# $Nb_3Sn$ High Field Magnet (HFM) activities at Saclay

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J.C. Perez - CERN

HFM meeting – 29/05/2024

# Development Plan towards 16 T $Nb_3Sn$ Dipoles

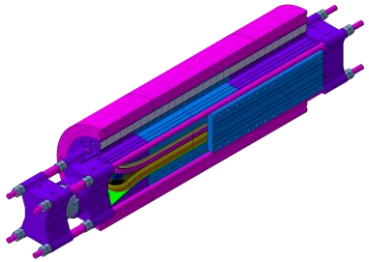
16 T demo

12-14 T demo

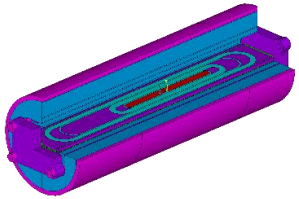
Subscales

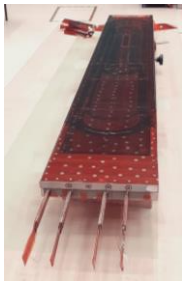
Powered samples

Non-powered samples

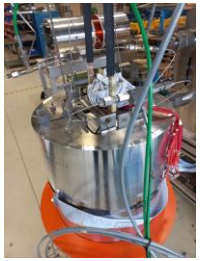


F2D2

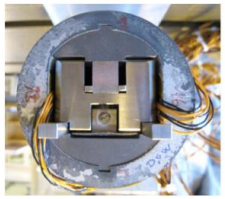


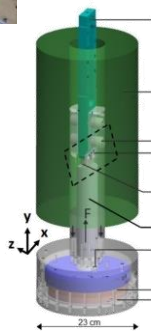


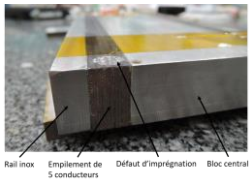
R2D2

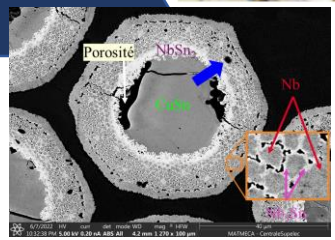


SMC





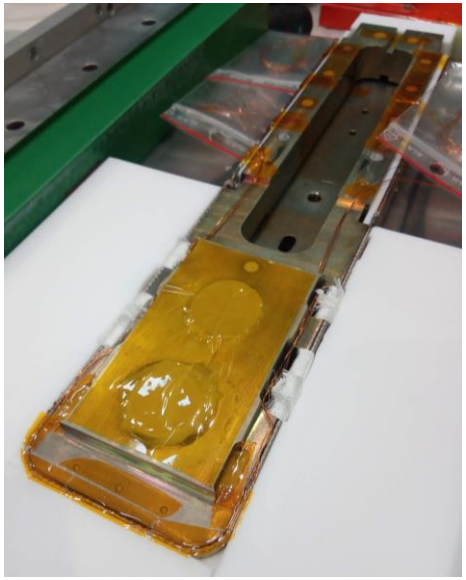



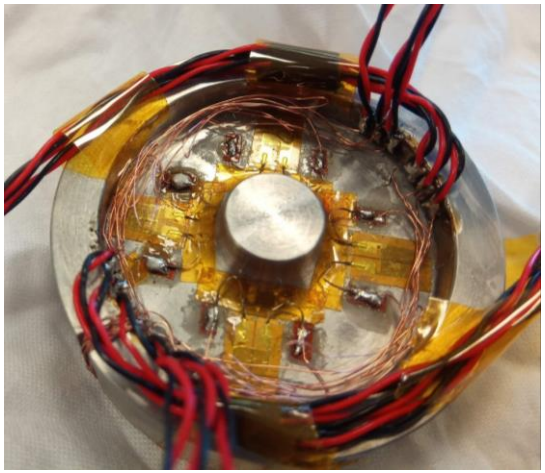



# 1. Powered samples

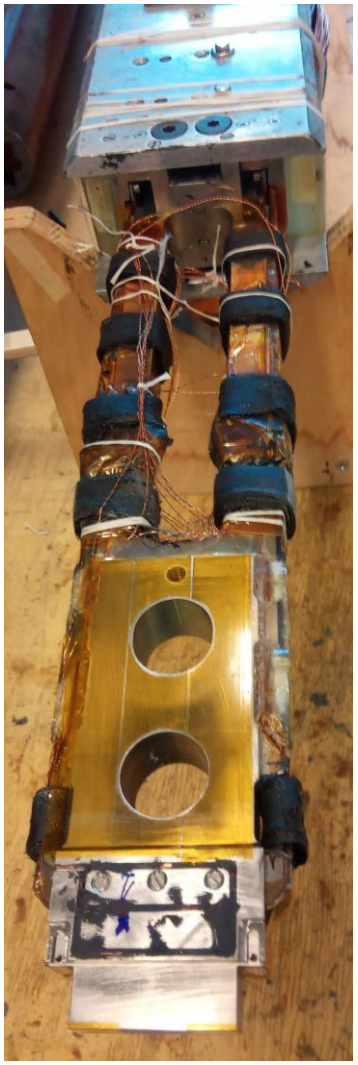
# deBOnding eXperiment n°1 - deBOX1

**PhD Thesis Guillaume Campagna**



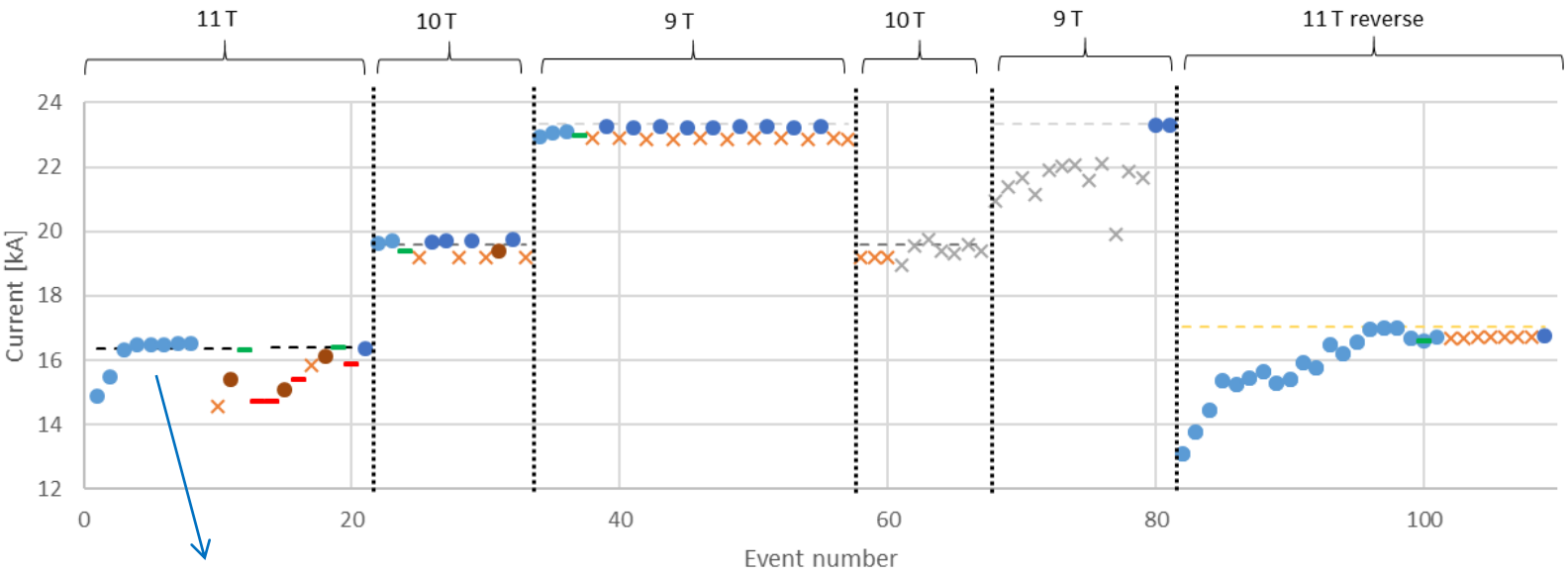


New instrumentation: two pick-up coils and a 7 kN load cell for cryogenic use



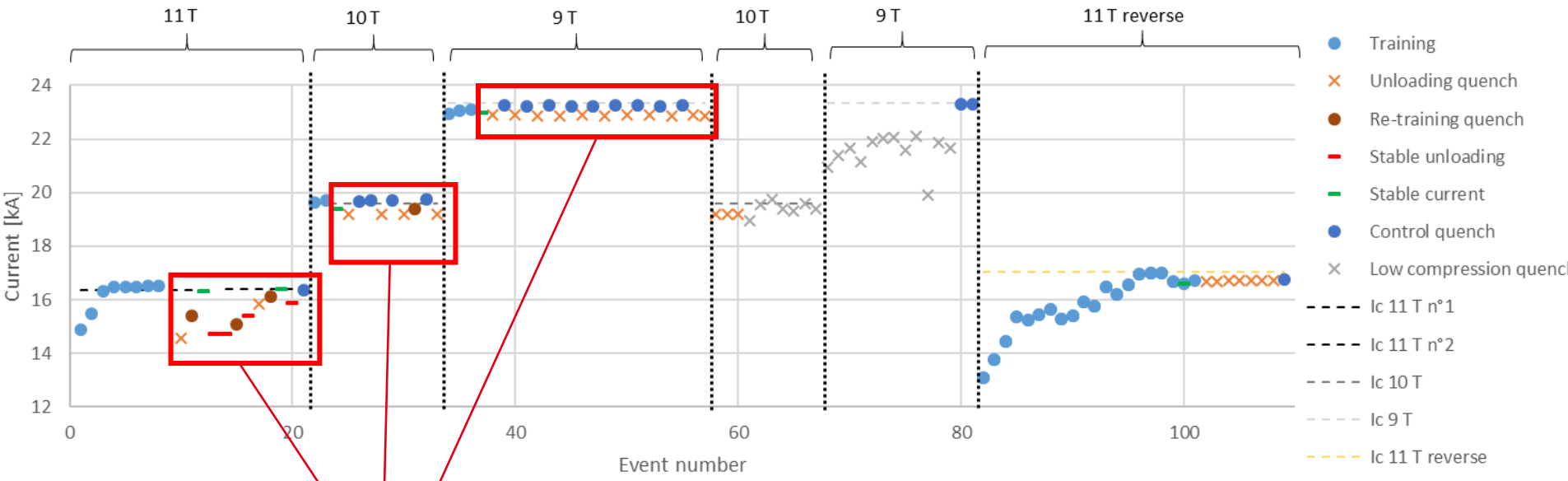
Twente sample holder : 11 T background, 100 kA transformer, up to 200 MPa compression

