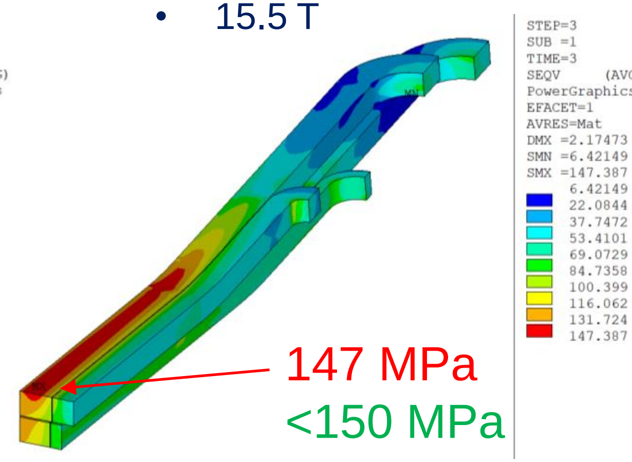
55 MPa
<150 MPa

- 1.9 K



163 MPa
<200 MPa

- 15.5 T

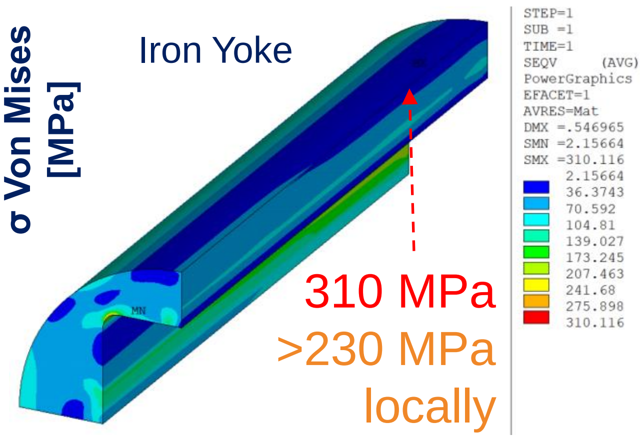


147 MPa
<150 MPa

σ Von Mises [MPa]

