



# The Grenoble Hybrid Magnet reached 42 T as a 1<sup>st</sup> Step

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# Outline

- Introduction
- Key Points of the Design
- Construction & Integration
- Commissioning Tests
  - Superconducting alone
  - Hybrid modes up to 42 T
- Summary & Next Steps

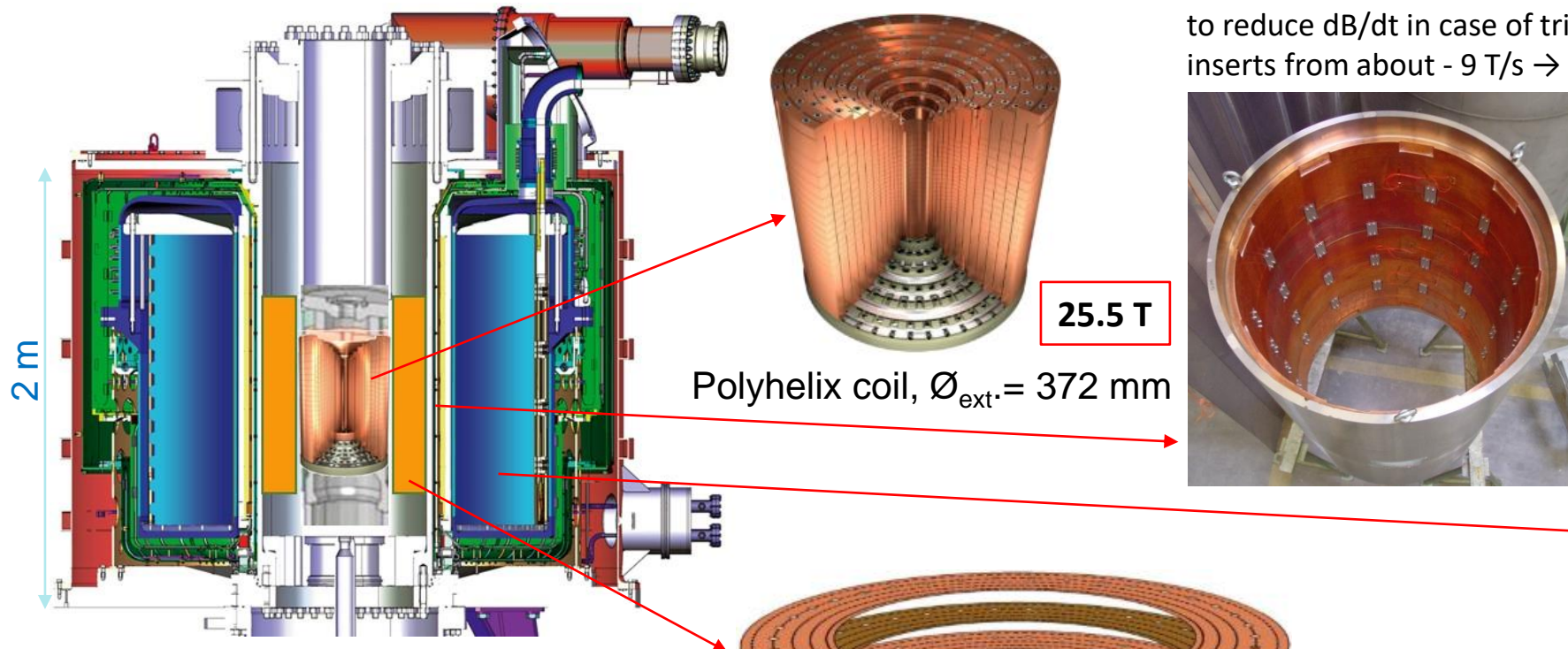


43+T Hybrid magnet: 53 tons  
Cold mass @ 1.8 K: 24 tons

# Resistive & Superconducting Coils separated by EC shield

Resistive Bitter & Polyhelix inserts (CuAg<sub>5%</sub>) designed for 12 + 12 MW

► Upgrade to 12 + 18 MW for Phase-2

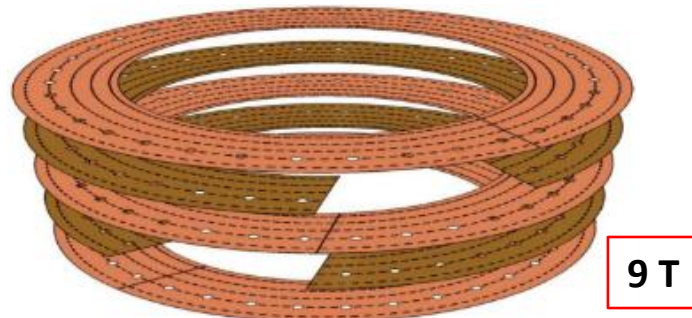


**Stainless Steel re-inforced Cu shield** at T= 50 K  
to reduce dB/dt in case of trip of resistive inserts from about - 9 T/s → - 0.5 T/s

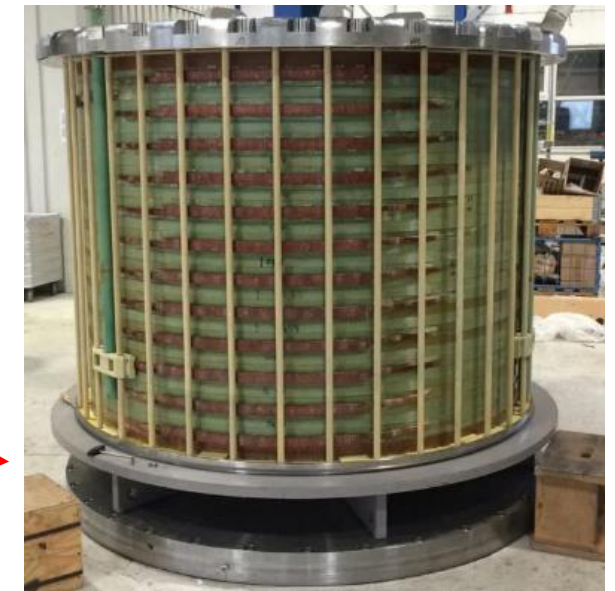


**25.5 T**  
Polyhelix coil,  $\varnothing_{\text{ext.}} = 372 \text{ mm}$

**43 T /  $\phi = 34 \text{ mm}$**



**9 T**  
Bitter coils (x2),  $\varnothing_{\text{ext.}} = 750 \text{ mm}$



Superconducting coil made of 37 double-pancakes connected in series  
 $\varnothing_{\text{int./ext.}} = 1100/1868 \text{ mm}$

**8.5 T**

Technologies : SC Nb-Ti/Cu & superfluide He

Hydraulic : 2 x 150 l/s

Stored Energy @ 43 T : 108 MJ

~ 26 kg de TNT

# Key Technologies for the Superconducting Outsert

## Nb-Ti/Cu Rutherford Cable On Conduit Conductor (RCOCC) specially developed with in-house assembly

- Internal cooling with stagnant superfluid He connected to the external bath
- Strict control of AC-losses

P. Pugat, R. Pfister, et al., *IEEE Trans. Appl. Supercond.* 28, 4301005 (2018)  
<https://indico.cern.ch/event/659554/contributions/2714073/>  
<https://indico.cern.ch/event/445667/contributions/2562521/>

