

Towards the first axion search results of the Any Light Particle Search II experiment

Li-Wei Wei^{a,*} on behalf of the ALPS collaboration

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

E-mail: li-wei.wei@desy.de

Any Light Particle Search II (ALPS II) is a dual optical cavity enhanced light-shining-through-a-wall (LSW) experiment at DESY in Hamburg looking for axions and axion-like particles with a target search sensitivity of $g_{a\gamma\gamma}$ down to $2 \times 10^{-11} \text{ GeV}^{-1}$ for masses $m_a \leq 0.1 \text{ meV}$. Two 120 m long strings of superconducting dipole magnets have been set up, each providing a magnetic field-length product of $560 \text{ T} \cdot \text{m}$. A resonant optical cavity with a record-worthy storage time of as high as 7 ms has been constructed to encompass one magnet string. During its initial data-taking phase ALPS II will be operated with a simplified optical configuration that facilitates the characterization of the experiment. The first ALPS II science run took place in May/June 2023 and achieved an estimated search sensitivity of $g_{a\gamma\gamma}$ of around $6 \times 10^{-10} \text{ GeV}^{-1}$ for $m_a \leq 0.1 \text{ meV}$. Data analysis and further data runs are under way. Final results on axion-photon coupling from the initial science runs of ALPS II are expected in early 2024.

28.08 – 01.09.2023
University of Vienna

*Speaker

1. Introduction

The axion is a highly-motivated hypothetical particle beyond the Standard Model of particle physics. It arises as a pseudo-Nambu-Goldstone boson from the spontaneous breaking of the Peccei-Quinn symmetry proposed to address the Strong CP problem in quantum chromodynamics (QCD) [1]. The axion is also a leading candidate particle of Dark Matter. The detection of the axion would therefore solve two puzzles coming from physics of very different scales [2].

Experimental attempts on the detection of the axion most often are based on its interaction with photons. In the presence of a magnetic field, an axion can convert into a photon and vice versa, via the so-called Sikivie and Primakoff effects [3]. The Any Light Particle Search II (ALPS II) experiment [4] at DESY Hamburg is also devised along these effects.

To address the Strong CP problem, the axion-photon field coupling strength, denoted as $g_{a\gamma\gamma}$ in the interaction Lagrangian $\mathcal{L} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$, where a is the axion field, and \vec{E} and \vec{B} are the electric and magnetic fields, respectively, must observe a relation with respect to the axion mass m_a . The generic properties of the axion can also be used to source a family of axion-like particles (ALPs) whose mass-coupling relation differs from that of the QCD axion, but instead satisfies certain astrophysical observations. The ALPS II experiment intends to seek exactly these ALPs.

The canonical benchmark coupling coefficients of the QCD axion is derived for its coupling to fermions (Dine-Fischler-Srednicki-Zhitnitsk, DFSZ model [5]) and quarks beyond the standard model (Kim-Shifman-Vainshtein-Zakharov, KSVZ model [6]). Recently, an alternative QCD axion model has been developed on the basis of the coupling of the Peccei-Quinn scalar field to magnetically charged fermions at high energies, and yields QCD axion coupling coefficients that differ drastically from the above-mentioned canonical models [7]. The ALPS II experiment is equipped with the sensitivity to also probe such alternative solutions for the QCD axion.

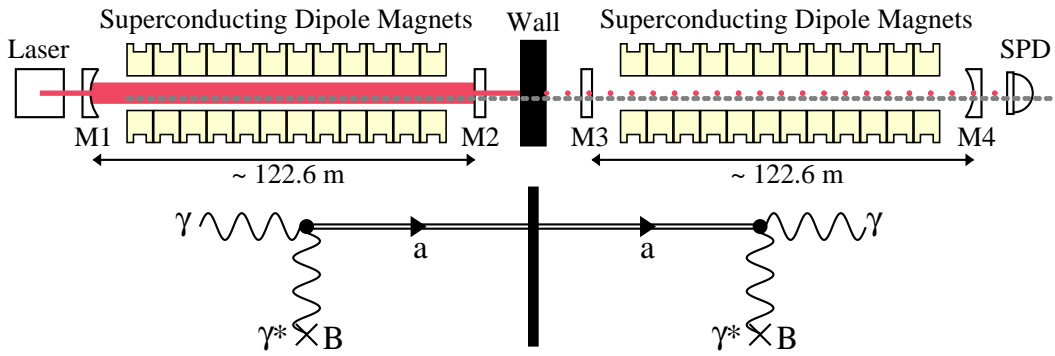


Figure 1: Schematic of the ALPS II experiment and the Feynman diagram illustrating the light-shining-through-a-wall process $\gamma \rightarrow a \rightarrow \gamma$ mediated by an axion-like particle a in the presence of a magnetic field B . M: Mirror; M1 and M2 form the (axion-) Production Cavity, and M3 and M4 form the (photon-) Regeneration Cavity; SPD: single-photon detector; dotted gray: axion-like particles; dotted red: regenerated photons.