# deBOnding eXperiment n°1 - deBOX1



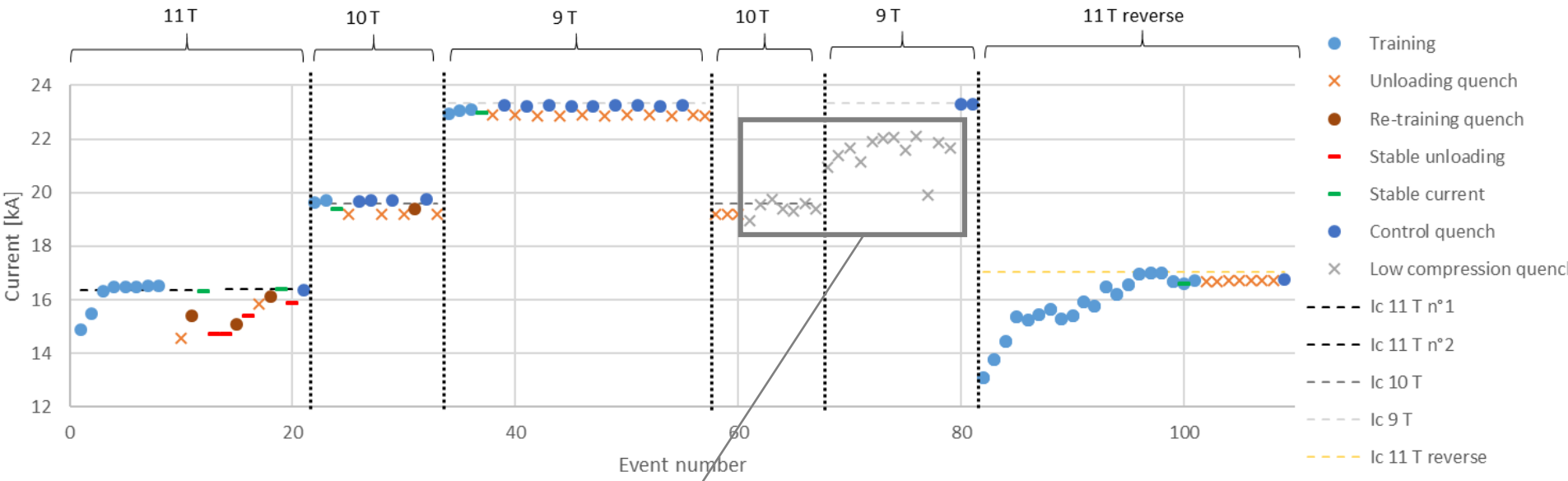

1. **Regular training** at 10 MPa → training to 100% of $I_c$

# deBOnding eXperiment n°1 - deBOX1




1. **Regular training** at 10 MPa → training to 100% of $I_c$
2. **Unloading quenches**:
   - Current maintained at 98% $I_c$
   - Pressure decreased until the cable quenches
   - "control" quench = reaches again $I_c$ (+sometimes 1 training quench)

# deBOnding eXperiment n°1 - deBOX1

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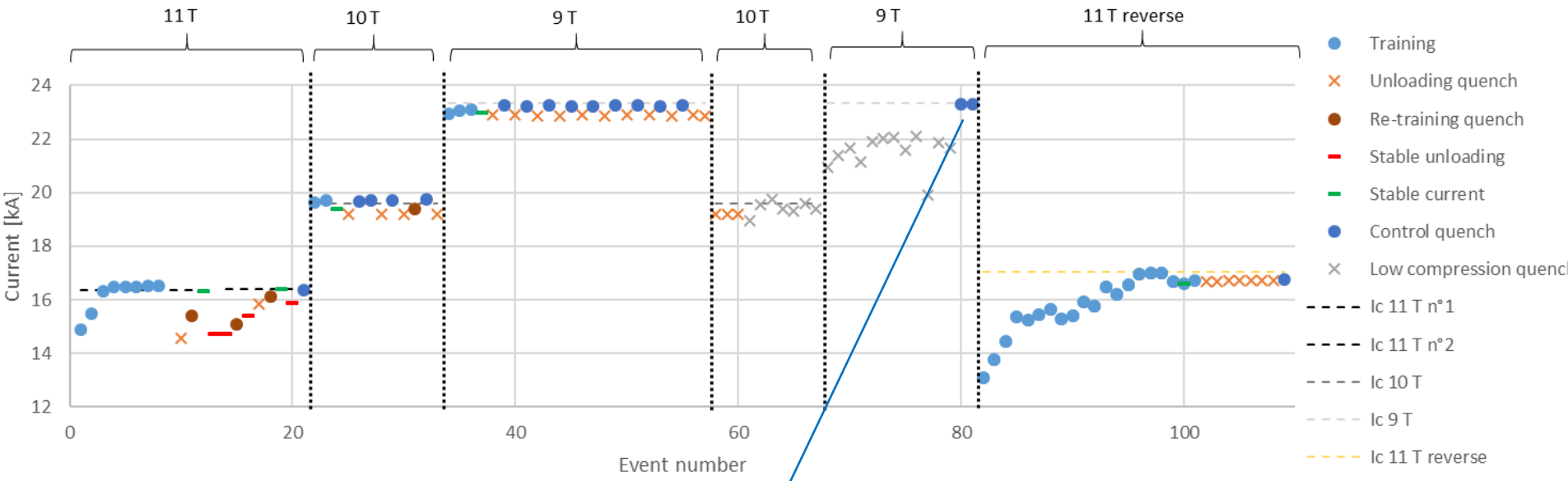
3. **Low compression quenches** at ~3 MPa
   - Long training with erratic current values.
   - Not able to reach $I_c$

# deBOnding eXperiment n°1 - deBOX1

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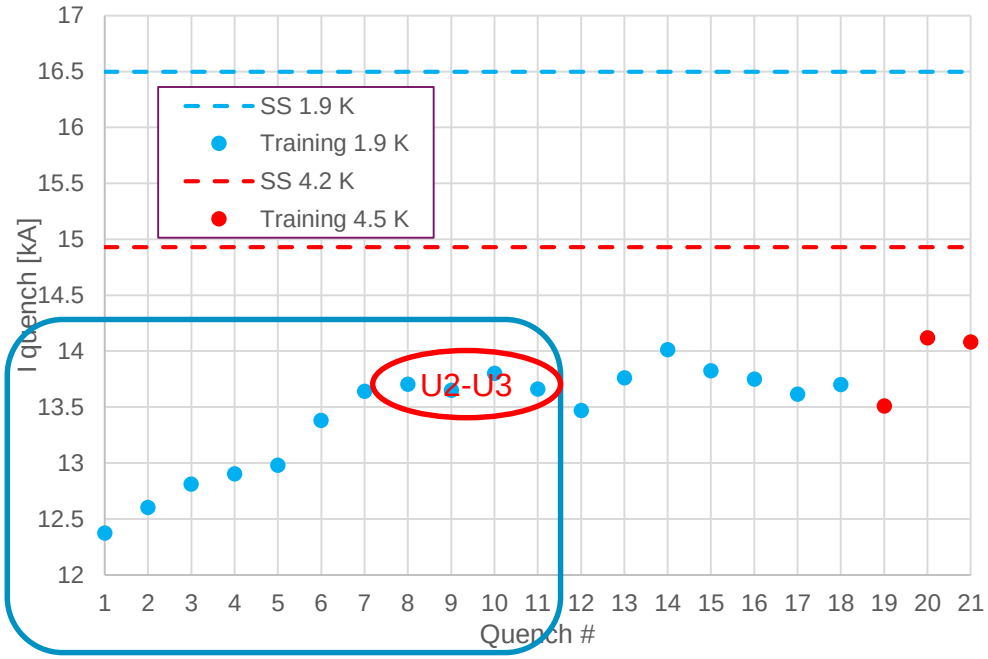
3. **Low compression quenches** at ~3 MPa
   - Long training with erratic current values.
   - Not able to reach $I_c$
4. **Recovery at 10 MPa** → perfect memory