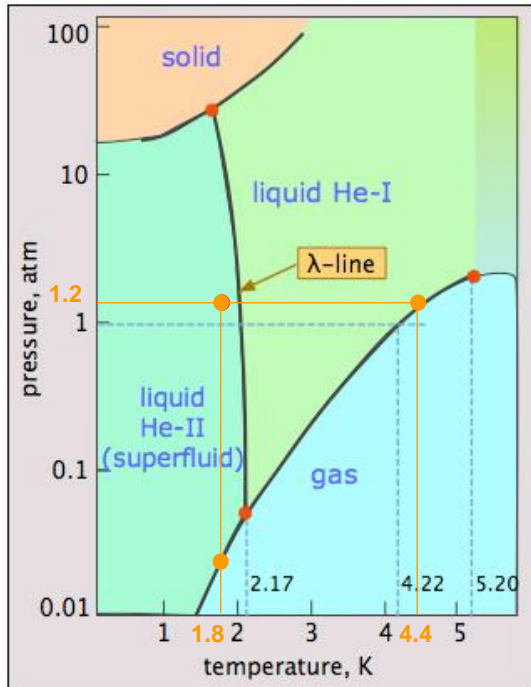


18 x 13 mm<sup>2</sup>



LNCMI

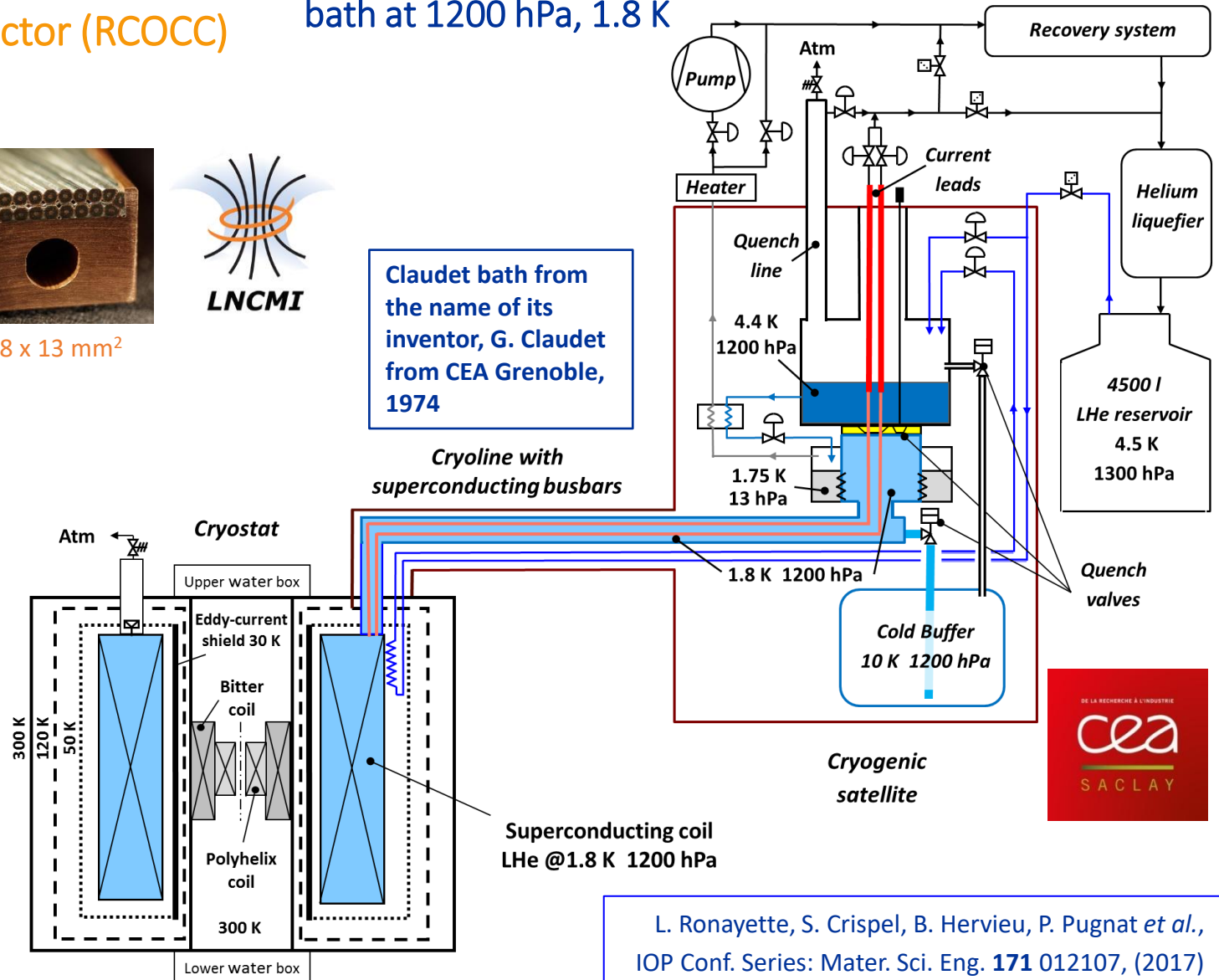
The cryogenic system principle: Pressurized superfluid He bath at 1200 hPa, 1.8 K



Superfluid pressurized LHe bath @ 1200 hPa, 1.8 K

Cooling of the sc. coil with  
 - 1420 l/60 l of pressurize/pumped superfluid He  
 - 155 LHe @4.4 K

Claudet bath from the name of its inventor, G. Claudet from CEA Grenoble, 1974



Superconducting coil LHe @1.8 K 1200 hPa

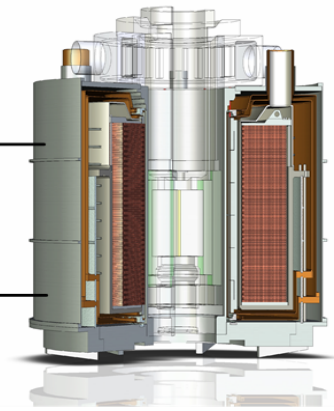
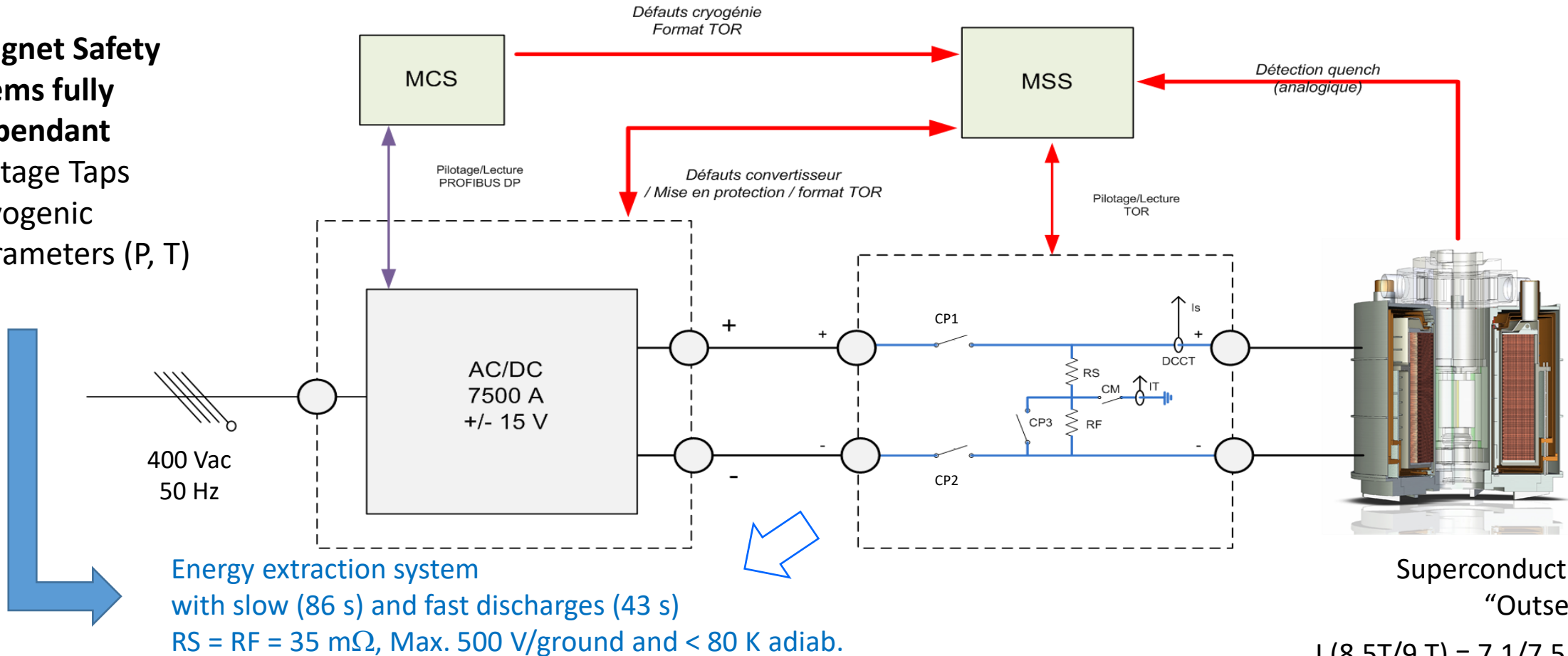
L. Ronayette, S. Crispel, B. Hervieu, P. Pugat et al., *IOP Conf. Series: Mater. Sci. Eng.* 171 012107, (2017)