2. The ALPS II Experiment

ALPS II is a dual optical cavity enhanced light-shining-through-a-wall (LSW) [8] experiment located at DESY Hamburg. Figure 1 shows the schematic of ALPS II. ALPS II aims at improving the search sensitivity by 3 orders of magnitude in terms of $g_{a\gamma\gamma}$ in comparison to previous LSW experiments [9]. The design sensitivity of $g_{a\gamma\gamma}$ of $2 \times 10^{-11} \text{ GeV}^{-1}$ of ALPS II delves into uncharted parameter space motivated by astrophysical observations [10] in a pure laboratory setting that is free from complex model assumptions.

At the target search sensitivity, the projected regenerated photon rate in ALPS II is:

$$\dot{N}_\gamma \approx 4 \times 10^{-5} \text{ Hz} \cdot \left(\frac{P_{\text{laser}}}{40 \text{ W}} \right) \cdot \left(\frac{\lambda_{\text{laser}}}{1064 \text{ nm}} \right) \cdot \left(\frac{\beta_{\text{PC}}}{5000} \right) \cdot \left(\frac{B \cdot L}{560 \text{ T} \cdot \text{m}} \right)^4 \cdot \left(\frac{g_{a\gamma\gamma}}{2 \times 10^{-11} \text{ GeV}^{-1}} \right)^4 \cdot \left(\frac{\beta_{\text{RC}}}{40000} \right),$$

where P_{Laser} is the laser power, λ_{Laser} is the laser wavelength, β_{PC} is the power build-up of the PC, $B \cdot L$ is the magnetic field-length product, and β_{RC} is the power build-up of the RC.

The ALPS II high-power laser source is a master oscillator power amplifier (MOPA) system at 1064 nm wavelength [11] that has a power output of about 60 W. After spatial-mode filtering and the injection optics, around 40 W of laser power is currently injected into the ALPS II experiment.

ALPS II reuses superconducting dipole magnets from the former HERA accelerator to construct its two magnet strings. Each string consists of 12 magnets. The magnets are straightened to increase the aperture from $\approx 37 \text{ mm}$ to $\approx 50 \text{ mm}$. Each magnet has a physical length of $\approx 10 \text{ m}$, and provides a magnetic field of 5.3 T over $\approx 8.8 \text{ m}$ [12]. The magnet strings were first powered on to a current level of 5700 A for a successful test in March 2022.

The power build-up of the optical cavities is given by $\beta = 4 \cdot T_{\text{input}}/\rho^2$, where T_{input} is the input mirror transmissivity and ρ is the round-trip loss of the cavity. The product of P_{laser} and β_{PC} gives the intracavity power of the PC. The laser intensity that can be withstood by the cavity mirrors sets a limit on the product of P_{laser} and β_{PC} . The power build-up of RC is limited by its round-trip loss, which in turn depends on the quality of the coated cavity mirrors. ALPS II has acquired cavity mirrors that project an expected β_{RC} of ≈ 16000 for the initial science run [13]. Acquisition of cavity mirrors of better quality is also planned.

The projected photon rate of $\dot{N}_\gamma \approx 4 \times 10^{-5} \text{ Hz}$ is equivalent to ≈ 3.5 photons per day, and requires high-sensitivity single-photon counters. ALPS II anticipates two detectors, the transition edge sensor (TES), which is a super sensitive calorimeter operated at cryogenic temperatures, and the heterodyne detector, which is based on the coherence properties of electromagnetic fields. The TES system developed for ALPS II has demonstrated an intrinsic dark count rate as low as $6.9 \times 10^{-6} \text{ Hz}$ [14]. The heterodyne detection scheme for ALPS II has also been shown to have a dark count rate of $\approx 10^{-5} \text{ Hz}$ after an integration time of 10^6 s [15]. Each of the two detection schemes requires a distinct optics setup. The two detection schemes therefore cannot be operated in parallel.

