2021 Annual Report

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The Grenoble Hybrid Magnet Project

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43+T Hybrid Magnet – General Overview and Progress Toward Commissioning

The Grenoble Hybrid magnet combining resistive and superconducting technologies will be a modular user platform with the objective to deliver to the scientific community various continuous high magnetic field and flux configurations. For the first step, they range from 43 T in 34 mm diameter using 24 MW of electrical power down to 9 T in 800 mm diameter, when the superconducting outsert magnet is used alone. The ongoing upgrade of the electrical power installation first up to 30 MW, and possibly up to 36 MW later on, has been anticipated since the first design phase of the hybrid magnet with target to reach a magnetic field of at least 46 T in 34 mm diameter. Further studies are ongoing for this challenging step considering realistic worst-case scenarios to calculate ultimate forces for dimensioning the support structure. It will also be based on the first years of experience gained with the hybrid magnet operation up to 43 T. Strain and temperature gauges have been installed in the most critical parts of the structure and the superconducting coil to develop a precise understanding of the mechanical and thermal behavior of the system up to 43 T and define the optimum path for the generation of fields well above 45 T.

In 2021, major milestones have been achieved for the final assembly phase of the hybrid magnet. Beginning of the year, the superconducting outsert coil of 1100 mm aperture weighting 18 tones has been equipped with instrumentation wires, thermometers, heaters for the warm-up and strain gauges. Lifting tests were also performed and the measured elastic deformation of the flanges was found to be in agreement with mechanical calculations. After a thorough preparation phase including several insertion trials with a mockup in wood of the same dimensions, the outsert superconducting coil has been successfully inserted inside the He vessel the 5th of May. The closure welds of the He vessel containing the large bore superconducting coil have been realized by the company SDMS following a strict procedure to not damage the coil, the instrumentation wires and the electrical ground insulation.

The cryogenic line connecting the magnet cryostat to the cryogenic satellite (figure 1) has been delivered by Cryo Diffusion to LNCMI-Grenoble, the 30th of June. Its positioning in its final location on its support for the acceptance test has been successfully achieved the 7th of July after delicate lifting and handling operations.

The 1.8 K cold mass assembly, *i.e.* the closed He vessel containing the superconducting coil, was then placed on the magnet support ferrule to pursue cryostating operations. Unfortunately, the mounting of the outer vacuum chamber has to be performed several times from September to November 2021. The reason was a leak detected on the upper part internal radius connection between the top plate and the warm central tube. It required some deep investigation to be properly located, identified and was then successfully repaired.

The next steps of the Grenoble hybrid magnet project can be summarized as follows. The pumping of the vacuum vessels of the magnet cryostat and cryogenic satellite is expected to start in February 2022. The beginning of the cooling of the superconducting magnet with a strict control of thermal gradients is planned for April or May 2022 and its powering alone can be expected for June or July 2022. This will then be followed by an evaluation program of the electromagnetic interactions between insert and outsert and the definition of the operating parameters that will allow safe operation of the hybrid magnet as a first step up to 43 T and later, to fields well above 45 T.

FIG. 1. *LNCMI site dedicated to the hybrid magnet with the magnet cryostat assembly containing the large bore superconducting coil outsert, the cryogenic line ready for busbar insertion prior to its interconnection, and in the back, the cryogenic satellite producing the superfluid He.*

This project is funded by the CNRS, the French Ministry of Higher Education and Research in the framework of the "Investissements pour l'avenir" Equipex LaSUP (Large Superconducting User Platform), the European Funds for Regional Development (FEDER) and the Rhône-Alpes region.

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Grenoble Hybrid Magnet – Insertion of the superconducting coil outsert inside the He Vessel and Closure Welds

The hybrid magnet combining resistive and superconducting technologies in construction at LNCMI-Grenoble has reached important milestones in 2021. After a thorough preparation phase, the outsert superconducting coil of 1100 mm aperture has been successfully inserted inside the He vessel (figure 1). Then the closure welds of the He vessel have been realized by the company SDMS (figure 2) following a strict procedure to not damage the coil, the instrumentation wires and the ground electrical insulation. The dye penetrant testing of the welds was successful as well as the pressure and leak tests.