# Magnet Control & Protection Systems

## 2 Magnet Safety Systems fully independant

- Voltage Taps
- Cryogenic parameters (P, T)



Superconducting "Outsert"

$I (8.5T/9 T) = 7.1/7.5 \text{ kA}$   
 Stored Energy = 76/84 MJ  
 $L = 3.03 \text{ H}$

### The rules

- Fast discharge (43 s) to lower maximum temperature increase in case of magnet quench
- Slow discharge (86 s) to reduce the mechanical force inside the magnet during insert trips with AC loss mitigation

# Electrical Power Circuits

Upgrade in 2024



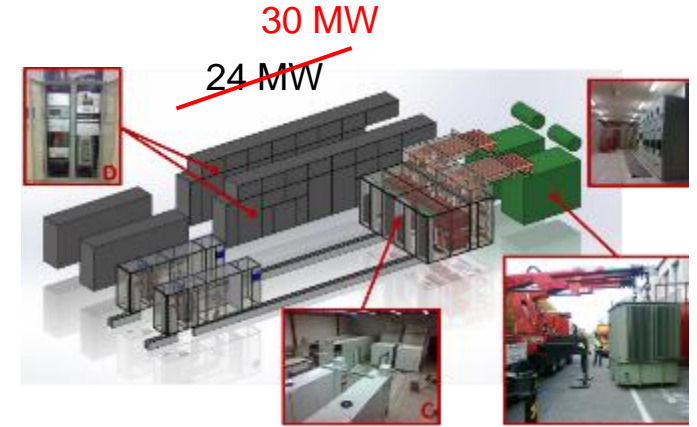
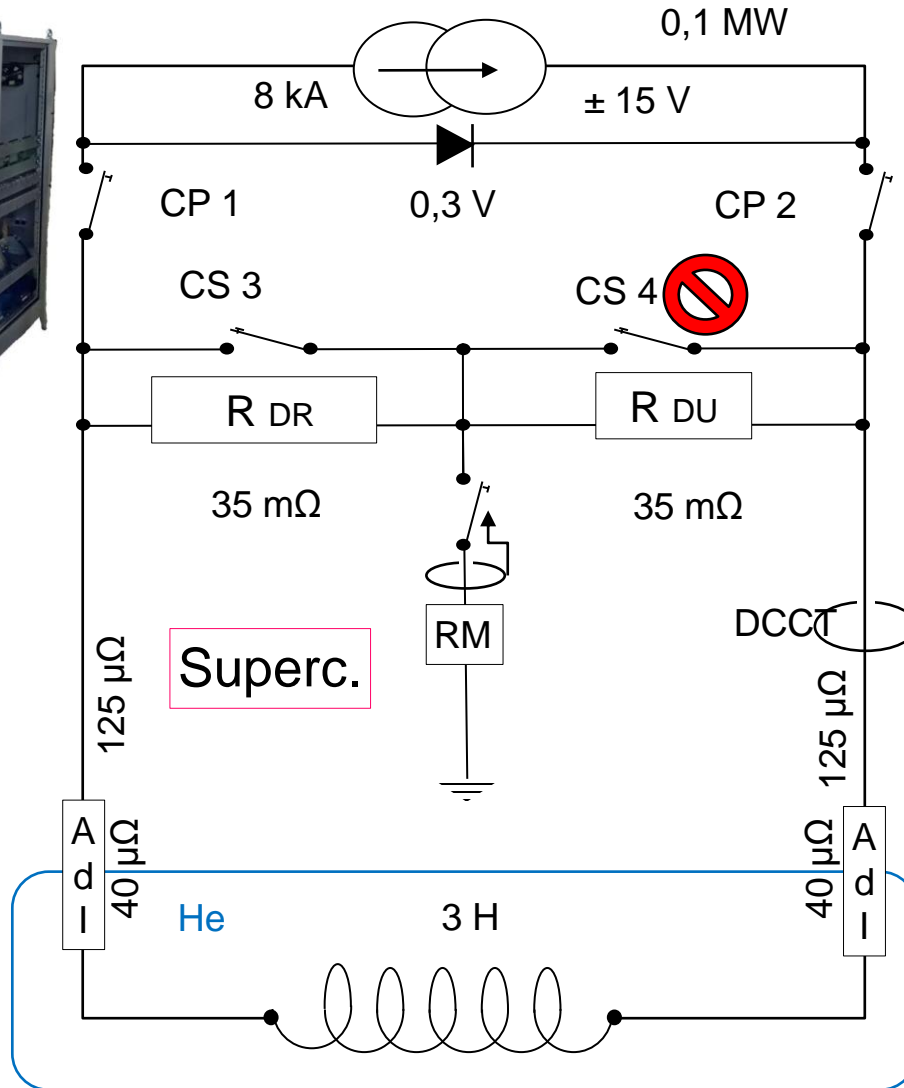
8 kA For Superc.



