



The Superconducting-Resistive Hybrid Magnet in Grenoble

P. Pugnats, and C. Simon

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Sunday July 6, 2025



Project Structure & Collaborations



Advisory Committee
 K. Brodzinski (CERN)
 A. Hervé (U. Visconsin-Madison)
 H. Schneider-Muntau (CS&T)*
 A. Siemko (CERN)

*Also external consulting

CNRS-DR11
 SFC
Administration LNCMI-Grenoble
 A. Pic, N. Hubert

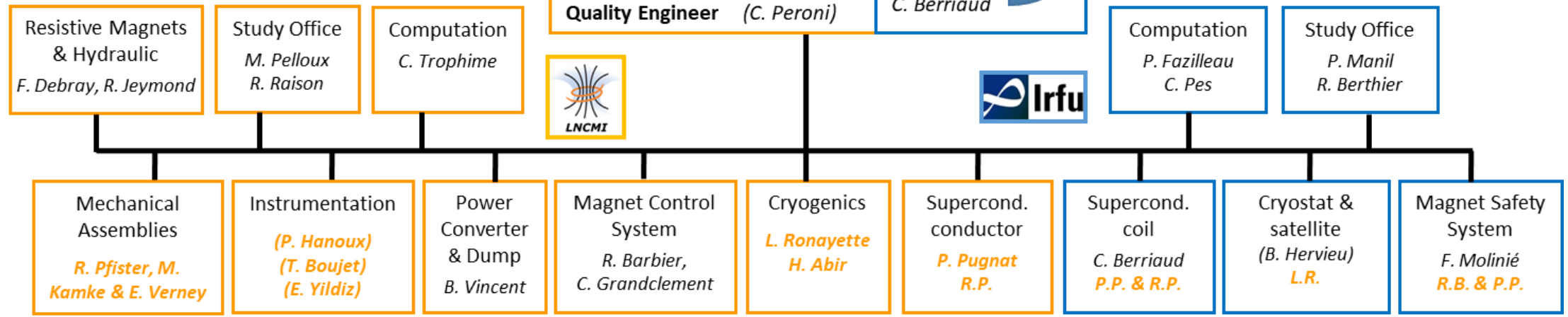
Project Leader
 P. Pognat

Deputies
 F. Debray
 L. Ronayette
 (C. Peroni)

Co-Project Leader
 (B. Hervieu)

Deputy
 C. Berriaud

Quality Engineer



LNCMI-Grenoble : 98 man-year including 79 engineer.year & 19 technician.year (2008-24)

CEA-irfu : 25 man.year (engineer.year)

Project Team : 21 collaborators from CNRS & CEA
 incl. the LNCMI core team (5 eng.+ 2 tec. in average)



Industrial Partners

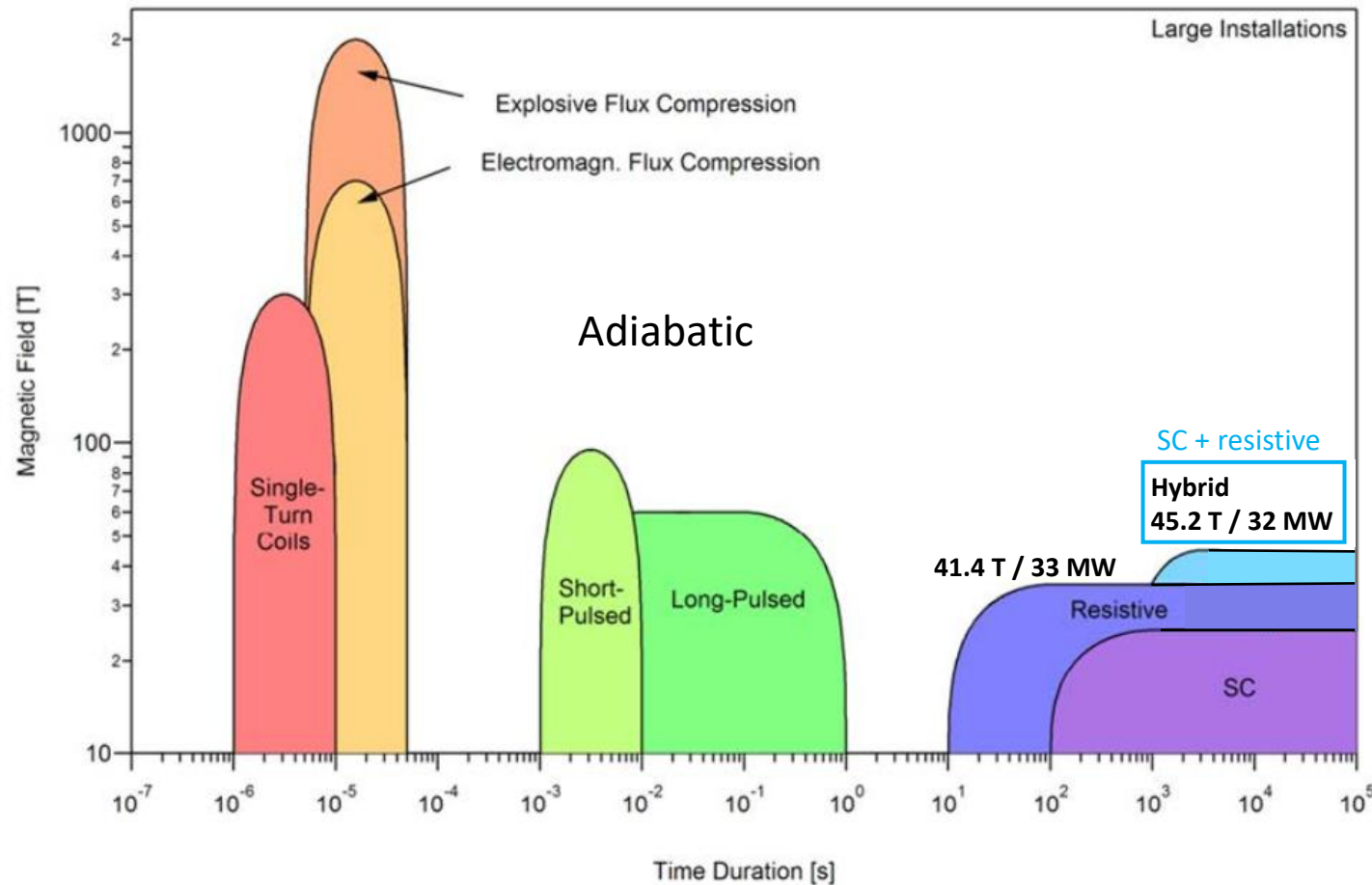


Outline

- Introduction
- Specificities of the Grenoble Hybrid Magnet
- Commissioning Tests & 1st operations for Science
- Installation of a New 60 MVA Transformer at LNCMI-Grenoble
- Why Limitation to 42 T as a 1st step ?
- Toward 60 T Hybrid Magnet (?)
- Need of Reduction of the Environmental Footprints of Research Infrastructures
- Conclusion & Outlook with GrAHal



High Magnetic Fields for Science Today



Adapted from K. Matsui, et al. *Review of Scientific Instruments* 92(2):024711 (2021)
<https://doi.org:10,1063:5,0032895>

Remarks on DC field produced by water cooled resistive magnets

$$1/ B \propto \text{Power}^{1/2}$$

2/ There is a "No Field Limit Theorem"*

But...

$$\phi_{\text{out}} / \phi_{\text{in}} = \exp (B/B_S)^2$$

with $B_S = (2\mu_0 \lambda \sigma_{\text{Hoop, max}})^{1/2}$ & considering a constant « Hoop stress current distribution »