# 2. SMC-11T

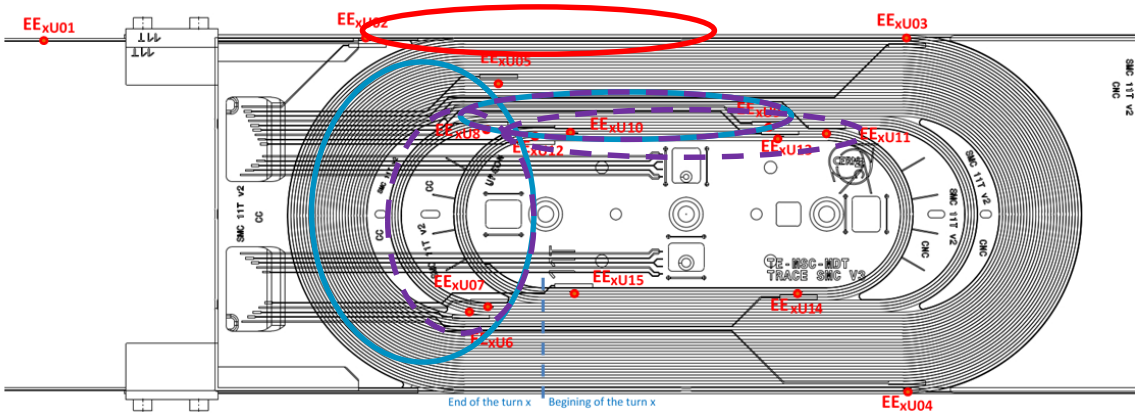
# SMC-CEA#101

- SMC-CEA #101 fabricated at Saclay in 2021
- Assembled and tested at CERN in 2022

# SMC-CEA#101 – training



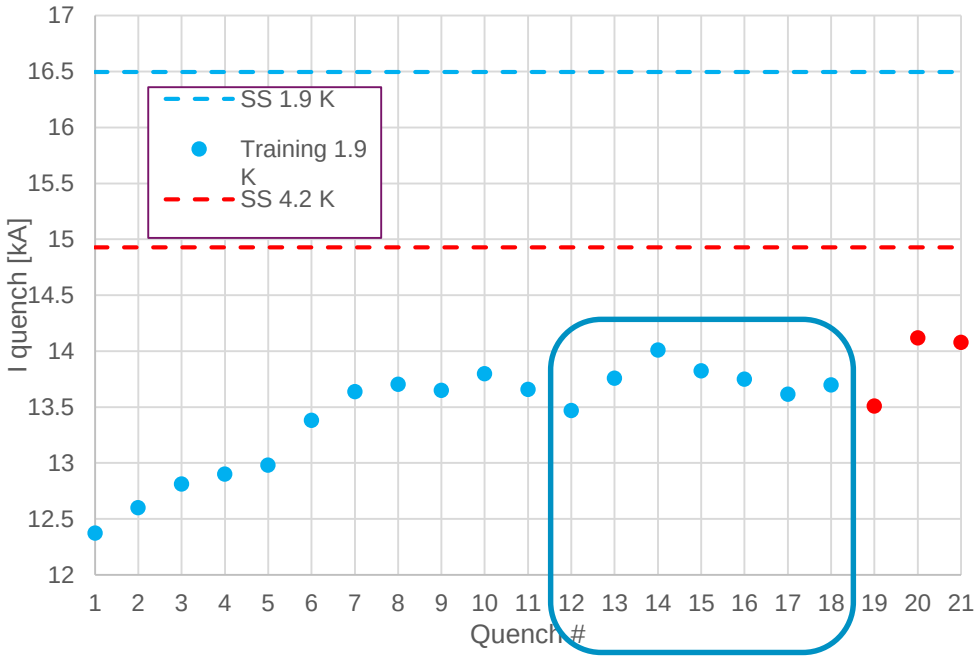

| | Bbore | Bpeak | I cable | | location |
|---|---|---|---|---|---|
| Quench | T | T | kA | %SS | |
| 1 | 7.34 | 10.98 | 12.375 | 75.0 | U5-U7 |
| 2 | 7.44 | 11.14 | 12.60 | 76.4 | L6-L7 L7-L8 |
| 3 | 7.54 | 11.29 | 12.81 | 77.7 | U7-U8 U8-U9 |
| 4 | 7.58 | 11.36 | 12.90 | 78.2 | L7-8 L8-L9 |
| 5 | 7.62 | 11.42 | 12.98 | 79 | L12-L11 |
| 6 | 7.80 | 11.71 | 13.38 | 81 | U7-U8 |
| 7 | 7.92 | 11.90 | 13.64 | 83 | U5-U7 |
| 8 | 7.95 | 11.95 | 13.71 | 83 | U2-U3 |
| 9 | 7.92 | 11.91 | 13.65 | 83 | U2-U3 |
| **10** | **7.99** | **12.01** | **13.80** | **84** | **U2-U3** |
| 11 | 7.93 | 11.91 | 13.66 | 83 | U2-U3 |



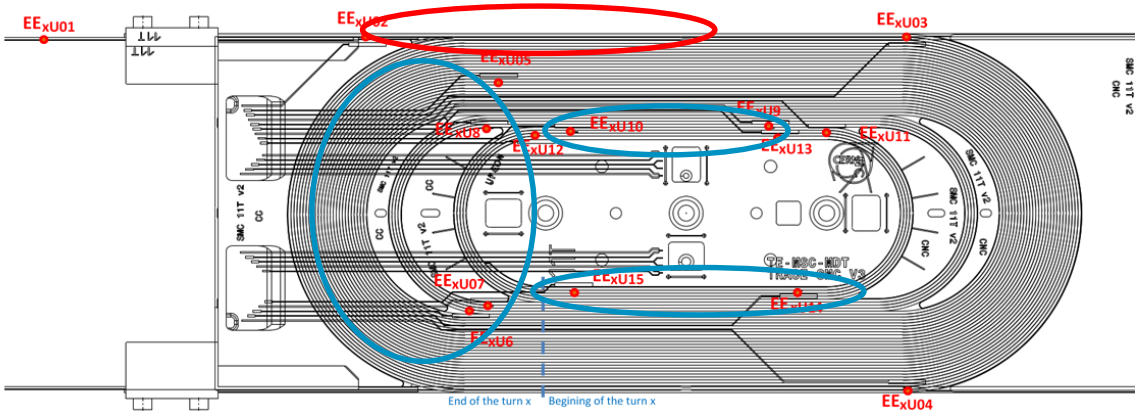

## 1. Training at 1.9 K

- Limitation at 84 % SS
- Close to ‘top’ splice
- 12 T peak on the coil

# SMC-CEA#101 – training

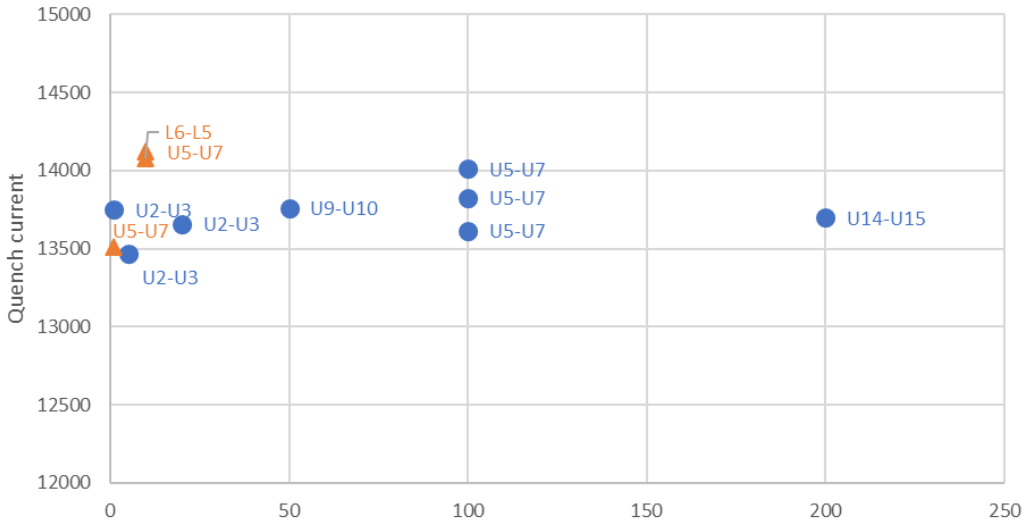



| | Ramp | Bpeak | I cable | | location |
|---|---|---|---|---|---|
| Quench | A/s | T | kA | %SS | |
| 12 | 5 | 11.77 | 13.47 | 82 | U2-U3 |
| 13 | 50 | 11.99 | 13.76 | 83 | U9-U10 |
| **14** | **100** | **12.17** | **14.01** | **85** | **U5-U7** |
| 15 | 100 | 12.03 | 13.83 | 84 | U5-U7 |
| 16 | 1 | 11.98 | 13.75 | 83 | U2-U3 |
| 17 | 100 | 11.88 | 13.62 | 83 | U5-U7 |
| 18 | 200 | 11.94 | 13.70 | 83 | U14-U15 |




