Physics Beyond Colliders

Particle Physics in Ultra-High Magnetic Fields

or

High-Field/High-Flux Magnets for Axion/ALPs Searches @ the Ultra-Low Energy Frontier

P. Pugnat, LNCMI-Grenoble/CNRS, EMFL

OSQAR
CERN
GrAHal
Grenoble Axion Haloscopes
LNCMI
EMFL
European Magnetic Field Laboratory
cnrs
UGA
Université
Grenoble Alpes

Outline

- Introduction
  - High magnetic fields & Laboratories worldwide
- Scientific case
  - Why exploring the Ultra-Low Energy Frontier of Particle Physics ?
- Experiment vs. Magnet types
- From OSQAR toward JURA (Joint Undertaking Research of Axions/ALPs)
  - Reminder about OSQAR & LHC dipoles operating at 9 T
  - Magnet requirements for JURA
- From GrAHal toward Super-GrAHal
  - BabyGrAHal and GrAHal
  - The 43+T Grenoble Hybrid Magnet in commissioning phase
  - Conceptual design optimization of a 60 T Hybrid Magnet


43+T Hybrid magnet: 52 tons
Cold mass @ 1.8 K: 24 tons

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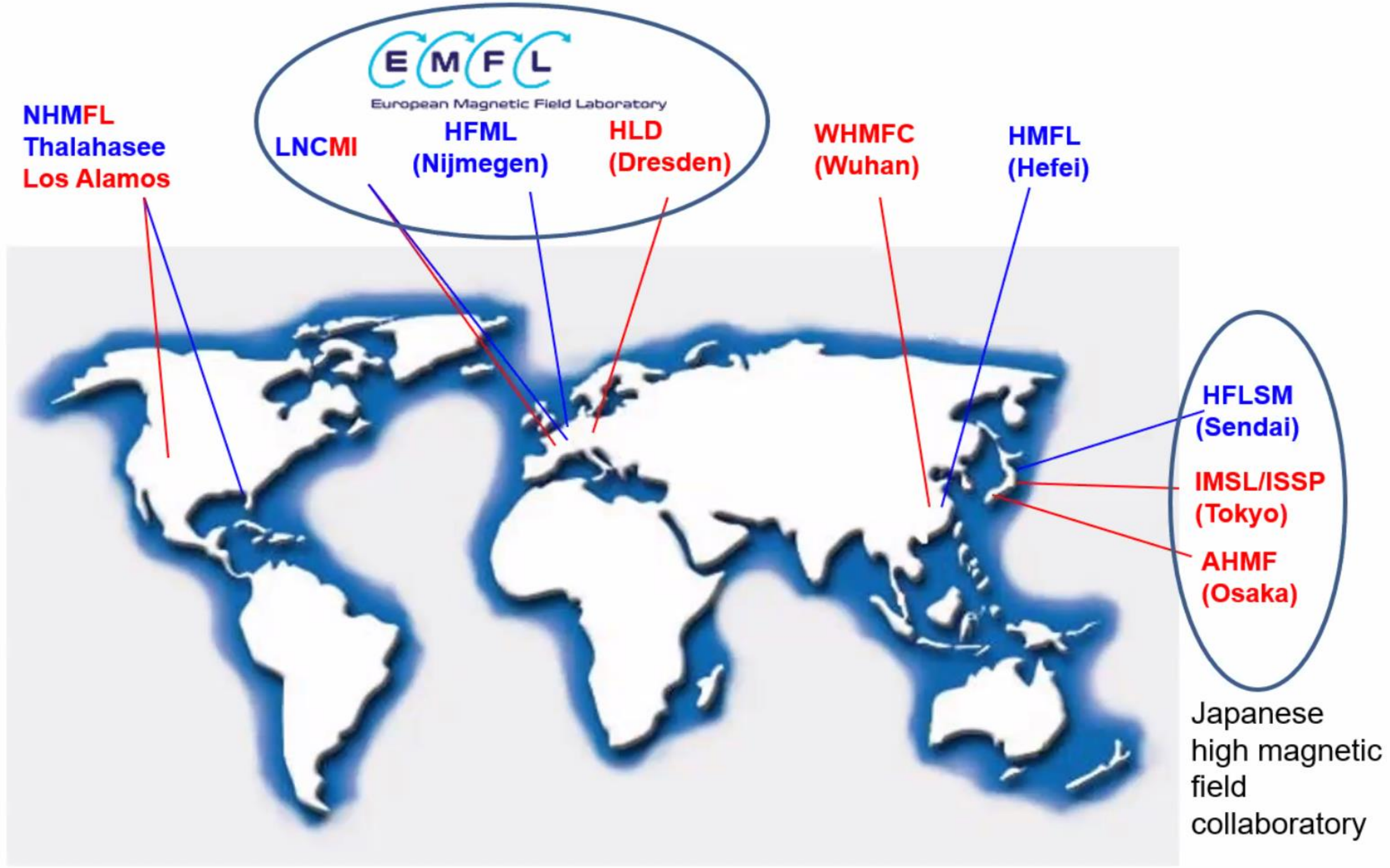
High Field Facilities - International Context

(**pulsed** and **DC**)



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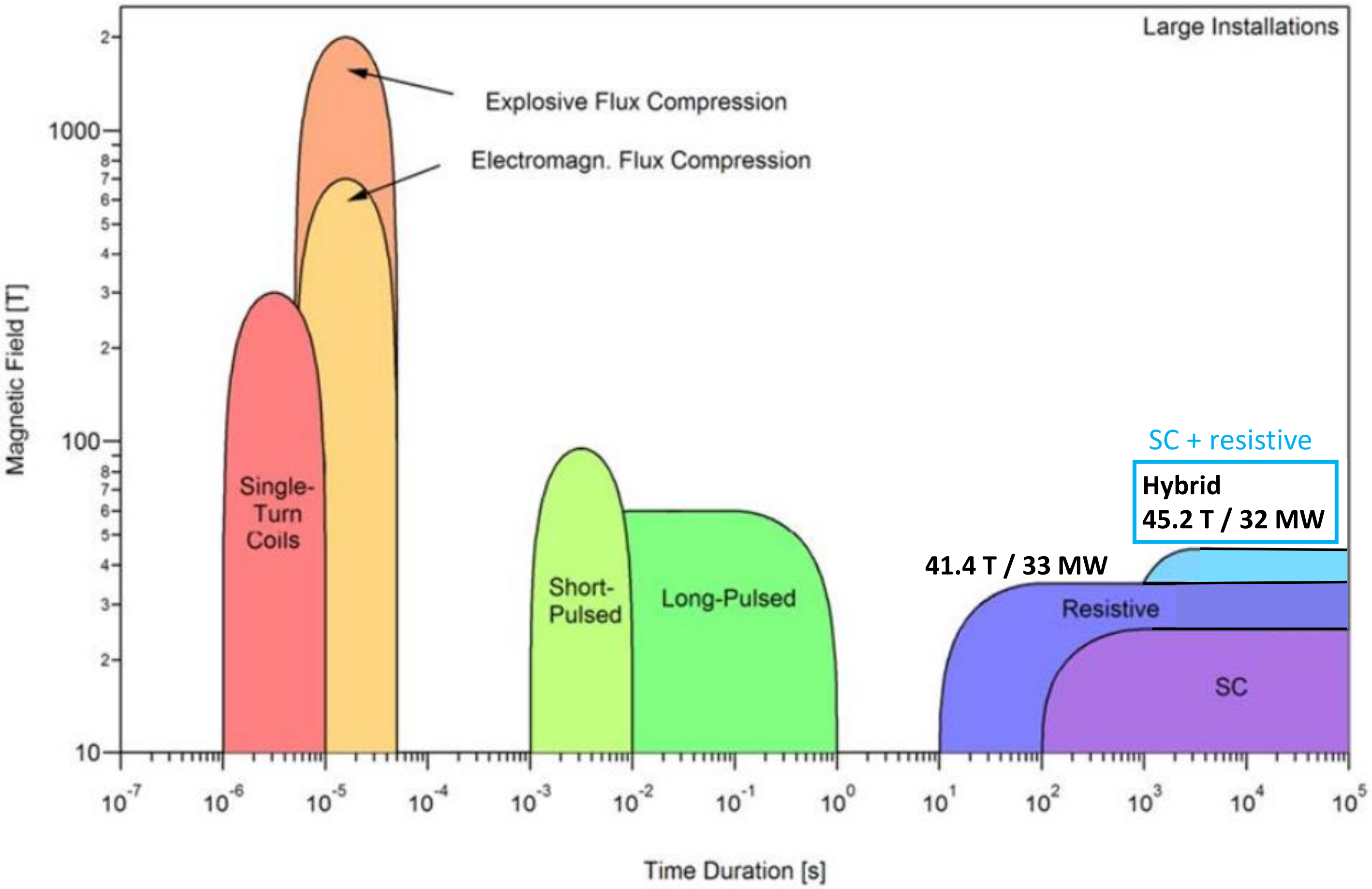
High Magnetic Fields for Science Today



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

Remarks for DC field produced by water cooled resistive magnets

1/ $B \propto P^{1/2}$

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

But…

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

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

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

*From G. Aubert, http://dx.doi.org/10.1088/0031-8949/1991/T35/036

Hybrid Magnets Worldwide Producing the highest DC-field

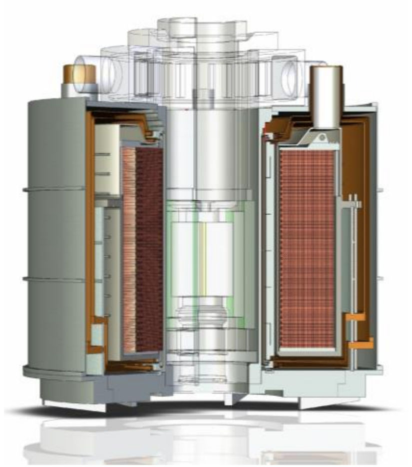
LNCMI

EMFL

HFML
Science in High Magnetic Fields

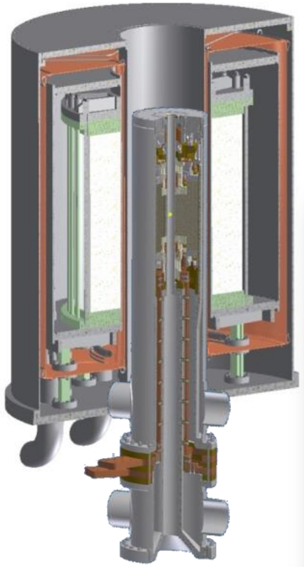
CHMFL

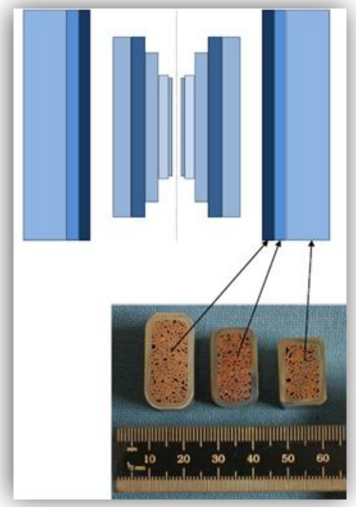
NATIONAL HIGH MAGNETIC FIELD LABORATORY

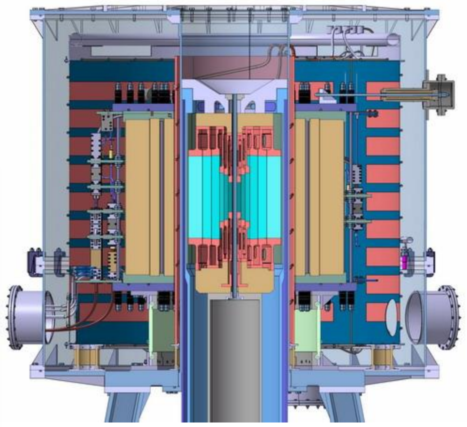


Specially developed
RCOCC conductor
13 x 18 mm^2

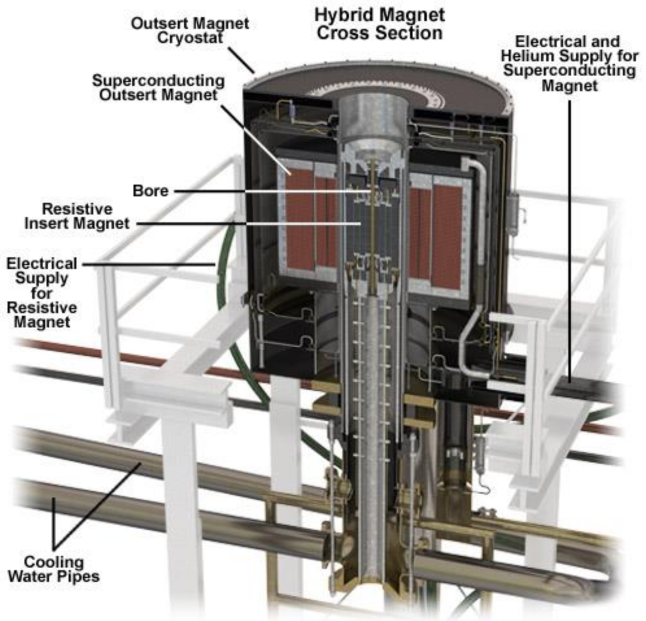
Key point
Modularity High field/high flux







Cooling by forced flow
supercritical He ~11g/s @ 5 bars



Grenoble, France	Nijmegen, Netherlands	Hefei, China	Tallahassee, FL
8.5 (9) + 34.5 (36+) = **43 (45+) T**	12 + 33 = **45 T**	11 + 34 = **45 T**	11.5 + 33.5 = **45 T**
34 mm, 24 (30) MW	32 mm, 24 MW	32 mm, 32 MW	32 mm, 32 MW
RCOCC Nb-Ti, 1.8 K	CICC Nb3-Sn, 4.2 K	CICC Nb3-Sn, 4.2 K	CICC Nb3-Sn, 4.2 K
7.1 kA, 1100/1826 mm dia.	20 kA, 720/1286 mm dia.	13.4 kA, 680/1650 mm dia.	10 kA
2025	**In construction**	**45.22 T Aug. 12, 2022**	**45.17 T June 26, 2000**

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Scientific case

- Why exploring the Ultra-Low Energy Frontier of Particle Physics ?