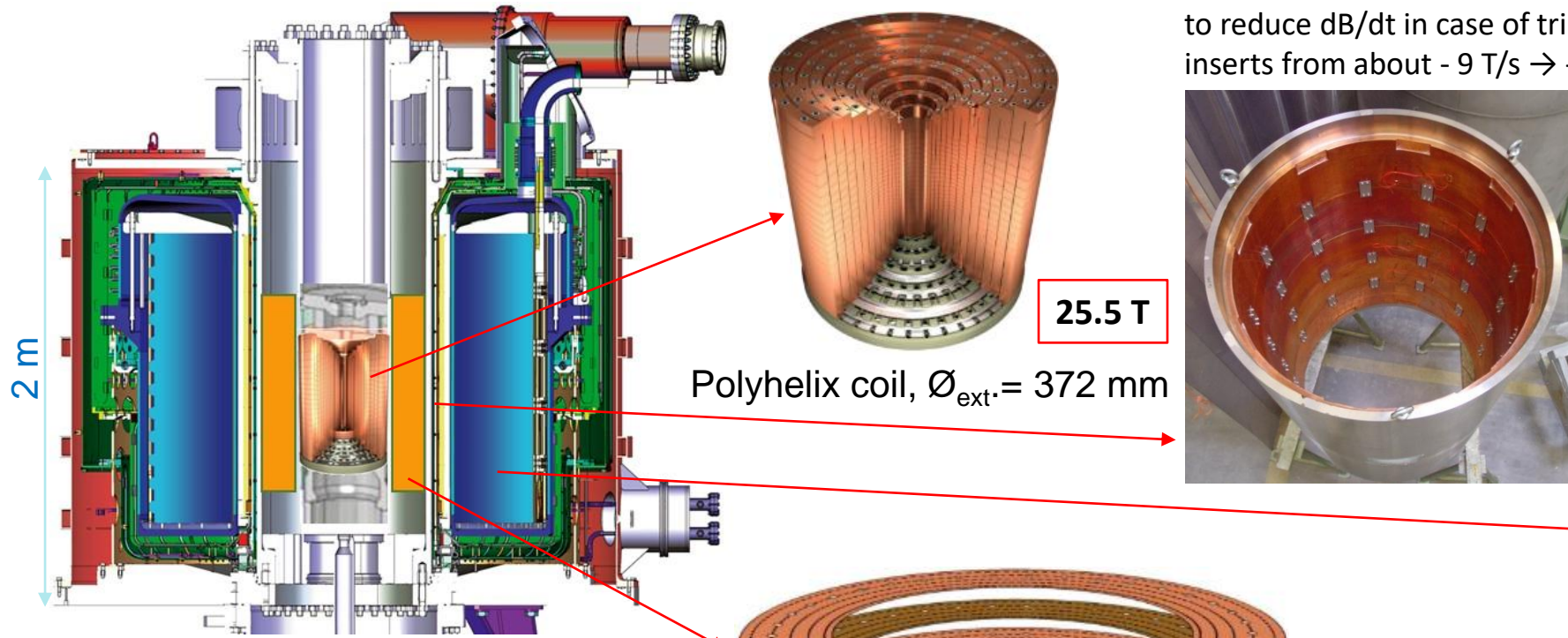
Typically, for 41.4 T, $\phi_{\text{out}} = 1 \text{ m}$ & $\phi_{\text{out}} / \phi_{\text{in}} \approx 31$

*From G. Aubert,
<http://dx.doi.org/10.1088/0031-8949/1991/T35/036>
 Assuming appropriate water cooling...

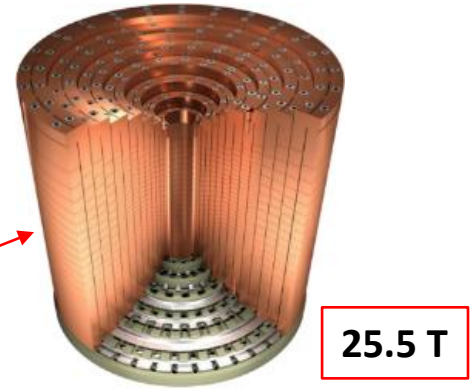
Resistive & Superconducting Coils separated by EC shield

Resistive Bitter & Polyhelix inserts ($\text{CuAg}_{5\%}$) designed for 12 + 12 MW

► Upgrade to 12 + 18 MW for Phase-2



Stainless Steel re-inforced Cu shield at $T = 50 \text{ K}$
to reduce dB/dt in case of trip of resistive inserts from about $-9 \text{ T/s} \rightarrow -0.5 \text{ T/s}$



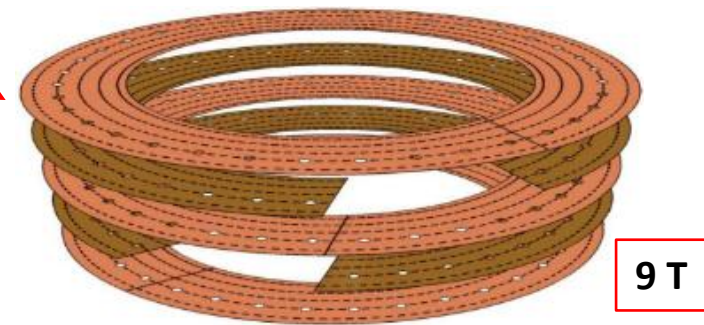
25.5 T

Polyhelix coil, $\text{Ø}_{\text{ext}} = 372 \text{ mm}$



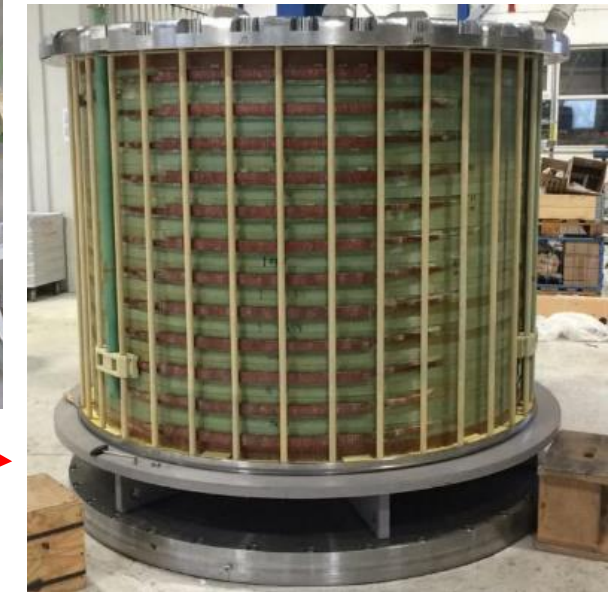
43 T / $\phi = 34 \text{ mm}$

Technologies : SC Nb-Ti/Cu & superfluide He
Hydraulic : 2 x 150 l/s
Stored Energy @ 43 T : 108 MJ
~ 26 kg de TNT



9 T

Bitter coils (x2), $\text{Ø}_{\text{ext}} = 750 \text{ mm}$



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

8.5 T

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

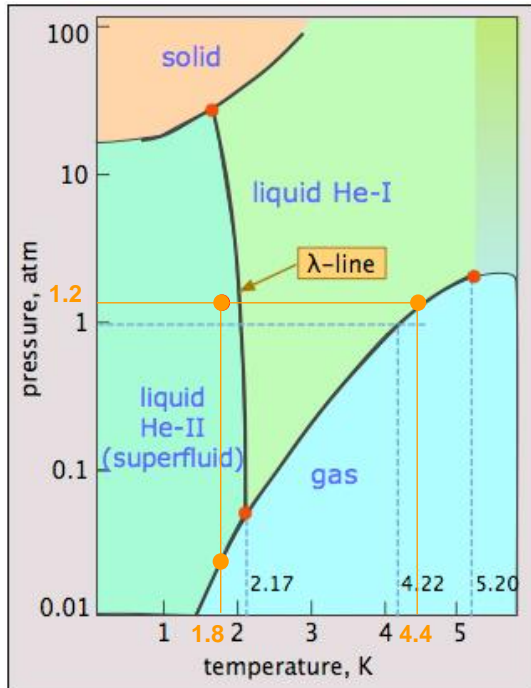
P. Pugat, R. Pfister, et al., *IEEE Trans. Appl. Supercond.* 28, 4301005 (2018)
<https://indico.cern.ch/event/659554/contributions/2714073/>
<https://indico.cern.ch/event/445667/contributions/2562521/>