## 2. Ramps at 1.9 K

# SMC-CEA#101 – training




| | Ramp | Bpeak | I cable | | location |
|---|---|---|---|---|---|
| Quench | A/s | T | kA | %SS | |
| 12 | 5 | 11.77 | 13.47 | 82 | U2-U3 |
| 13 | 50 | 11.99 | 13.76 | 83 | U9-U10 |
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| 15 | 100 | 12.03 | 13.83 | 84 | U5-U7 |
| 16 | 1 | 11.98 | 13.75 | 83 | U2-U3 |
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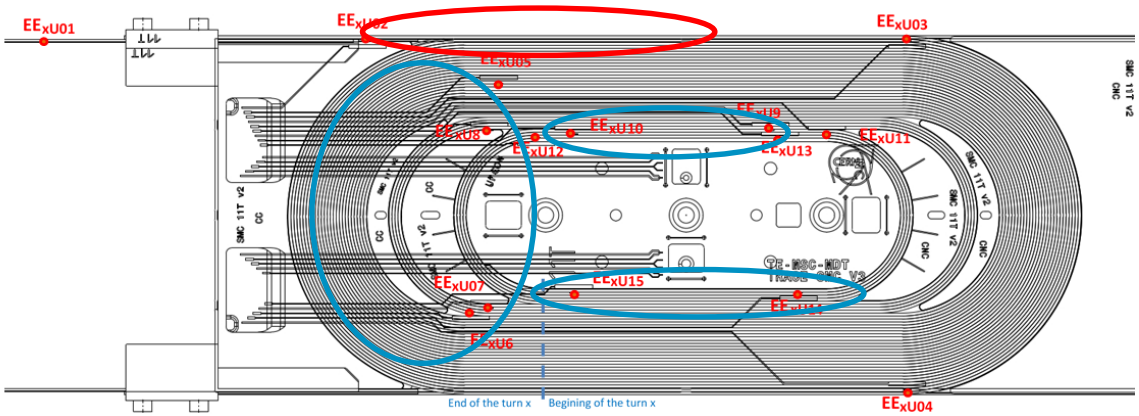
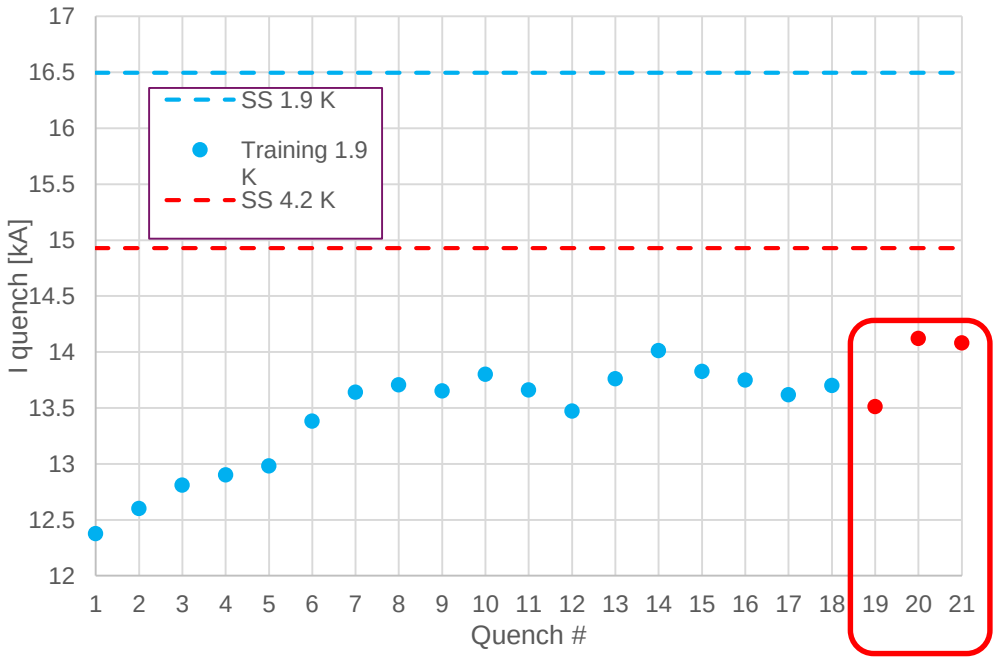


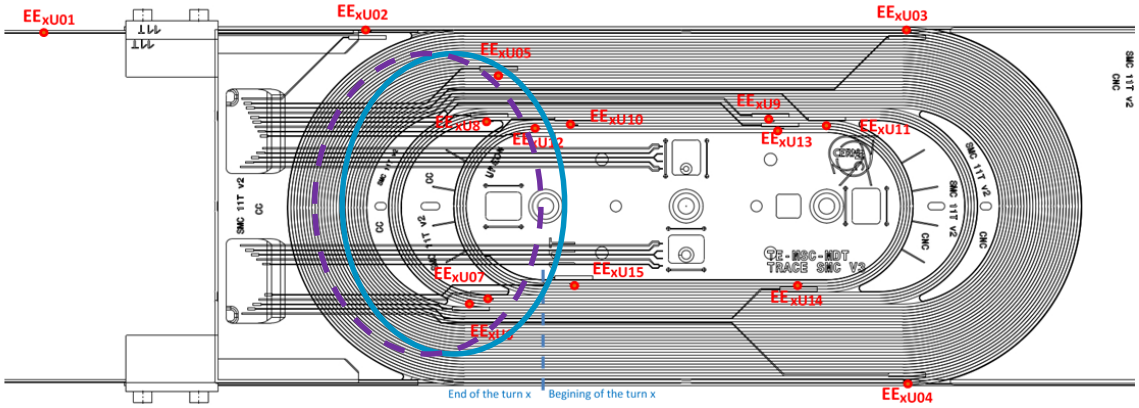

## 2. Ramps à 1.9 K

- Fast ramps allows « bypassing » the limiting zone U2-U3
- 85 % SS at max

# SMC-CEA#101 – training




| | Bbore | Bpeak | I cable | | location |
|---|---|---|---|---|---|
| Quench | T | T | kA | %SS | |
| 19 | 7.86 | 11.80 | 13.51 | 90 | U5-U7 |
| **20** | **8.13** | **12.25** | **14.12** | **95** | **U5-U7** |
| 21 | 8.12 | 12.22 | 14.08 | 94 | L6-L5 |



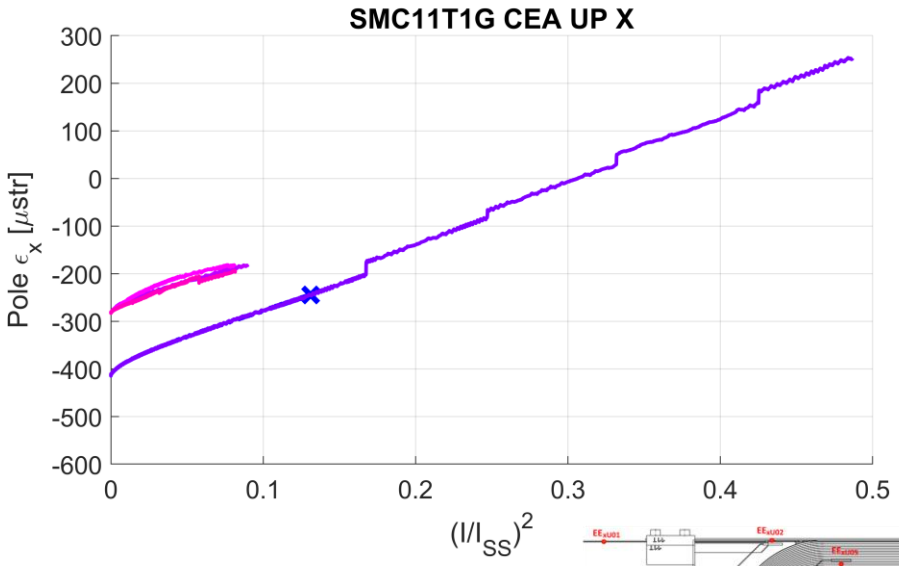

## 3. Training et 4.5 K

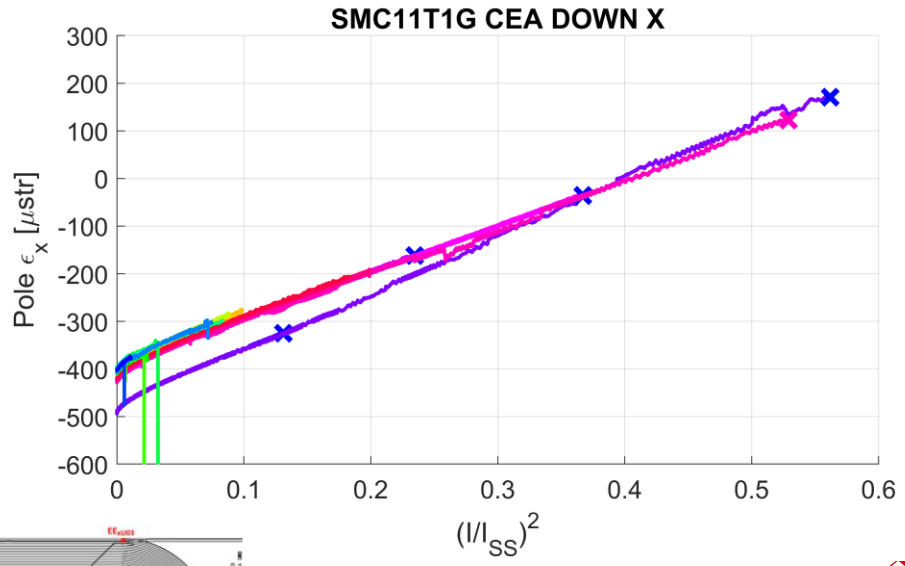
- No limiting zone
- **95 % SS !**
- Unfinished training?
  Test station unavailable

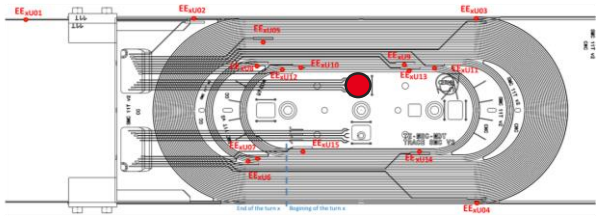
# SMC-CEA#101 – training

Other observations:

- No VI increase observed = no $I_c$ degradation
- Joint resistances <0.25 nΩ at 12 kA
- Linear stress on the pole, no observable detachment



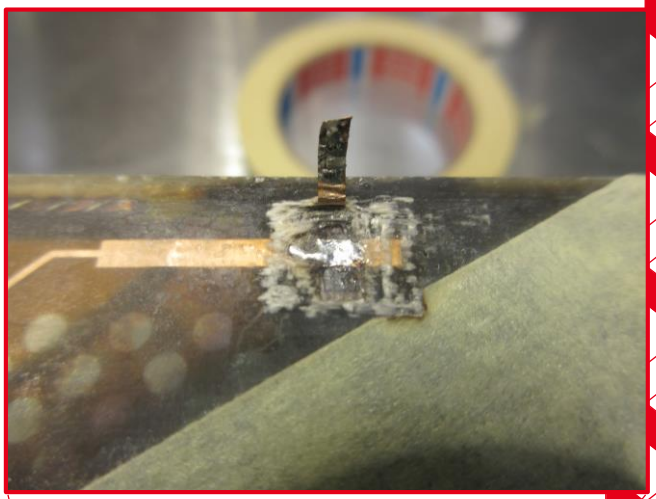



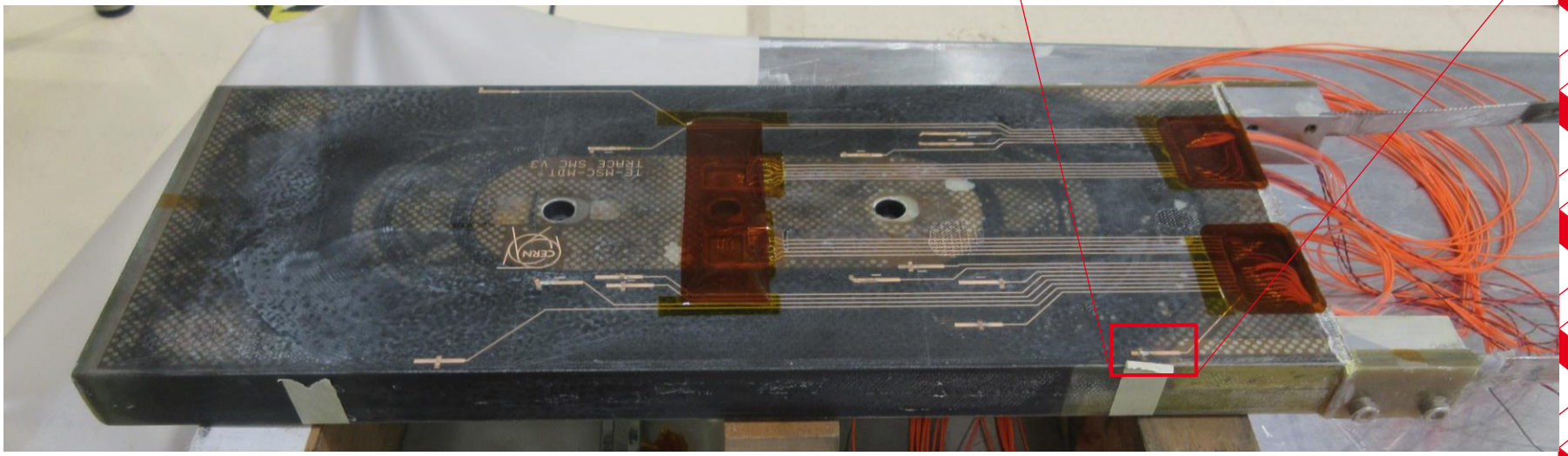
# SMC-CEA#102

- Introduction of the CTD flexibilizer
- **2 shortcuts detected after impregnation**

→ **repaired, electrical tests passed !**

- Fabrication finalized April 2024
- Coil delivered to CERN in may
- Assembly in the structure foreseen in the coming weeks

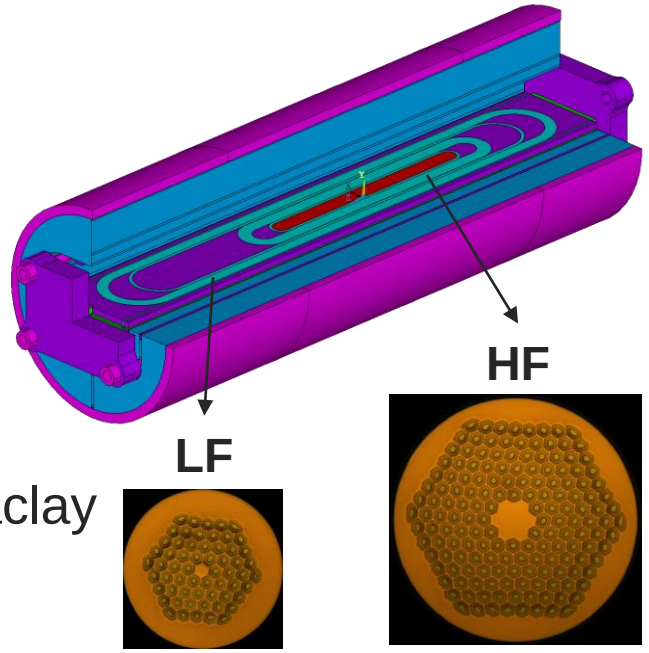




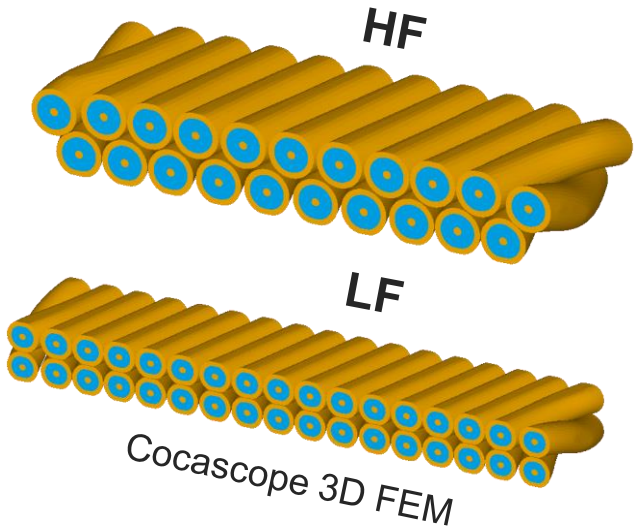
# 3. R2D2

# Conductor production and qualification

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



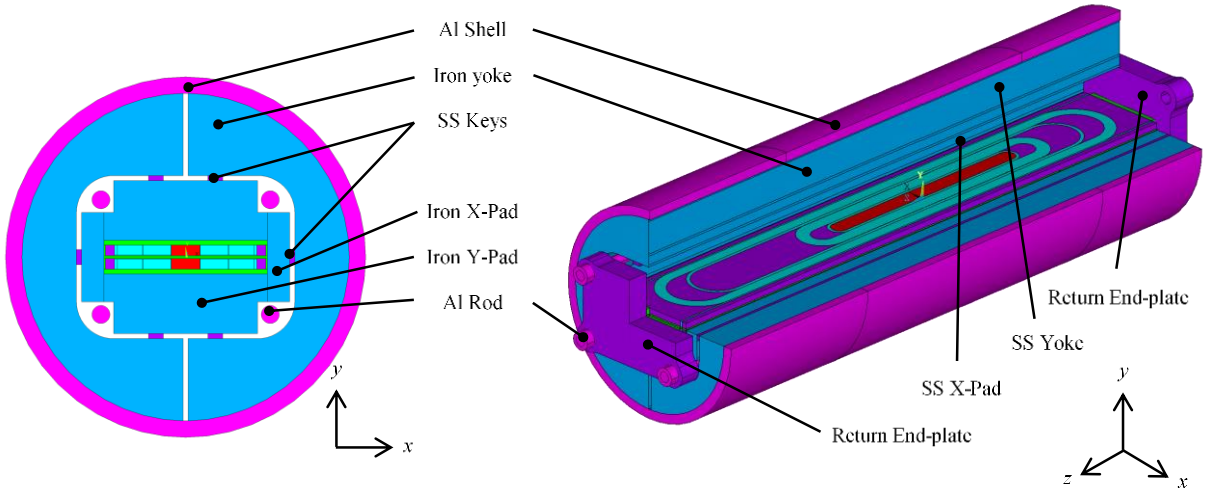

| Parameter | Unit | HF cable | LF cable |
|---|---|---|---|
| Strand type | | DEM-1.1 | DEM-0.7 |
| Strand layout | | RRP® 162/169 | RRP® 60/91 |
| Strand diameter | mm | 1.1 | 0.7 |
| Number of strands | | 21 | 34 |
| Cable mid-thickness | mm | 1.969 ± 0.010 | 1.253 ± 0.010 |
| Cable width | mm | 12.579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