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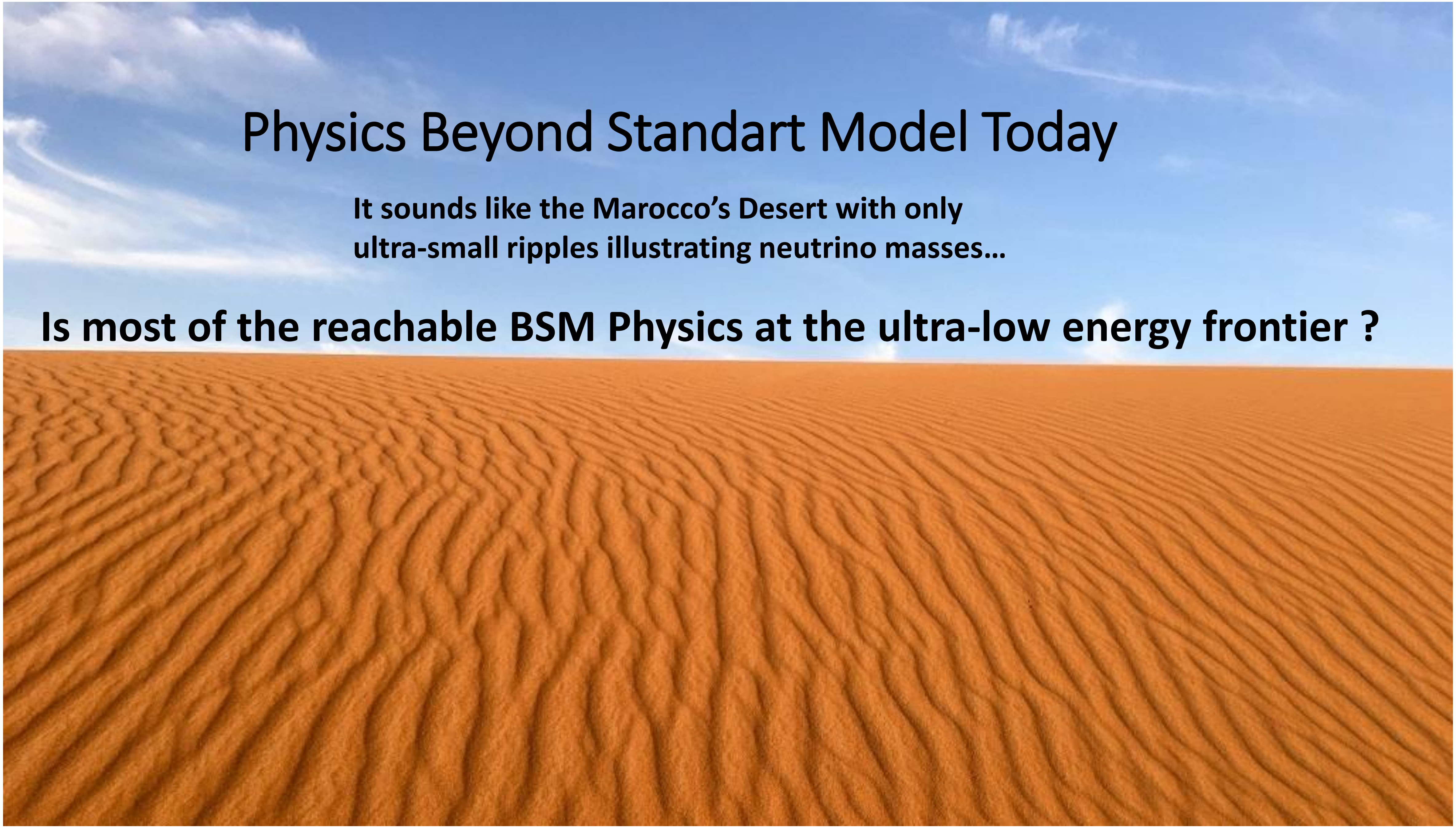
Physics Beyond Standart Model Today



It sounds like the Marocco's Desert with only ultra-small ripples illustrating neutrino masses…

Is most of the reachable BSM Physics at the ultra-low energy frontier ?

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

- Strong CP problem

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

$$L_{\cancel{CP}} = (\theta_{gluons} + \theta_{quarks}) \frac{\alpha_S}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

From precise measurements of the neutron EDM,

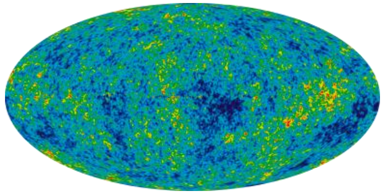
$$\theta_{gluons} + \theta_{quarks} < 10^{-10}$$

Nearly perfect compensation originating from 2 independant physics !! … Why ?

Why the CP symetry is so badly broken by QCD ?

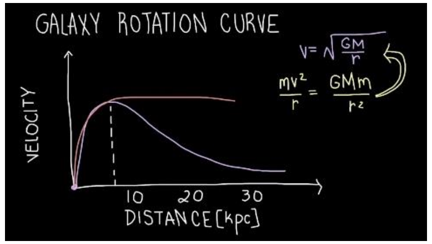
By adding a new global quasi-symmetry U(1)$_{PQ}$, which can be spontaneously broken, the axion appears as a natural Golston boson & the signature of the solution to the strong CP problem

- Standart Model of Cosmology $\supset$ Dark Matter



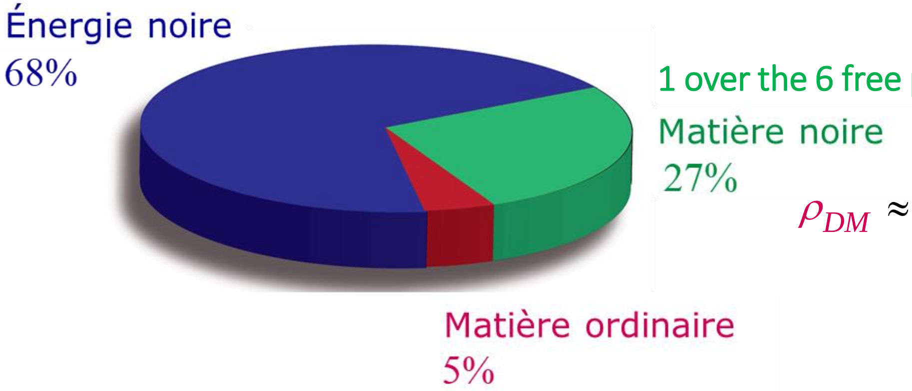
CMB

Bullet cluster



Galaxy rotation …

More than 10 experimental facts in favour of CDM



1 over the 6 free parameters of Λ-CDM

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

This in the context of none supersymetry detected at LHC nor WIMPS in underground experiments…

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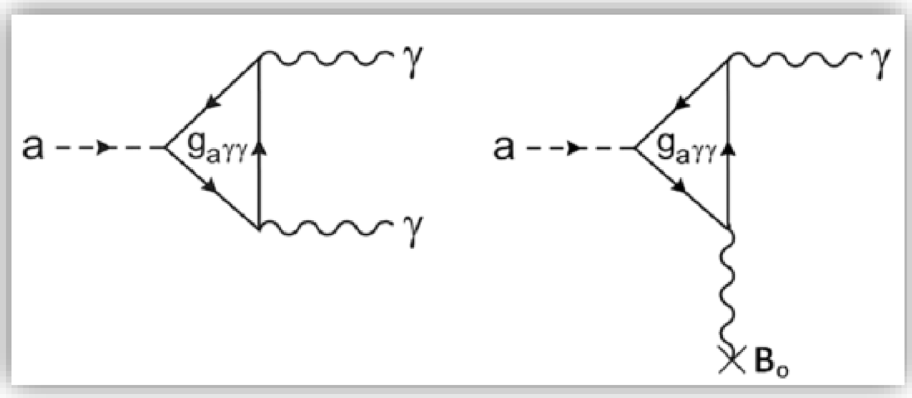
Why High Magnetic Fields & Flux for Axion/ALPs search ?

To observe the inverse Primakoff Effect



The key ingredient of most of the experiments

$$P_{LSW} \propto g_{a\gamma\gamma}^{4}\, B^4 L^4$$

$$P_{Haloscope} \propto g_{a\gamma\gamma}^{2}\, B^2 V$$

Note: This "non-trivial" interaction is related to the chiral anomaly, i.e. a purely quantum phenomenon first studied in particle physics in 1969 (Adler, Bell and Jackiw) explaining the neutral pion decay in 2 photons ($\pi \rightarrow \gamma\ \gamma$) anticipated and observed by Primakoff in 1951. The puzzle was the anomalous nonconservation of a chiral current.

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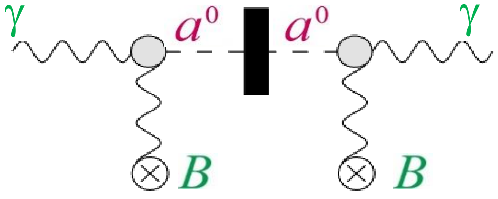
Main caracteristics of the QCD & CDM Axion

CDM Axion mass & density: $m_a = (1-1000)\,\mu eV \rightarrow \rho_{DM} \approx (10^{11} - 10^{14})\; axions / cm^3$

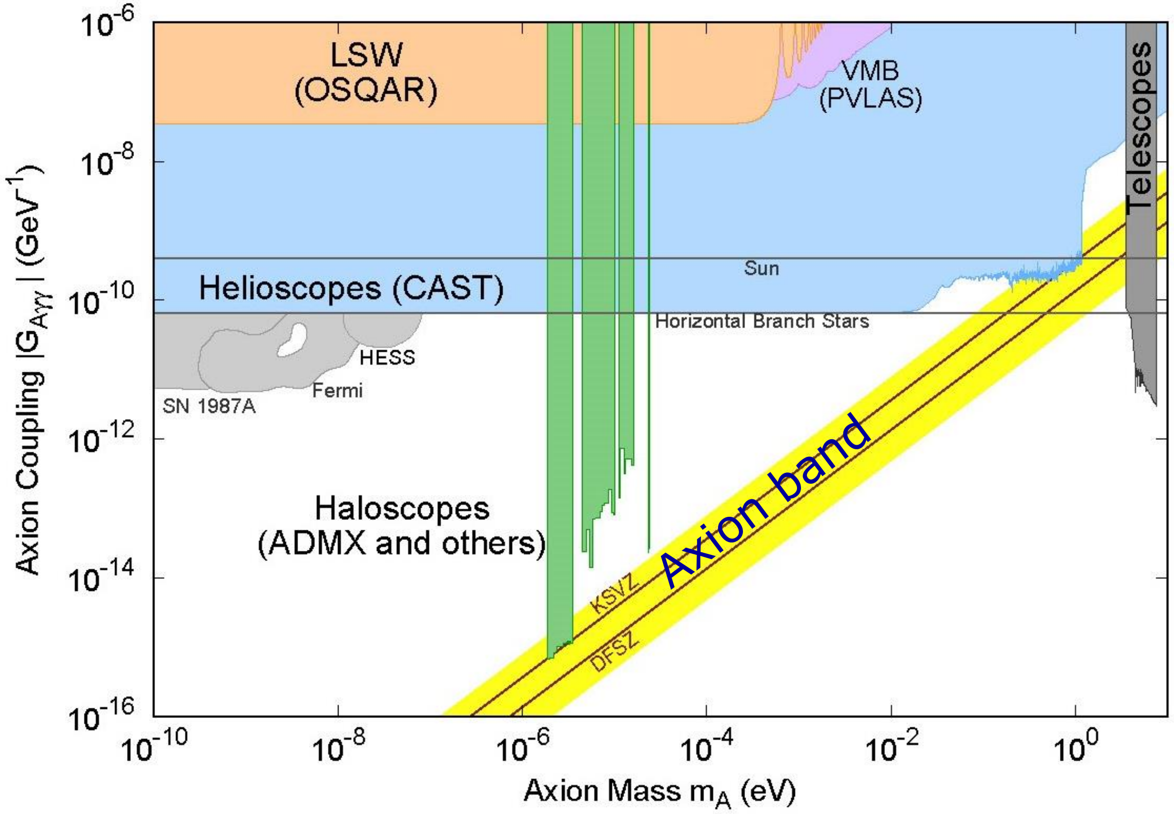
Coupling to 2-photons via inverse Primakov Effect: $G_{a\gamma\gamma}$ inversely proportional to m_a for QCD axion not for ALPs

