PROCEEDINGS OF SCIENCE

Axion and ALP search with the Any Light Particle Search II experiment at DESY

I.Oceano[a] **on behalf of the ALPS II collaboration**

[a] *Deutsches Elektronen-Synchrotron DESY,*
Notkestr. 85, 22607 Hamburg, Germany

E-mail: isabella.oceano@desy.de

The Any Light Particle Search II (ALPS II) is a Light-Shining-Through-a-Wall experiment at DESY in Hamburg, Germany, which hunts for axions and axion-like particles in the sub-meV mass range with an axion-photon-photon coupling $g_{\alpha\gamma\gamma} > 2 \times 10^{-11}$ GeV^{-1}, improving the sensitivity by a factor of 10^3 compared to its predecessors. For this purpose, a high-power laser is directed through a long string of superconducting dipole magnets and a mode-matched optical cavity, where some photons can convert into a beam of axion-like particles. The latter passes through a light-tight barrier, another strong magnetic field and mode-matched optical cavity, where some of the axion-like particles can convert back into photons and be detected.

In May 2023, the ALPS II experiment started the initial phase of data taking, in which it employs a heterodyne detection method (HET). Upgrades that will allow ALPS II to reach its full design sensitivity are planned for 2024. In this paper, the status of the initial data taking with ALPS II and the experience gained are described.

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1. Introduction

The Standard Model of particle physics effectively describes the visible matter in the Universe, from stars to the inner workings of atoms and nuclei. Most of its predictions have been experimentally verified with sub-per-mille accuracy at the Large Hadron Collider (LHC) and other experiments. Despite these many successes, the Standard Model leaves many pressing experimental questions unanswered. Indeed, it cannot explain the cosmological asymmetry between matter and antimatter. Moreover, multiple astronomical observations agree upon the fact that the visible matter described by the Standard Model represents only a small part of the total density of the Universe. There is, indeed, more invisible matter in the universe, the so-called "dark matter". This puzzle could be solved through a hypothetical particle known as the axion. Initially proposed as an explanation for the absence of CP violation in the strong nuclear interaction [1], axions were soon recognised as a promising dark matter candidate. Furthermore, Axion-Like Particles (ALPs), which share similar characteristics to the axion, could explain some astrophysical anomalies. Theory predicts interactions between visible particles and axions (ALPs). ALPS II exploits the Sikivie-effect [2] in which the axion can interact with an external magnetic field and convert it into a photon. The "Light-Shining-Through-a-Wall" (LSW) experiment is a powerful technique to search for axions (ALPs) via this channel in a model-independent way that does not rely on astrophysical or cosmological models of the process that generates the axions.

2. The Any Light Particle Search II experiment

Any Light Particle Search II (ALPS II) [7] is the second generation of LSW experiments at DESY and is the largest and most sensitive LSW experiment ever built [8] [4]. ALPS II is searching for axions, scalar and pseudoscalar axion-like particles with masses in the sub-meV/c^2 range, as well as other very lightweight and very weakly interacting particles. It will improve the sensitivity of axion-photons coupling by a factor of 10^3 compared to its predecessors going beyond indirect limits from astrophysics and solar axion searches [3]. This jump in sensitivity will be achieved by two arrays of superconducting dipole magnets and two mode-matched optical cavities before and after the light-tight wall, as first proposed in 1991 [6]. Fig. 1 shows the fundamental parts of ALPS

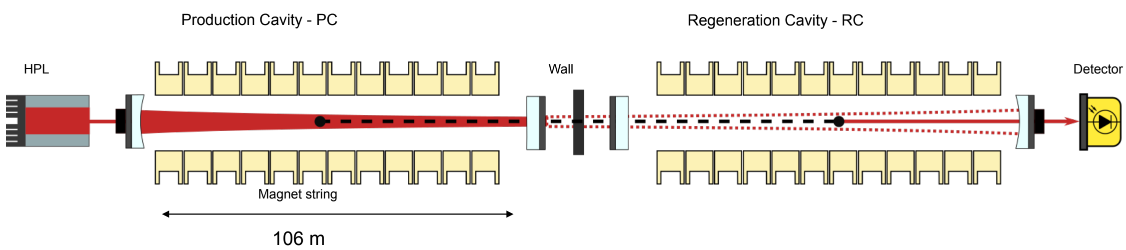

Figure 1: Schematic layout of the ALPS II experiment.