18 x 13 mm²



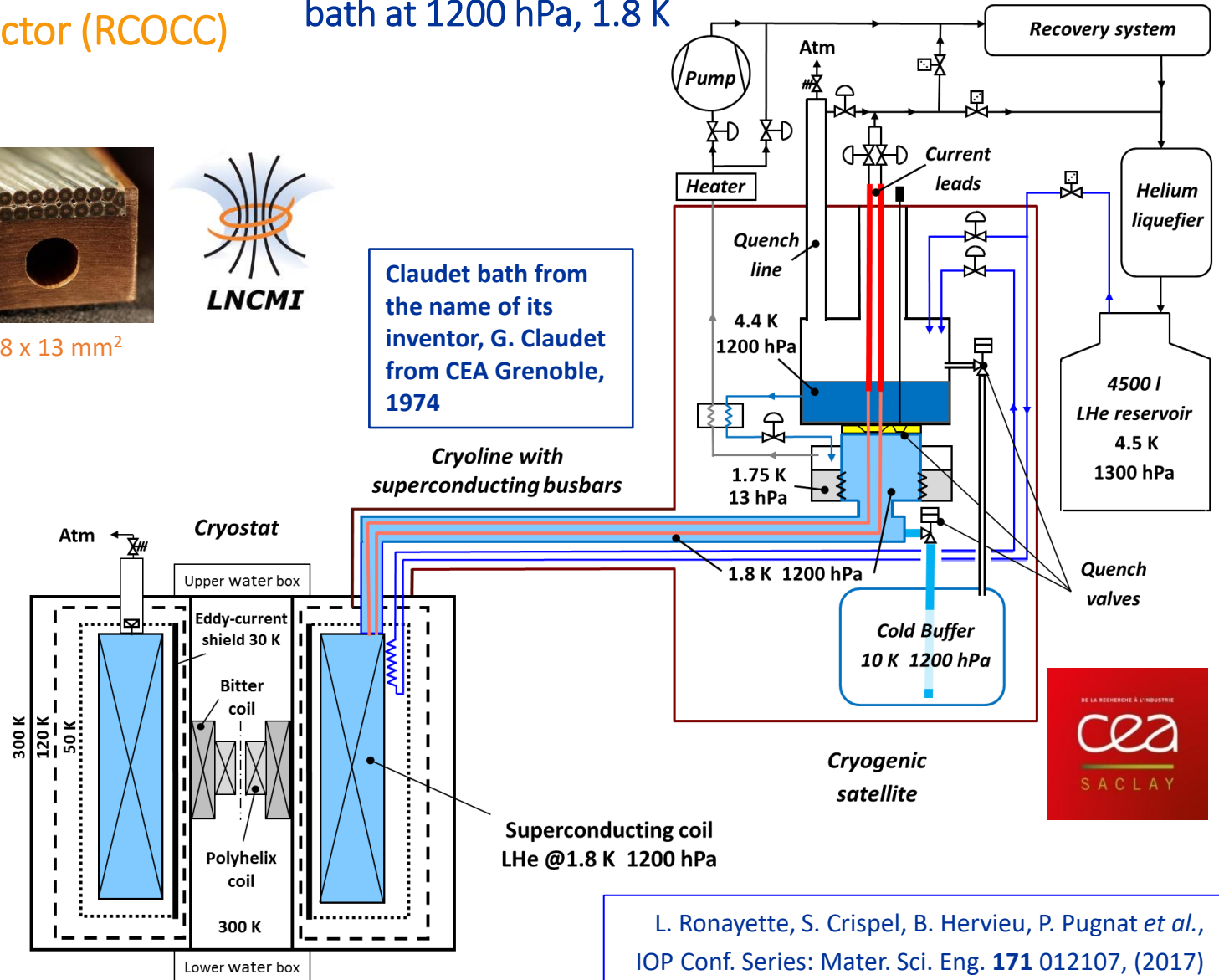
The cryogenic system principle: Pressurized superfluid He bath at 1200 hPa, 1.8 K



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

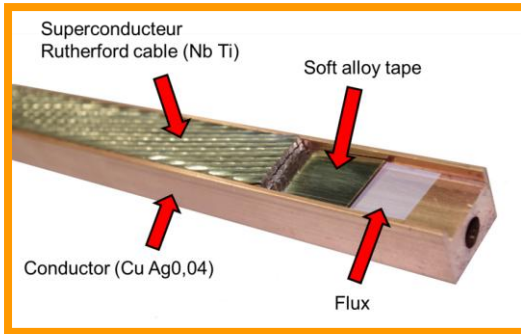
Claudet bath from the name of its inventor, G. Claudet from CEA Grenoble, 1974



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



In house assembly of the RCOCC



Innovative developments have been achieved based on induction heating for soft-soldering of 12 km of RCOCC with strict control of AC losses.

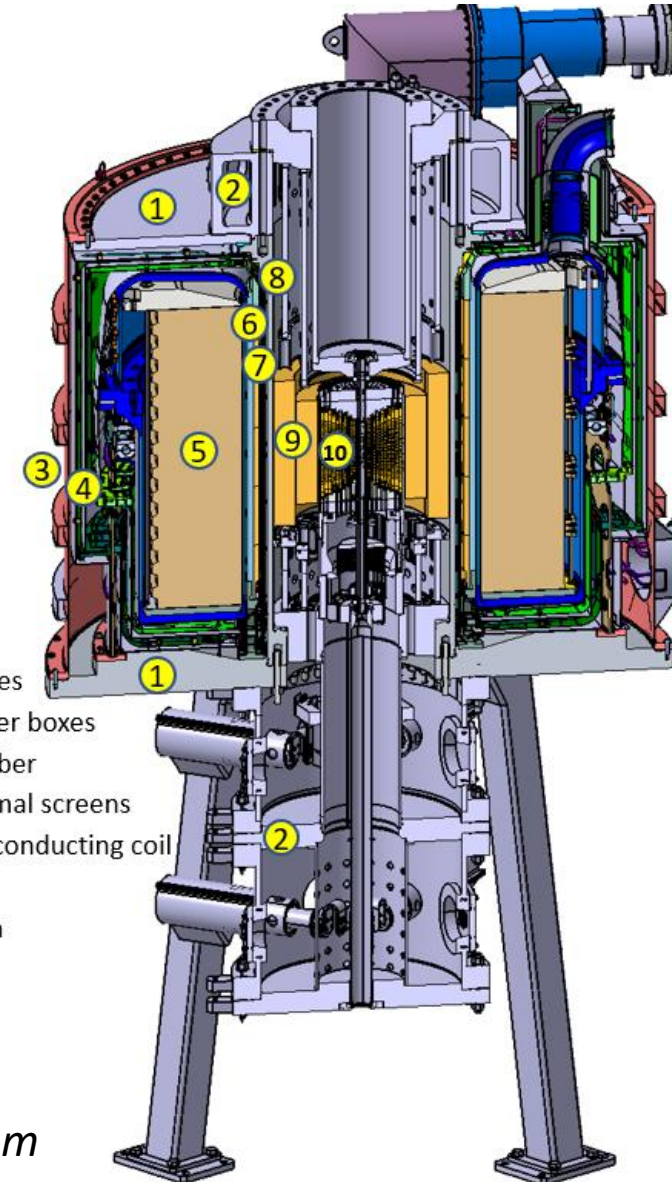
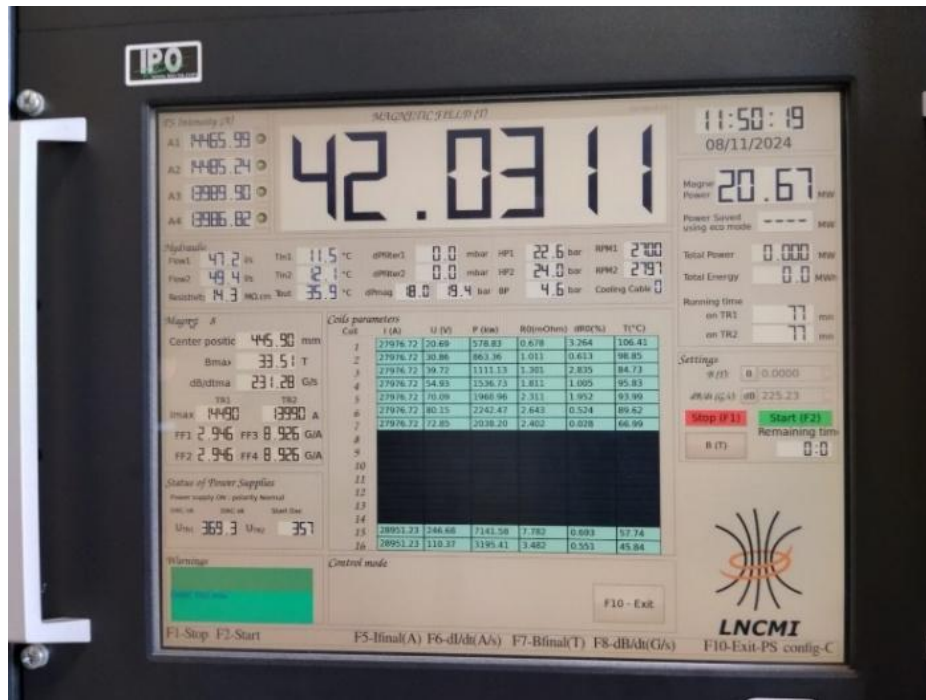
Industrial Production Line Developed, Built, Installed & Operated at LNCMI