Experiments

Light Shining through Wall

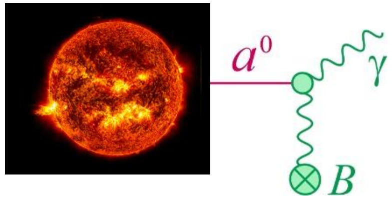


Reactoscope

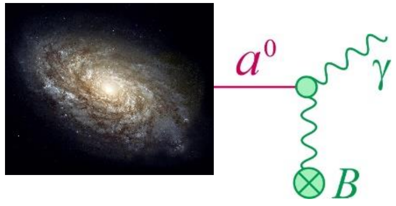


Observatories

Helioscopes



Haloscopes



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Various approaches for Axion/ALPs searches

	Magnet Type
Purely Laboratory Experiments	
- LSW *i.e.* Light Shining through Wall (BFRT, ALPs, OSQAR, ALPs-II, JURA)	Dipole/Racetrack
- Quantum vacuum polarization measurements (BFRT, PVLAS, BMV, VMB@CERN)	Dipole/Racetrack
- Reactoscopes *i.e.* with nuclear reactor	Dipole or Solenoid
"Model dependent" Experiments/Observatories	
- Helioscopes (CAST, BabyIAXO, IAXO)	Dipole/Racetrack
- Sikivie's Haloscopes (ADMX, CAPP-MAX, GrAHal,…)	Solenoid
- Dielectric and other Haloscopes (MADMAX, ALPHA…)	Dipole or Solenoid

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From OSQAR toward JURA (Joint Undertaking Research of Axions/ALPs)

- Reminder about OSQAR & LHC dipoles operating at 9 T
- Magnet requirements for JURA

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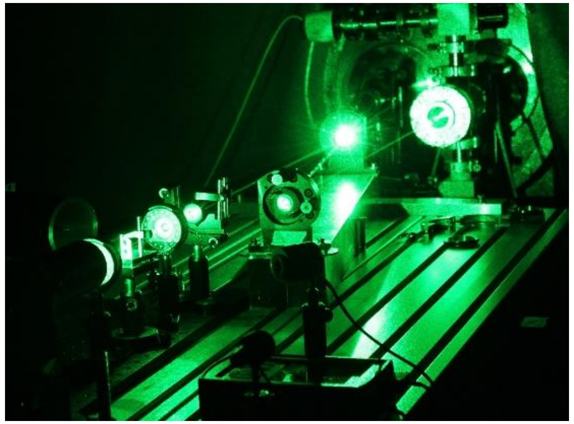
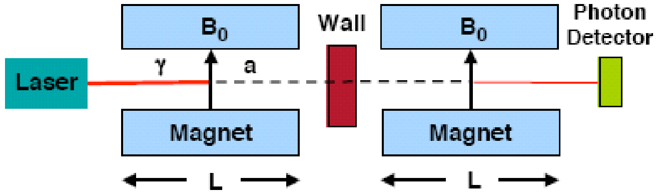
OSQAR – LSW (Light Shinning through Wall)

ALPs search from laser based experiment

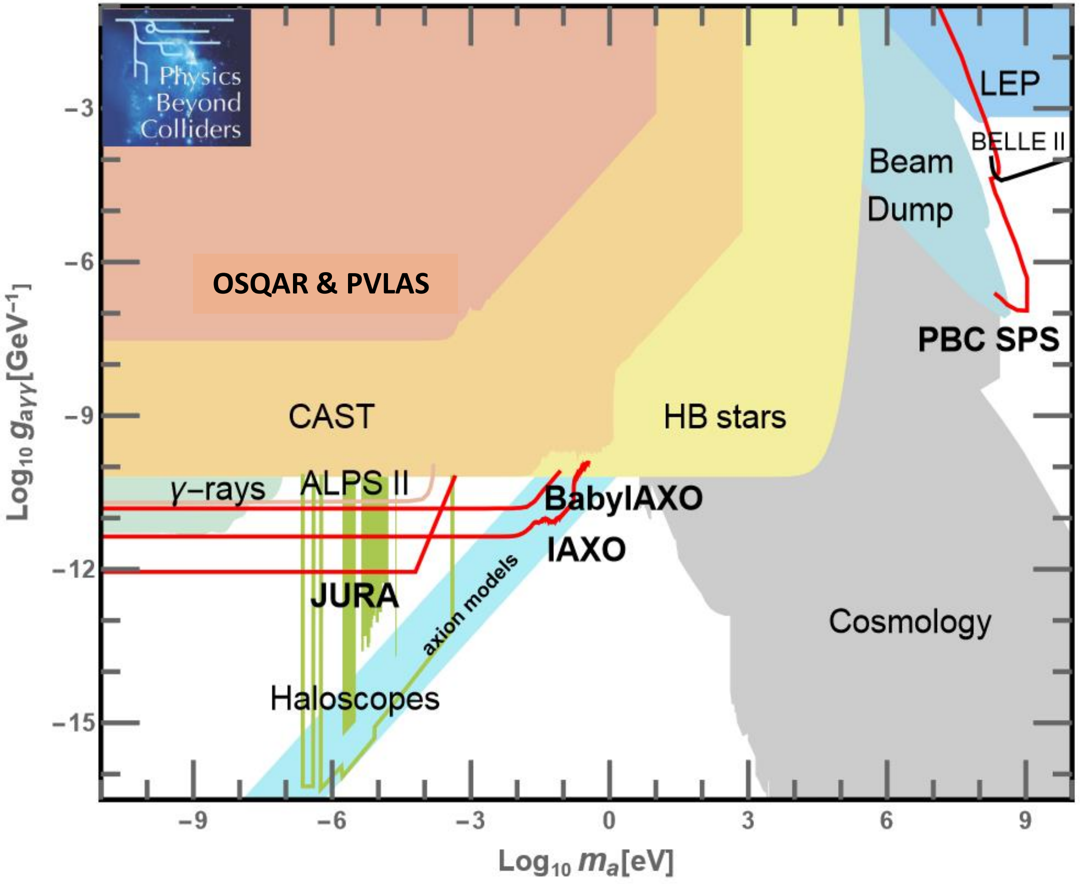
- Present reference results* for laser experiment based on the use of 2 LHC dipoles **powered up to 9 T** in CERN-SM18 hall



**OSQAR, Phys. Rev. D 92, 092002 (2015)*



Magnetic Figure Of Merit (MFOM)
B L = 14.3 x 9 = **129 T m**



https://arxiv.org/pdf/1902.00260.pdf

- OSQAR will be soon overpassed by ALPS II at DESY with 12 + 12 Hera dipoles providing B L ≈ 12 x 9 x 5 = **540 T m** and more powerful optics
- Future within JURA (Joint Undertaking Research of Axion)
  - OSQAR+ within the framework of Baby-JURA (under consideration with more than 2 LHC dipoles)
  - JURA could be based on the use of up to 15 + 15 spare LHC dipoles providing B L ≈ 15 x 14.3 x 9 = **1930 T m**

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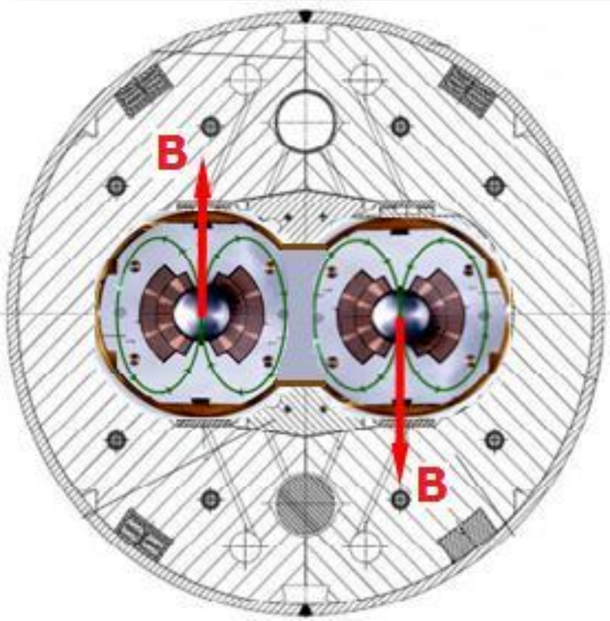
Can we built better dipoles than LHC ones ? Yes we can,… but the key question for FCC-hh is how many T.m more for a serie production ?

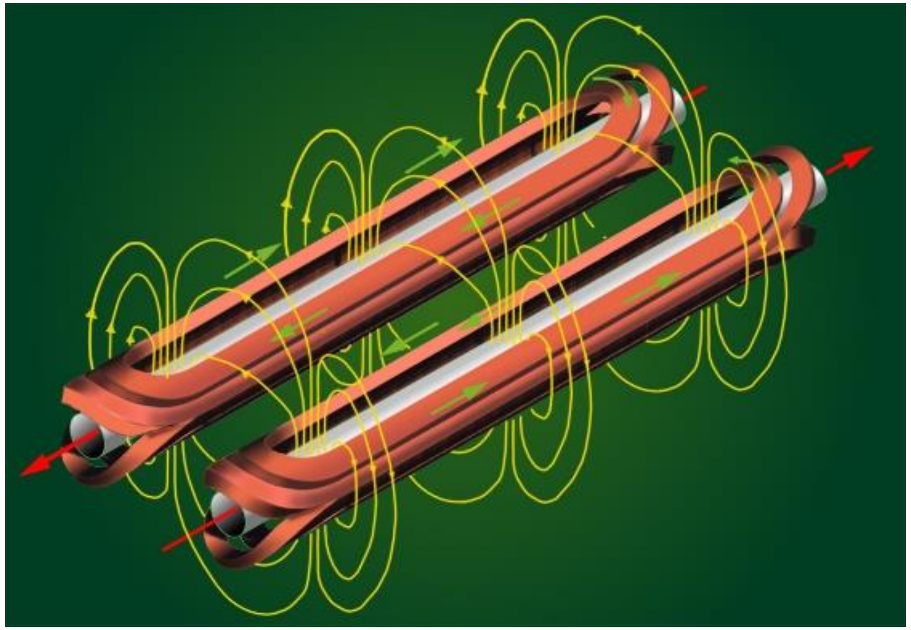
The present target for FCC-hh is 16 T Nb_3Sn dipole either block or $cos\theta$ structure with 14.3 m magnetic length, which is already very challenging…

If one assumes 15 + 15 FCC dipoles of 16 T, the MFOM becomes 15 x 14.3 x 16 = **3432 T m,** a gain in sensitivity less than 2 with respect to LHC dipoles… Wouldn't it better to try to push LHC dipoles up to 9.5 T giving MFOM(15) = 2038 T.m or/and use more LHC dipoles ? T**his is for me the MORE REALISTIC WAY…**



2-in-1 LHC dipole
providing 9 T over 14.3 m

Let me ask an embarassing question: Why so many training quenches of LHC dipoles in the tunnel and why the nominal field of 8.3 T not yet reach ?



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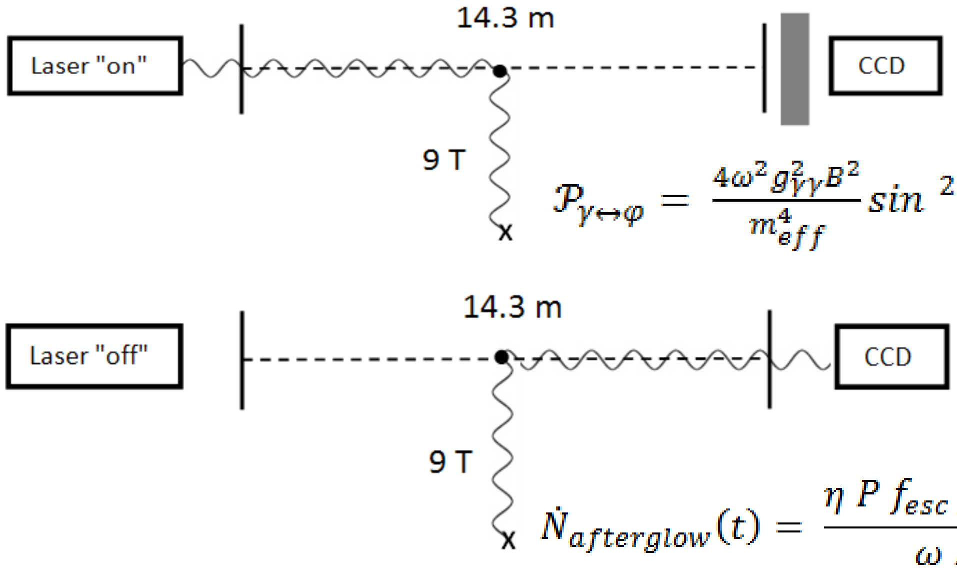
OSQAR – CHASE (CHAmeleon Search Experiment)

Chameleon afterglow search from laser based experiment

Contact: pierre.pugnat@lncmi.cnrs.fr

- Chameleon is an hypothetical scalar particle with mass dependent of the surrounding density, which could explain Dark Energy

