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Proceeding Paper

Progress in GrAHal-CAPP/DMAG for Axion Dark Matter Search in the 1–3 μeV Range [†]

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Abstract

Two outstanding problems of particle physics and cosmology, namely the strong-CP problem and the nature of dark matter, can be solved with the discovery of a single new particle, the axion. The modular high magnetic field and flux hybrid magnet platform of LNCMI-Grenoble, which was recently put in operation up to 42 T, offers unique opportunities for axion/axion-like particle search using Sikivie-type haloscopes. In this paper, the focus will be on the 350–600 MHz frequency range corresponding to the 1–3 μeV axion mass range requiring a large-bore RF-cavity. It will be built by DMAG and integrated within the large-bore superconducting hybrid magnet outsert, providing a central magnetic field up to 9 T in 812 mm warm bore diameter. The progress achieved by Néel Institute in the design of the complex cryostat with its double dilution refrigerators to cooldown below 50 mK the ultra-light Cu RF-cavity of 650 mm inner diameter and the first stage of the RF measurement chain are presented. Perspectives for the targeted sensitivity, assuming less than 2-year integration time, are recalled.

Keywords: axion; ALPs; dark matter; haloscope; large-bore superconducting solenoid; RF-cavities; large scale 3He/4He dilution refrigerator; cryogenics

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1. Introduction

Axion was predicted independently by S. Weinberg [1] and F. Wilczek [2] from the Peccei and Quin [3] symmetry breaking and constitutes one of the most attractive solutions to the strong-CP problem [4,5], one of the remaining sand grains in the gear of the standard model of particle physics. Moreover, string theory naturally contains a large number of axions or axion-like particles (ALPs), which serve as a basic underlying feature [5,6]. Interest in the search for axions/ALP extends beyond particle physics, since such a hypothetical light spin-zero particle is a serious candidate for cold dark matter [7–10] and one of the rare non-supersymmetric ones; in this context, no signature for supersymmetry has been observed to date at the LHC or in underground experiments [11]. Furthermore, axion or ALPs could explain several astronomical issues, such as the universe's transparency to very-high-energy photons (>100 GeV) [12], anomalous white dwarf cooling [13], and gamma ray excesses in galaxy clusters [14].

In 1983, Pierre Sikivie demonstrated that if the cold dark matter of our galaxy halo consists of "invisible" axions, they can be detected in the laboratory through their conversion to nearly monochromatic photons in a haloscope, i.e., a microwave cavity immerged in a strong magnetic field [15]. Assuming the validity of the Dick radiometer equation [16], the signal-to-noise ratio (SNR) of a haloscope can be written as follows:

$$\mathrm{SNR} = (\mathrm{P}/\mathrm{k_B T_{syst}})(\Delta t/\Delta \nu)^{1/2} \tag{1}$$

where P is the detection power awaited to be around 10^{-21}–10^{-24} W depending of the frequency range, k_B is the Boltzmann constant, $T_{syst} = T + T_N$, i.e., the sum of the physical temperature T and the intrinsic amplifier noise temperature T_N, Δt is the time integration, and $\Delta \nu$ is the amplifier frequency bandwidth. The detection power P scales as B^2V Q, i.e., the square of the magnetic field multiplied by the volume of the RF-cavity and its quality factor Q. The resonant conversion condition is obtained when the frequency of the cavity is equal to the unknown axion m_A, i.e., $h\nu = m_A c^2 [1 + O(\beta \cdot^2)/2]$, where $\beta \approx 10^{-3}$ is the galactic virial velocity, and h and c are the Planck constant and the speed of light in vacuum, respectively. The search for axions is performed by tuning the cavity frequency in small overlapping steps. The main figure of merits of haloscopes given by (1) are B^2V and T_{syst}, requiring developments of high-field magnets and operation at ultra-low temperature, i.e., down to few tens of mK, combined with the use of microwave cavity with $Q \approx 10^5$–10^6 and ultra-low noise amplifier working possibly down to the quantum limit. In this framework, the GrAHal-DMAG collaboration gathers key expertise with high magnetic field provided by LNCMI-Grenoble, ultra-low temperature cryostat made by Institut Néel (Grenoble, France), and large-bore ultra-light Cu RF-cavities developed by DMAG (ex. CAPP) [17]. This paper focuses on the progress made in the production of high-DC magnetic fields and in the design of a large-volume, low-temperature cryostat.