P. Pugnat, R. Pfister *et al.*, *IEEE Trans. Appl. Supercond.* **26**, 4302405 (2016)



Crimping, soft-soldering, calibration & winding in single pancakes for delivery to **Bilfinger**
<https://www.youtube.com/watch?v=cp5NIR2cN5s>

Grenoble Hybride Magnet

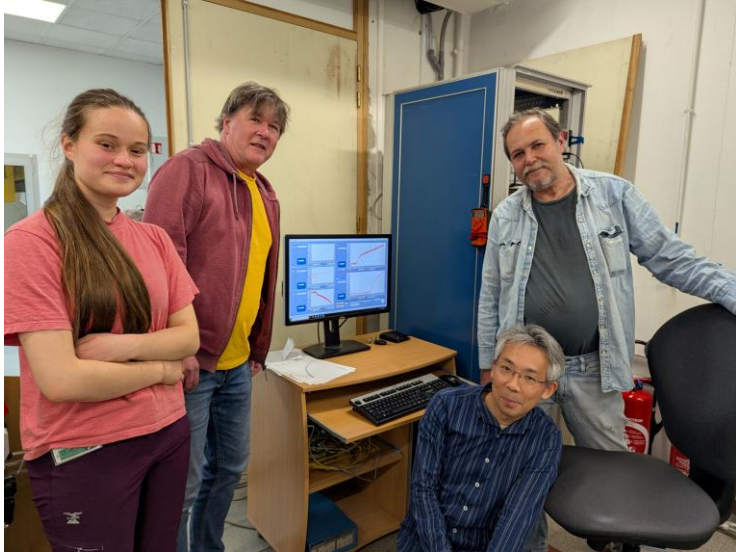


42 T reached on 8 November 2024 !!

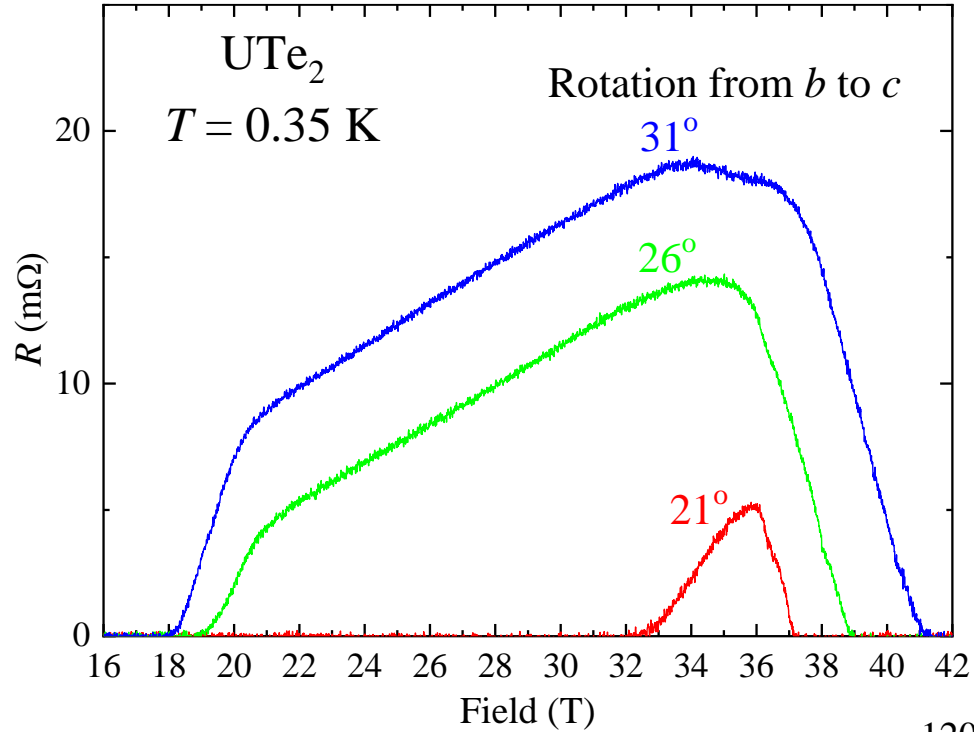
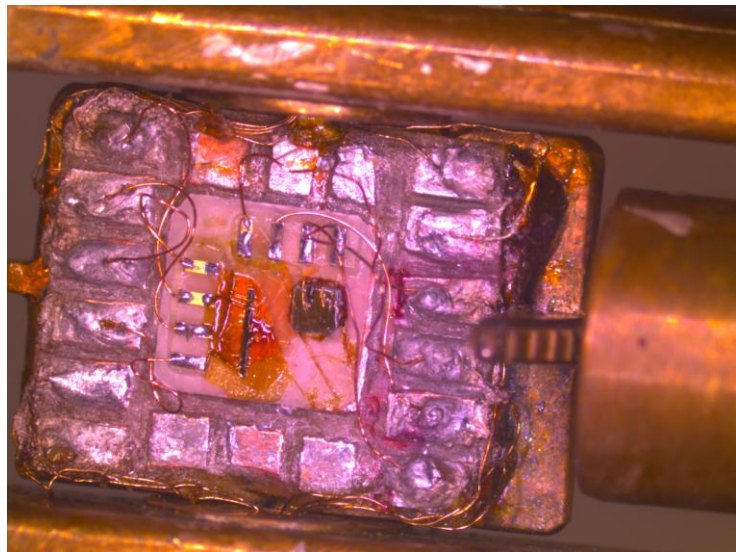
<https://lncmi.cnrs.fr/en/actualite/lncmi-hybrid-magnet-reaches-42-tesla/>