The cold mass assembly weighting 23.4 tones, *i.e.* the enclosed large bore superconducting coil inside the He vessel, was then covered by the first set of superinsulation layers of the 4 K thermal shield, before being installed on the support ferrule of the cryostat (figure 3) for the next cryostating steps.

FIG. 1. *Successful insertion of the superconducting coil in the He vessel. In the most constraint part at the bottom, the mechanical clearance with respect to the radius is equal to 0.4 mm.*

FIG. 2. *Closure welding of the He vessel with the superconducting coil inside requiring a strict control of the temperature to not damage the electrical insulation (contractor SDMS).*

FIG. 3. *Installation of the cold mass with its first layers of superinsulation on the support ferrule of the cryostat.*

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Grenoble Hybrid Magnet – Delivery of the Cryogenic Line and Assembly Tests

The cryogenic line of the Grenoble hybrid magnet connects the superconducting magnet cryostat to the cryogenic satellite producing the pressurized superfluid He. It is made by a super-insulated vacuum transfer line for cryogenic fluids of about 5.5 meter long, which contains also the superconducting busbars to power the superconducting magnet as well as about 700 instrumentation wires travelling either in the central helium pipe or in the vacuum chamber. The insulation vacuum of the cryoline is segmented by a vacuum barrier separating the vacuum of the magnet cryostat from the one of the cryogenic satellite.

The cryogenic line has been design by CEA Saclay and built by Cryo Diffusion. It was delivered to LNCMI-Grenoble the 30th of June. To be able to position the cryoline weighting 1.4 tones to its final location in between the cryogenic satellite and the magnet cryostat, a dedicated lifting tool (trebuchet) has been design and built by Barciet Rhône Alpes (figure 1).

FIG. 1. *Delicate handling operation of the cryogenic line in the hall of LNCMI-Grenoble with dedicated lifting tool.*

Assembly tests for bolts connections to the cryogenic satellite and magnet cryostat took about 2 days and allow some minor mechanical adjustments. For this, the cryoline was installed and fixed on its support foot bolted to the ground (figure 2). Figure 3 shows the cryoline connected to the cryogenic satellite. Once the trial assembly was achieved, both ends of the cryoline was disconnected. It was then installed temporary in such a way to not interfering with the mounting of the magnet cryostat.

The final assembly on the LNCMI site of the cryoline with its welded and bolt connections to the magnet cryostat and cryogenic satellite is expected starting in January 2022.

FIG. 2. *Fixation* of *cryogenic line to its support foot. In the background, the connection to the magnet cryostat.*

FIG. 3. *View of the cryogenic line with in the background its connection to the cryogenic satellite.*

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Grenoble Hybrid Magnet – Assembly of the Magnet Cryostat and Leak Tests

The cryostat of the Grenoble hybrid magnet outsert is mostly made by three thermal shields at 100 K, 40 K and 4.2 K, to intercept the heat transfer from 300 K to 1.8 K. They have been successfully assembled (figure 1-2) together with the outer vacuum chamber (OVC) (figure 3) prior to perform the leak test with a He leak detector from Pfeiffer Vacuum.

Unfortunately, a leak was detected in the warm part of the vacuum chamber. It was precisely localized on the upper circular junction of the OVC with the internal warm bore. Decision has been taken for the disassembly of the OVC and repairing of the identified defective part. It was a poor glued assembly on the top plate of the OVC that was replaced by a welded one. The OVC has been then put back in place and the pumping has been restarted.

The last leak test still reveals a tiny leak signal $\leq 3.10^{-8}$ mbar.l/s, which is 3 times larger than the technical specification but nevertheless judged acceptable. To reduce this measured value, much longer pumping duration would have been required and it was decided to go on with the cryostat assembling and the welding of the quench line.