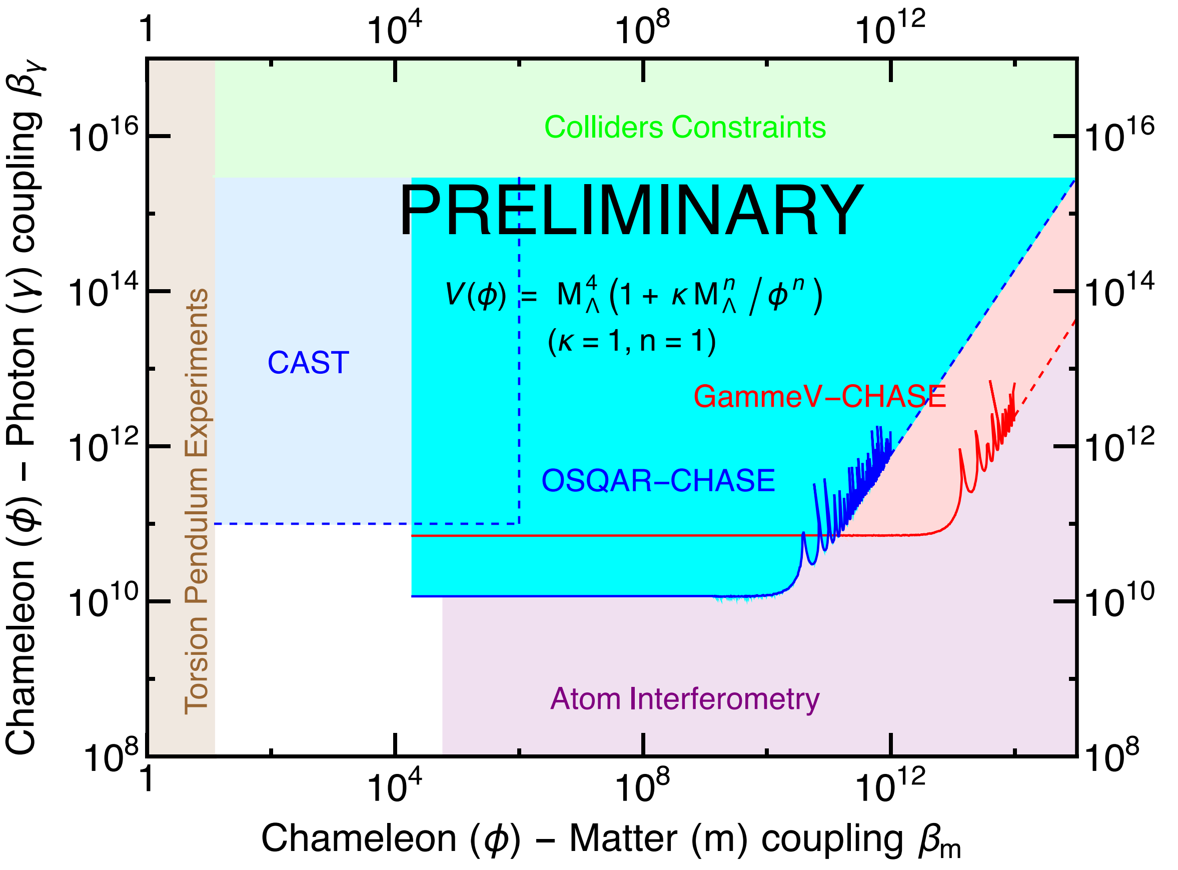
- Experiment in 2 steps



$$\mathcal{P}_{\gamma\leftrightarrow\varphi} = \frac{4\omega^2 g_{\gamma\gamma}^2 B^2}{m_{eff}^4} sin\,^2(\frac{m_{eff}^2 L}{4\omega})$$

$$\dot{N}_{afterglow}(t) = \frac{\eta\ P\ f_{esc}\ f_{vol}\ \mathcal{P}_{\gamma\leftrightarrow\varphi}\,^2\ c}{\omega\ \Gamma\ L_{total}}(1 - e^{-\Gamma\Delta t})e^{-\Gamma t}$$

A.S. Chou et al., Phys. Rev. Lett. **102** 030402 (2009)



OSQAR, NIMA 936 (2019) 187-188 & to be published

http://cds.cern.ch/record/2001850/files/SPSC-P-331-ADD-1.pdf

From GrAHal toward Super-GrAHal

- BabyGrAHal & GrAHal
- The 43+T Grenoble Hybrid Magnet in commissioning phase
- Conceptual design optimization of a 60 T Hybrid Magnet

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Few Words from P. Sikivie (Haloscopes proposed in 1983, Rev. Mod. Phys. 93, 015004)

Visit of Olympie during 2nd Patras Workshop in 2006 at Patras

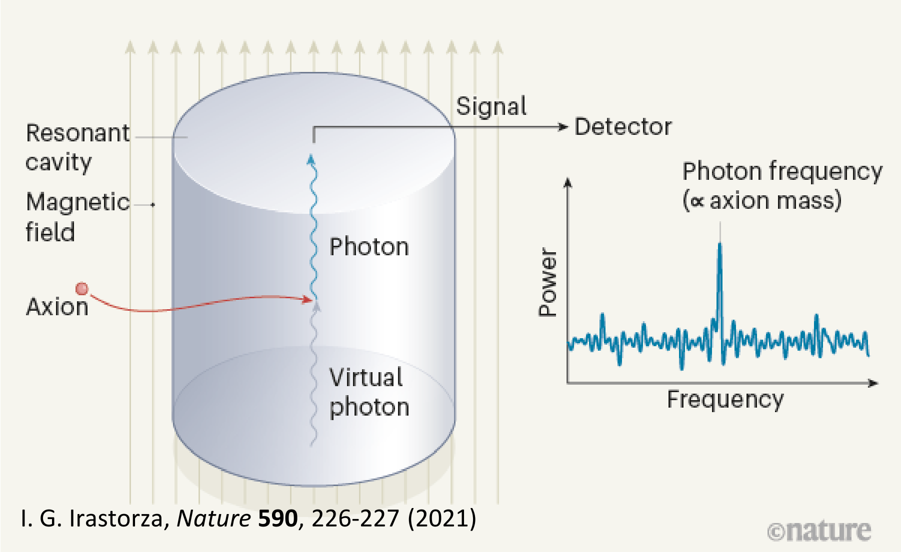
Axion electrodynamics

$$\nabla \cdot \mathbf{E} = g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = g_{a\gamma\gamma} \left(\mathbf{E} \times \nabla a - \mathbf{B} \partial_t a \right)$$

$$\nabla \times \mathbf{E} + \partial_t \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$



I. G. Irastorza, *Nature* **590**, 226-227 (2021)

“ Most importantly, the cavity experiment uses a variety of technologies - microwave engineering, ultra-low noise receivers in a high magnetic field environment, cryogenics - which are not typically used by high energy physicists and which had to be specially developed.

… Feynman's advice to young scientists aspiring to great discoveries. He said: "You have to develop your own tools". ”

https://ep-news.web.cern.ch/content/qa-pierre-sikivie

Context of GrAHal

Grenoble Axion Haloscopes

Key expertise at CNRS-Grenoble for High magnetic fields, Extreme Low Temperatures & Quantum Detectors

Université Grenoble Alpes

European Magnetic Field Laboratory

LNCMI

Dresden/LNCMI-Toulouse, pulsed up to 95/91 T, 1-10 ms

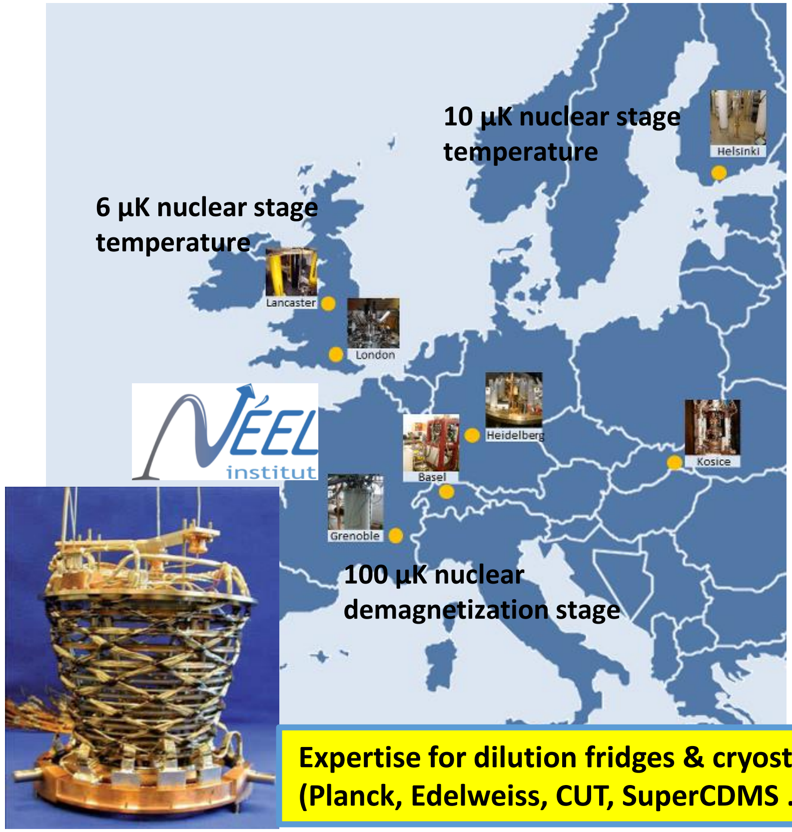
Nijmegen/**LNCMI-Grenoble**, DC up to 38/36 T, Projects 45/43+ T

https://emfl-users.lncmi.cnrs.fr/SelCom/proposals.shtml

European Microkelvin Platform

20 leading ultralow temperature physics & technology Institutes in Europe including 7 submilliK facilities

http://emplatform.eu/about/facilities

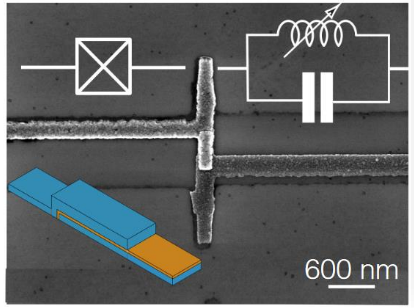


Expertise for dilution fridges & cryostats (Planck, Edelweiss, CUT, SuperCDMS …)

institut Néel

https://www.cnrs.fr/cnrsinnovation-lalettre/actus.php?numero=743

JPA Achievements



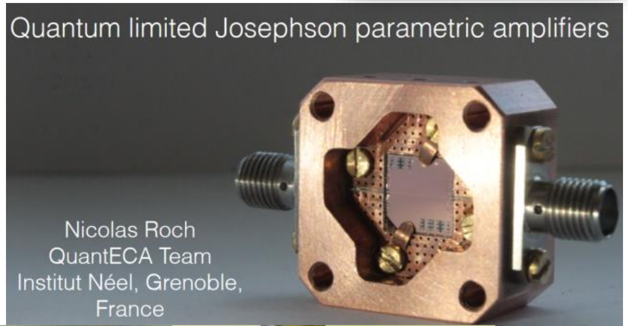
$1\ \text{GHz} < f_o < 10\ \text{GHz}$

$G \geq 20\ \text{dB}$

$BW \sim$ 2 GHz

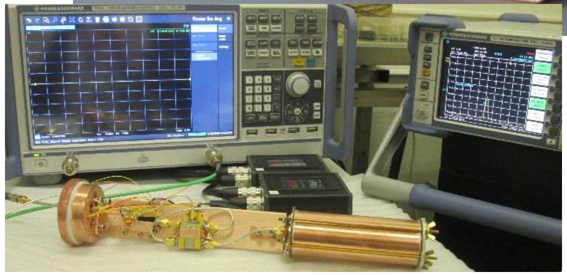
$T_N \gtrsim \frac{hf_o}{2k_B}$

$P_{1dB} \sim -100\ \text{dBm}$



Quantum limited Josephson parametric amplifiers

Nicolas Roch
QuantECA Team
Institut Néel, Grenoble,
France



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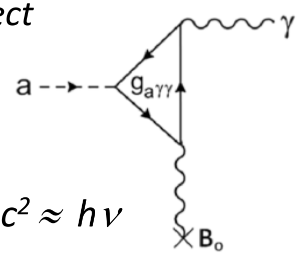
GrAHal

Grenoble Axion Haloscopes

► The key element : The modular Grenoble Hybrid Magnet combining sc and resistive technologies (ongoing commissioning up to 43 T)