2. The Modular Grenoble Hybrid Magnet Platform of LNCMI

The highest DC magnetic fields are produced today with hybrid magnets, i.e., magnets combining resistive and superconducting technologies. The Grenoble hybrid magnet is composed of Cu-Ag resistive inserts made of polyhelices [18] and Bitter coils [19] surrounded by a large-bore Nb-Ti/Cu superconducting solenoid (Figure 1). Its unique feature is to be modular, with the multiple configurations listed in Table 1, which were recently successfully commissioned, with a maximum field of 42 T reached as a first step for the "full" hybrid magnet configuration [20]. The details of the high electric power installation as well as the cryogenic infrastructure needed to operate such a hybrid magnet are reported in [21] (see also Supplementary Materials).

All hybrid magnet configurations listed in Table 1 can, in principle, be equipped with RF-cavities of different diameters, allowing several axion mass ranges to be probed [22].

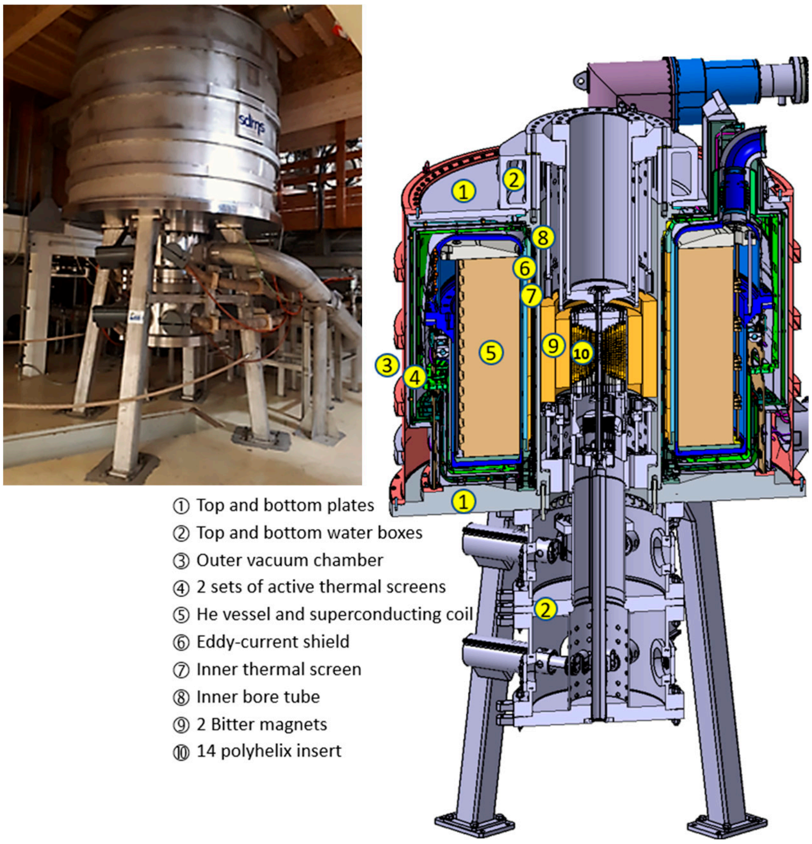

Figure 1. Exploded view of the Grenoble hybrid magnet with an image in the inset. The height is about 5.4 m with a total weight of 53 tons, including the cold mass at 1.8 K of 24 tons.

Table 1. High magnetic field and flux configuration of the Grenoble hybrid magnet.

Field in T (Nominal Field)	Warm dia. in mm	Grenoble Hybrid Magnet Configurations	Electrical Power in MW [2]
42 (43) [1]	34	14 helix + 2 Bitter + superc.	20.7 + 2.8 + 0.4
34 (35)	34	14 helix + superc.	10.6 + 1.1 + 0.4
17.3 (17.5)	375	2 Bitter + superc.	10.9 + 1.1 + 0.4
8.5 (9.5)	812	Superc. alone	0.4 [3]

[1] Magnetic field reached are indicated without parenthesis; 42 T = 25 T + 8.5 T + 8.5 T, [2] including magnet powering, water cooling pumps, and cryogenics, respectively. [3] Power needed for cryogenics, including He liquefier, 1.8 K pumps, and cryoplant ancillaries.

3. Haloscope Cryostat for Cooling the Cu RF-Cavity and First-Stage RF-Amplification

3.1. Generalities

The overall cryogenic system is too specific to be procured by external companies, requiring dedicated in-house developments. The cryostat will house two dilution refrigerators (DR1 and DR2); the first one is for cooling the large lightweight Cu RF-cavity down to 50 mK and the second one is for cooling the first RF amplification stage inside the compensation coil (Figure 2) below 100 mK. The cooling requirements of DR1 and DR2 are listed in Table 2 and are well within the capabilities of classical systems, but they require a specific cryogenic environment.