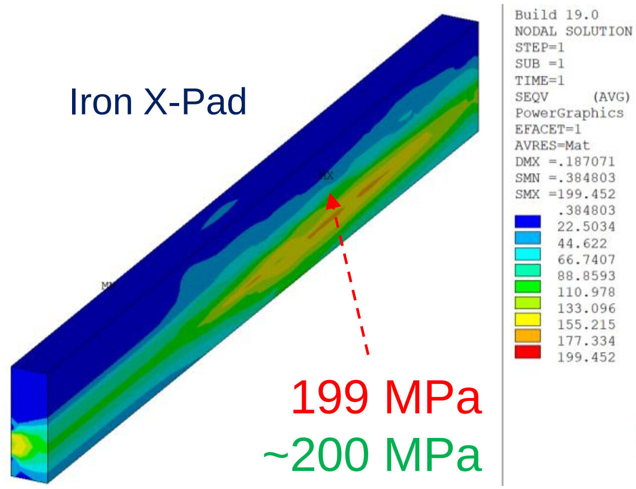
- 0.6 mm interference

Iron Yoke



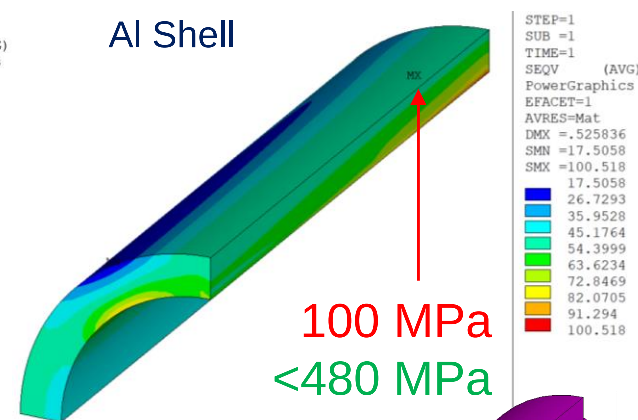
310 MPa
>230 MPa
locally

Iron X-Pad



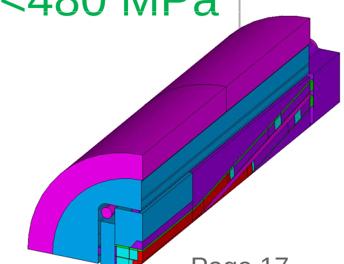
199 MPa
~200 MPa

Al Shell



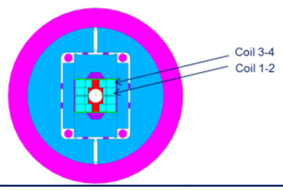
100 MPa
<480 MPa

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



FROM F2D2 TO R2D2

- CEA-RD-2.1: Demonstrator conceptual design (F2D2)
- CEA-RD-2.2: FD engineering design (F2D2 partial assembly with coils 3-4 only) + associated tooling
- CEA-RD-3.1: Fabrication of one Cu coil 3-4
- CEA-RD-3.2: Fabrication of one Nb_3Sn coil 3-4
- CEA-RD-4.1: Procurement and validation of the F2D2 support structure
- CEA-RD-4.2: Assembly of the Nb_3Sn coil with the Cu coil in a "FD" configuration (coils 3-4 at the right position + coils 1-2 filler) and delivery at CERN by end of 2021



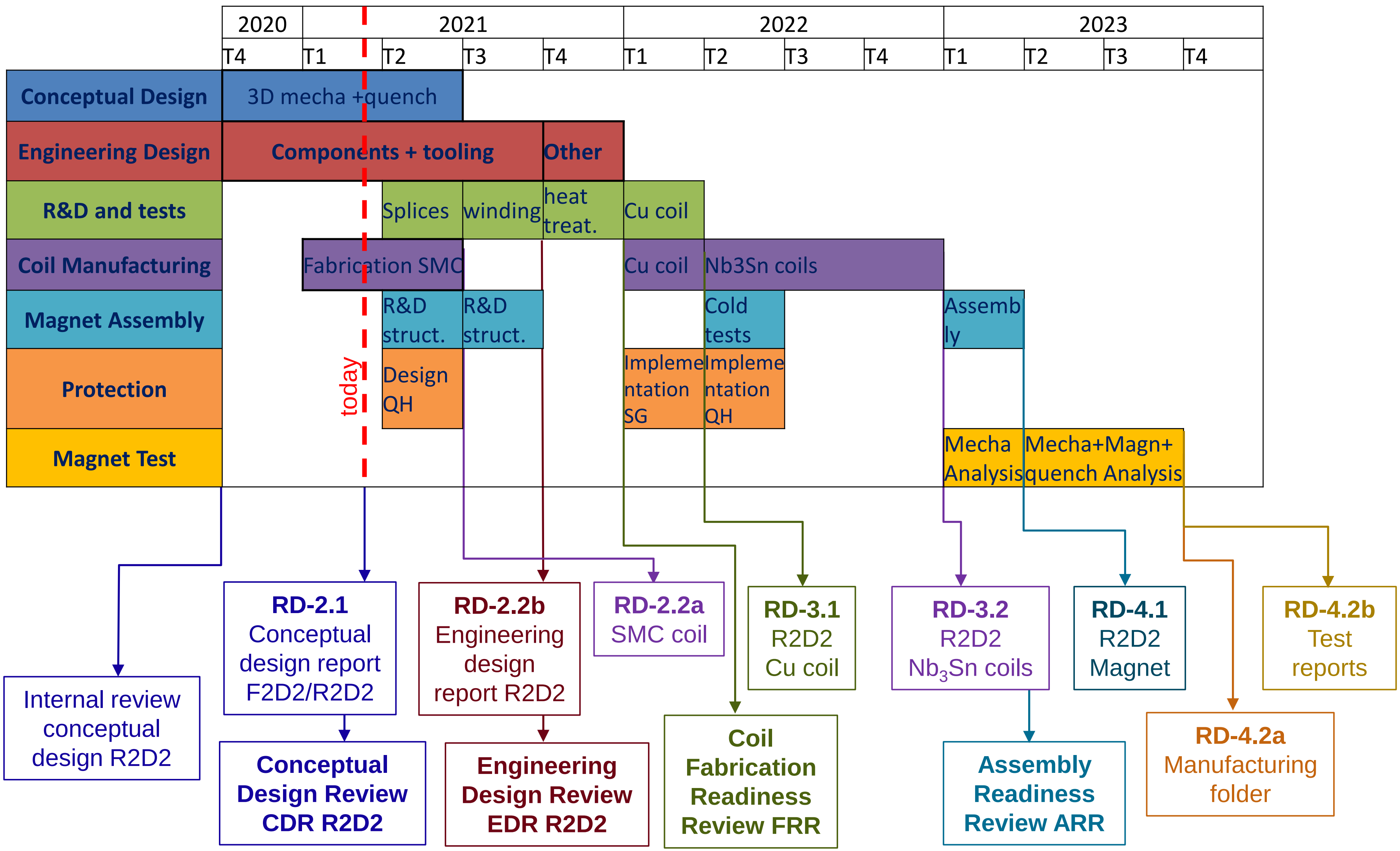
- CERN acknowledged good progress on the design
- Concerns expressed by CERN based on HL-LHC experience:
  - High risk of conductor loss
  - Call for a further improvement of the technology
  - Demonstrating progess is paramount to the credibility of the HFM development programs
  - LS2 activities impacts CERN ability to support technically the collaboration
- CEA agrees