$R_{DR} + R_{DU}$

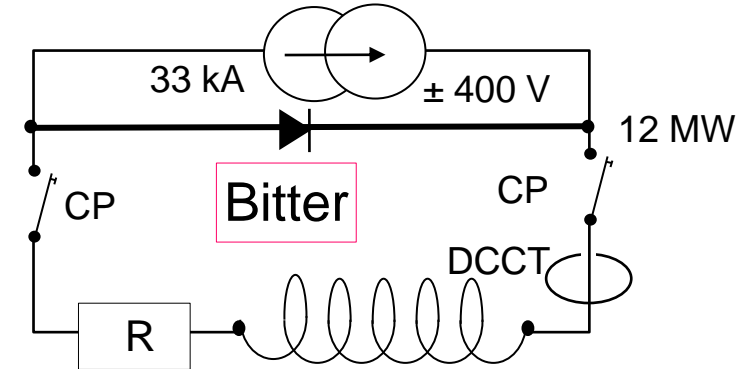


Top parts of AdI



30 MW

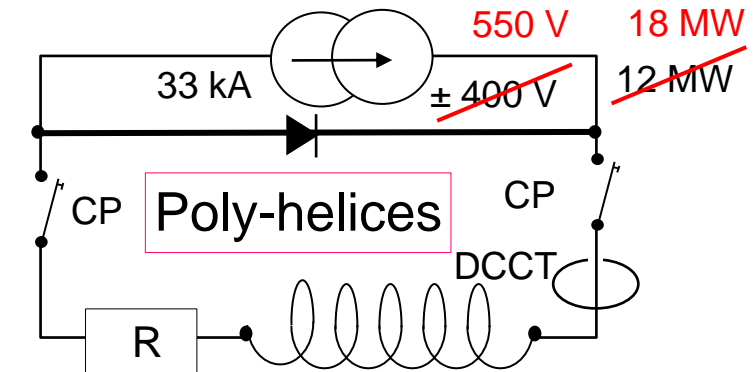
~~24 MW~~



Bitter



LNCMI



Poly-helices

550 V

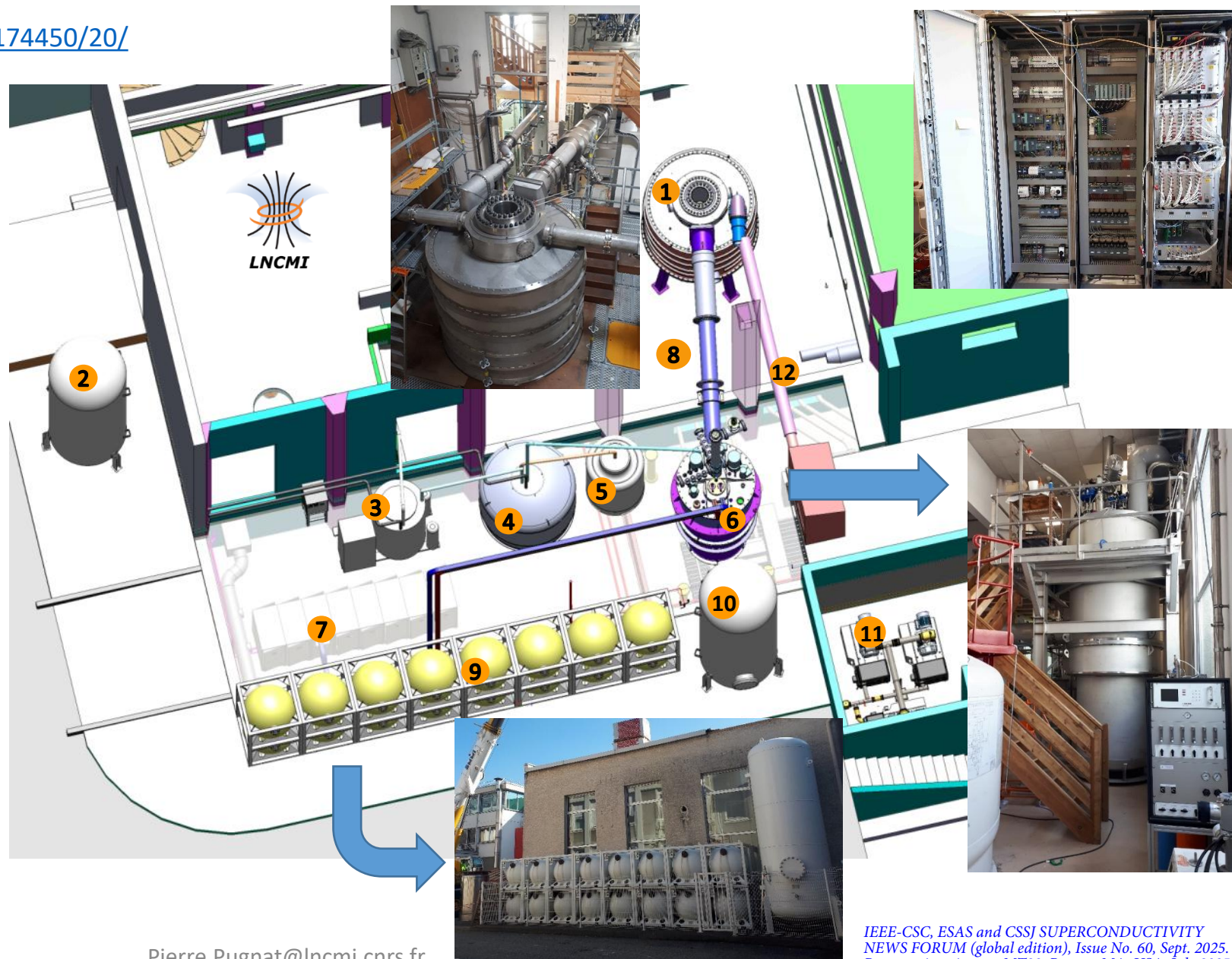
~~18 MW~~

~~12 MW~~

# Integration of the Grenoble Hybrid Magnet with its Cryogenic Plant

Virtual Tour : <https://storage.net-fs.com/hosting/6174450/20/>

- 1 Superconducting Magnet
- 2 LN<sub>2</sub> tank 27 000 litres.
- 3 He liquefier coldbox 150 l/h @ 4.5 K , 1.3 bar
- 4 Main LHe Dewar 4500 litres
- 5 Secondary LHe Dewar 1700 litres
- 6 Cryogenic satellite to produce the 1.8 K LHe bath
- 7 DC power converter 7500 A , 30 V (underground)
- 8 Cryoline with busbars @ 1,8 K
- 9 High pressure gaseous He tanks 16 x 1 m<sup>3</sup> @ 200 bars
- 10 Liquefier pure He buffer tank 15 m<sup>3</sup> @ 20 bars
- 11 Helium pumping system 6000 m<sup>3</sup>/h @ 10 mbar, 20 °C
- 12 Quench line

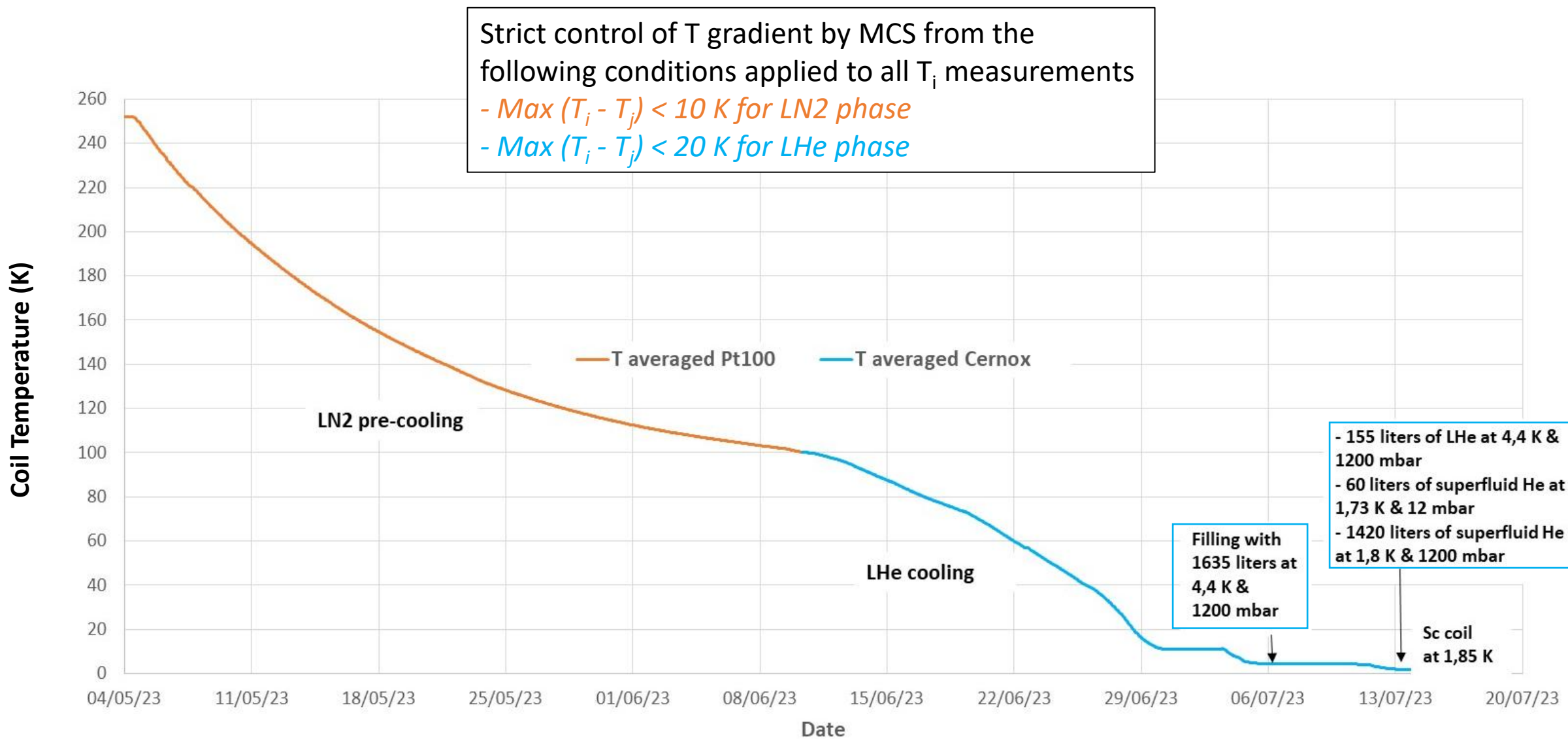


Not shown (located in other areas)