3. Initial Science Run

The installation of the ALPS II experimental setup with the heterodyne detection scheme was completed in September 2022. To facilitate stray light hunting and mitigation, ALPS II is carrying

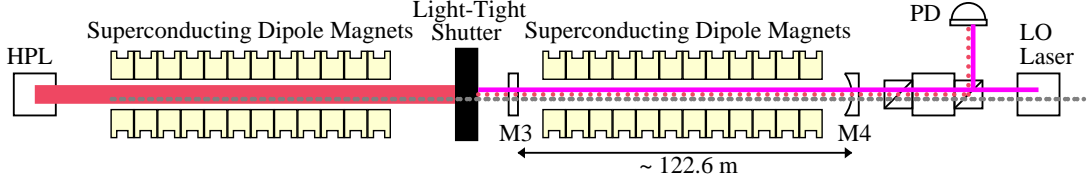


Figure 2: Schematic of the ALPS II initial science run with the heterodyne detection scheme. HPL: high-power laser; M3 and M4 form the (photon-) Regeneration Cavity. The local oscillator (LO) laser interferes with the regenerated photon signal to generate a radio-frequency signal detected by the photodiode (PD).

out its initial science run without the PC in place; the laser power impinging on the wall is increased by a factor of around 40. The wall is in practice a light-tight shutter. By operating the experiment with the magnets off and the shutter closed, we measure the background of the heterodyne detection scheme in situ. The schematic of the ALPS II initial science run is shown in Figure 2.

We have so far measured a cavity storage time of up to 7.04 ms for the RC. To the best of our knowledge, this corresponds to the longest storage time of a two-mirror optical cavity reported to date. Nonetheless, the excess cavity round-trip loss is higher than anticipated, and the corresponding β_{RC} is 7705, which falls short of the anticipated value of 16 000. We notice the dependence of the cavity round-trip loss with respect to the laser beam spot position on the cavity mirrors, and are looking into a more comprehensive study of the effect to potentially identify locations that result in higher β_{RC} .

The initial science run of ALPS II took place in May/June 2023. The polarization of the high-power laser was set to be perpendicular to that of the magnet field. The experiment in such configuration is insensitive to pseudo-scalar particles such as the axion and therefore enables a measurement of the background (as well as scalar particles, whose coupling to photons is nevertheless much more stringently bounded). We have accumulated around 150 000 s of science data. First analysis on the data has identified stray light as the main limit in the sensitivity of the initial science run of the ALPS II experiment. The estimated sensitivity reach in $g_{a\gamma\gamma}$ based on the first data is around $6 \times 10^{-10} \text{ GeV}^{-1}$ for $m_a \leq 0.1 \text{ meV}$. ALPS II will continue to take data in its current configuration until early 2024 to accumulate 10^6 s worth of data.

In the heterodyne detection scheme of ALPS II the weak axion-photon signal is interfered with a strong electromagnetic field with controlled frequency offset of several tens of MHz between the HPL and the LO laser (Figure 2). For the signal to remain coherent for the duration of heterodyne detection, the frequency offset needs to be stable to better than $3 \mu\text{Hz}$ over the integration time of 10^6 s. The coherence time of stray light on the other hand is expected to be shorter than that of the axion-photon signal. The initial science run data suggests a destructive interference of the stray light at the 10^6 s timescale such that it stops being the dominating background of the experiment.

4. Summary and Outlook

After years of preparation, ALPS II started data-taking in May 2023 and has achieved an estimated sensitivity reach that is close to two orders of magnitude better than its predecessors so far. ALPS II is currently operating without the PC in place to facilitate the identification and mitigation of stray light. First data suggest that the impact of stray light might be mitigated by

extending the integration time to 10^6 s. ALPS II is currently taking data in the search mode for scalar particles. This will be followed by the search for pseudo-scalar particles. Final results on axion-photon coupling from the initial science runs of ALPS II are expected in early 2024.

The PC will be installed during the course of 2024 after the initial science runs, which will improve the sensitivity reach of ALPS II via its power build-up as well as the reduction of laser power impinging on the wall, which we believe is the main source of stray light. Upgraded mirrors for the RC are being planned for late 2024 / early 2025 to improve the sensitivity of ALPS II towards its final design goal of $2 \times 10^{-11} \text{ GeV}^{-1}$ in terms of $g_{a\gamma\gamma}$ for masses $m_a \leq 0.1 \text{ meV}$.