Courtesy H. Felice

Steering committee recommendation on May 9th 2019:

- re-examine the modified proposal, discuss the idea of completing the F2D2 engineering design, but wind SMC/eRMC/RMM class coils that would allow "unitary tests" of novel technology (grading) with relevant cable and field
- Call for a technical discussion (timescale 2 weeks) for final agreement by steering committee by the end of June 2019

R2D2 Simplified Schedule



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OPEN QUESTIONS REQUIRING R&D

a. What are the safe bending parameters for **coil winding**? (see **5**, M. Durante)

b. How to handle cables in **graded coils** ? (see **4** P. Manil + **5**)

c. How to deal with longitudinal contraction during **heat treatment**? (see **5**, M. Durante + EDR)

Splices R&D

d. How to guide and secure the **exits** to the outside of the coils?

e. How to provide **margins** (geometric, magnetic, mechanical…) to the exit path? (see **2**, V. Calvelli + **4**, P. Manil + EDR)

f. How to perform all the **joints** in a compact area? (see **5**, M. Durante)

g. How to apply **longitudinal pre-stress** without damaging the joint area? (see **4**, P. Manil + EDR)

Structure R&D, further review

h. What will be the **mechanical behavior** of the coils?

i. What level of **transverse pre-stress** to apply?

j. How to guarantee the **pre-stress** is controlled and reproducible?

Charge of the Review

a. Have the goals of the project been clearly stated/explained?
b. Is the design overall solid? Magnetic design, protection, and mechanics.
c. **Are the field and current levels sufficient to validate the grading concepts?**
d. Are there unidentified risks associated to the design?
e. Is there a sufficient level of tests and R&D?
f. Does the maturity of the design allow moving to the engineering design phase? For example: winding two grades, dealing with contraction during heat treatment, concept of longitudinal support…
g. **In particular: is the concept of external splices adequate for R2D2? Are there enough tests foreseen?**
h. Does the schedule seem reasonable for the engineering and fabrication steps?
i. Are the design tools appropriate for this project?
j. Is the team sufficiently benefiting from past experiences?

Charge of the Review

What is outside of the CDR scope:

- Conceptual design of F2D2 → design for the long term
- Detailed (engineering) design of R2D2 → covered in the EDR
- Fabrication of SMC → covered in the FRR

Review Agenda

Pacific time	Paris time	Title	Presenter	Duration
Day 1: Monday, March 9				
7:00-7:20	16:00-16:20	Introduction	E. Rochepault	20’
7:20-8:20	16:20-17:20	Magnetic Design and protection	V. Calvelli	40’+20’
8:20-8:50	17:20-17:50	Mechanical design	E. Rochepault	20’+10’
Day 2: Tuesday, March 10				
7:00-7:40	16:00-16:40	Engineering design	P. Manil	30’+10’
7:40-8:10	16:40-17:20	Coil R&D	M. Durante	30’+10’
8:10-9:00	17:20-18:00	Wrap-up and Discussion	All	40’

Conclusion – Goals of the CDR

- Goals of the project:
  1. Rely when possible on **proven technology**
  2. **Develop grading** → Compact coils, high current density
  3. **Build and test a short model**
- Rescoping from F2D2 to R2D2

  → Reducing the overall difficulty

  → Conceptual design finalized
- Difficulties related to grading:

  → External joints, need for R&D

  → Longitudinal preload

Are these concepts sufficiently solid for the project?