- Liquefier cycle compressor @ 14.5 bars
- He recovery balloon : 30 m<sup>3</sup> @ Patm
- He recovery compressor @ 200 bars
- 32 x 0.5 m<sup>3</sup> high pressure gaseous He tanks @ 200 bars
- Magnet Safety and Magnet Control Systems

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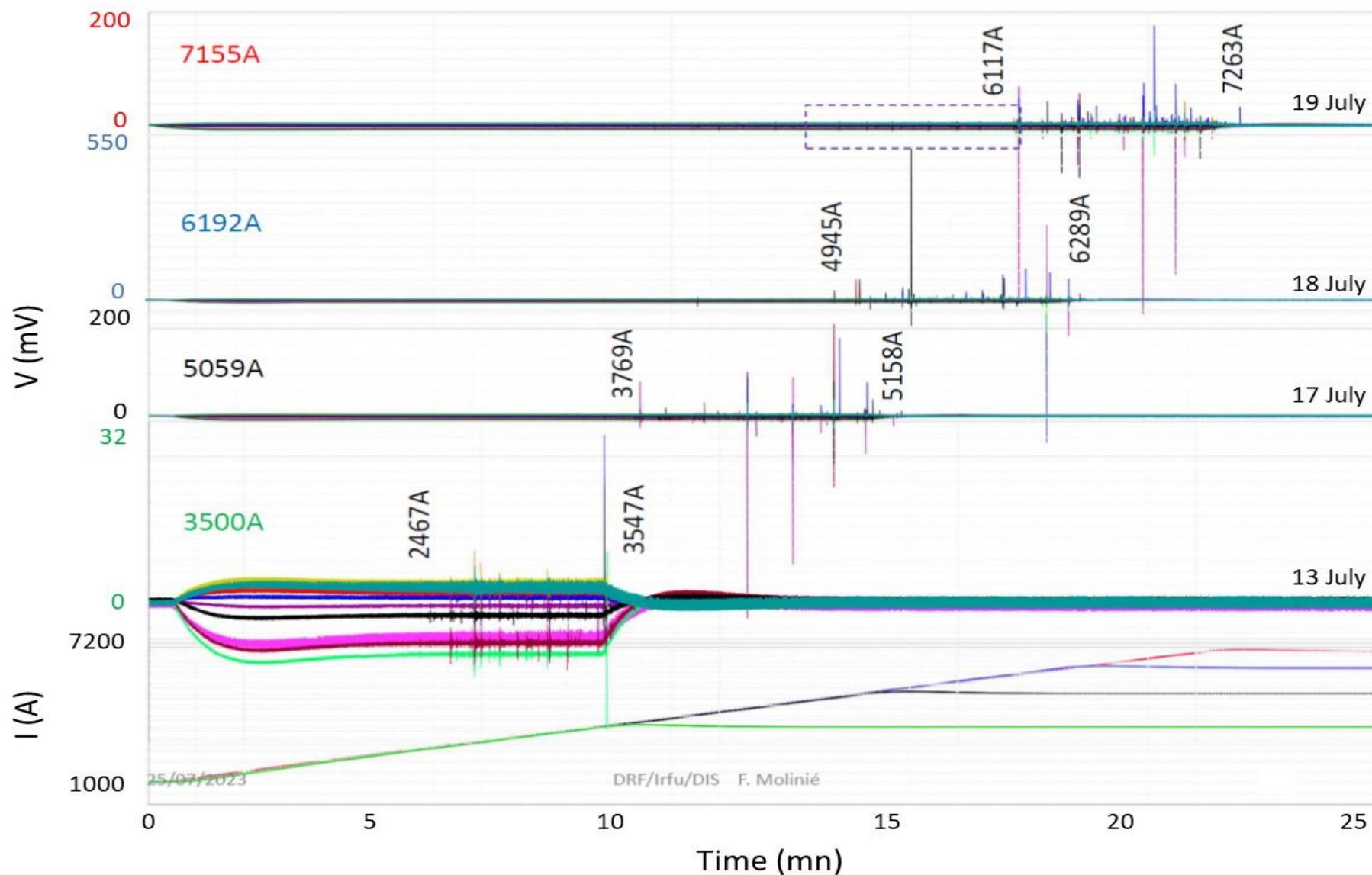
# May 2023, 2<sup>nd</sup> Magnet cooldown, this time from 250 K



# SC Magnet Seismicity\* during 1<sup>st</sup> Powering up to the Nominal Field of 8.5 T

[IEEE TASC 34, 1 \(2023\)](#)

\*Pioneering work in 2001: DOI 10.1109/77.920111



No training quenches but full/partial Kaiser effect observed

Most of the spikes are located at the interface between flanges and first & last DP

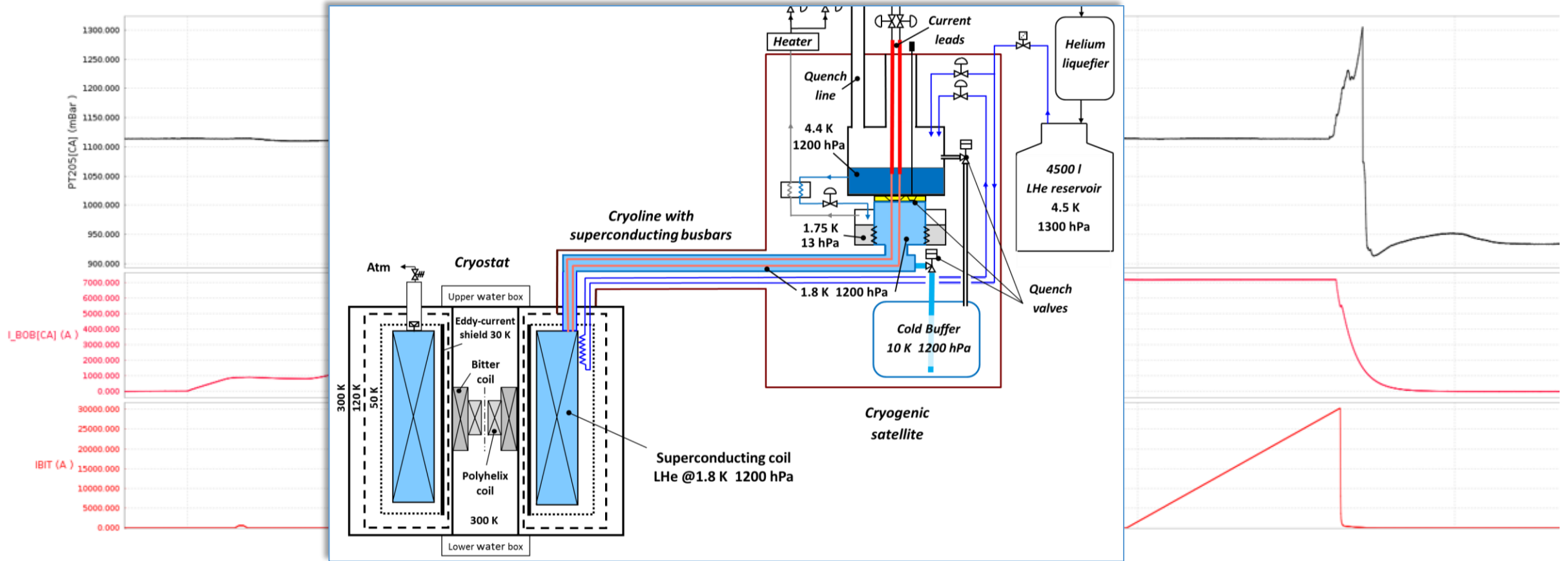
Followed by energy discharge Tests  
Sc magnet fully operational up to 8.5 T