Acknowledgments. We are grateful to numerous enthusiastic engineers, technicians, administrators and other helpful colleagues at DESY and elsewhere who contributed to get ALPS II going. We acknowledge support by the Deutsche Forschungsgemeinschaft (Germany), European Research Council (grant No. 948689), Max-Planck Society (Germany), National Science Foundation (USA, NSF PHY-2309918), Heising-Simons Foundation (USA, 2020-1841), Helmholtz Association (Germany), Science and Technology Facilities Council (UK, ST/T006331/1) and the Volkswagen Stiftung (Germany).

References

- [1] R. D. Peccei and H. R. Quinn, *CP conservation in the presence of pseudoparticles*, *Phys. Rev. Lett.* **38** 1440 (1977).
- [2] J. E. Kim and G. Carosi, *Axions and the strong CP problem*, *Rev. Mod. Phys.* **82** 557 (2010); F. Chadha-Day, John Ellis and D. J. E. Marsh, *Axion dark matter: What is it and why now?* *Sci. Adv.* **8** eabj3618 (2022); Y. K. Semertzidis and S. Youn, *Axion dark matter: How to see it?* *Sci. Adv.* **8** eabm9928 (2022).
- [3] H. Primakoff, *Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson*, *Phys. Rev.* **81** 899 (1951); P. Sikivie, *Experimental Tests of the "Invisible" Axion*, *Phys. Rev. Lett.* **51** 1415 (1983).
- [4] R. Bähre *et al.*, *Any light particle search II — Technical Design Report*, *J. Instrumentation* **8** T09001 (2013).
- [5] M. Dine, W. Fischler, and M. Srednicki, *A simple solution to the strong CP problem with a harmless axion*, *Phys. Lett. B* **104** 199 (1981); A.R. Zhitnitsky, *On Possible Suppression of the Axion Hadron Interactions (In Russian)*, *Sov. J. Nucl. Phys.* **31** 260 (1980).
- [6] J. E. Kim, *Weak-Interaction Singlet and Strong CP Invariance*, *Phys. Rev. Lett.* **43** 103 (1979); M. A. Shifman, A. Vainshtein, and V. I. Zakharov, *Can confinement ensure natural CP invariance of strong interactions?* *Nucl. Phys. B* **166** 493 (1980).
- [7] A. V. Sokolov and A. Ringwald, *Photophilic hadronic axion from heavy magnetic monopoles*, *J. High Energ. Phys.* **2021** 123 (2021).

- [8] A.A. Anselm, *Arion \leftrightarrow Photon Oscillations in a Steady Magnetic Field (In Russian)*, *Sov. J. Nucl. Phys.* **42** 1480 (1985); K. Van Bibber *et al.*, *Proposed experiment to produce and detect light pseudoscalars*, *Phys. Rev. Lett.* **59** 759 (1987).
- [9] K. Ehret *et al.*, *New ALPS results on hidden-sector lightweights*, *Phys. Lett. B* **689** 149 (2010); P. Pugnat *et al.*, *Search for weakly interacting sub-eV particles with the OSQAR laser-based experiment: results and perspectives*, *Eur. Phys. J. C* **74** 3027 (2014).
- [10] M. Meyer, D. Horns, and M. Raue, *First lower limits on the photon-axion-like particle coupling from very high energy gamma-ray observations*, *Phys. Rev. D* **87** 035027 (2013); A. Ayala *et al.*, *Revisiting the Bound on Axion-Photon Coupling from Globular Clusters*, *Phys. Rev. Lett.* **113** 191302 (2014).
- [11] F. Thies *et al.*, *Nd:YVO4 high-power master oscillator power amplifier laser system for second-generation gravitational wave detectors*, *Opt. Lett.* **44** 719 (2019).
- [12] C. Albrecht *et al.*, *Straightening of superconducting HERA dipoles for the any-light-particle-search experiment ALPS II*, *EPJ Techn. Instrum.* **8** 5 (2021).
- [13] M. Diaz Ortiz *et al.*, *Design of the ALPS II optical system*, *Phys. Dark Universe* **35** 100968 (2022).
- [14] Rikhav Shah *et al.*, *TES Detector for ALPS II*, *PoS EPS-HEP2021* **801** (2022).
- [15] Z. R. Bush *et al.*, *Coherent detection of ultraweak electromagnetic fields*, *Phys. Rev. D* **99** 022001 (2019).