DE LA RECHERCHE À L'INDUSTRIE

BACKUP SLIDES

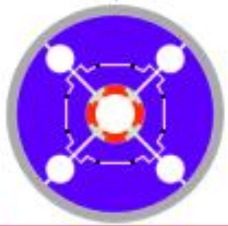
www.cea.fr

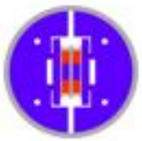
FAMILY TREE TOWARD MQXF FOR HL-LHC

Subscale Quadrupole SQ
0.3 m long
110 mm bore

LBNL Subscale Magnet SM
0.3 m long
No bore

Technology Quadrupole TQS - TQC
1 m long
90 mm bore



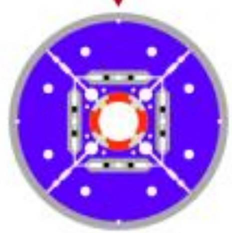


Long Racetrack LRS
3.6 m long
No bore

Technology selection:
Shell based support structure for LARP

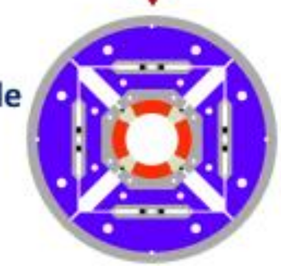
1st assembly: 2009
Last assembly: 2012

Long Quadrupole LQS
3.7 m long
90 mm bore



1st assembly: 2010
Most recent: 2013

High Field Quadrupole
1 m long
120 mm bore



Courtesy H. Felice

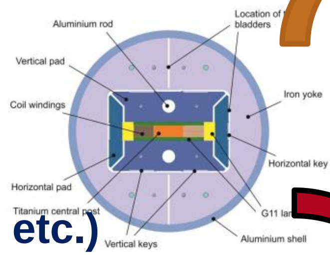
BERKELEY LAB
Lawrence Berkeley National Laboratory

U.S. LARP

IDEAS ON AN INTEGRATED STRATEGY

SMC 11T

- Conductors
- Pre-stress
- Materials (Insulations etc.)

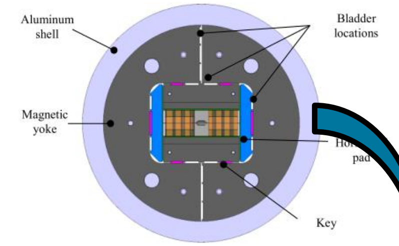


+Field

ERMC

(= 'reduced' RMM)

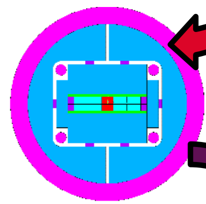
✓ Demonstrate 16 T



+Grading

R2D2

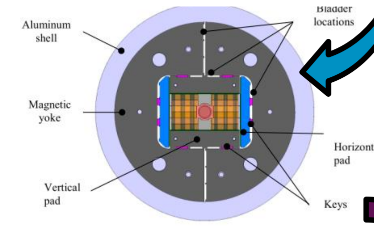
Demonstrate Grading ≥ 12 T



+Aperture

RMM

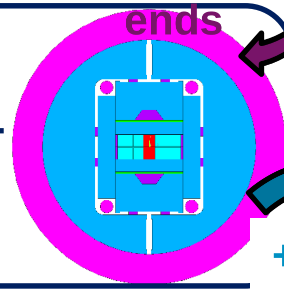
Demonstrate aperture =16 T



+Flared ends

'Reduced' demo. (FD?)

Grading + **Flared-ends ≥ 14 T**

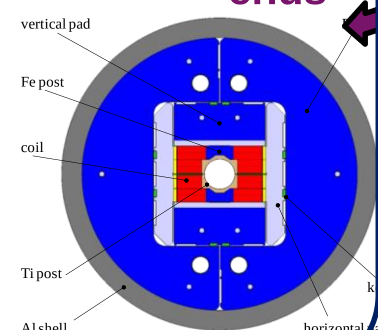


+Flared ends

FRESCA2 (but 100 mm aperture)