Total height of 5.4 m
Total weight of 53 tons

First Experiment using the Grenoble hybrid magnet up to 42 T

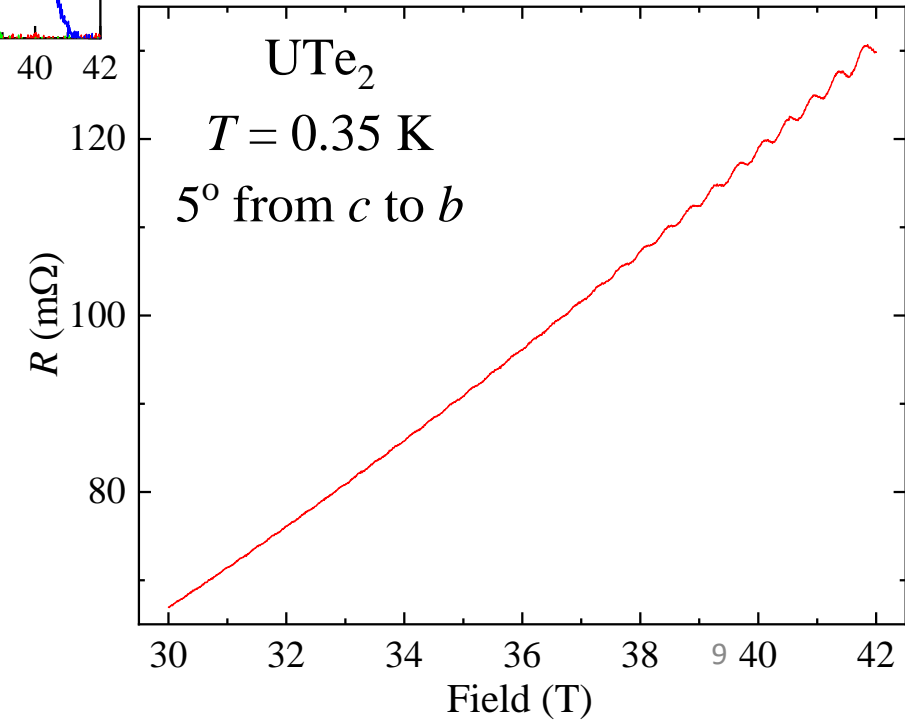


May 15th – 26th 2025: Transport meas. on 2 samples of UTe_2 using ^3He cryogenic insert



Field-induced reentrant superconductivity

Shubnikov-de Haas oscillations



Heavy-fermion paramagnetic ladder compound UTe_2

The first **NMR** experiment in Grenoble hybrid magnet: field characterization and $\text{SrCu}_2(\text{BO}_3)_2$ at **42 T** and 0.4 K

Field data as expected:

Center profile at 42 T (nominal value):

$$B = 41.885 \text{ T} \{1 - 18 \text{ ppm/mm}^2 [z^2 - (x^2 + y^2)/2]\}$$

RMS fluctuations: $\sigma = 5 \text{ ppm}$, drift during 1 hour $\sim 2\text{-}3\sigma$

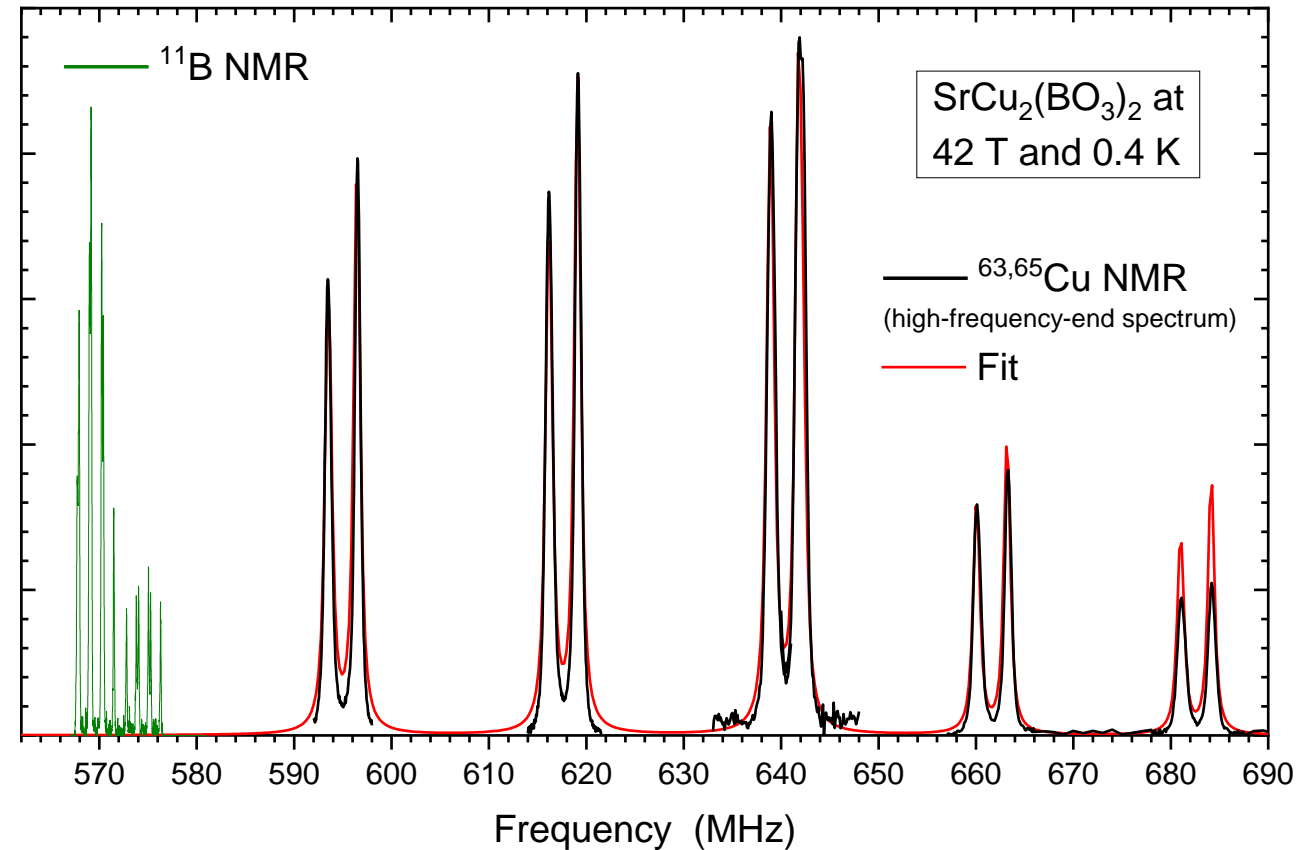
Long-time stability over full experimental time of 6.5 hours



I. Vinograd, S. Krämer and M. Horvatic

4-6 June 2025

The first ever ultra-broad-band NMR spectrum (210-700 MHz; only the high frequency end shown below) recorded above 40 T:



Summary of 1st science runs with the Hybrid Magnet: 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, *i.e. in routine operation*.

LNCMI DC Facility & High Field Magnets



Delivery on CNRS site (Sept.2023) of the 60 MVA & 225/15 kV transformer to obtain 12 + 18 MW on the magnet sites → 1st operation in April 2024 (Contact: Benjamin.Vincent@lncmi.cnrs.fr)