FIG. 1. *Cryostating step with the assembly of the 40 K thermal shield. The cryogenic line connecting the magnet cryostat to the cryogenic satellite is visible in the background.*

FIG. 2. *Last superinsulation layers covering the 100 K thermal shield installed prior to the mounting of the outer vacuum chamber.*

FIG. 3. *Mounting of the Outer Vacuum Chamber (OVC).*

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THE 43+T GRENOBLE HYBRID MAGNET: MAJOR ACHIEVEMENTS FOR FINAL ASSEMBLY

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The hybrid magnet, combining resistive and superconducting technologies and that is under construction at LNCMI-Grenoble, has reached important milestones in 2021 despite the Covid-19 sanitary crisis. After a thorough preparation phase, we successfully inserted the outsert superconducting coil of 1100 mm aperture into its He vessel (Figure 1). Supported by the company SDMS, we then realized the closure welds of the He vessel (Figure 2) following a strict procedure to not damage the coil, the instrumentation wires, and the ground electrical insulation. After a successful dye penetrant test of the welds, we will further perform pressure and leak tests. On June 30, Cryo Diffusion delivered the cryogenic line to LNCMI-Grenoble. We achieved an overall dummy assembly with the cryogenic line connecting the magnet cryostat to the cryogenic satellite that shall produce pressurized superfluid He (Figure 3). This step allowed us to ensure final mechanical adjustments prior to the final closure welds. We expect the superconducting magnet cooldown to start in the second quarter of 2022.

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Figure 2: Closure welding of the He vessel with the superconducting coil inside requiring a strict control of the temperature to not damage the electrical insulation (contractor SDMS).

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Figure 1: Successful insertion of the superconducting coil in the He vessel. In the most constraint part, the radial clearance is 0.4 mm.

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Figure 3: Trial assembly of the cryogenic line (contractor Cryo Diffusion) connecting the cryogenic satellite in the back to the superconducting magnet cryostat in the front.

This project is realized in collaboration with CEA-Saclay. It is supported by CNRS, Université Grenoble-Alpes, the French Ministry of Higher Education and Research in the framework of the "Investissements pour l'avenir & Equipements d'excellence" Equipex LaSUP (Large Superconducting User Platform), and the European Funds for Regional Development (FEDER) and Rhône-Alpes region.

First results from GrAHal (Grenoble Axion Haloscopes) and perspectives with the Grenoble hybrid magnet modular user platform

Particle physics is not only confined to the high energy frontier. There are unexplored territories at ultra-low energies, *i.e.* sub-eV, which are also promising for major discoveries. The emblematic particle of this physics is the axion, a pseudo-scalar particle predicted independently by S. Weinberg and F. Wilczek in 1978 to solve the fundamental problem of the apparent non-violation of the CP symmetry by the strong interaction. Standard axion at the electroweak scale has been excluded after extensive experimental searches but letting fully open the case for “almost” invisible axion, *i.e.* with mass and coupling to other particles extremely weak. If the axion mass is typically in the range 1-1000 μeV, this particle could also be the main dark matter component of our universe and is one of the rare non-supersymmetric candidates. In this context, a synergy is being built between three main laboratories from CNRS and Univ. Grenoble-Alpes gathering key recognized expertise to build several Sikivie’s haloscopes for Axion search with unprecedented sensitivity. The Grenoble hybrid magnet user platform close to completion at LNCMI will offer unique opportunity to detect in laboratory axion DM particles or any other axion like particles (ALPs) within the mass range 1-150 μeV.