II: the High Power Laser (HPL), the magnets, the light-tight wall, the cavities and the detector. The two strings of twelve straightened, long HERA dipole magnets built for the HERA proton accelerator are generating a field of 5.3 T, resulting in B_0L = 560 Tm on each side. Inside the magnetic string on the left side of the wall, some of the photons from the HPL will be converted into axion-like particles. These weakly interacting particles pass through the wall and enter the second magnet string, where some are converted back into photons indistinguishable from the original laser photons. To increase the number of axion-like particles generated, the laser field before the wall is resonantly enhanced to approximately 150 kW using a 122.7 m long optical cavity, called the Production Cavity (PC). Similarly, a Regeneration Cavity (RC) is installed on the other side of the wall to resonantly increase the number of regenerated photons. The probability for light converting to axions and axions converting back to light is given by (for axion masses below 0.1 meV):

$$P_{\gamma \to a \to \gamma} = \frac{1}{16} \beta_{PC} \beta_{RC} (g_{a\gamma\gamma} BL)^4 \tag{1}$$

resulting in 10^{-25} for the ALPS II parameters $\beta_{PC} = 5000$, $\beta_{RC} = 40000$, $B = 5.3$ T, $L = 105.6$ m and $g_{a\gamma\gamma} = 2 \times 10^{-11}$ GeV^{-1} (motivated by astrophysics). Thus, with 40 W of 1064 nm photons injected into the PC, about 2 photons/day behind the wall are expected. To detect the regenerated field, ALPS II is employing a HETerodyne (HET) detection scheme [9]. Later, this search will be followed by the implementation of a Transition Edge Sensor (TES) [11] to verify and confirm the HET results.

3. Heterodyne detection

The HETerodyne (HET) detection system exploits the interference of two fields at a non-zero difference frequency. It can detect very weak photon fields, at the shot-noise limit, as demonstrated in [9]. By optically mixing the regenerated field with a much stronger optical field, called a Local Oscillator (LO), a "beat note" signal is generated at the frequency difference of the two fields:

$$V(t) = GP_{sig} + GP_{LO} + 2G\sqrt{P_{sig} P_{LO}} \cos(2\pi \Delta f t + \Delta \phi) \tag{2}$$

where G is the conversion gain of the photodetector, P_{sig} is the power of the regenerated light, P_{LO} is the power of the LO and $\Delta f(\phi)$ is the frequency (phase) difference. The time-dependent component of the detected signal has an amplitude that depends on the power of the regenerated field, which is expected to be low, boosted by the LO power. Moreover, if P_{LO} is sufficiently large, the system noise is dominated only by photon counting statistics so that the signal-to-noise ratio (SNR) no longer depends on the LO power: $SNR \propto \frac{\sqrt{P_{LO} P_{sig}}}{\sqrt{P_{LO}}} = \sqrt{P_{sig}}$. In ALPS II the number of regenerated photons per second expected in the RC is $\sim 10^{-5}$, and we will strengthen it by injecting $\sim 10^{16}$ photons with the LO. By performing a phase and quadrature (I/Q) demodulation at the frequency difference between the two optical fields and integrating both quadratures for a long measurement time, a quantity proportional to the regenerated photon rate can be obtained. This heterodyne function z is proportional to the power of the regenerated light $z \propto P_{sig}$ in the presence of a coherent signal, while $z \propto 1/t$, where t is the integration time, in the absence of any coherent signal, like the shot-noise. The detection method is essentially a discrete single-interval Fourier transform, in which the bandwidth of the single interval decreases progressively with the inverse of the integration time. The key point of detection is to keep Δf and $\Delta \phi$ constant for the entire acquisition time; if these parameters exceed μ Hz and 0.01 rad respectively, the signal is lost. This

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is the main challenge of the experiment since even a very small shift of the optical components (due to ground motion, changes in temperature or humidity, etc.) will lead to a change in the phase of the signal [10].

4. Initial science run

The goal of the initial science run is to test the whole system and characterise the stray light detected coming from the HPL, which could mimic the signal and become the main background source. To characterise the stray light in a short time, for the initial science run, data is collected without the PC. During this initial phase, in the case of a system limited by shot noise, we expect to improve the sensitivity by a factor of 100 compared to previous LSW experiments. The remaining factor of 10 towards design sensitivity will be achieved with the installation of the PC. Figure 2 shows the scheme of the ALPS II experiment for the initial science run.

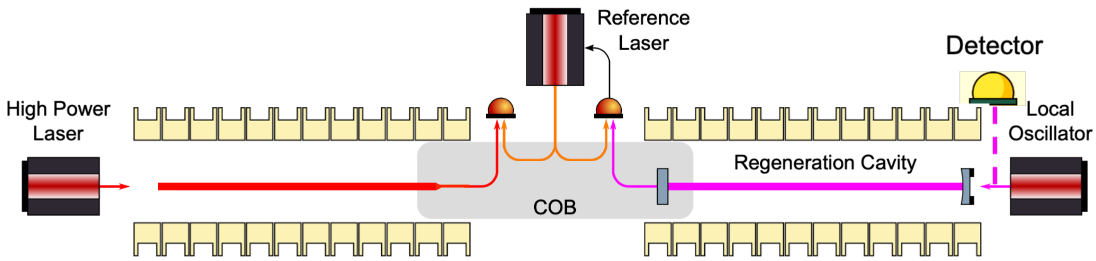

Figure 2: Schematic layout of the ALPS II experiment developed for the initial science run.