Inverse Primakoff Effect



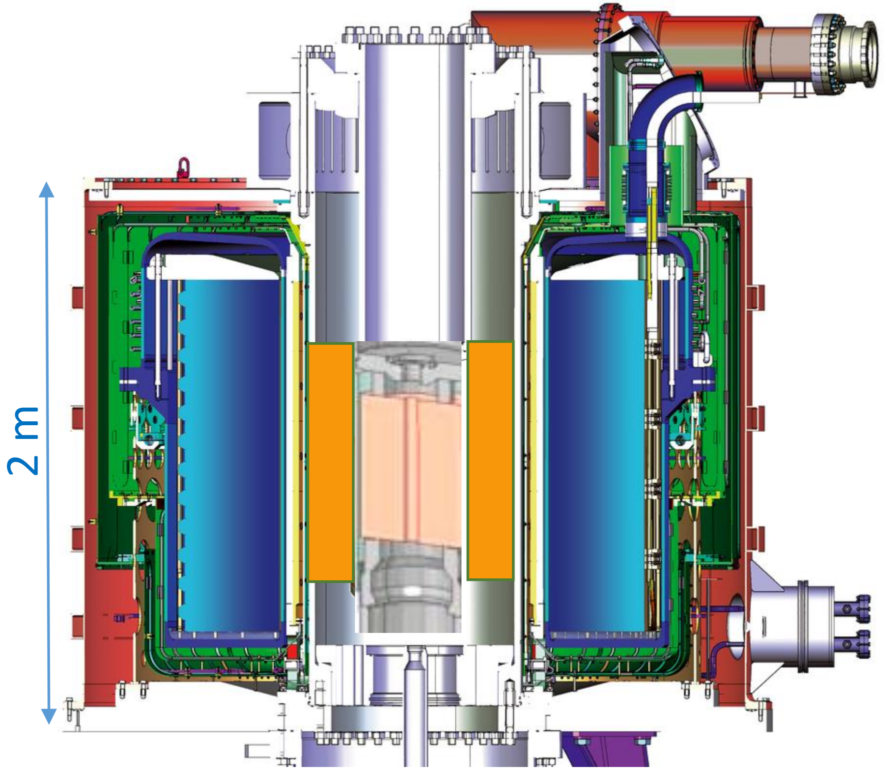
$m_a c^2 \approx h\nu$

Sikivie's haloscope, i.e. with RF cavity

$11.5\ \mathrm{GHz}/f_{TM010} = R/1\ \mathrm{cm}$

$P\ \alpha\ g_{a\gamma\gamma}^2 B_0^2 V < 10^{-25}\ W$

$df/dt\ \alpha\ B_0^4 V^2$



Field	Warm dia.	Power	RF-cavity dia.	f_{TM010}	Axion mass	B^2V (T^2m^3)
43 T	34 mm	25.4 MW	20 mm	11.5 GHz	47.2 μeV	0.5
40 T	50 mm	25.4 MW	34 mm	6.76 GHz	27.8 μeV	0.6
27 T	170 mm	19 MW	86 mm	2.67 GHz	11 μeV	3.5
17.5 T	375 mm	12.9 MW	291 mm	0.79 GHz	3.2 μeV	6.6
9 T	800 mm	0.4 MW	675 mm	0.34 GHz	1.4 μeV	40

► Operation end of 2024-25 with HTS RF cavity in collaboration with CAPP/IBS-KAIST

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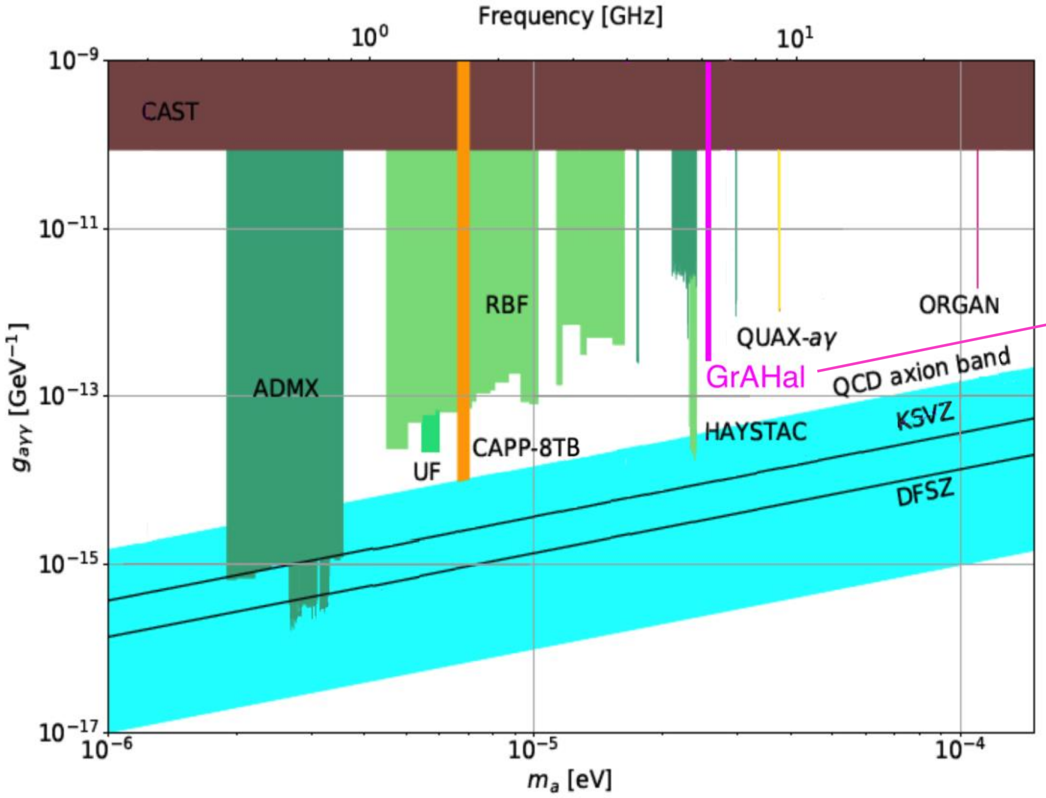
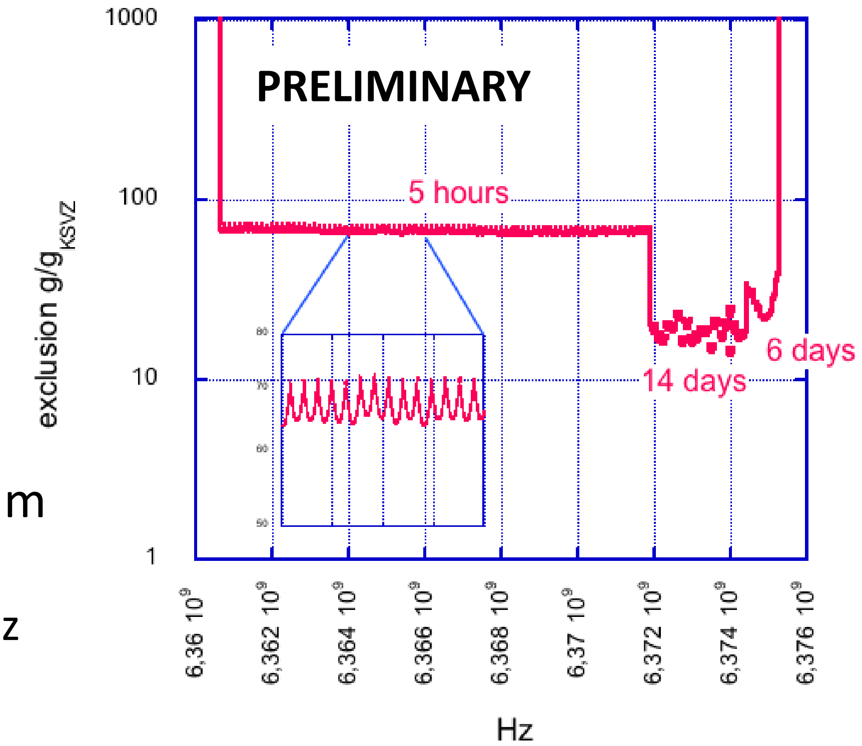
Baby-GrAHal 1: Experimental Runs Ended



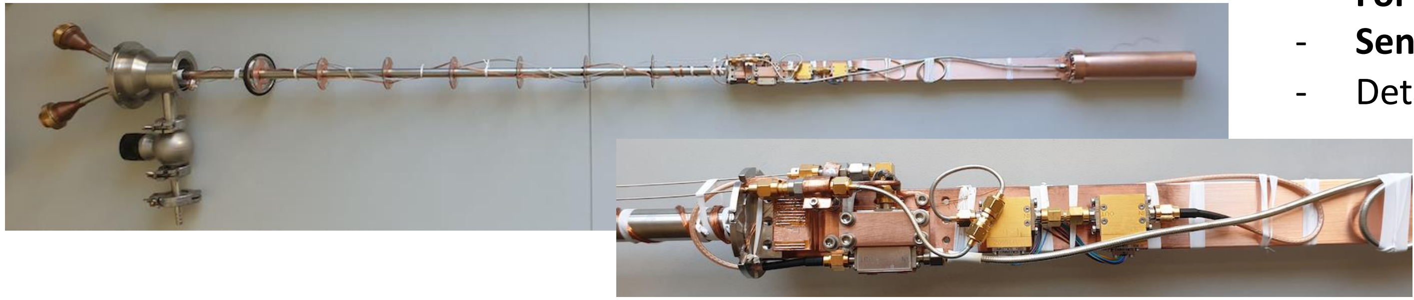


14 T @ 4 K in 36 mm cavity dia.

i.e. around 6.375 GHz or 26.37 μeV

The RF-cavity resonant frequency was tuned & scanned by varying the GHe pressure around the cavity :

- **For the range 1-1200 mbar, excursion Δf = 20 MHz, i.e. ~ 0.1 μeV**
- **Sensitivity in the range of 20-25 x KSVZ @ 4.4 K**
- Detailed data analysis close to completion (to be published)



T. Grenet et *al.*
https://arxiv.org/abs/2110.14406

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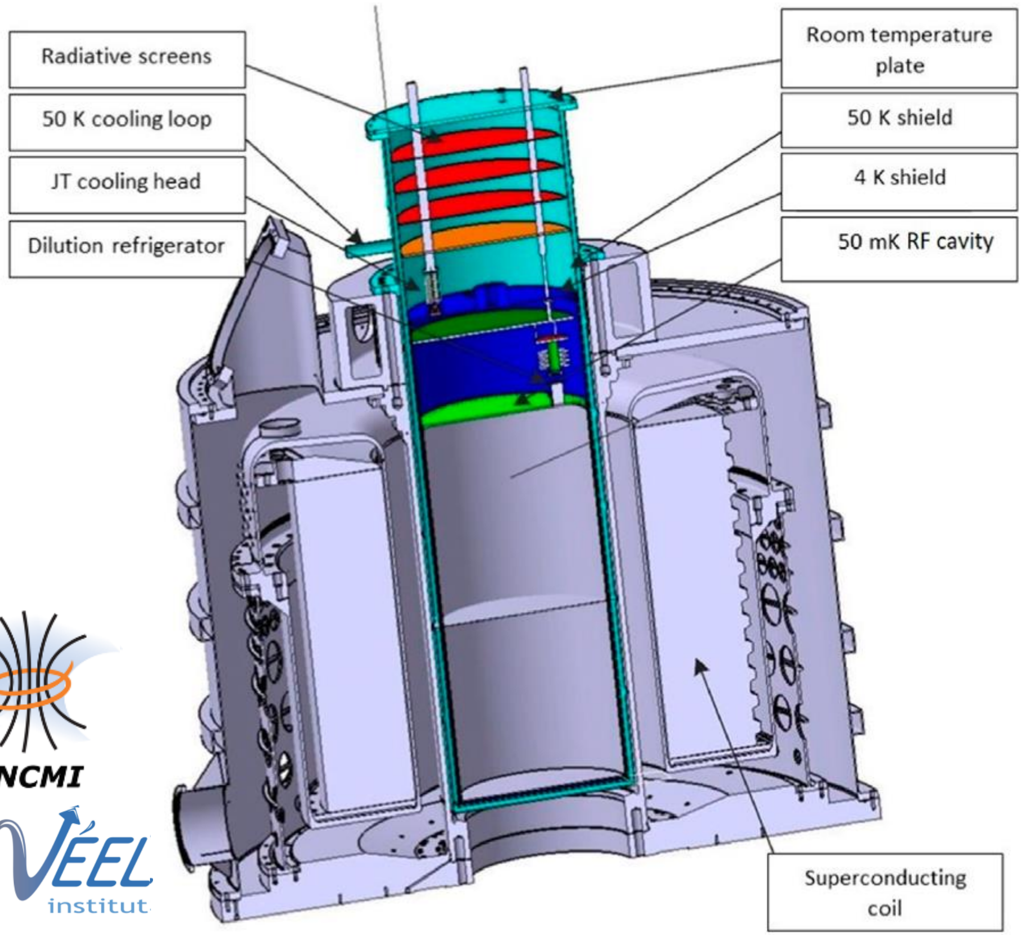
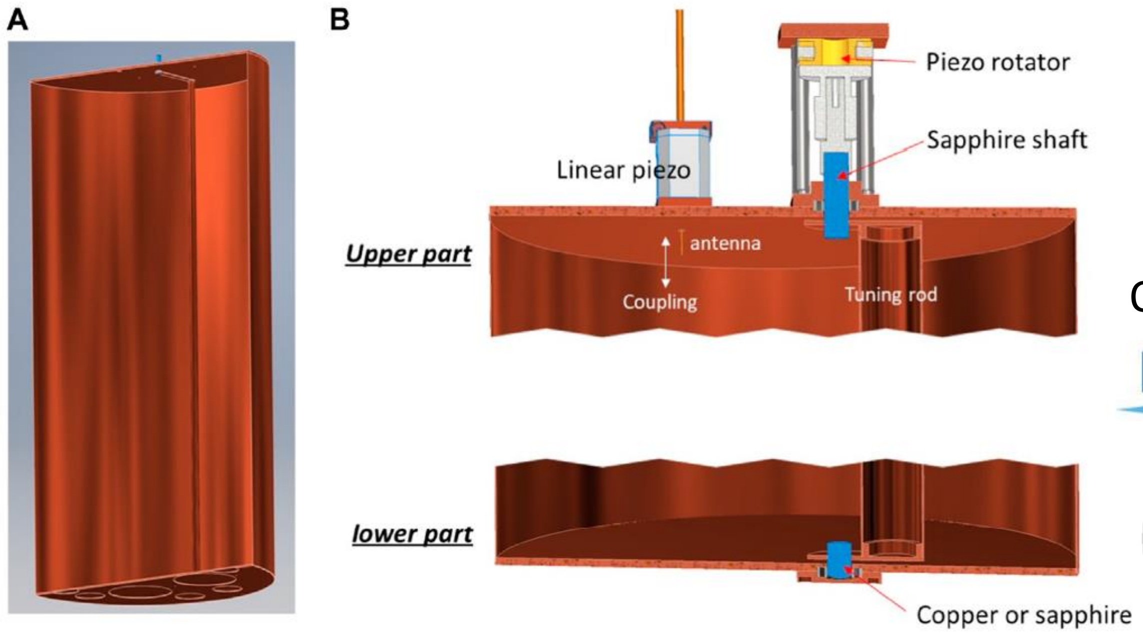
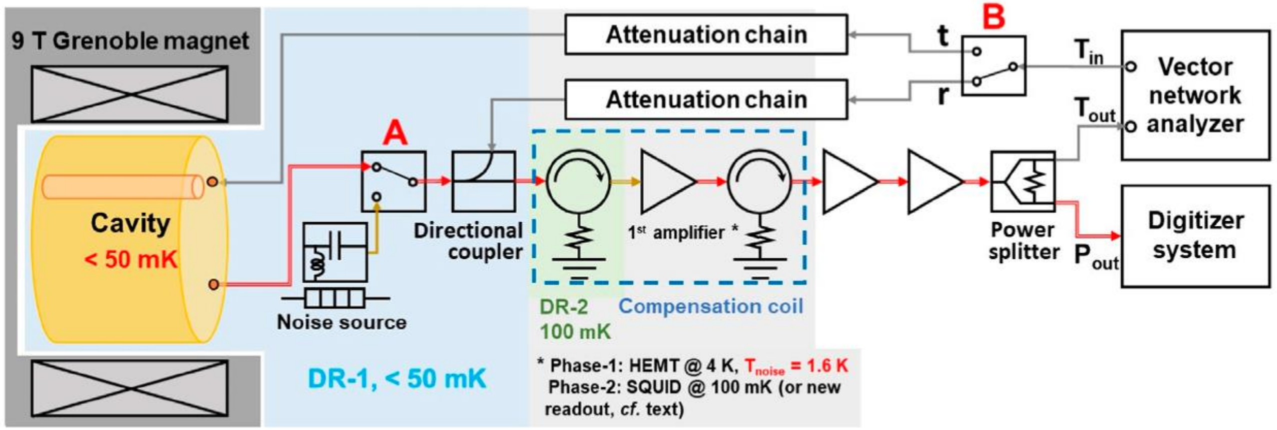
GrAHal-CAPP ► *Focus on 1-3 μeV axion mass (200-600 MHz)*