# Overview of the R2D2 design

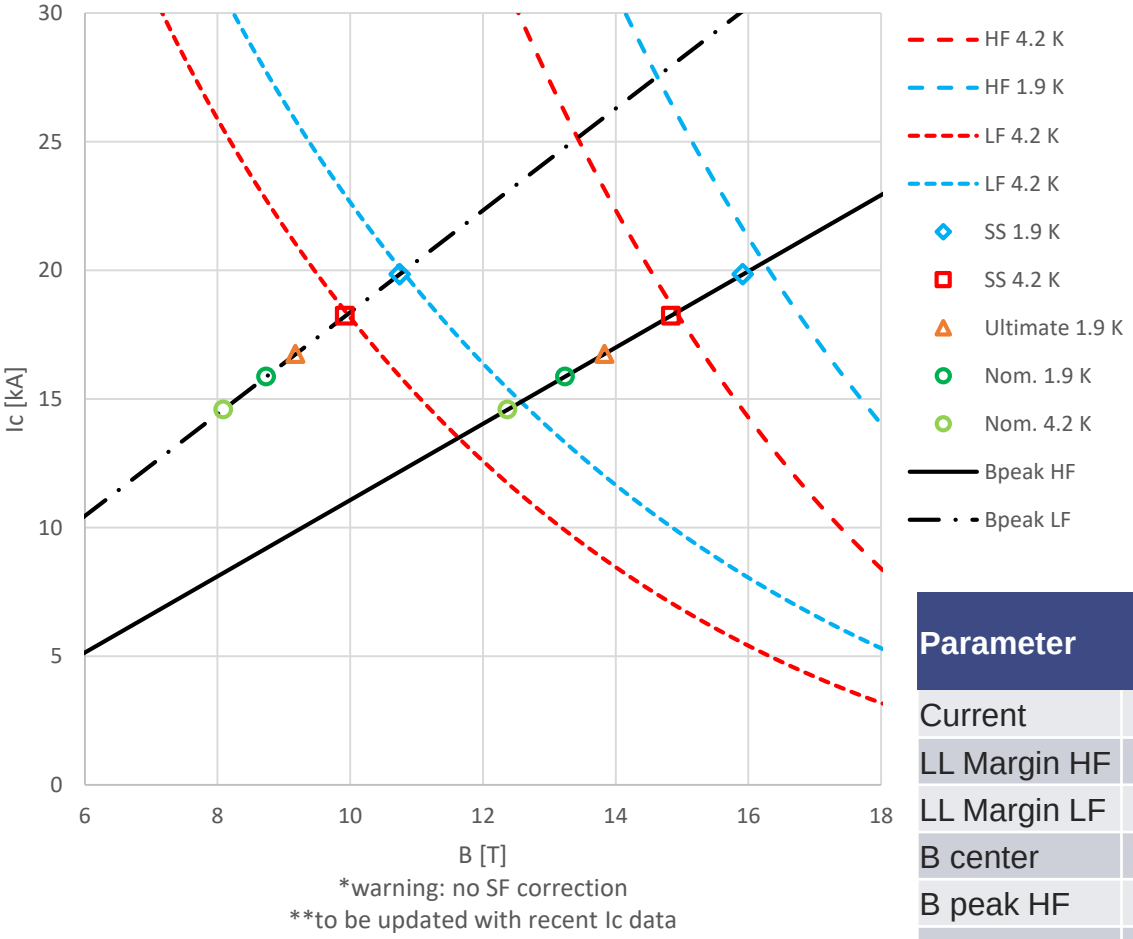
- CEA conceptual design validated by an external committee
- Fabrication, assembly and pre-stress at Saclay
- Tests at cold at CERN
- **Main goal: demonstrate feasibility of grading**
  - Winding two cables on top of each other
  - Heat treating two different cables together
  - Jonctions of the 2 cables → 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 | 11.1 T |
| Ultimate central field | 12.0 T |
| Nominal peak field | 12.7 T |
| Ultimate peak field | 13.7 T |

# Overview of the R2D2 design



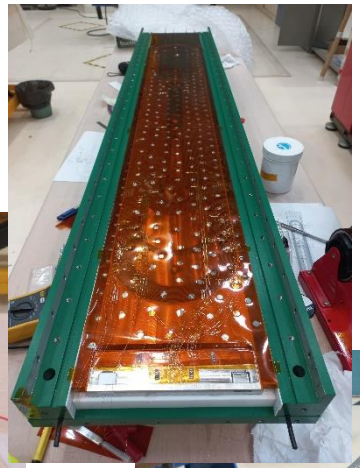

*warning: no SF correction

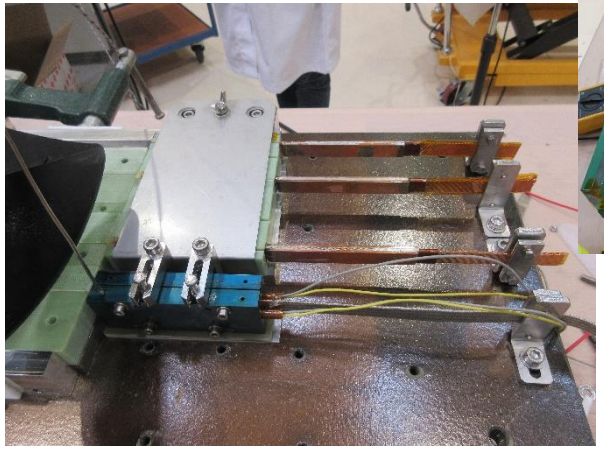
**to be updated with recent Ic data

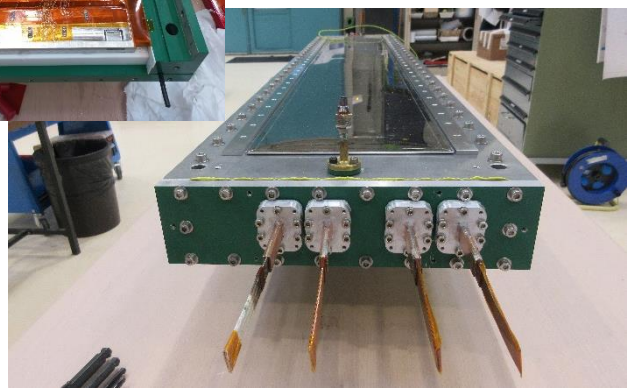
| Parameter | Nom. 4.2 K | Nom. 1.9 K | Ultimate 1.9 K | SS 4.2 K | SS 1.9 K | Unit |
|---|---|---|---|---|---|---|
| Current | 14.6 | 15.9 | **16.8** | 18.2 | 19.8 | kA |
| LL Margin HF | 20.5 | 21.9 | **17.5** | 0.7 | 2.3 | % |
| LL Margin LF | 20.3 | 20.4 | **16.0** | 0.3 | 0.5 | |
| B center | 10.89 | 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 |
| Hotspot HF | 91 | 152 | **189** | 255 | 1058 | K |
| Hotspot LF | 132 | 264 | **351** | 506 | 1333 | |
| J block HF | 474.0 | 515.8 | **544.3** | 592.5 | 644.8 | |
| J block LF | 694.9 | 756.1 | **797.8** | 868.6 | 945.1 | |

# R2D2 Cu prototype coil fabrication

- ✓ Winding / heat treatment
- ✓ Junctions and operations pre-impregnation
- ✓ Impregnation
- ✓ Operations post-impregnation
- ✓ Qualification tests







# Fabrication of R2D2 $Nb_3Sn$ coil CR01

- ✓ Winding
- ✓ Heat treatment
- ➢ Junctions ongoing
- ➢ Impregnation for mid-June
- ➢ Operations post-impregnation for end of June
- ➢ Qualification tests for July

- ➢ Start of CR02 for July

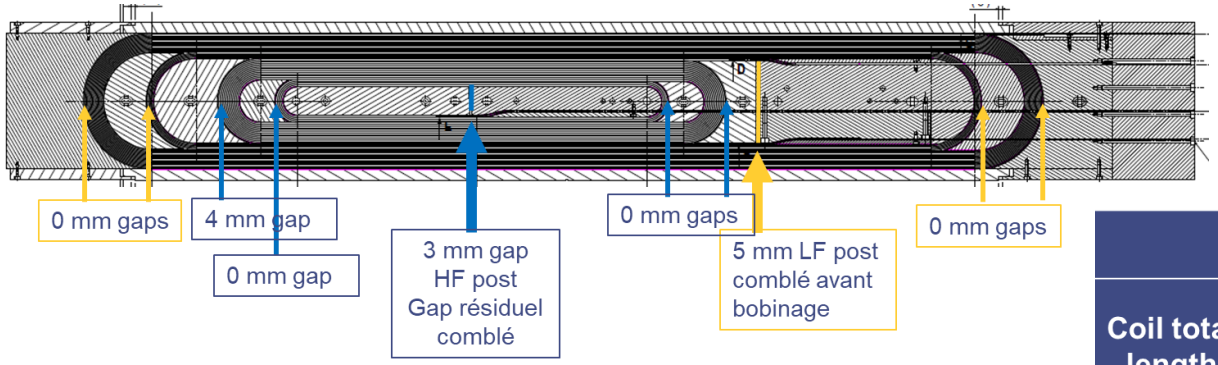


# Dimensional changes during Heat Treatment

- Measurements on short coils :

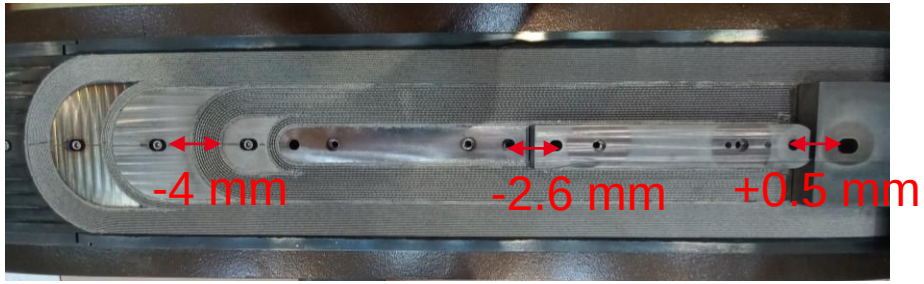
| | Short coils | |
|---|---|---|
| | Length variation /$L_0$ (mm) | Central gap variation /M1 (mm) |
| HF coil | -0.06% | -0.35% |
| LF coil | -0.34% | -0.55% |