✓ Flared-ends

+ aperture ≥ 14 T

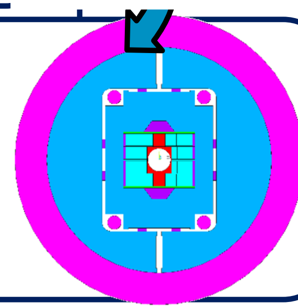


+Aperture

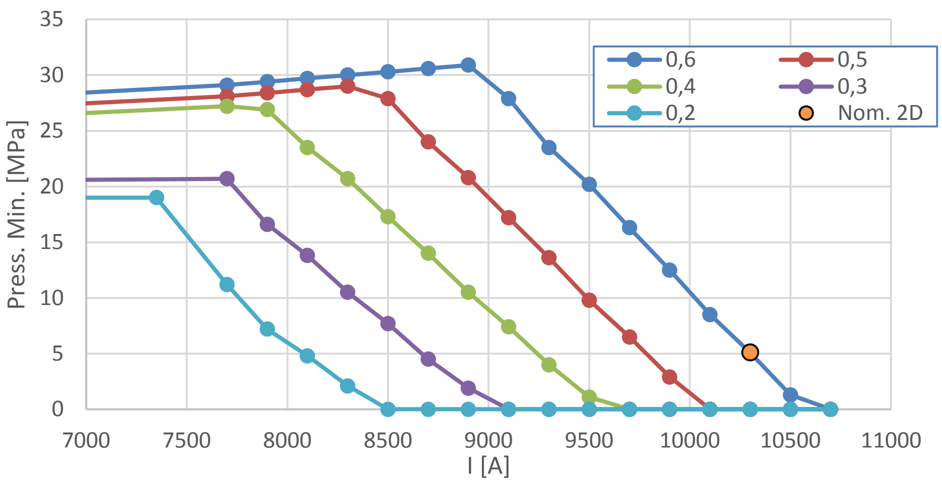
+Grading

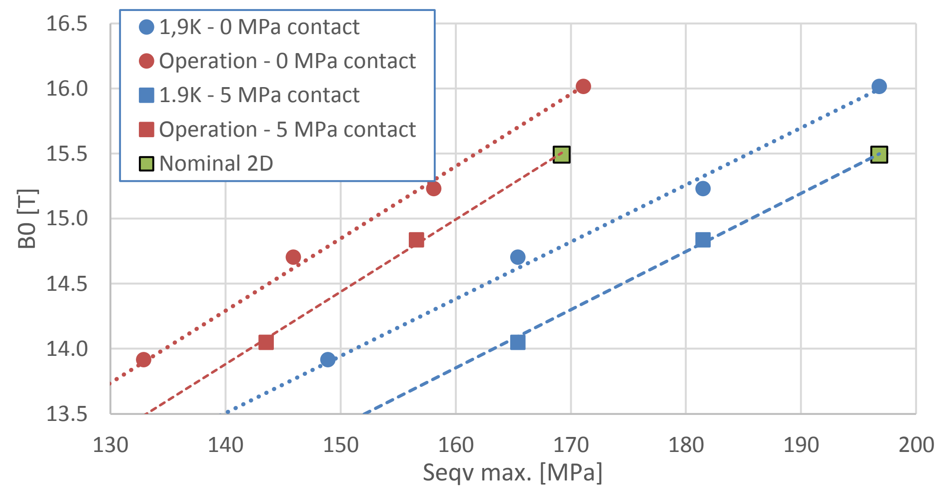
"Demonstrator" (F2D2?)