O. Kwon

KAIST



* Phase-1: HEMT @ 4 K, T_{noise} = 1.6 K
Phase-2: SQUID @ 100 mK (or new readout, *cf.* text)

Cryogenic challenge
T ≤ 50 mK in 538 liters with ^{3}He dilution refrigerator
Ph. Camus & J. Vessaire (Institut Néel)

https://doi.org/10.3389/fphy.2024.1358810

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GrAHal

Grenoble Axion Haloscopes

Center for Axion and Precision Physics Research

LNCMI NÉEL institut KAIST IBS

Toward the most sensitive Haloscope worldwide

► *Focus first on 1-3 μeV axion mass (200-600 MHz)*

GrAHal-CAPP : Phase 1 @ 4K

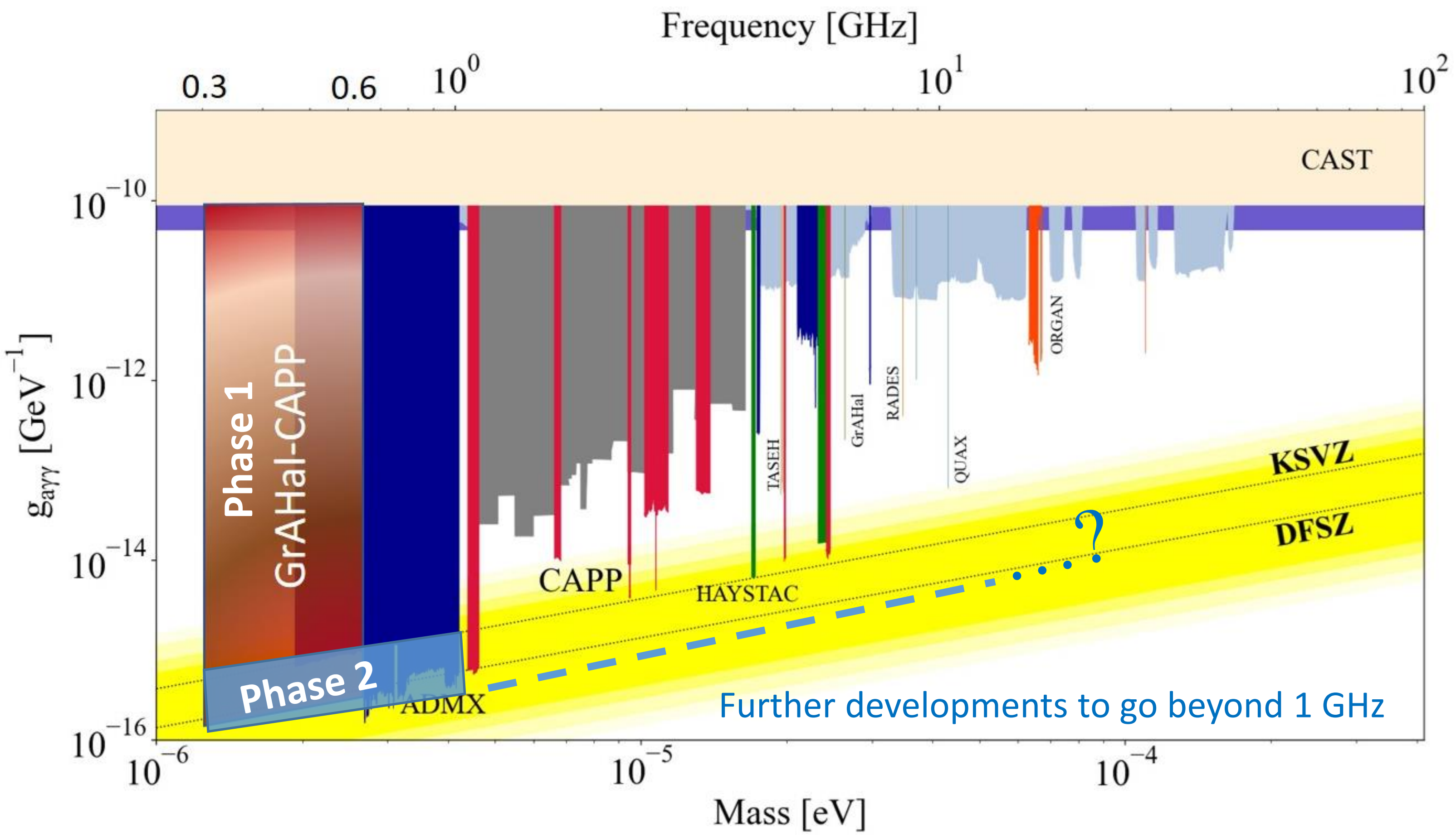
- 50 K cryo-stage operational @ t_0+18 months
- 4 K cryo-stage operational @ t_0+24 months

→ *1st run*

GrAHal-CAPP : Phase 2 @ 50 mK

- Operational @ t_0 + 42 months

→ *2nd run reaching DFSZ, in 2-year integration time*



Further developments to go beyond 1 GHz

https://doi.org/10.3389/fphy.2024.1358810

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The 43+T Grenoble Hybrid Magnet in commissioning phase

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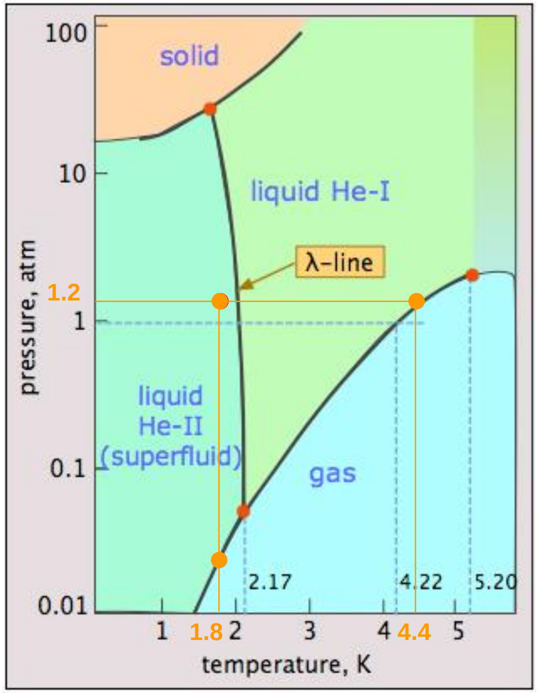
Technological Choices

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. Pugnat, R. Pfister, *et al.*, *IEEE Trans. Appl. Supercond.* 28, 4301005 (2018)
https://indico.cern.ch/event/659554/contributions/2714073/

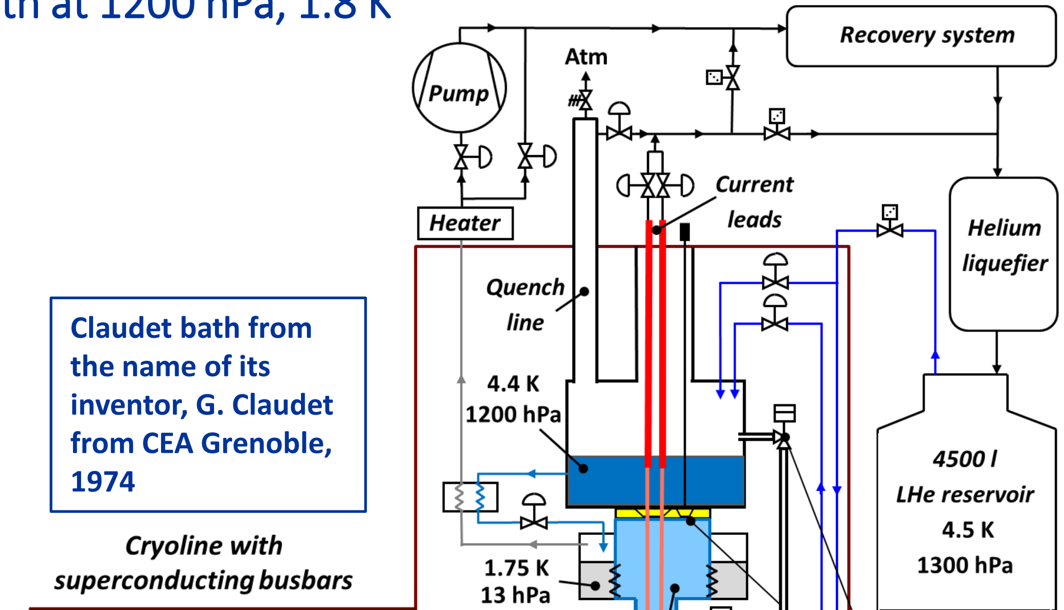
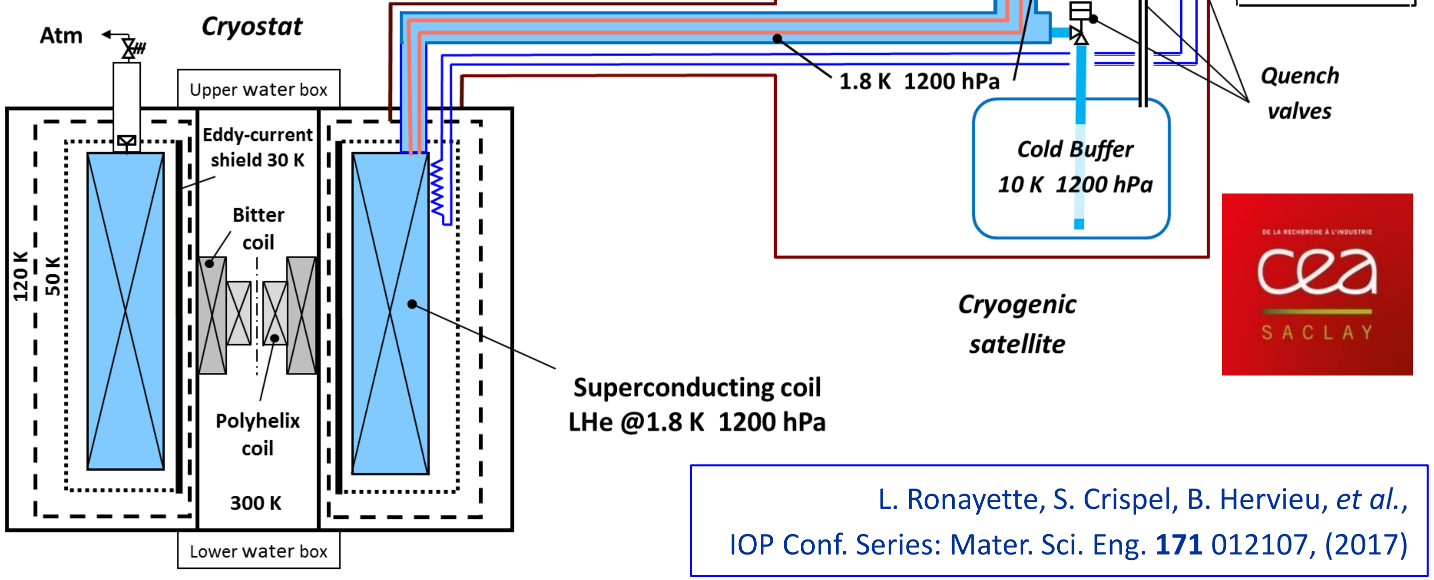
18 x 13 mm^2