# 1<sup>st</sup> Full Powering in Hybrid Modes

- ▶ Superconducting + Bitter coils
- ▶ Superconducting + Polyhelix coils
- ▶ Superconducting + Bitter + Polyhelix coils

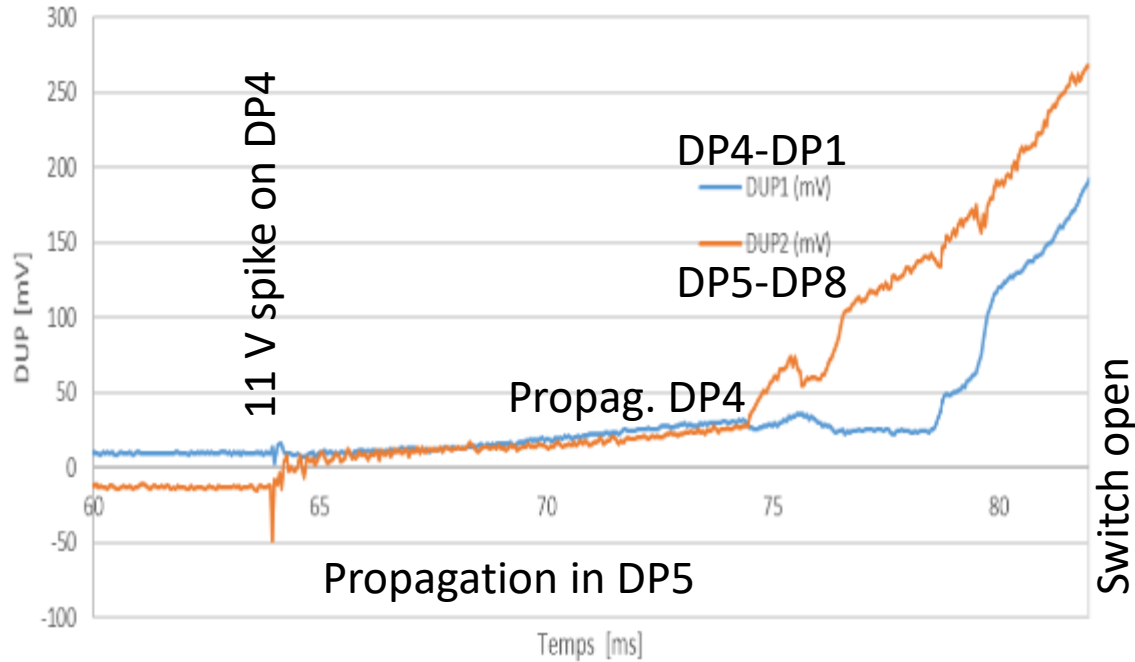
# Quench during the Powering of Sc + Bitter @ 8.5 + 8.9 = 17.4 T

- Quench detection via  $\Delta P \uparrow$ , 18.5 s after a **huge spike of 11 V**, 0.5 s before quench detection via voltage taps.



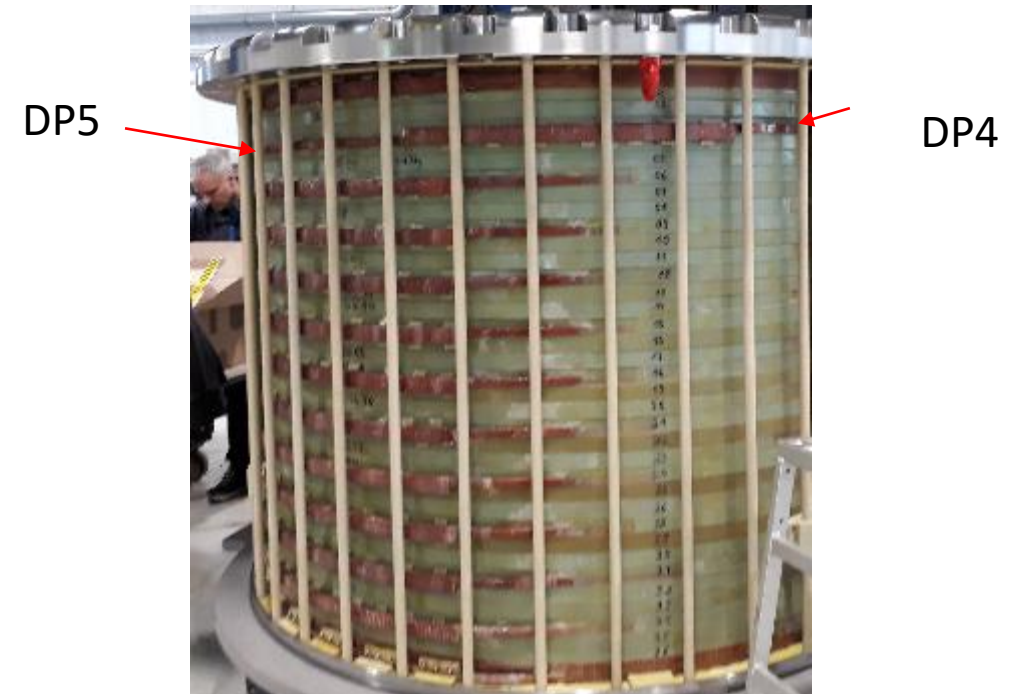
- Precise quench location from voltage taps at the conductor overlength for the connexion between DP4&DP5 where a non-conformity was instructed during the coil winding.