The technical choice for the GrAHal cryostat is based on the dry approach, avoiding the use of cryogenic liquids and relying on a powerful pulse tube cryocooler for long-time operation in stable conditions. Several improvements with respect to the previous conceptual study [17] were driven by detailed studies and are reported in this paper together with solved integration issues within the Grenoble hybrid magnet. All other parts, namely the large-bore ultra-light RF-cavity in Cu and the RF-detection chain, remain unchanged.

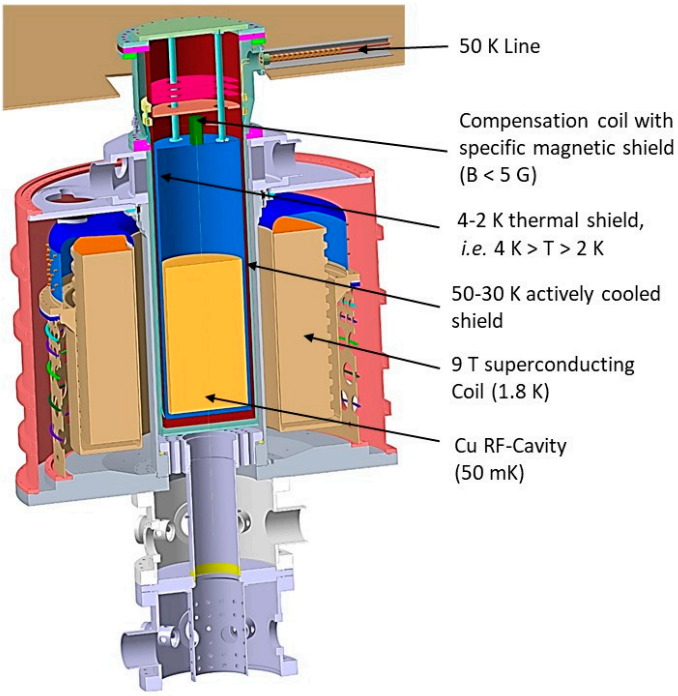

Figure 2. New architecture of the GrAHal-DMAG/CAPP cryostat inserted inside the 9 T/812 mm configuration of the Grenoble hybrid magnet.

Table 2. Cooling requirements for the dilution refrigerator systems DR1 and DR2.

DR Id	Volume (m^3)	Cooling Requirements (μW)	T (mK)
DR1	0.466	75	50
DR2	0.008	50	100

3.2. Main Changes and Improvements

3.2.1. Removal of the Lower Part of the 300 K Shield

Because of the integration constraints of the cryostat within the hybrid magnet structure (Figure 1) and keeping the diameter of the light Cu RF-cavity as large as possible to probe the axion mass range down to about 1 µeV, we decided to remove the lower part of the 300 K shield of the cryostat and use, for this purpose, the 300 K inner bore tube of 812 mm diameter of the hybrid magnet structure (Figure 2). This new design makes it necessary to guarantee the leak tightness between the external parts of the 50–30 K shield of the cryostat and the inner bore tube of the hybrid magnet, which comprises several interfaces, including the upper water box one. Dedicated tests will be conducted to validate this point. The targeted inner diameter of the Cu RF-cavity is now fixed to 650 mm.

3.2.2. 50–30 K Actively Cooled Shield with Its Cooling Loop System

The intermediate temperature shield requires an active cooling loop (Figure 3) and multilayer insulation separated by vacuum space to intercept radiative loads. The cooling loop will be couple to a powerful cryocooler (AL630 100W@20 K or AL325 100W@25 K). This overall subsystem is independent of other parts of the cryostat and is fully funded. It will provide a configuration for making first RF-cavity tests in 9 T magnetic field at LNCMI and possibly preliminary axion search run at T < 50 K.

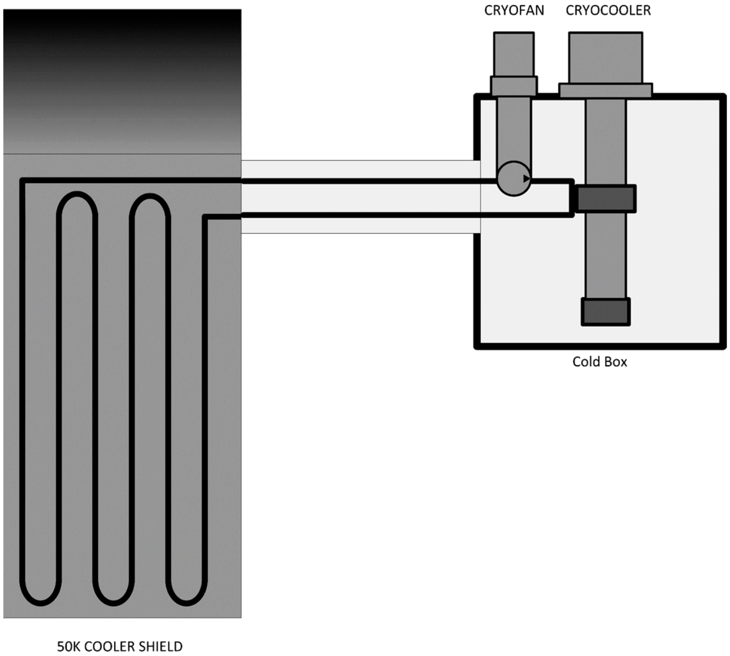

Figure 3. Principle of the active cooling loop for the 50–30 K shield.