Superfluid pressurized LHe bath @ 1200 hPa , 1.8 K

Cooling of the sc. coil with 1100 l of pressurized superfluid He

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

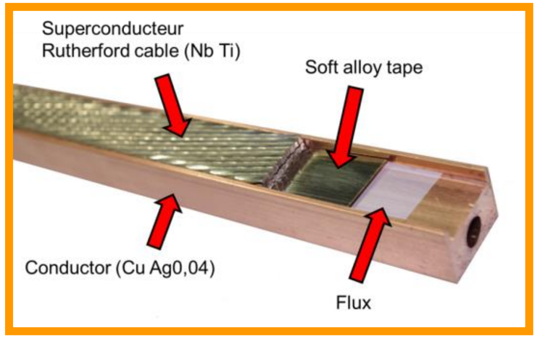



Claudet bath from the name of its inventor, G. Claudet from CEA Grenoble, 1974

Superconducting coil LHe @1.8 K 1200 hPa

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

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



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

P. Pugnat, R. Pfister *et al., IEEE Trans. Appl. Supercond.* **26**, 4302405 (2016)
https://indico.cern.ch/event/659554/contributions/2714073/

Crimping, soft-soldering, calibration & winding in single pancakes (260 m & 4 m hight) for delivery to the magnet manufacturer https://www.youtube.com/watch?v=cp5NlR2cN5s

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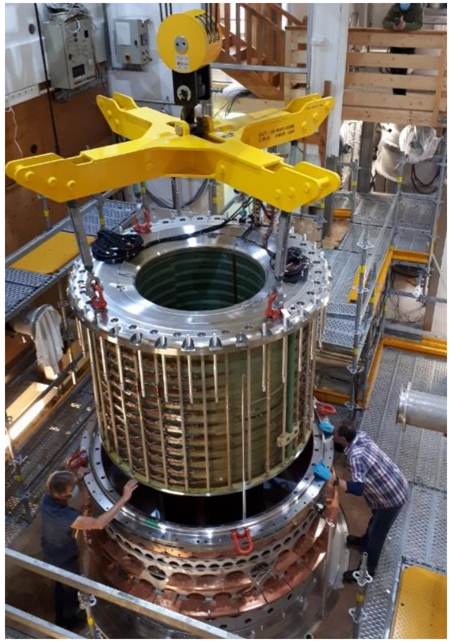
Some Assembly Steps



Insertion of the superc. coil inside the He vessel

sdms
la chaudronnerie
blanche ®

Welding of the He vessel

Assembly of the thermal shields

Installation of the last MLI sheet

Installation of the OVC

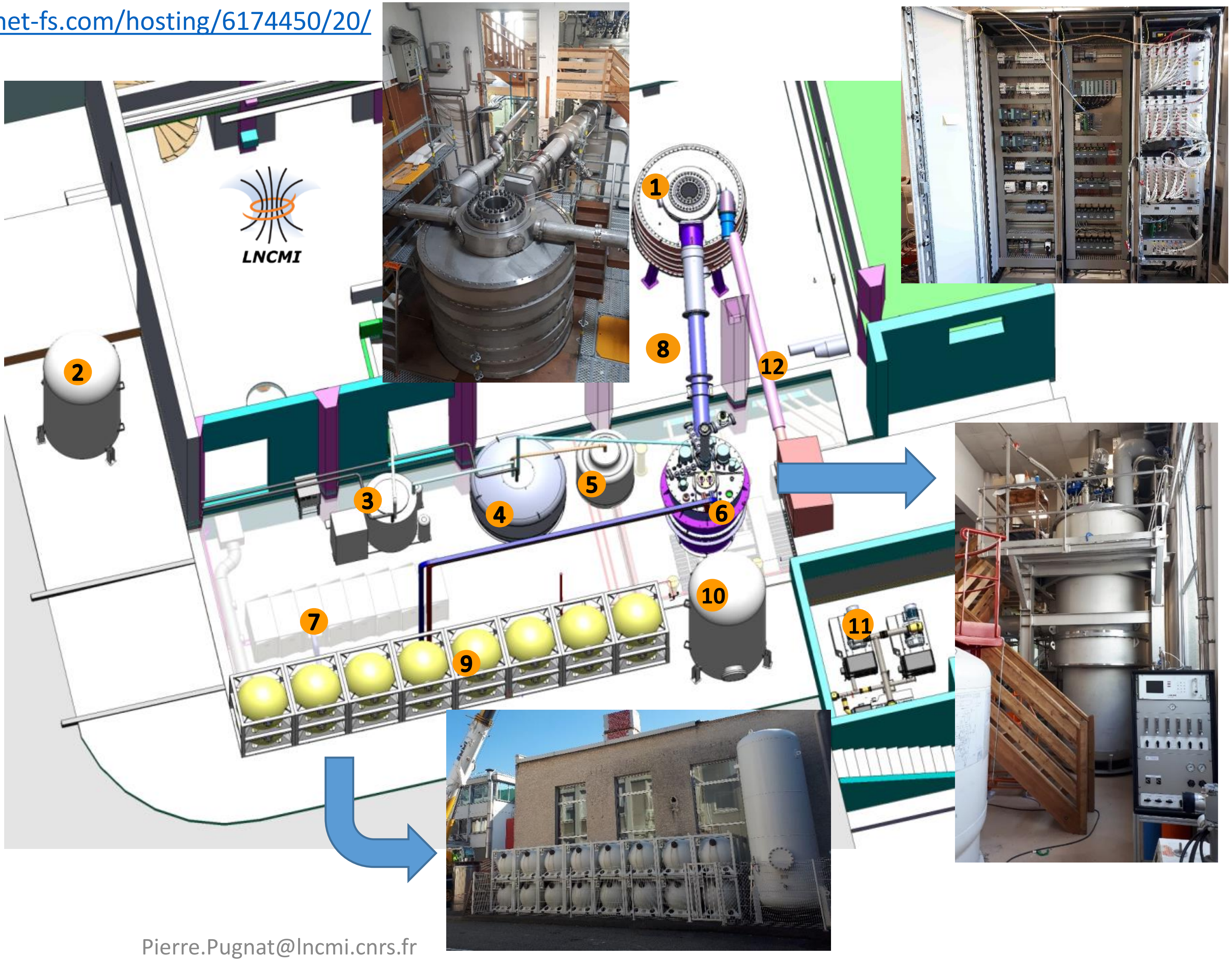
IEEE Transactions on Applied Superconductivity, vol. 32, no. 6, pp. 1-7, Sept. 2022, Art no. 4300607, doi: 10.1109/TASC.2022.3151838

Integration of the Grenoble Hybrid Magnet with its Cryogenic Plant

- All equipment built
- Final Assembly & Integration completed
- Commissioning Tests ongoing (final phase)

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

1	Superconducting Magnet
2	LN_2 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^3 @ 200 bars
10	Liquefier pure He buffer tank 15 m^3 @ 20 bars
11	Helium pumping system 6000 m^3/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^3 @ Patm
- He recovery compressor @ 200 bars
- 32 x 0.5 m^3 high pressure gaseous He tanks @ 200 bars
- Magnet Safety and Magnet Control Systems

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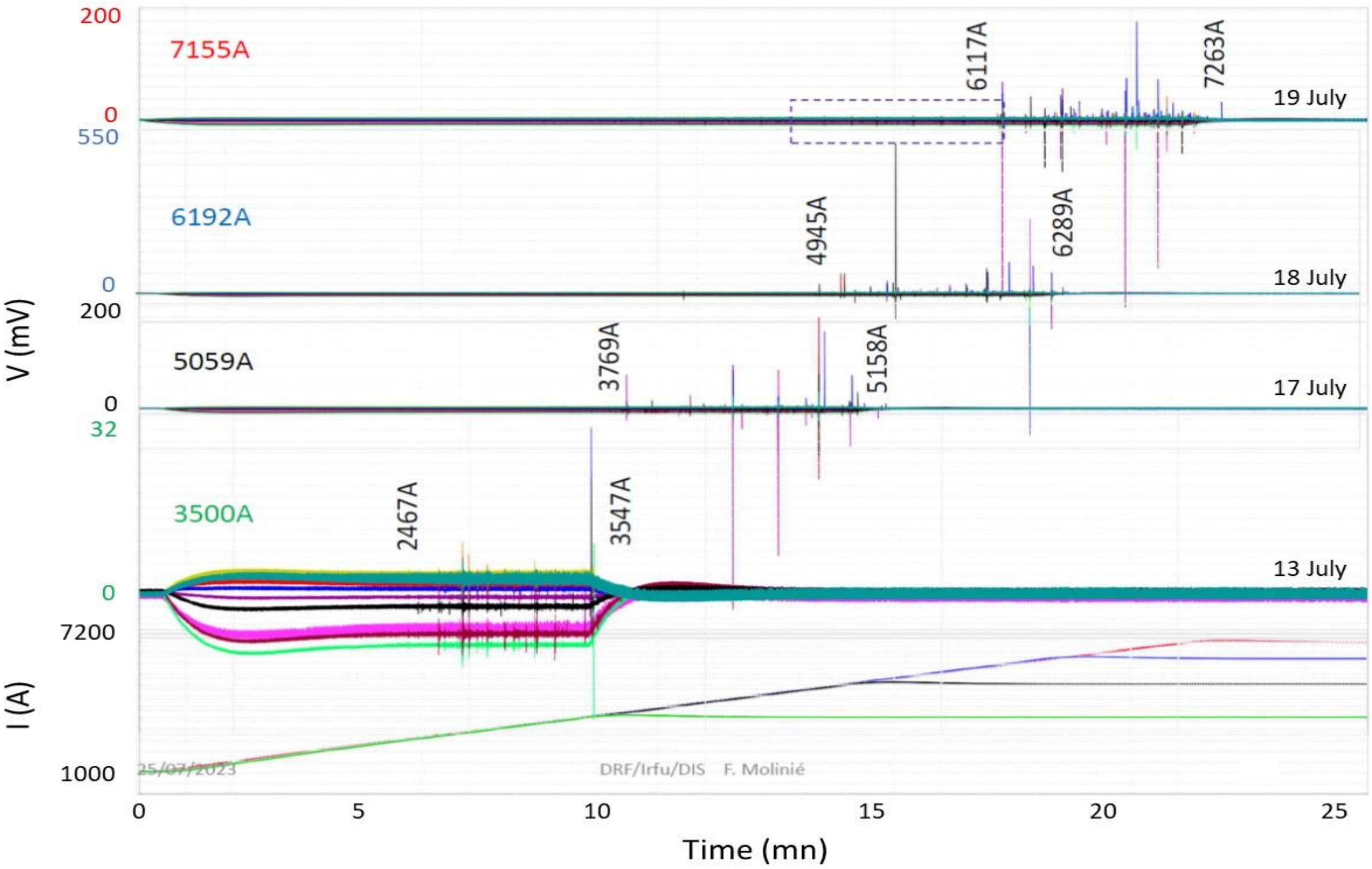
SC Magnet Seismicity* during Powering up to the Nominal Field of 8.5 T

[IEEE TASC 34, 1 (2023)]

*Pioneering work in 2001: DOI 10.1109/77.920111



No training quenches but Kaiser effect observed

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

Sc magnet fully operational at 8.5 T

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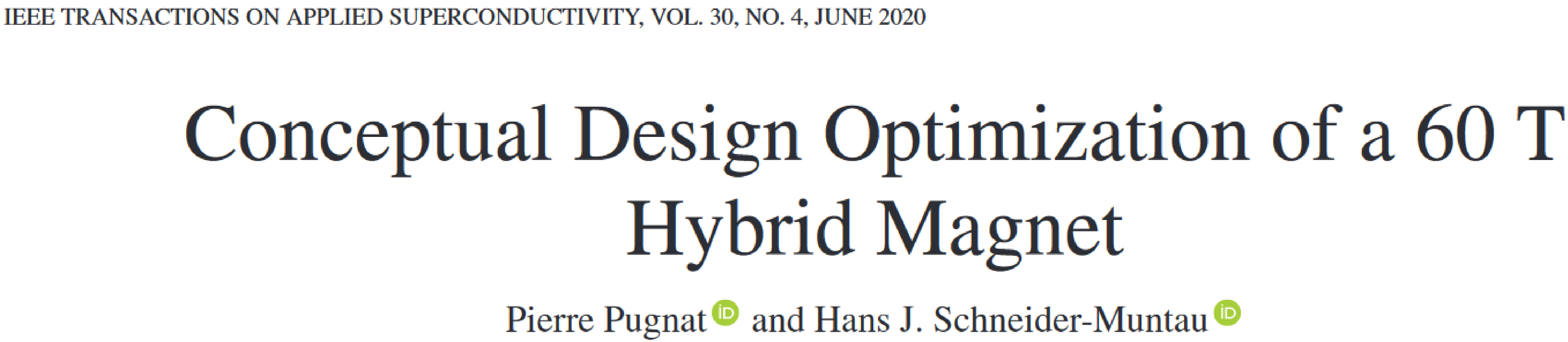


IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 30, NO. 4, JUNE 2020

Conceptual Design Optimization of a 60 T Hybrid Magnet

Pierre Pugnat and Hans J. Schneider-Muntau

doi: 10.1109/TASC.2020.2972498

See also the more detailed presentation of H. J. Schneider-Muntau at MT26
https://indico.cern.ch/event/763185/contributions/3416454/

Results of our Optimization Study 1)

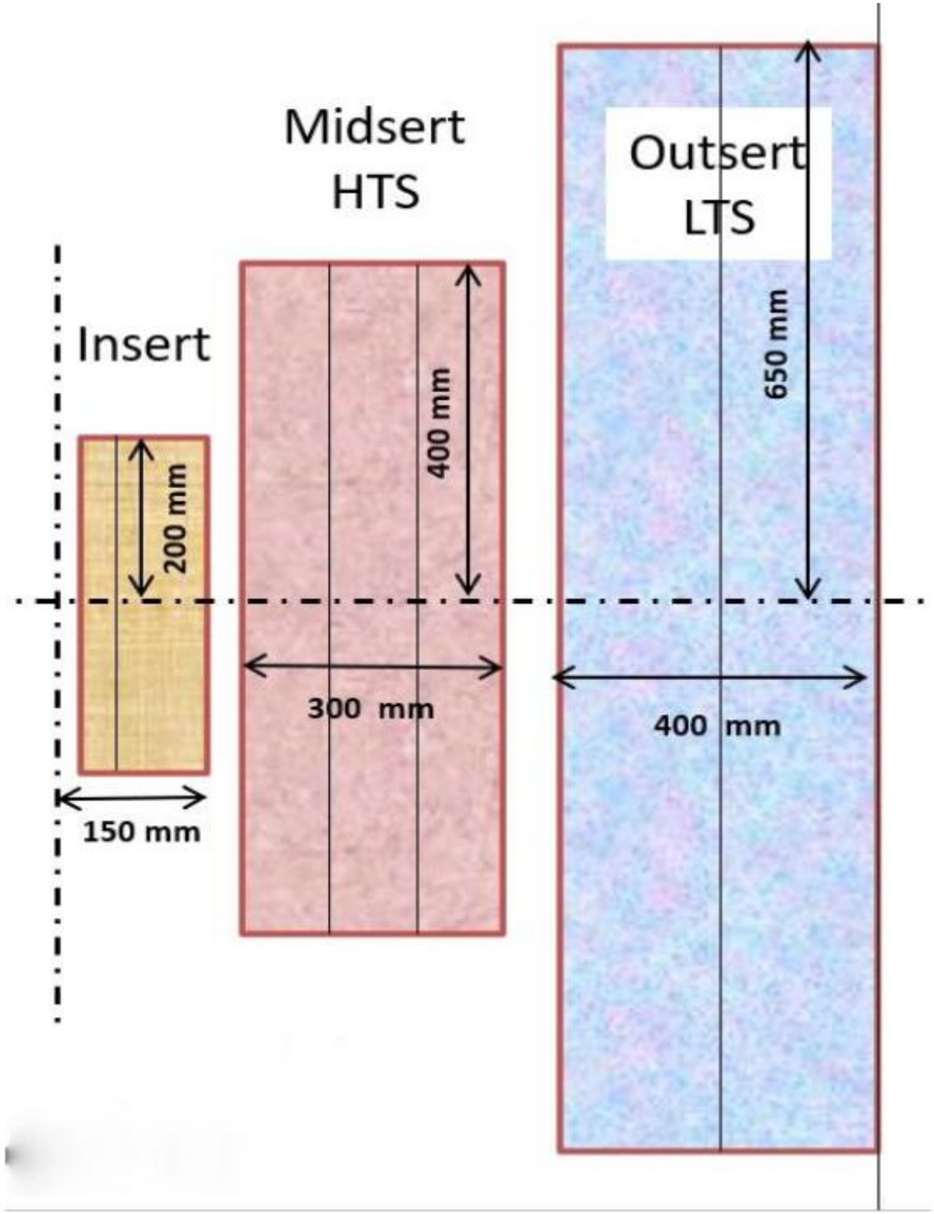
Conductors:

- 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 !

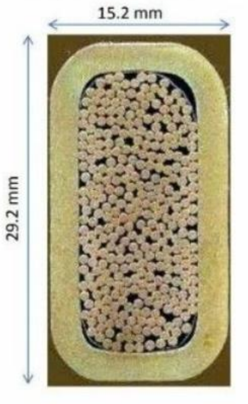


1) P. Pugnat and H. J. Schneider-Muntau,
Conceptual Design Optimization of a 60 T Hybrid Magnet,
IEEE Trans. Appl. Supercond., vol. 30, no. 4, June 2020
Art. ID. 4300507.

Superconducting Conductors

LTS conductor 2) for the Outsert

LTS:
- $J_{e\ strand}$: > 200 A/mm² (20 T)
- J_e: 80 A/mm² (20 T)
- S_m: 1050 MPa

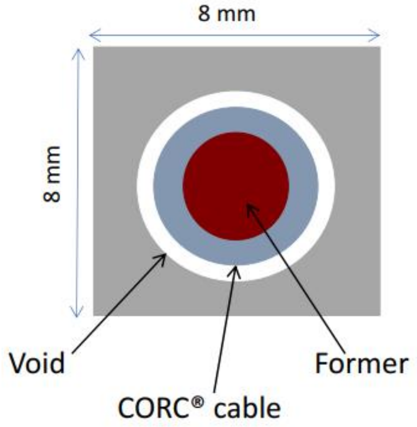


Nb_3Sn CICC
(Copy of Nijmegen Hybrid)

2) M. Field et al., Bruker OST, Nb3Sn strand designs and heat treatments for high field magnet applications, presentation at MT-25, 2017

HTS conductor 1 3) for the Midsert

HTS:
- J_e: 90 A/mm² (40 T)
  109 A/mm² (30 T)
  148 A/mm² (20 T)
- S_m: 930 MPa



Jacketed CORC cable
(Advanced Conductor Technologies)

3) D.C. van der Laan et al, A CORC® cable insert solenoid: the first high-temperature superconducting insert magnet tested at currents exceeding 4 kA in 14 T background magnetic field, Superconductor Science and Technology, Volume 33, Number 5

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The Nightmare for the Midsert Quench Protection

Optimized resistive insert with Cu-7Ag-0.12Zr discs

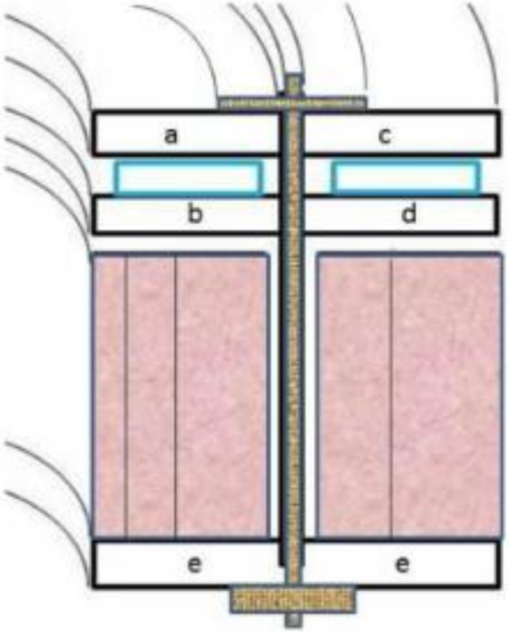
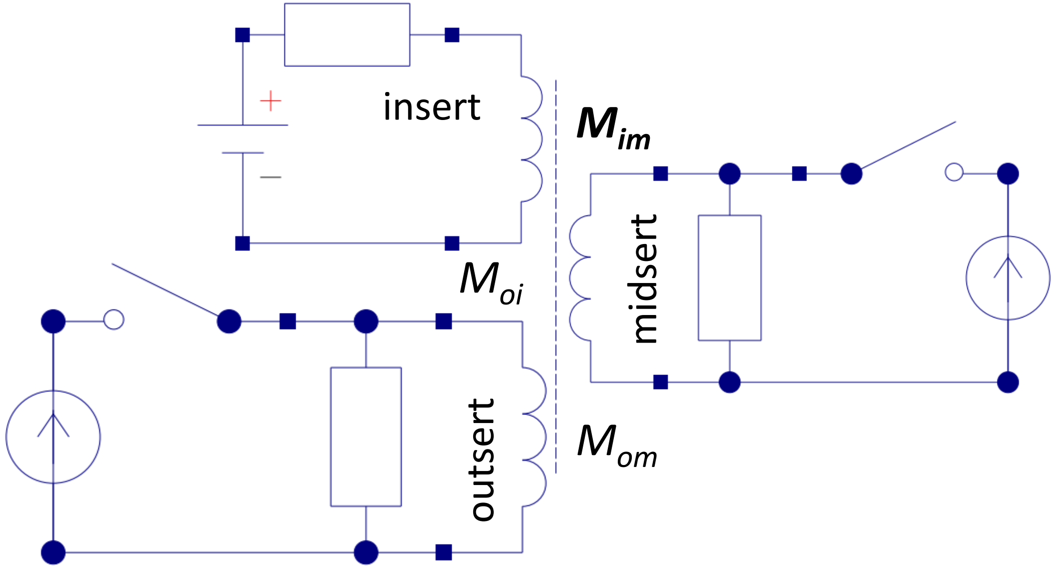


Fig. 5. Sketch (vertical cut) of a layout of a high-efficiency hybrid insert, consisting of two groups of a few parallel Florida-Bitter coils (three and two, in red) connected in series via (e). The two groups are separately hydraulically clamped (blue elements). The clamping force is transmitted via the central Zylon cylinder (brown) between top (a), (c) and bottom flanges (e). It serves also as insulation.

From doi: 10.1109/TASC.2020.2972498

Principle for the Midsert Protection

Quench detection will trigger a trip of the resistive insert to spread the quench via inductive coupling $\boldsymbol{M_{im}}$ driving AC losses



Next Steps toward a 60 T Hybrid Magnet

Proposed technical program

a) Parameter study of optimized conductor lay-out
by choice of materials, geometry, cooling, protection, manufacturability…

b) Define conductor HTS	Finalize conductor LTS	Resistive conductor ?
Goal: 40 T in 400 mm bore	20 T in 1 m bore	YS = 1060 MPa, 60 % IACS

c) Make test coils

d) Develop industrial manufacturing technology for conductors

e) …

Rough first cost estimate

Studies, prototyping, tests	5 MEuros during 5 – 10 years
Construction	50 MEuros during 10 – 15 years

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Conclusion / Summary

- There is an exciting opportunity to discover a new BSM physics at the low energy frontier, *i.e.* Sub-eV, thanks to very high field & high flux magnets.
- Despite significant progresses in HTS technologies, uttermost high field/flux magnets still requiere resistive insert(s) only limited by the available electrical power.
- Today & considering user magnets only, the highest DC fields produced vs. technologies are :
  - 45.2 T/32 mm with hybrid magnet combining LTS and resistive magnets; 2 pre-conceptual studies have been proposed to reach 60 T with LTS, HTS and resistive magnets 1); The development of 60 T hybrid is included in the new US road map 2);
  - 41.4 T/32 mm with resitive magnets alone (Florida Bitter+) and 33 MW; presently under discussions at NHMFL if this energy-intensive way will be maintained…
  - 28.5 T/54 mm fully superconducting (LTS + HTS) from Bruker (1.2 GHz NMR magnet).

1) M D Bird, I Dixon and J Toth, IEEE Transactions on Applied Superconductivity 25 1–6 (2014); P Pugnat and H J Schneider-Muntau IEEE Transactions on Applied Superconductivity 30 1–7 (2020)

2) https://www.nationalacademies.org/our-work/the-current-status-and-future-direction-of-high-magnetic-field-science-in-the-united-states-phase-ii

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More Information / Outline

Few references

- *"High magnetic fields for fundamental physics": https://arxiv.org/pdf/1803.07547.pdf*
- *OSQAR: https://ep-news.web.cern.ch/content/osqar-experiment-sheds-light-hidden-sector-cerns-scientific-heritage , https://arxiv.org/abs/1506.08082*
- *GrAHal: https://bib-pubdb1.desy.de/record/395493 ; https://arxiv.org/abs/2110.14406 ; https://www.frontiersin.org/journals/physics/articles/10.3389/fphy.2024.1358810/full*
- *VMB@CERN: https://cds.cern.ch/record/2649744*

EU COST Action : COSMIC WISPers in the Dark Universe: Theory, astrophysics and experiments

- *https://www.cost.eu/actions/CA21106/ (MoU, Organization, Objectives)*
- ***You can apply to working groups of the network from*** *https://www.cost.eu/actions/CA21106/#tabs+Name:Working%20Groups%20and%20Membership*
- *Kick-off Meeting at Rome* 23-24 February 2023 https://agenda.infn.it/e/CosmicWispersKickOff

High Field Magnet Proposal submission open twice a year: *https://emfl.eu/apply-for-magnet-time/*

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