The HPL is an amplified Non-Planar Ring Oscillator (NPRO), which demonstrated over 60 W of power at 1064 nm with > 95% of power in fundamental mode. It is capable of injecting ~ 40 W to the magnet string before the wall, which is the working power of ALPS II. The HPL light passes through 12 repurposed HERA dipole magnets operating at 5.3 T field strength with a nominal current of 5700 A. The central optical bench (COB) is installed inside the light-tight housing to reduce stray light as is the remotely operated shutter that acts as a "wall". Behind that the RC is installed, a half-confocal, 122.7 meters long cavity with a Free Spectral Range FSR of 1.22 MHz, features a power build-up of 7.7×10^3. The regenerated field is then mixed with the LO, producing the beat note that will be detected with a photodiode. A third laser, called the Reference Laser (RL), is located in the central area and is used as an intermediate reference. It transfers the actual resonance frequency information from the RC to the HPL and controls the relative phase alignment of the two lasers by avoiding a direct connection between the output fields, reducing possible light contamination. Table 1 lists the frequencies of the beat notes measured during the initial science run.

The key point of HET detection is phase and frequency stability, in particular, the measured signal has to be demodulated with a signal that is coherent with the frequency difference between the HPL and the LO. In addition, resonant enhancement in the RC, and thus power increase, is only achieved when the frequency of the HPL is resonant within the RC. To achieve all these criteria

Table 1: Summary of ALPS II main frequencies during the initial science run.

	Frequency [MHz]
RC Free Spectral Range	1.222632
HPL-LO beat note	24.452636
RL-LO beat note	12.220000
HPL-RC beat note	36.652636

and not have the HPL and LO fields interfere directly, the RL is used with cascaded phase-locked loops.

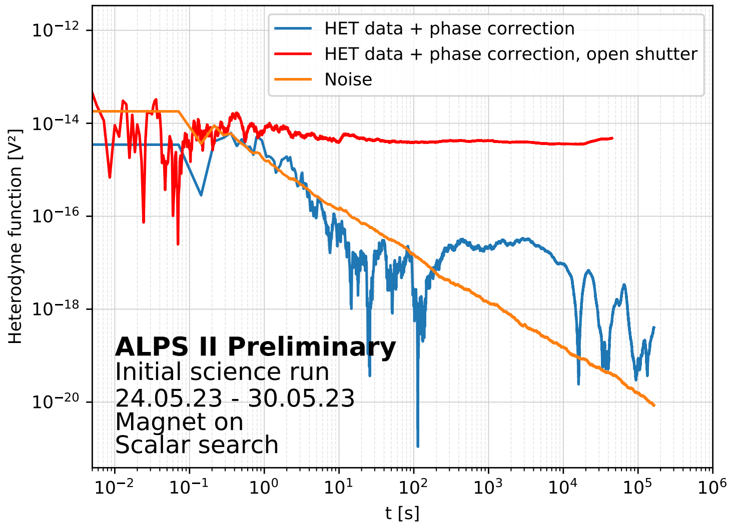

Figure 3: Heterodyne functions obtained with the initial science data. In red phase-corrected data collected with open shutter is shown. The orange trend corresponds to the noise limit extracted by averaging 100 heterodyne functions obtained by demodulating the closed-shutter data with 100 different wrong frequencies. Finally, the blue trend corresponds to the closed shutter data demodulated with the correct frequency. As can be seen, after ~ 300 s some stray light is detected, but for longer integration time, the HET function decreases again, showing a non-prolonged coherence of the stray light.

Starting on 24 May 2023, ALPS II collected data for one week. To reliably reconstruct the phase evolution and monitor some of the calibration parameters, open shutter data was collected every ~ 5 hours for an integration time of ~ 10 minutes. Otherwise, the shutter was closed to stop all photons produced by the HPL. In addition, periods when the magnets were on were alternated with those when the magnets were off to characterise the background of the experiment. The preliminary analysis of the collected data is shown in Figure 3. The red line corresponds to the phase-corrected open shutter data, where the detector measured photons from the HPL. As one can see, the expected $z \propto P_{sig}$ is obtained. The orange line is obtained by averaging 100 heterodyne functions obtained by demodulating the closed-shutter data with 100 different wrong frequencies, allowing to extract

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the noise. As it is shown, it evolves with integration time as $z \propto 1/t$, as expected. Finally, the blue trend corresponds to the closed shutter data demodulated with the correct frequency. As can be seen, after $\sim$ 300 s some stray light is detected, but for $t > 4000$ s of integration time, the HET function decreases again, showing a non-prolonged coherence of stray light. Nonetheless, the data presented are still dominated by stray light.

5. Conclusion

ALPS II is a challenging experiment, which aims to probe axion and ALPs hypotheses in a model-independent way by using the LSW technique. The HET detection system exploits the coherent nature between the regenerated field and the LO. This is expected to filter out all background photons, as only light at the exact frequency and a constant phase will generate a signal. However, this coherence condition places very stringent requirements on the long-term stability of the system compared to a photon counting scheme. The initial science run data demonstrated that ALPS II is capable of detecting weak fields using HET. It served to define a strategy to control the phase stability and to characterise stray light, which is demonstrated to behave as a non-coherent signal. With only $\sim$ 45 h of collected data during the initial science cycle, ALPS II is already able to exceed the limits of the other LSW experiments by a factor of $\sim$ 30. Works are ongoing to improve the SNR and the acquisition process for a new, longer data acquisition by the end of the year.

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