3.2.3. Cryogenic Link and JT2K System

The 4 K thermal shield needs to intercept the radiative loads from the 50 to 30 K shield. For this, an innovative solution has been proposed based on the use of a superfluid helium (HeII) loop to provide the heat sink. Instead of building a JT4K cooler (Joule–Thomson cooler at 4 K) and a conductive link for the 2 K shield, a JT2K cooler (lower suction pressure) will be implemented with a piping network filled with HeII. This SUPERLINK concept (Figure 4) is based on the fact that the thermal conductivity of HeII is about 1000 times that of Cu OFHC at the same temperature. The cooling power needed for GrAHal is estimated to be around 2 W. A prototype SUPERLINK system is presently under development to validate the concept, keeping as a backup solution the use of a JT4K with a circulation on the radiative protection shield similar to the one of the 50–30 K shield.

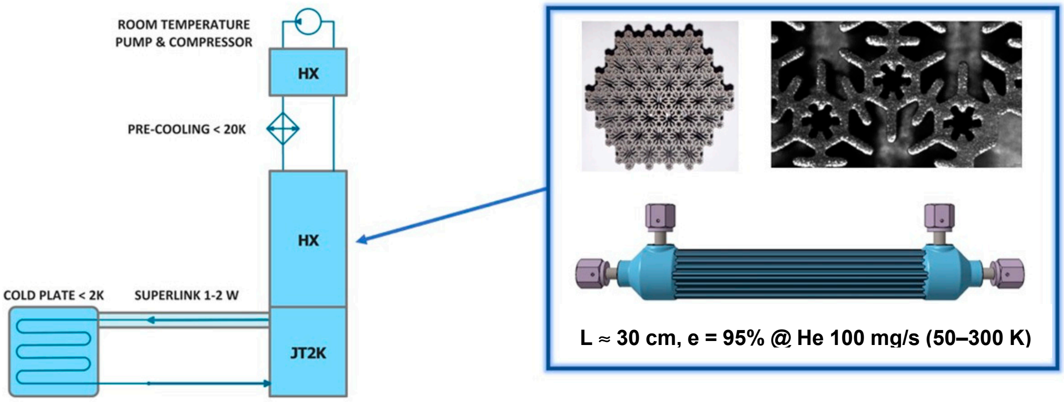

Figure 4. SUPERLINK concept as proposed by P.C. and J.V. with the heat exchanger on the right side obtained from additive manufacturing (3D NewShape factory).

4. Targeted Sensitivities Versus Frequency Range

The reduction in the inner diameter of the Cu RF-cavity of about 7% with respect to the previous conceptual study [17] will increase the lowest targeted frequency up to 353 MHz. Efforts will be devoted on decreasing this lower frequency by using, for example, several tuning rods and/or dielectrical ones.

Concerning the targeted sensitivities, an axion search running phase with the 50–30 K sub-cryostat alone is under evaluation as a preliminary step. It will be followed by both operation phases already described in [17], the first one with DR1 alone and the second one with DR1 and DR2 to implement the quantum amplifier (SQUID) for the first RF amplification stage. With the scan rate conservatively estimated to be around 0.5 MHz/day at DFSZ sensitivity, the range 353–600 MHz can be covered in less than 2 years of integration time.

Supplementary Materials: A virtual tour of the LNCMI-Grenoble to visualize the hybrid magnet experimental site can be found at https://storage.net-fs.com/hosting/6174450/20/ (accessed on 10 October 2025). Follow the link Hybrid magnet site M8 in the header RESISTIVE MAGNETS.

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Abbreviations

The following abbreviations are used in this manuscript:

ALP(s)	Axion like particle(s)
CP	Charge parity symmetry
Cu	Copper
DFSZ	Dine–Fischler–Srednicki–Zhitnitskii limit
DMAG	Dark Matter search Axion Group
DR1/2	Dilution refrigerator 1/2
GrAHal	Grenoble Axion Haloscopes

HeII	Superfluid helium
JT2K/4K	Joule–Thomson 2K/4K cooling system
LHC	Large Hadron Collider
SQUID	Superconducting Quantum Interference Device

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