- Extrapolation on CR01:



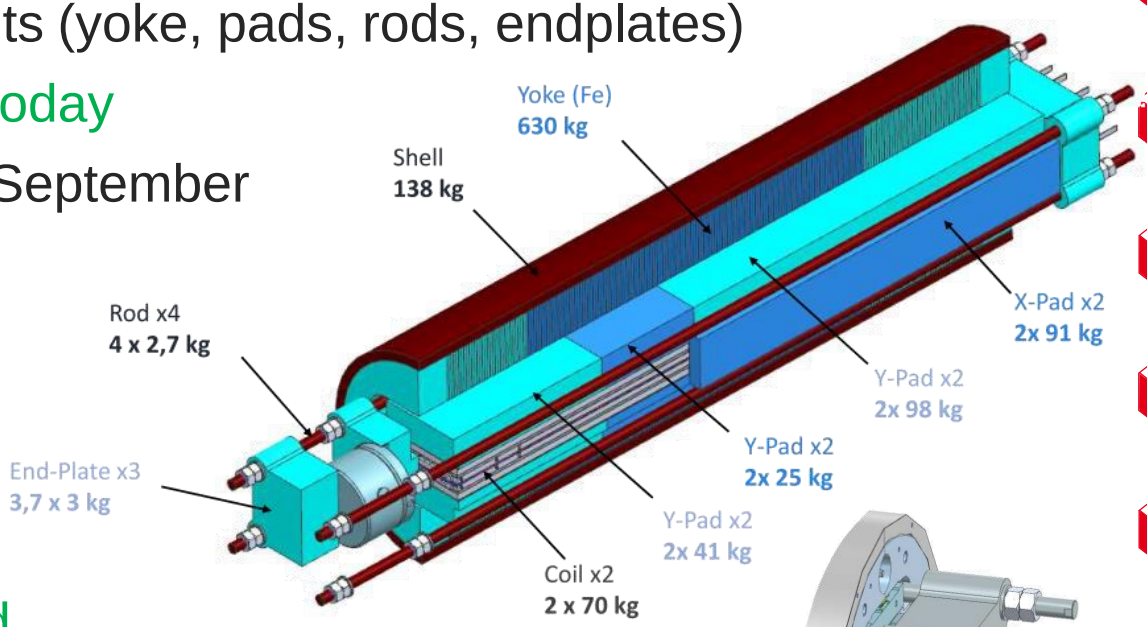

| R2D2 coils | | | |
|---|---|---|---|
| Coil total length (mm) | Mandrel length (mm) | Expected Coil lenght variation (mm) | Expected Central gap variation (mm) |
| 688 | 631 | -0.39 | -2.19 |
| 1300 | 1250 | -4.36 | -6.81 |

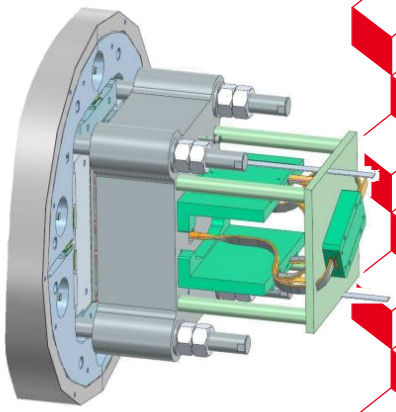
- Preliminary measurements on CR01:



# R2D2 structure procurement

- ✓ Shell segments received at CERN
- Structure components (yoke, pads, rods, endplates)
  - ➢ opening of the bids today
  - ➢ Delivery expected ~September



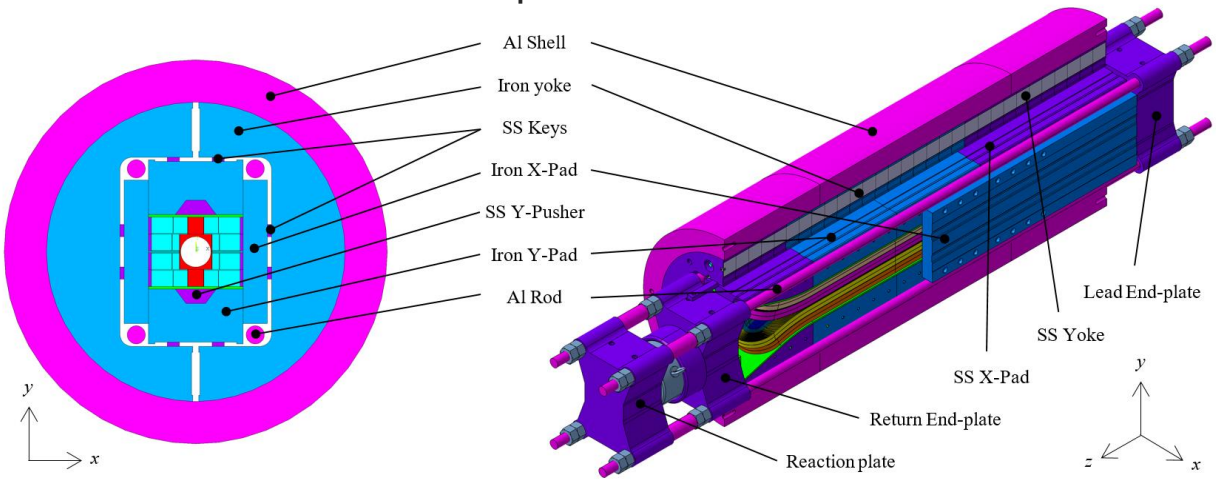
- Connection box:
  - ✓ 3D design finalized
  - ➢ To be validated with a mockup
- Magnet schedule :
  - ➢ Dummy assembly at Saclay to validate the mechanical behavior of the structure → Q4 2024
  - ➢ Selection of the 2 best coils for assembly → Q1 2025
  - ➢ Delivery at CERN for cold tests → mid-2025

# 4. FD/F2D2

# F2D2 16T demonstrator magnet

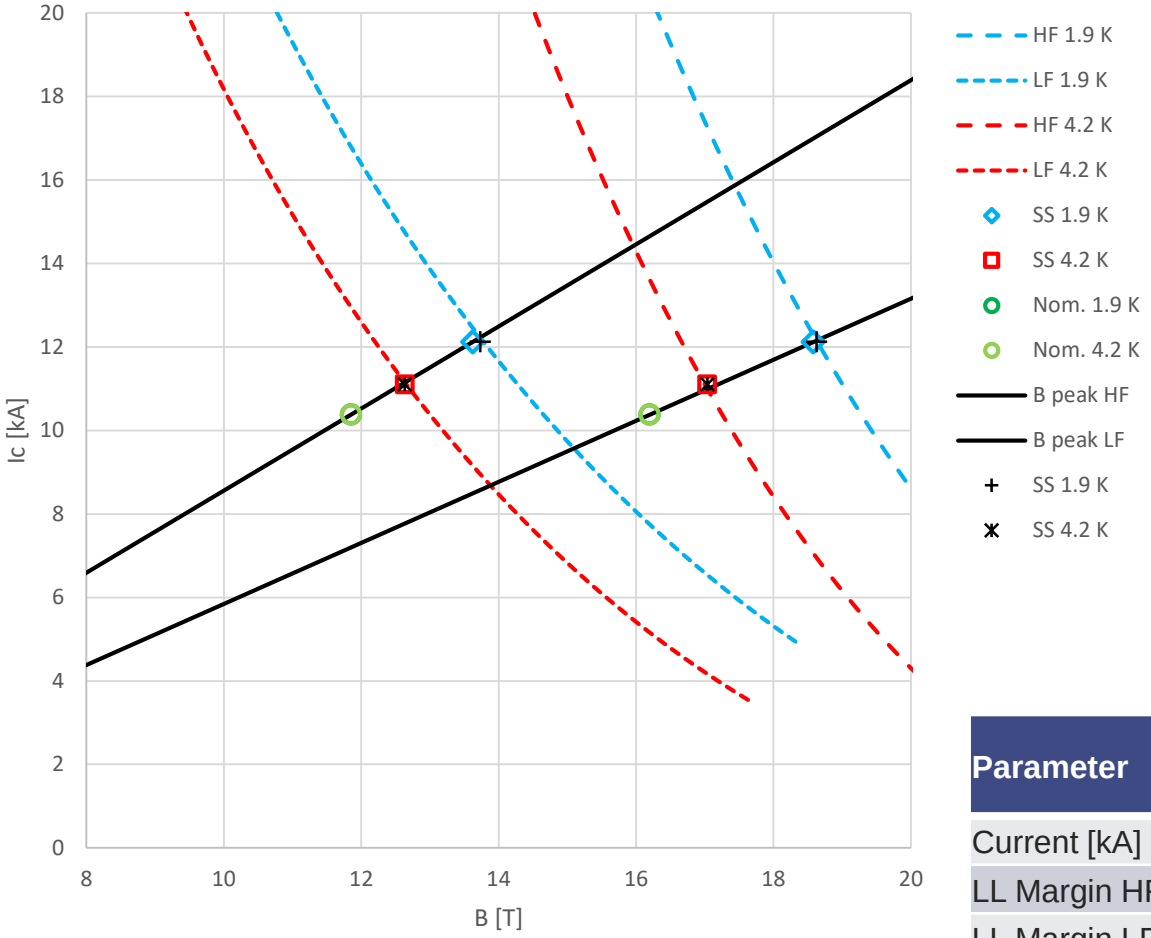
- **Conceptual design stage**
- Fabrication, assembly and pre-stress at Saclay
- Tests at cold at CERN
- **Main goal: demonstrate all technologies**
  - Representative of high field magnets: grading, joints, flared-ends, high field and high stress
  - Representative of accelerator magnets: 50 mm bore,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