Grading + Flared-ends + **Aperture = 16 T**



2D Mechanical Design - Finalized

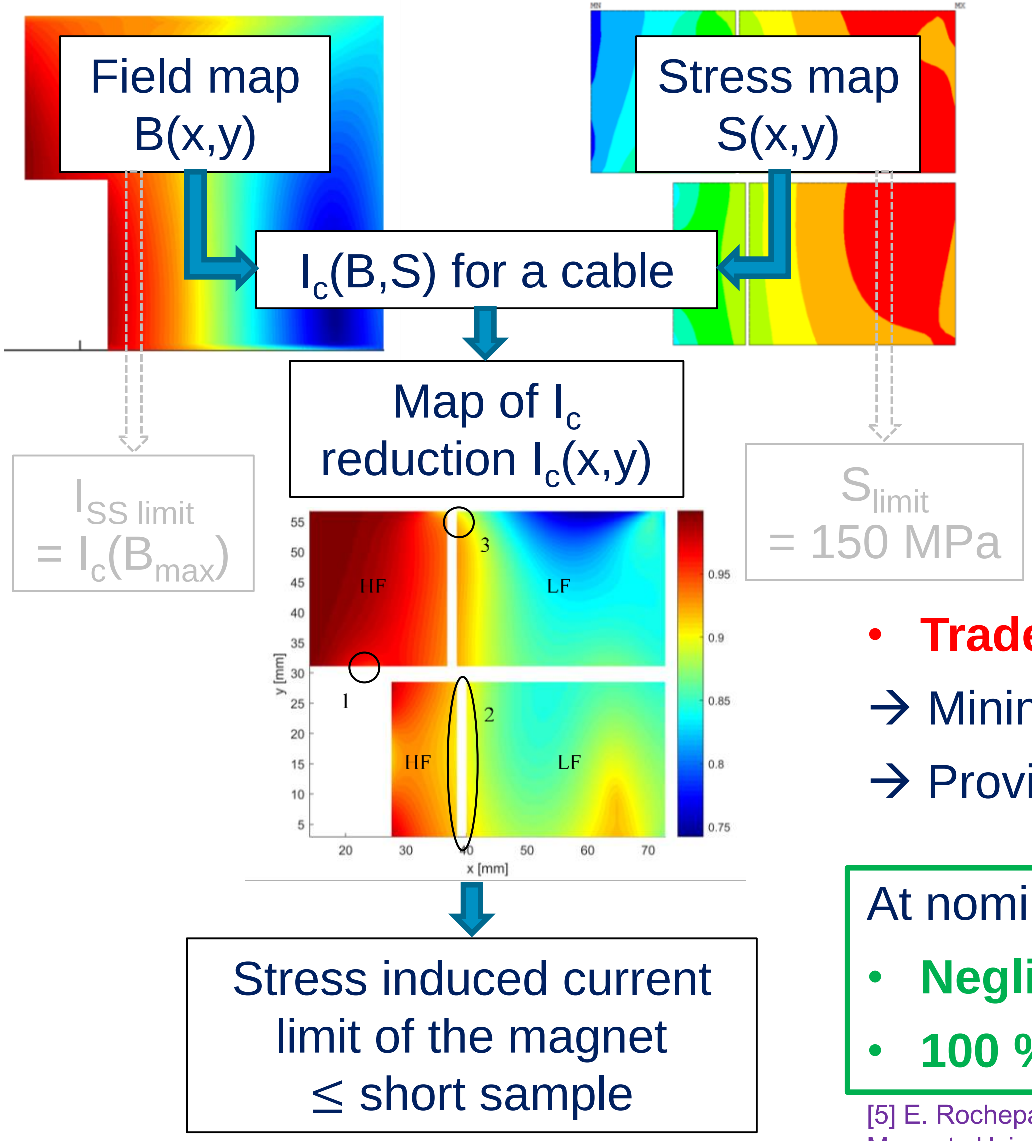


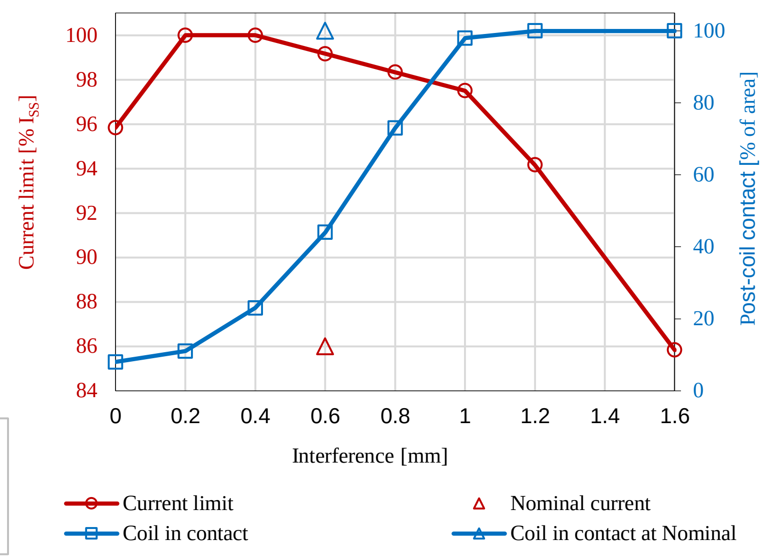


Different fields depending on stress conditions:

Criterion	Interf. [mm]	Seqv peak [MPa] 1.9 K	Seqv peak [MPa] Operation	Min. Press. [MPa]	Margin @1.9 K [%]	B_0 [T]
150 MPa at 1.9 K	0,31	**150**	135	0	24	14.0
150 MPa at operation	0,44	171	**150**	0	18	14.9
Nominal 14% margin	0,53	186	162	0	14	15.5
Nominal 14% margin	**0,6**	**197**	**170**	**5**	**14**	**15.5**
200 MPa at 1.9 K	0,62	**200**	173	0	10	16.1
Short sample	0,84	237	202	**0**	**0**	17.7