# Powering sc + Bitter: (Training ?) Quench at 8.5 + 8.9 = 17.4 T



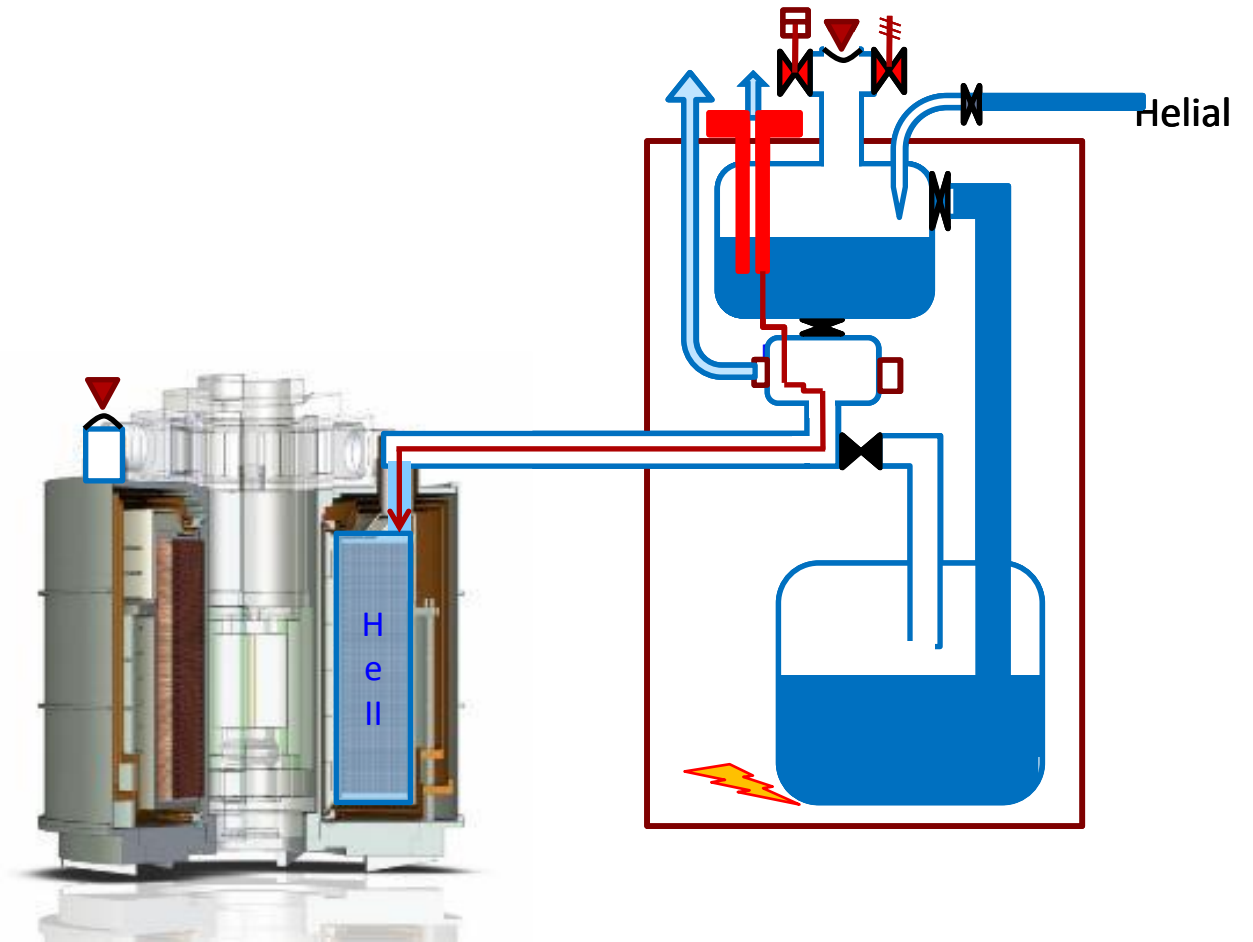
- Quench origin at the interface DP4 & 5
  - Different connection due missing turn in DP4 ! **NCR**
  - To solve this, external part of the conductor has been extended.

- Silent quench killer detected by pressure change
  - Quench velocity of ~ 9 cm/s
  - 20 s for the quench detection !
  - No transverse propagation of the quench
  - Massive cooling slowing down quench propagation
  - $T_{\text{Hot Spot}} < 100 \text{ K}$



# Management of LHe during a Quench

- The sc magnet is cryostable (Steakly), but with low cooling capacity (critical flux  $\sim 0.2$  W/DP).
- After a quench, the cold buffer allows to recuperate LHe and the cooling down from 4 K à 1.8 K takes  $\sim 5$  jours.
- During the quench the recuperation system for LHe was succesfully validated.

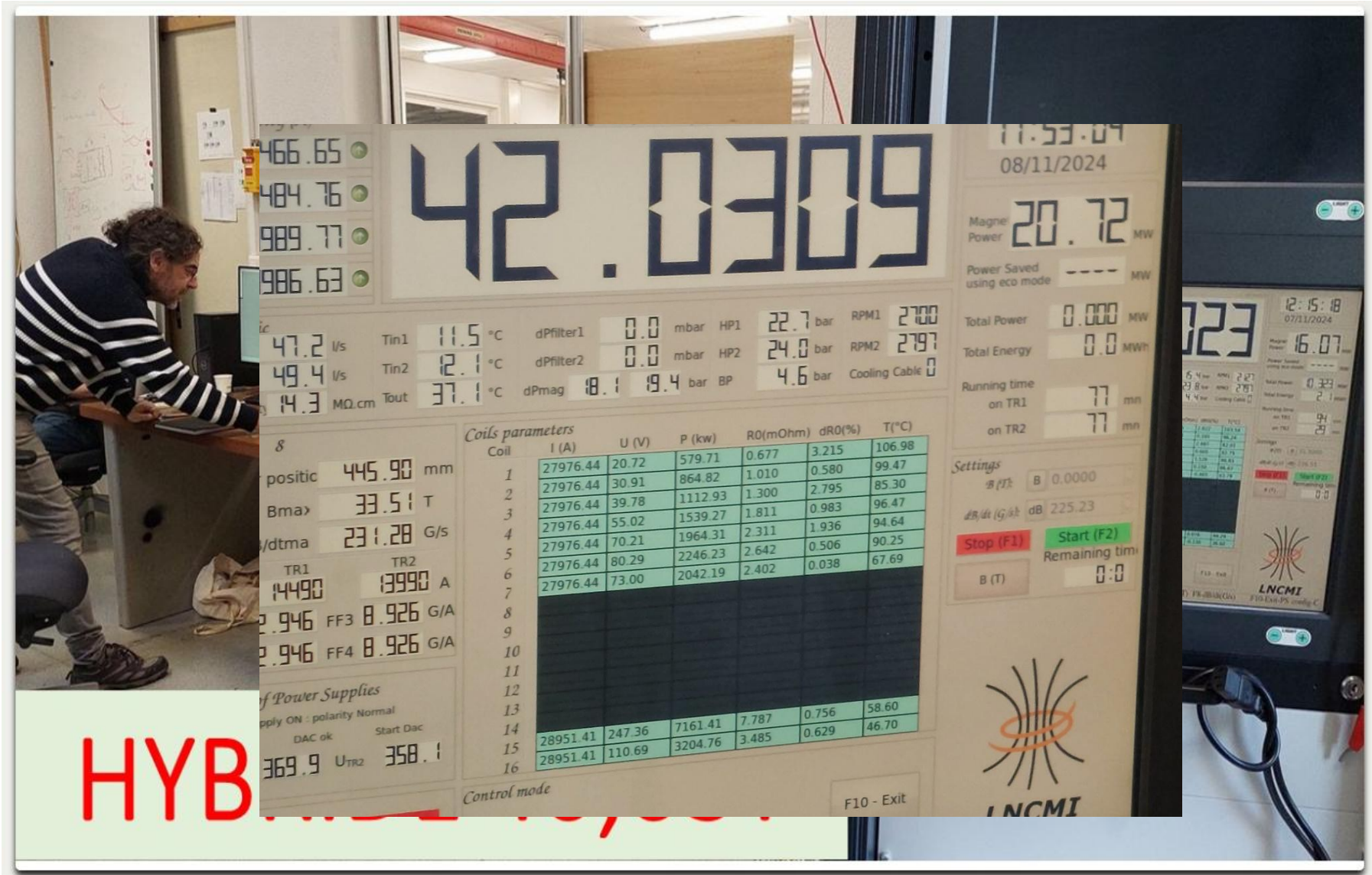


Magnet Cryostat

Cryogenic satellite



# Result of 8 Nov. 2024 : 8.5 + 8.5 + 25 = 42 T without quench

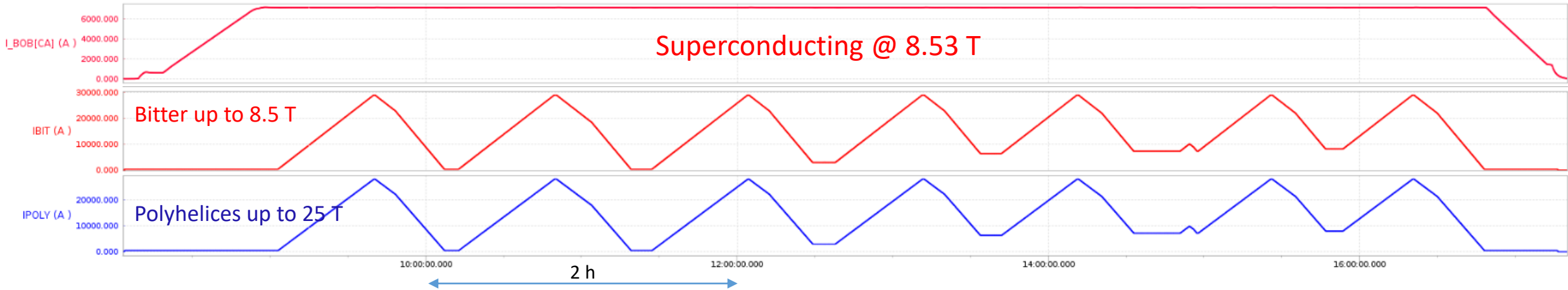


**As a 1<sup>st</sup> step,**  
There is still  
Room  
to go to Higher  
Field(s)... But  
priority given to  
Science Runs

