The Any Light Particle Search experiment at DESY

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The Any Light Particle Search (ALPS II) is a light shining through a wall (LSW) experiment searching for axion-like elementary particles in the sub-eV mass range, which are motivated by astrophysics and cosmology and fulfill the requirements for being dark matter. ALPS II aims to measure an axion-to-photon coupling of $2 \times 10^{-11}$ GeV$^{-1}$, which is several orders of magnitude better than that of previous LSW experiments and will thus investigate a new parameter range. The increased performance is achieved by enhancing the magnetic field interaction length to $2 \times 10^6$ m and by amplifying the signal in an optical cavity on each side of a light-tight barrier. The expected signal is in the order of 1 photon per day, which will be measured by photon detectors with very low dark count rates of $O(10^{-6}$ Hz). This article gives a technical overview on the experiment design, previous and ongoing investigations and the current status with focus on the single photon detection.

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I. INTRODUCTION

Axions are hypothetical particles arising from quantum chromodynamics to solve the strong CP problem \[1, 2\]. From this, the class of axion-like particles (ALPs) can be derived, which have the same properties as axions but do not solve the strong CP problem: They have a low mass of less than 1 meV and they interact only feebly with normal matter and weakly with photons. These Weakly Interacting Sub-eV Particles (WISPs) are promising targets for light shining through a wall (LSW) experiments and any detection could have an impact on the dark matter problem. Here, laser light passes through a strong static magnetic field onto an opaque barrier. Some photons from the laser source are converted via the Primakoff effect into ALPs, which can pass the barrier. If some of the ALPs are converted back into photons, light can be detected behind the barrier. For increasing the probabilities of the conversion and reconversion process strong magnetic fields over long interaction distances are required \[3\].

ALPS I, the predecessor of ALPS II, had a production cavity (PC) in front of the barrier to increase the number of photons circulating in the magnetic field to 1 kW which enhanced a hypothetical ALP flow through the opaque barrier \[4\]. A special feature in ALPS II, shown in Fig. 1, is a second, so-called regeneration cavity (RC), which increases the probability behind the barrier that ALPs are converted back into photons. A further improvement in ALPS II is the usage of 24 magnets instead of one. Both, the dual-cavity and the magnetic field increase, will improve the sensitivity for the ALP search and targets an axion-to-photon coupling coefficient of $2 \times 10^{-11}$ GeV$^{-1}$ which provides new insights into an unknown parameter space \[5\] which is populated not only by ALP but also by QCD axion candidates \[6, 7\]. This area is interesting for unexplained astrophysical phenomena, which could be explained by the existence of ALPs \[8-10\].

In this article, we give an overview on the technological approaches we use in ALPS II to achieve this sensitivity.

II. ALPS II EXPERIMENT

A simplified sketch of the ALPS II experiment is shown in Fig. 1. A high power laser (HPL) with a wavelength

FIG. 1. Sketch and Feynman diagram of the ALPS II experiment. The production cavity (PC) enhances the light of the high power laser (HPL). The central optical bench (COB) houses optical components and the light-tight barrier. Behind the barrier, the probability for the ALPs-photon reconversion process is increased by using a regeneration cavity (RC). An additional laser is used to readout the RC length.
of 1064 nm and up to 70 W optical power can be injected into the PC. The PC can provide a power buildup factor of 16,000, allowing 150 kW (for initially 10 W injected power) to circulate in the optical cavity and produce ALPs in the presence of a magnetic field \[11\]. The central optical bench (COB) houses components of the optical system and the opaque barrier through which only ALPs can pass. An RC power buildup factor of 40,000 for 1064 nm light has been anticipated in the ALPS II technical design report \[5\] to boost the probability of ALPs converting back into photons.

A. Optical system

To achieve these high power buildup factors in the optical cavities, resonance conditions must be fulfilled, which requires a sophisticated optical control system whose functionality has been tested and verified in prototype experiments \[12, 13\].

The length of the PC is stabilized to the frequency of the HPL, while a second laser, having an offset frequency or wavelength, is stabilized to the RC length. The frequency offset allows to distinguish between the locking light and the detected signal generated from ALPs at 1064 nm. Depending on the detector type (see next section), either a local oscillator with a small offset frequency of a few MHz is used (for a heterodyne detection scheme) or a local oscillator beam with a wavelength of 532 nm is used, which is generated from a 1064 nm reference laser by means of a second harmonic generation (SHG) crystal to double the frequency (for a transition edge sensor). In the latter case, a dichroic mirror system filters remaining 1064 nm photons from the SHG. Tilt changes in both cavities are registered by using using quadrant photodiodes \[5, 11, 14\].

To maintain the ALP field coupling to the RC, the two optical cavities must share the same frequency and spatial mode with respect to each other. This results in a series of control loops: The frequency of the local oscillator beam is stabilized to the RC length, whereby the reference laser is kept phase-stable to the local oscillator beam. Reference laser and HPL, transmitted from the PC, are interfered with each other and the length of the PC is stabilized by actuating on the curved end mirror. Its position is thereby stabilized to within one picometer (see next section), either a local oscillator with a small offset frequency of a few MHz is used (for a heterodyne detection scheme) or a local oscillator beam with a wavelength of 532 nm is used, which is generated from a 1064 nm reference laser by means of a second harmonic generation (SHG) crystal to double the frequency (for a transition edge sensor). In the latter case, a dichroic mirror system filters remaining 1064 nm photons from the SHG. Tilt changes in both cavities are registered by using using quadrant photodiodes \[5, 11, 14\].