2D Magneto-Mechanical Design - Finalized





- **Trade-off on the pre-stress**:

→ Minimize I_c reduction

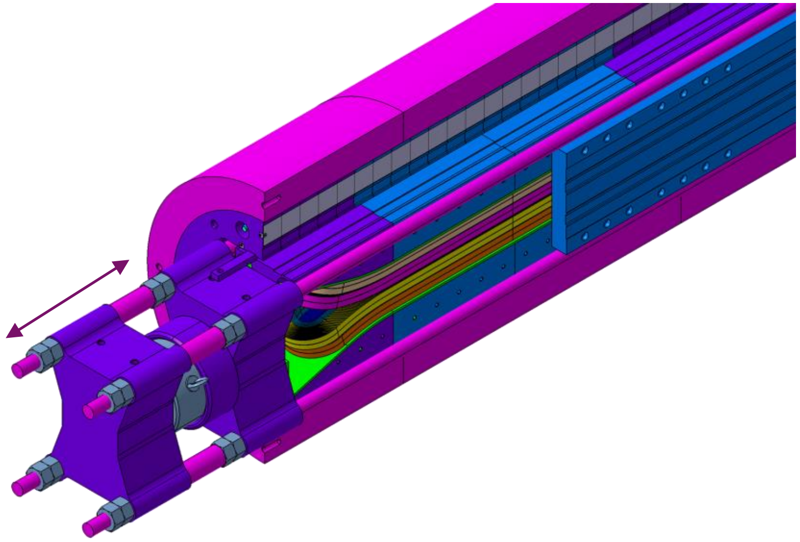
→ Provide sufficient pre-stress

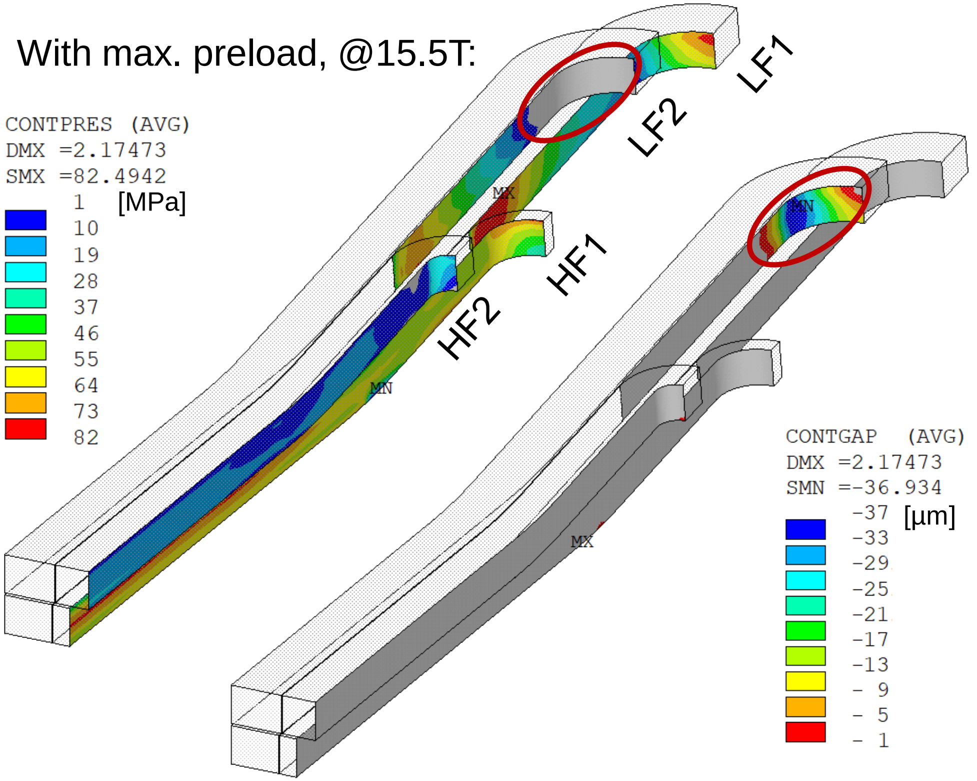
At nominal current :

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

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

	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