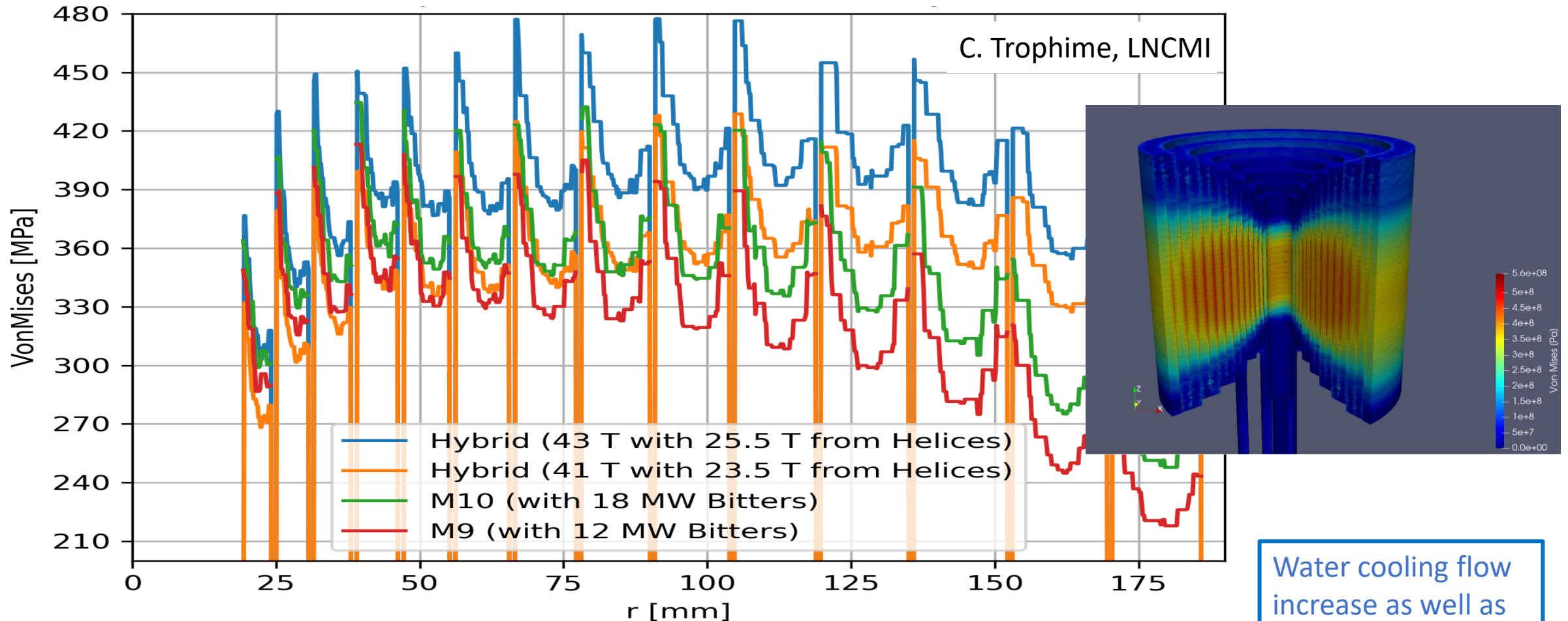
More margins for 24 MW magnets & Resistive magnet to be tested up to 39 T
→ 2025-2026

Hybrid magnet tested & operational up to 42 T in November 2024
→ New transformer not required for this 1st step;
→ Its installation & commissioning bring some delays for the hybrid magnet project (about 1 year);
→ This new transformer open the possibility to reach magnetic field well above 43 T...



Why limitation to 42 T ?

Current Polyhelices are made from cold spray of $\text{CuAg}_{5\%}$ alloy corresponding to Yield stress of 495 MPa @ 100°C and 460 MPa @ 150°C from <https://www.mdpi.com/2312-7481/10/3/15>



For 43 T with 25.5 T produced by polyhelices, Christophe calculated VonMises @ 480 MPa on the most constraint ones and as we do **NOT** know precisely the peak temperature...



Water cooling flow increase as well as development of $\text{CuAg}_{11\%}$ polyhelices

Limitations of The 43+T Grenoble Hybrid Magnet

- **Resistive inserts**

- Poly-Bitter up to 9 T but there is room to go to 9.5 T (not now, kept as a margin)

9 T

- Poly-Helices from 25 T to 27+T

- . About + 30 MPa/Tesla with cooling re-enforcement (+20 % water flow)

- . To study more in details,... 39 T test for resistive inserts foreseen with CuAg11% end of 2025

+ 27 T

- **Superconducting Outsert (Operating Temperature ≤ 1.85 K)**

- **Limitation from mechanics, not from superconducting properties**

- . For Nb-Ti, $B_{c2}(1.6/1.9 \text{ K}) \approx 13.76/13.5 \text{ T}$, corresponding to central fields of $\sim 12.5/12.3 \text{ T}$

- . $I = 7500 \times 12.3/9 = 10\,000 \text{ A} > I_c(12.3 \text{ T}, 1.9 \text{ K})$ **BUT** $< I_c(11.5 \text{ T}, 1.9 \text{ K})$, meaning a maximum central field of $\sim 10.45 \text{ T}$

- . **The true limitation is coming from mechanical stress :**

- For 10 T central field, Maximum Hoop stress $\approx 10 \times 1,1 \times 27 \times 0,55 \times 10/8,5 = 192 \text{ MPa}$

- Measured Re0.2% of the Cu conductor profile alone $> 285 \text{ MPa}$ at cold, *i.e.* $f = 285/192 = 1.48$ close to 1/3 of margin and more if one adds the mechanical properties of the soldered Rutherford cable (NB: conductor sorting during the assembly...)

- **10 T central field should not be a problem** (to confirm from specific FEM calculations)

- **Really conservative**, Iseult is operating at 11.72 T with the same technologies (Nb-Ti/Cu & superfluid He)

+ 9.5 T
45.5+T

To be confirmed

Toward a New 60 T Hybrid as a Next Step (?)

Results of our Optimization Study ¹⁾

Conductors:

Results based on precisely defined conductors with achievable realistic values

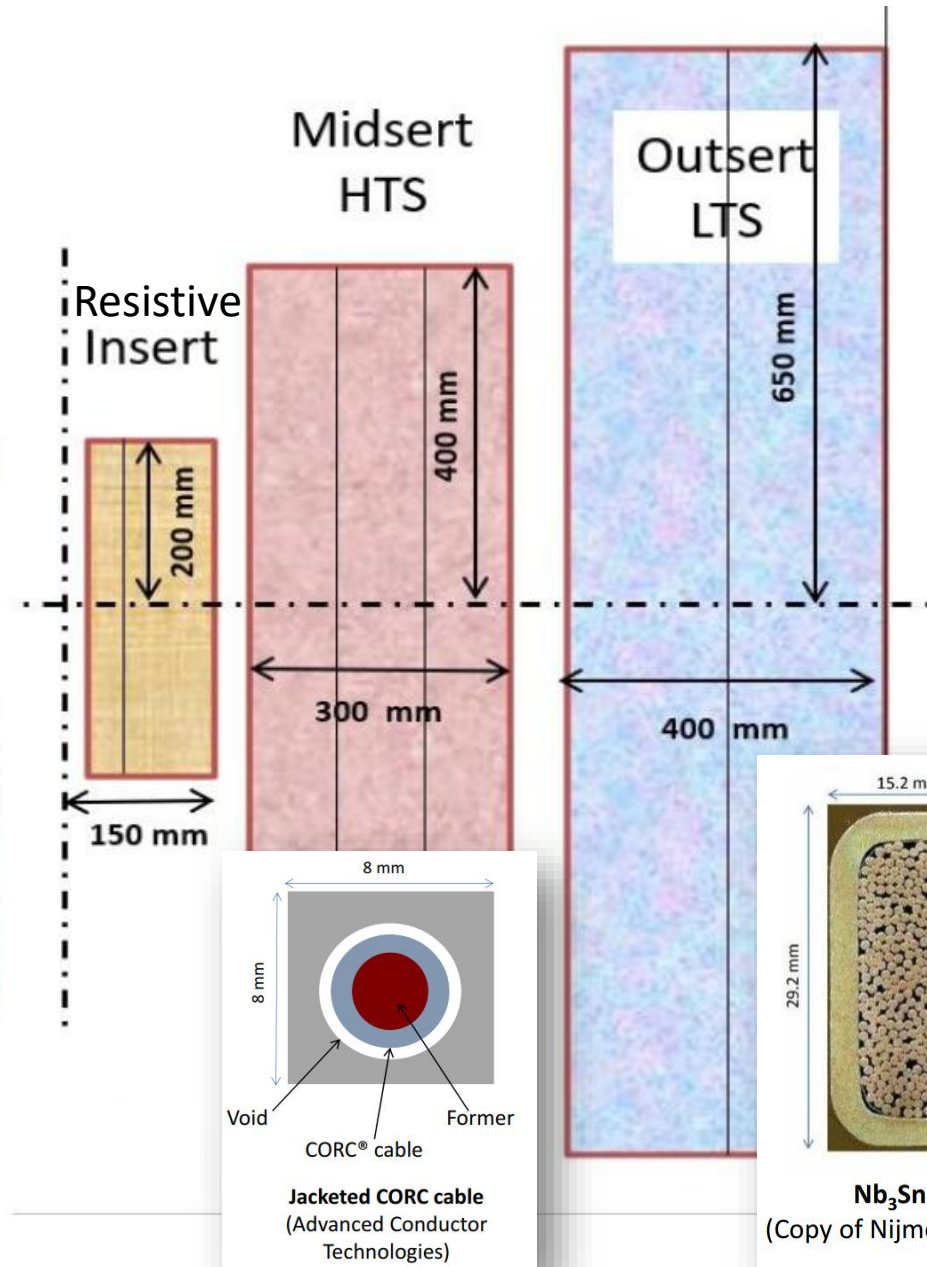
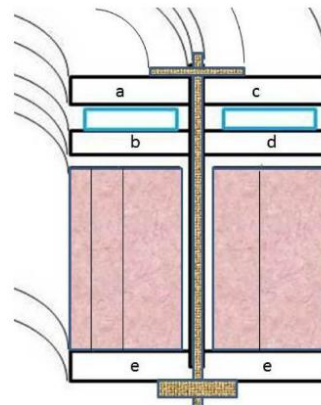
Have to be developed, characterized, confirmed