The haloscope principle relies on the following two main assumptions: *i)* the major part of the DM galactic halo is made of weakly interacting axions or ALPs, *ii)* they decay into photons in strong magnetic fields. If a resonant RF cavity is added to amplify the signal, the power increase due the axion conversion into photon can be written as:

$$P = g_{a\gamma\gamma}^{2}(\rho_{halo}/m_a)\,\mathbf{B}^2\,\mathbf{V}\,C\,Q/2 \qquad (1)$$

where $g_{a\gamma\gamma}$ is the unknown axion-diphoton coupling constant, $\rho_{halo} \approx 450$ MeV cm^{-3} is the assumed halo DM density, m_a the probed axion mass ($m_a \approx \omega$, in units with $c = \hbar = 1$), B the magnetic field, V the cavity volume, $C \approx 0.5$ the coupling factor of the electromagnetic mode and $Q \approx 10^4$-10^5 the quality factor of the cavity. The instrumental challenge lies in the weakness of the awaited signal (of the order of 10^{-23} W) requiring specific ultra-low noise amplifiers as well as ultra-low temperature to minimize thermal noise.

GrAHal’s path finding run took place during in July 2021 from a first built haloscope prototype working at liquid He temperature. It consists of an oxygen free copper cylindrical RF cavity (inner diameter 36 mm, length 150 mm) without tuning system as a first step and with a TM010 mode frequency close to 6.373 GHz at low temperature (axion mass close to 26.37 μeV). It was maintained at liquid He temperature inside a 52 mm bore 14 Tesla magnet. Its unloaded quality factor Q_0 is 37000 ± 10%, the main antenna coupling constant is $\beta = 1.2$ and we take $C = 0.69$ for the TM010 mode coupling factor. The signal emerging from the cavity main port was amplified a first time by a cryogenic high-electron mobility transistor amplifier from Low Noise Factory. A second stage amplification has been obtained by the Rhode & Schwarz ZVL13 analyzer used for signal processing. The total gain of the receiver chain was calibrated using the power emitted by a heated load connected at the location of the RF cavity. A few tuning steps has been obtained by increasing the He exchange gas pressure leading to a slight increase of the dielectric permittivity of the cavity. The proper functioning of the haloscope was carefully checked by measuring fake axion signals injected in the cavity through the weakly coupled antenna port.

No signal above the noise was detected. From a statistical analysis, the axion-diphoton coupling constant $g_{a\gamma\gamma}$ can be constrained at 95 % confidence level to be less than 2.2×10^{-13} GeV^{-1}, *i.e.* $g_{a\gamma\gamma} < 22\times g_{KSVZ}$, around 6.373 GHz corresponding to axion mass of 26.37 μeV. This new result has been inserted as a thin exclusion line inside figure 1 showing exclusion limits obtained from worldwide axion search experiments as well as highlighting GrAHal perspectives.

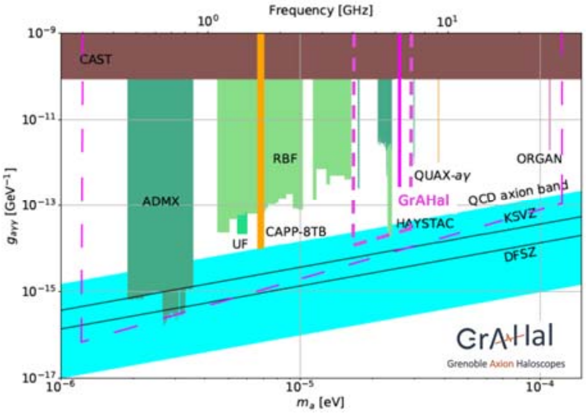

FIG. 1. *Exclusion limits for the axion-diphoton coupling versus axion mass and frequency for past and existing experiments. Pink dashed thick lines define the exclusion limit range targeted in phase-1 of GrAHal corresponding to the 4-7 GHz frequency range. The pink solid line highlights the first GrAHal results obtained in 2021 (exclusion limit down to* $g_{a\gamma\gamma}/g_{KSVZ} = 22$ *for the frequency range 6.372-6.374 GHz). Pink dashed thin lines correspond to the high sensitivity GrAHal upgrade, i.e. phase-2, using the Grenoble hybrid magnet modular platform, which will allow accessing to the unexplored limits from 0.3 to 30 GHz with a sensitivity down to the KSVZ/DFSZ theoretical predictions.*

More information in https://arxiv.org/abs/2110.14406

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