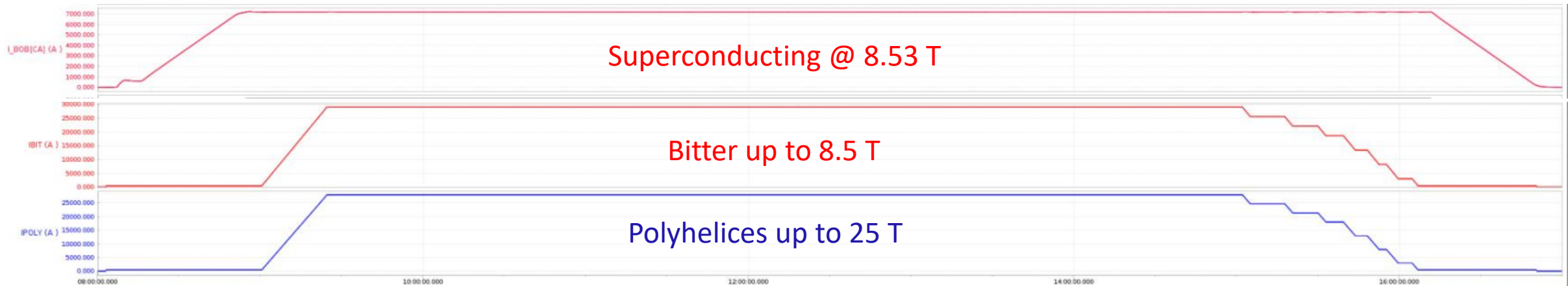
# Exemples of Hybrid Magnet Powering Cycles during Science Runs



► Typical 8 h-day running up to 42 T with 7 powering cycles for resistive inserts for transport measurements



► Typical 6 h-day running up to 42 T with a single powering cycle for RMN measurements



**Summary of 1<sup>st</sup> science runs:** 2 experiments in May-June 2025 (transport & RMN) requiring 46 cycles up to 42 T in total, with flat top duration ranging from few seconds up to ~ 6.6 h with no time limitation detected.

# Summary & Next Steps

- Commissioning Tests of the Hybrid Magnet
  - **Phase-1** in 2022 (sc & resistive alone, *cf. Presentation to MT27*)
    - . 1.85 K during 14.5 days & no time limitation encounter
    - . B/I of the sc outsert measured with RMN probe = 1.176 T/kA
    - . Off-centering between resistive and sc magnets measured ( $\Delta z = 13$  mm,  $\Delta r \leq 1$  mm)
  - **Phase-2 & 3** in 2023 (sc alone up to 8.5 T, coupling with Bitter up to 5 T, *cf. Presentation to MT28*)
    - . Axial off-centering reduced to 9 mm prior to start
    - . Sc nominal field of 8.5 T reached 4 times without quench
    - . Progressive validation of the proper functioning of MSS-1&3 (Fast & slow discharge tests by step of 25 %)
  - **Phase-4**, April-June 2024 (coupling between sc & Bitter, sc & polyhelice)
    - . Sc nominal field of 8.5 T reached 4 additional times without quench
    - . Powering sc + Bitter: Quench at  $8.5 + 8.9 = 17.4$  T (MSS-1&3 worked perfectly)
    - . Powering sc + polyhelice:  $8.5 + 25.5 = 34$  T reached without quench
      - ▶ Then, **problem with the power converter of the sc outsert**  $\Rightarrow$  **Investigation & successful repairing**
  - **Phase-5**, October-November 2024
    - ▶ **40 T & then 42 T reach for 1<sup>st</sup> time in Europe.**
- Operation Phase, May-June 2025
  - 2 experiments performed (Transport & NMR measurements requiring 46 cycles up to 42 T in total) **and more to come, in particular GrAHal ▶ Grenoble Axion Haloscopes for axion/ALPs dark matter search**

# If you want to know more about

- GrAHal
- Why limitation to 42 T as a first step ?
- Which maximum field can be expected ?
- And more...

Please come to the special session

Sun-Mo-Spe1-01



## Thank You for Your Attention !

# Outline/More information

## Selection of Articles about the Grenoble Hybrid Magnet

- “Study and Development of the Superconducting Conductor for the Grenoble Hybrid Magnet”, <https://ieeexplore.ieee.org/document/6111264>
- “A New Test Station to Measure the Critical Current of Superconducting Strands”, <https://ieeexplore.ieee.org/document/6096388>
- “Two-Dimensional and Three-Dimensional Mechanical Analyses of the Superconducting Outsert of the LNCMI Hybrid Magnet”, <https://ieeexplore.ieee.org/document/7384490>
- “Role and Impact of the Eddy Current Shield in the LNCMI-G Hybrid Magnet”, <https://ieeexplore.ieee.org/document/7403872>
- “Cryogenic system for the 43 T Hybrid Magnet at LNCMI Grenoble: from the needs to the commissioning”, <https://iopscience.iop.org/article/10.1088/1757-899X/171/1/012107>
- “In-House Industrial Production of the Superconducting Conductor for the 43 T Hybrid Magnet of LNCMI-Grenoble”, <https://ieeexplore.ieee.org/document/8268078> ; poster@ <https://indico.cern.ch/event/659554/contributions/2714073/>
- “Progress in the Construction of the 43 T Hybrid Magnet at LNCMI-Grenoble ”, <https://ieeexplore.ieee.org/document/8169052>
- “Ultimate Forces of the Grenoble Hybrid Magnet”, <https://ieeexplore.ieee.org/document/8207621>
- “From Manufacture to Assembly of the 43 T Grenoble Hybrid Magnet ”, <https://ieeexplore.ieee.org/document/8986553>
- “43+T Grenoble Hybrid Magnet: From Final Assembly to Commissioning of the Superconducting Outsert ”, <https://ieeexplore.ieee.org/document/9714155>
- “Commissioning Tests of the 43+T Grenoble Hybrid Magnet”, <https://ieeexplore.ieee.org/document/10359164>

## Selection of Articles/Talks for Axion Dark Matter searches

- OSQAR Experiments @ CERN: <https://ep-news.web.cern.ch/content/osqar-experiment-sheds-light-hidden-sector-cerns-scientific-heritage> , <https://arxiv.org/abs/1506.08082> ; <https://doi.org/10.1140/epjc/s10052-014-3027-8>
- “High magnetic fields for fundamental physics”: <https://arxiv.org/pdf/1803.07547.pdf>
- “The Grenoble Axion Haloscope platform (GrAHal): development plan and first results”, <https://arxiv.org/abs/2110.14406> (to be published)
- “GrAHal-CAPP for axion dark matter search with unprecedented sensitivity in the 1–3  $\mu\text{eV}$  mass range”, <https://www.frontiersin.org/journals/physics/articles/10.3389/fphy.2024.1358810/full>
- Last Talk @ CERN PBC: <https://indico.cern.ch/event/1418701/contributions/5965951/attachments/2933887/>