Coils:

Each coil contributes 20 T
seems to be close to optimum
LTS maximum: 20 T in 1.1 m
Insert limited by materials

No show-stoppers !

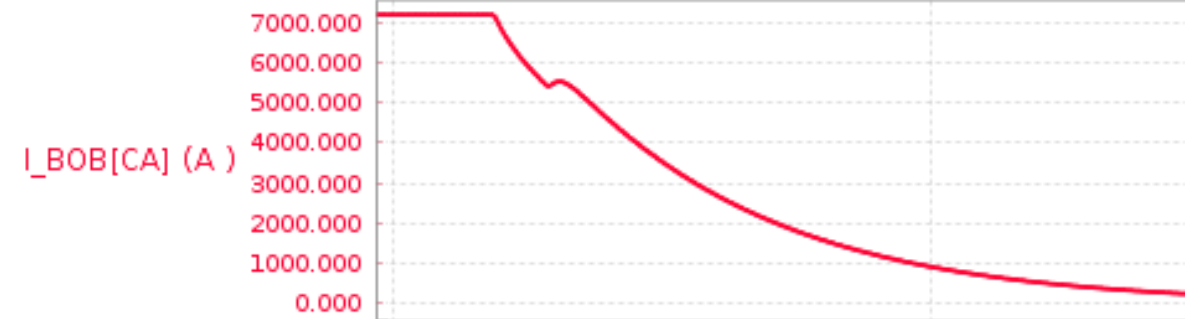
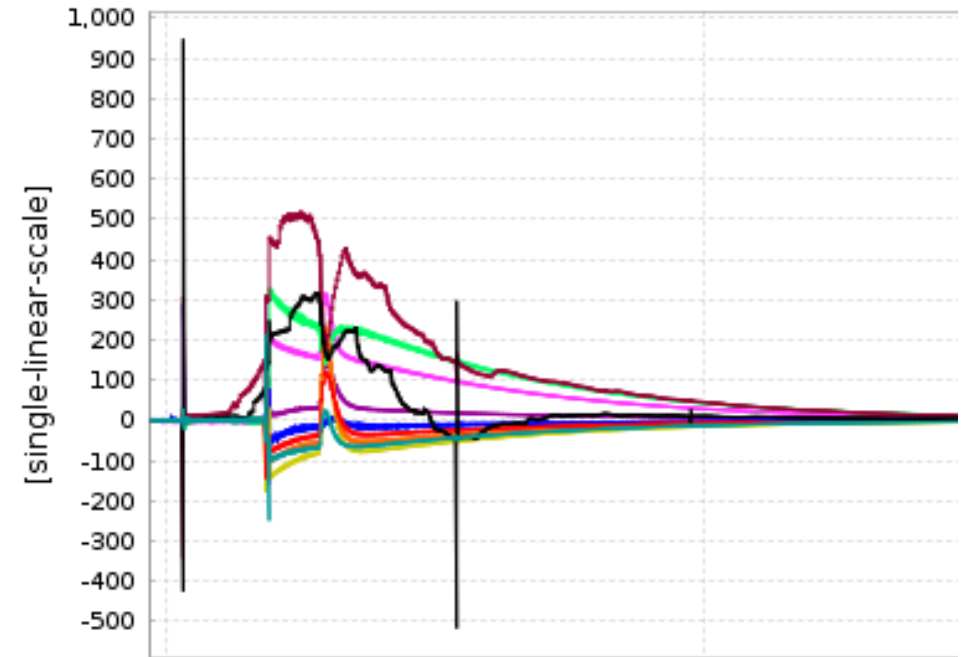
1) P. Pagnat and H. J. Schneider-Muntau, Conceptual Design Optimization of a 60 T Hybrid Magnet, IEEE Trans. Appl. Supercond., vol. 30, no. 4, June 2020 Art. ID. 4300507.



One of the main issues for our 60 T hybrid¹⁾ is the protection of the HTS Midsert...

- Use the 43+T Grenoble Hybrid also as a test bench to validate new concepts and technologies such as Numeric Magnet Protection Systems
- Proposal to trigger resistive insert trip as inductive quench heater for the Midsert¹⁾
- Indeed, this could have been already observed during the quench of the Grenoble Hybrid (to be confirmed from a more detail analysis...)

1) P. Pugnât and H. J. Schneider-Muntau, Conceptual Design Optimization of a 60 T Hybrid Magnet, IEEE Trans. Appl. Supercond., vol. 30, no. 4, June 2020 Art. ID. 4300507.

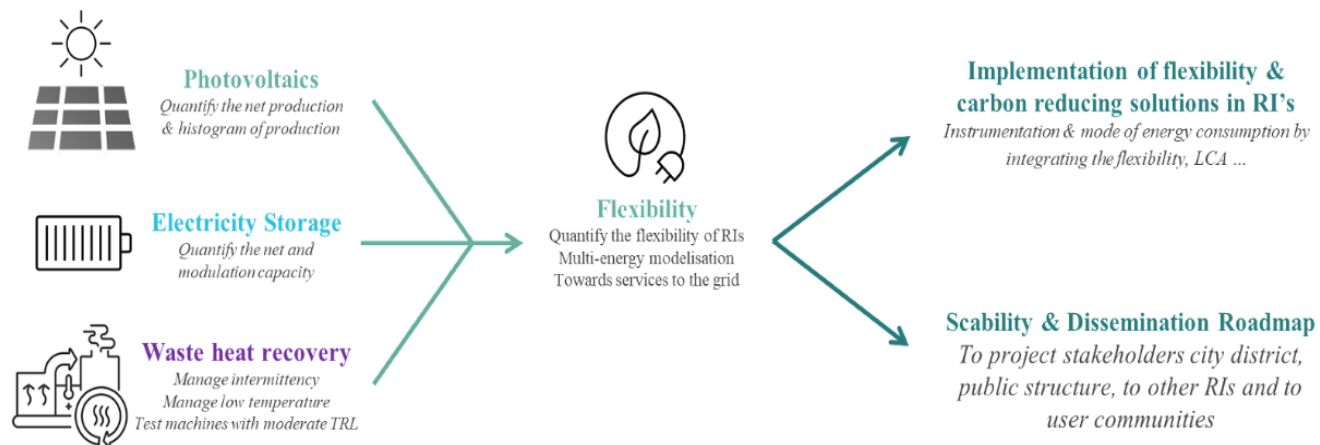


- ➔ Increase the long-term sustainability of European Research Infrastructures by reducing their environmental footprints;
- ➔ Contribute to the resilience of the European energetical system.