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




| | |
|---|---|
| Aperture | 50 mm |
| Outer diameter | 650 mm |
| Structure length | 2.0 m |
| Nominal central field | 15.5 T |
| SS central field | 17.8 T |
| Nominal peak field | 16.2 T |
| SS peak field | 18.6 T |

# F2D2 16T demonstrator magnet

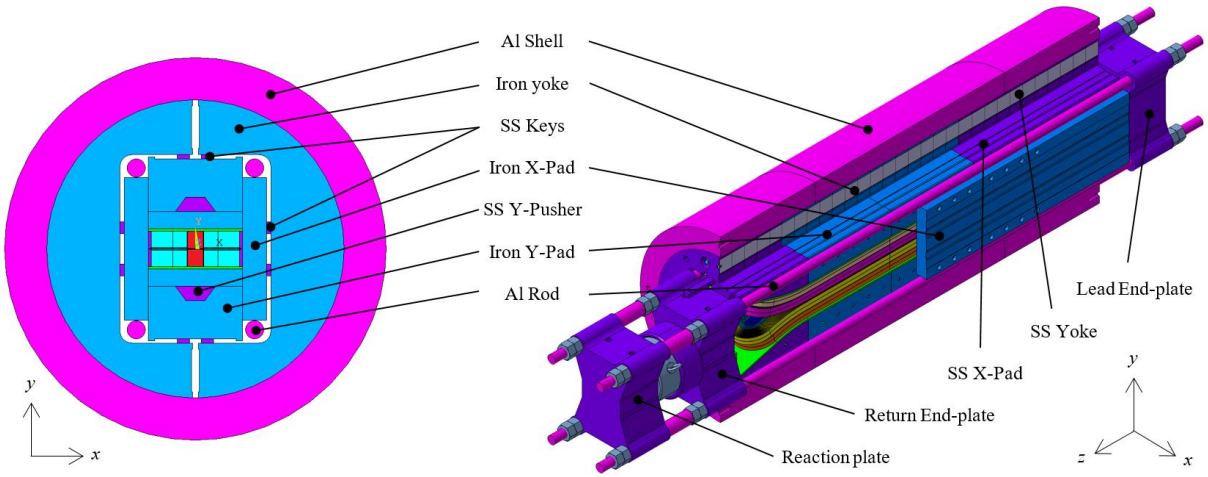



| Parameter | Nom. 4.2 K | Nom. **1.9 K** | SS 4.2 K | SS 1.9 K | Unit |
|---|---|---|---|---|---|
| Current [kA] | 10.4 | **10.4** | 11.1 | 12.1 | kA |
| LL Margin HF | 5.6 | **14.6** | -1.0 | 0.3 | % |
| LL Margin LF | 6.9 | **15.1** | 0.4 | 0.9 | |
| B center | 15.54 | **15.54** | 16.48 | 17.81 | T |
| B peak HF | 16.20 | **16.20** | 17.04 | 18.58 | T |
| B peak LF | 11.85 | **11.85** | 12.63 | 13.62 | T |
| J block HF | 337.2 | **337.2** | 360.7 | 393.8 | |
| J block LF | 494.3 | **494.3** | 528.7 | 577.2 | |

# FD 14T demonstrator magnet

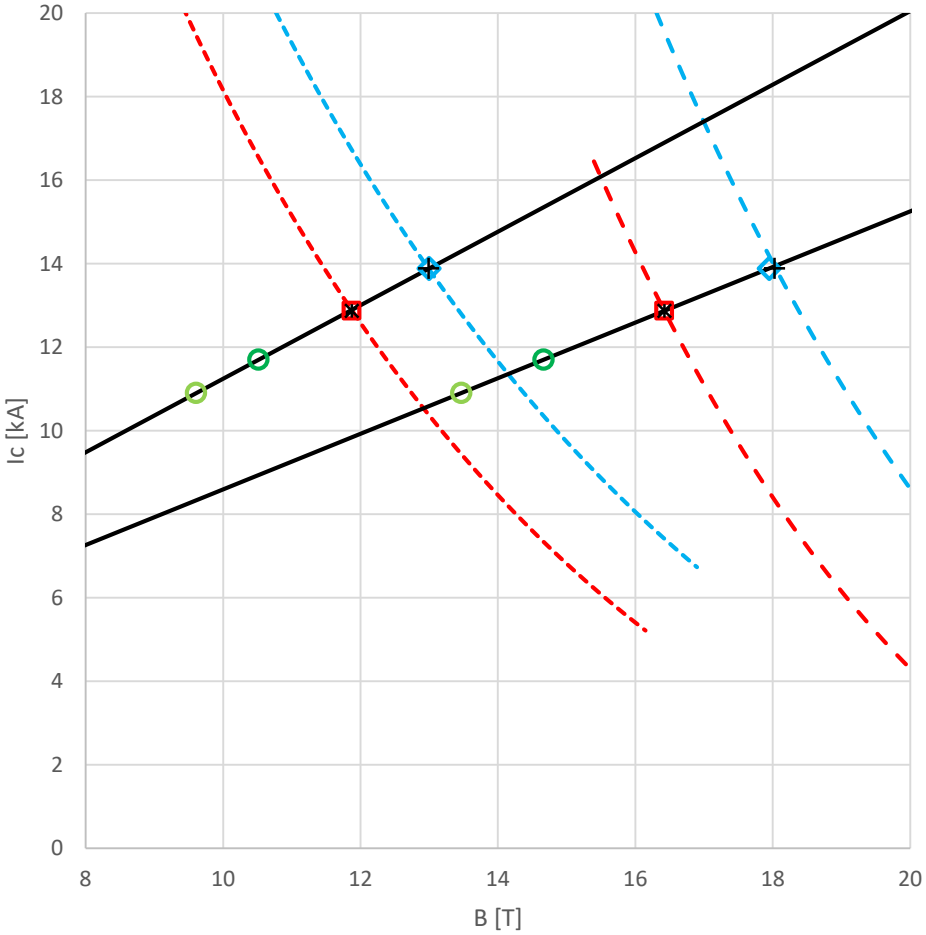
- **Conceptual design stage**
- Fabrication, assembly and pre-stress at Saclay
- Tests at cold at CERN
- **Main goal: demonstrate key technologies**
  - Representative of high field magnets: grading, joints, flared-ends, high field and high stress
  - Some simplifications: 1 type of coils, no bore

**FD** = **F**lared **D**ipole




| | |
|---|---|
| Aperture | None |
| Outer diameter | 650 mm |
| Structure length | 2.0 m |
| Nominal central field | 14.0 T |
| SS central field | 17.2 T |
| Nominal peak field | 14.7 T |
| SS peak field | 17.9 T |

# FD 14T demonstrator magnet




| Parameter | Nom. 4.2 K | Nom. **1.9 K** | SS 4.2 K | SS 1.9 K | Unit |
|---|---|---|---|---|---|
| Current [kA] | 10.9 | **11.7** | 12.9 | 13.9 | kA |
| LL Margin HF | 15.3 | **16.1** | 0.0 | 0.4 | % |
| LL Margin LF | 15.5 | **15.7** | 0.2 | 0.0 | |
| B center | 12.89 | **14.04** | 15.72 | 17.18 | T |
| B peak HF | 13.47 | **14.67** | 16.42 | 17.95 | T |
| B peak LF | 9.61 | **10.52** | 11.87 | 13.00 | T |
| J block | 354.2 | **380.2** | 418.2 | 451.2 | |
| | 519.2 | **557.3** | 613.0 | 661.4 | |

# Future steps after R2D2: FD and F2D2

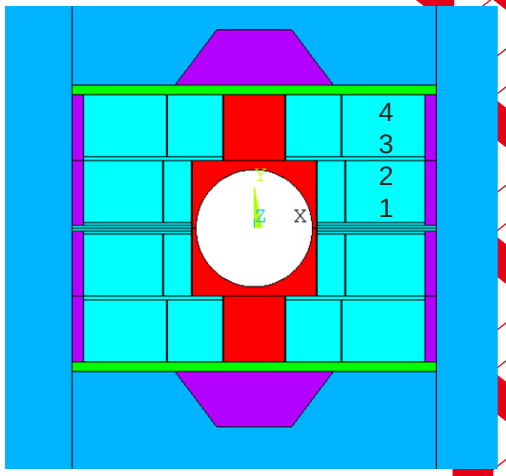
1. In parallel of the fabrication of R2D2:

→ detailed design of F2D2

- **FD magnet = intermediate assembly of F2D2**
  - Same F2D2 structure
  - Only 1 type of coil (layers 3-4)
  - Flared-ends, but no bore

  → validation of the grading with flared-ends
  - Faster design and turnover compared to F2D2

  (1 type of coil and tooling)




2. If R2D2 test is validated:

→ fabrication of coils 3-4 for assembly in FD

3. In parallel → finalization of detailed design of coils 1-2 (aperture)
4. If FD test is validated:

→ fabrication of coils 1-2 for assembly in F2D2


**Merci !**
**Thank you !**

# Backup slides