Flexrican (2024-2026) gathers 3 Research Infrastructures:
 the Extreme Light Infrastructure (**ELI**)
 the European Magnetic Field Laboratory (**EMFL**)
 the European Spallation Source (**ESS**)
& 2 Industrial Partners: Energy Pool & Alfa Laval



FlexRICAN concept:
from intermittency to flexibility & services to networks



FlexRICAN strength: a variety of energy usages within the consortium :

- A hyper-variability of electrical consumption with peaks up to 30 MW at the two EMFL DC facilities (FR & NL),
- A quite uniform consumption along the year at ELI facilities (CZ & HU), with the highest priority set on regulation and securing the availability of electricity,
- 3 levels of consumption at the ESS facility (SE) comprising a full operation mode during 240 days a year up to 35 MW.



Funded by
the European Union

Summary

- Key point of the Grenoble Hybride Magnet : High-magnetic field/flux modularity
 - *Project phases @ 24 MW (without parenthesis = magnetic fields reached)*

Field (nominal)	Warm dia.	Configuration	Total Electric Power*
42 (43) T	34 mm	14 helices + 2 Bitter + SC	20.7 + 2.8 + 0.4 MW
34 (35) T	34 mm	14 helices + SC	10.6 + 1.1 + 0.4 MW
17.3 (17.5) T	375 mm	2 Bitter + SC	10.9 + 1.1 + 0.4 MW
8.5 (9.5) T	812 mm	SC	0.4 MW**

(25 + 8.5 + 8.5) T

*Magnet powering + water cooling pumps + cryogenics
**He liquefier + 1.8 K pumps + cryoplant ancillaries

In Routine Operation

- **Project phases @ 30 MW**

- ▶ 43+ T in 34 mm dia. in study & development
- ▶ Test @ 39 T with Resistive Magnets alone by the end of 2025

- A New 60 T Hybrid Magnet looks feasible but requires fully dedicated R&D
- Scientific Community should be exemplary by reducing its environmental footprint

▶ On going activities at LNCMI funded by the European Union



Two Experiments Performed in 42 T And Many More to Come !!!

The quest of GrAHal

Grenoble Axion Haloscopes



A practical example of Science requiring very high magnetic field or flux that will be carried on with the unique modular Grenoble hybrid magnet platform...

Two outstanding problems of Particle Physics & Cosmology can be solved by the discovery of a single particle: The Axion

- Strong CP problem

Standard Model of Particle Physics contains 19 free parameters, in which θ is problematic

$$\mathcal{L}_{CP} = (\theta_{gluons} + \theta_{quarks}) \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

From precise measurements of the neutron EDM,

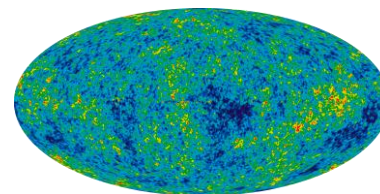
$$\theta_{gluons} + \theta_{quarks} < 10^{-10}$$

Nearly perfect compensation originating from 2 independent physics !! ... Why ?

Why the CP symmetry is so badly broken by QCD ?

By adding a new global quasi-symmetry $U(1)_{PQ}$, which can be spontaneously broken, the axion appears as a natural Goldstone boson & the signature of the solution to the strong CP problem

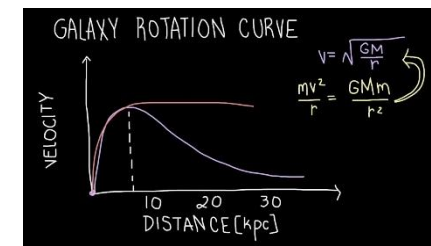
- Standard Model of Cosmology \Rightarrow Dark Matter



CMB



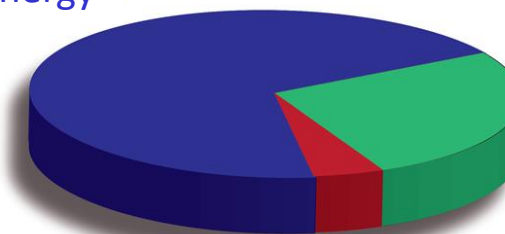
Bullet cluster



Galaxy rotation ...

More than 10 experimental facts in favour of CDM

Dark Energy
68%



1 over the 6 free parameters of Λ -CDM
Dark Matter

27%

$$\rho_{DM} \approx 0.4 \text{ GeV} / \text{cm}^3$$

Ordinary Matter
5%

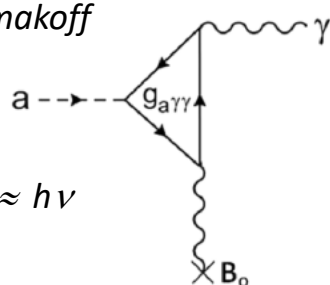
This in the context of none supersymmetry detected at LHC nor WIMPS in underground experiments...

Grenoble Axion Haloscopes

$$m_a = (1 - 1000) \mu\text{eV}$$

$$\rightarrow \rho_{DM} \approx (10^{11} - 10^{14}) \text{ axions / cm}^3$$

Inverse Primakoff Effect

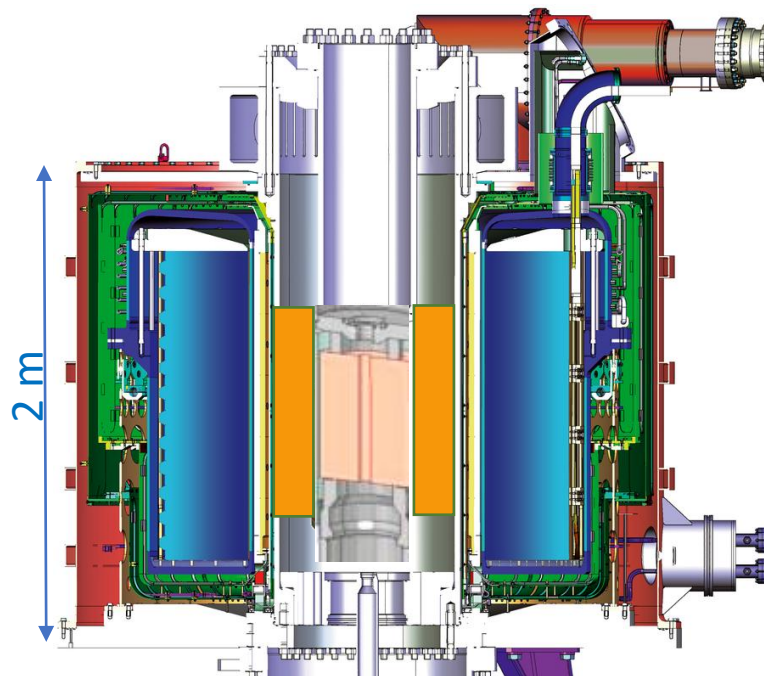


$$m_a c^2 \approx h\nu$$

Sikivie's haloscope
i.e. with RF cavity

$$11.5 \text{ GHz} / f_{\text{TM}010} = R / 1 \text{ cm}$$

$$P \propto g_{a\gamma\gamma}^2 B_0^2 V < 10^{-23} \text{ W}$$



Field	Warm dia.	RF-cavity dia.	Frequency	Axion mass
43 T	34 mm	20 mm	11.5 GHz	47.2 μeV
40 T	50 mm	34 mm	6.76 GHz	27.8 μeV
27 T	170 mm	86 mm	2.67 GHz	11 μeV
17.5 T	375 mm	291 mm	0.79 GHz	3.2 μeV
9 T	800 mm	675 mm	0.34 GHz	1.4 μeV



Grenoble Hybrid now in routine operation, 1st run of GrAHal in October 2025

► BabyGrAHal is already running

Stay Tuned, Major Discovery or Important Non-Discoveries in Progress...



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 μeV 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/>