To check whether both cavities fulfill the dual resonance condition, the opaque barrier is equipped with a shutter, which can be opened if the spatial overlap between RC and PC needs to be checked \[11\]. The concept for mounting the optics and quadrant photodiodes with off-the-shelf high-stability mounts and a more compact custom-made clamping mount fulfill the stability requirements of ALPS II, just like the autocollimator-based alignment procedure of the COB \[15\].

B. Magnets

ALPS II uses 24 superconducting dipole magnets, each having a magnetic field of 5.3 T and 8.8 m length. Former magnets from the HERA accelerator are used, which were curved to steer proton beams along an arc. This curvature of the magnets restricts the aperture and thus the length of the two cavities, PC and RC, because of clipping loss. Therefore, the magnets were straightened and installed, increasing the aperture from 37 mm to 49 mm on average. Magnets having larger apertures are installed at the outer ends of the magnet strings, magnets having smaller apertures close to the middle of the ALPS II COB to follow the laser beam profile \[16\]. Twelve magnets form one magnet string with a length of 106 m and thus 560 T·m magnetic length \[11\]. The use of multiple magnets over 2 × 106 m effects significantly the improvement of sensitivity over ALPS I. The limiting factor for not using more magnets is the maximum length of the HERA tunnel which measures 250 m.

C. ALP signal

Assuming an axion-to-photon coupling coefficient of \[g_{\alpha \gamma} = 2 \times 10^{-11} \text{GeV}^{-1}\], this results in a very weak signal of 1 photon per day. In order to claim a detection with 5σ confidence interval and assuming a measurement period of 20 days and 50% detection efficiency, the dark noise rate of the detector must not exceed 7 μHz \[5, 11, 17, 18\].

\[N_\gamma = \frac{1}{16}(g_{\alpha \gamma} BL)^4 \cdot \eta \beta_{RC} \cdot P_{PC} \cdot \tau\]

The level of statistically significant ALP detection during the 20 days experiment is \[N_\gamma \leq 7 \mu\text{Hz}\] with 5σ confidence.

III. PHOTON DETECTION

Two independent techniques will be used to detect photons at an extremely low rate in the ALPS II experiment. A heterodyne detection scheme will be implemented first in ALPS II \[19\]. Second, a superconducting single photon detector, a transition edge sensor (TES),
will be installed. Two TESs are currently in an experimental setup at DESY to characterize their efficiency and dark noise rates \cite{18,20}.

A. Heterodyne detection

ALPS II will initially be equipped with a heterodyne detection scheme where the weak signal field is overlapped with a local oscillator beam having a known offset frequency. An interference beatnote is measured with a photodetector if a photon of the optical frequency has been generated from the ALP \cite{19}. It has been shown that a dark count rate of $10^{-6}$ photons per second is achievable. The fundamental limit is shot noise of the local oscillator, which follows the Poisson statistics, and decreases by increasing the integration time. The coherence of the signal is used to filter out background photons which do not have the exact right frequency. For ALPS II, an integration time of approximately 20 days should be required to claim a 5σ confident detection by using this technique \cite{21}. However, this method requires a total of three frequency-shifted lasers and has more stringent requirements on the long-term stability of the setup. Phase coherence is achieved by using a Mach-Zehnder-like heterodyne interferometer on a central optical bench (COB) made of a thermally stable glass ceramic to ensure necessary stability \cite{21}.

B. Transition edge sensor (TES)

The second detector that will be installed in ALPS II is a superconducting transition edge sensor (TES). While the heterodyne detection scheme measures photon rates, a TES can resolve single photons \cite{22,23}, whose recorded pulses are characterized using pulse shape analysis \cite{18} or principal component analysis \cite{24}. We currently investigate the performance of machine learning and deep learning algorithms for time series classification (see e.g. Ref. \cite{24}) in order to improve the pulse characterization, i.e., signal and background discrimination.

Fig. 2 shows a sketch of the experimental setup that is used to characterize two TESs at DESY. They are provided from NIST and made of tungsten, which is held at its critical temperature of about 140 mK with He3/4 mixture and an electric biasing current at the edge of superconductivity (see inset 2(b)) \cite{26}. If the TES absorbs energy, e.g., in form of a photon, the material heats up and changes its resistance in the direction of normal conductance (sharp increase of resistance). The resulting current change is measured via a superconducting interference device (SQUID) and appears as pulse in a time series, which can be described by two exponential function with rise and decay time and other parameters that can be fitted (see inset 2(c)). Using these fit parameters, the signal can be discriminated from background events and a dark noise rate of 7.7 µHz could be achieved. The energy resolution is less than 10% and might be limited by electronic noise \cite{18}. However, as soon as an optical fiber is connected to the TES, the dark counts increases. Potential noise sources are thermal emission in the fiber \cite{27}, black body from the laboratory \cite{28}, fluorescence in fused silica \cite{29} or optical parametric noise \cite{30}. These photons can be suppressed by using optical filters in the cold, but this will reduce the system detection efficiency (SDE) \cite{31}.

The setup to measure the SDE of a TES, as shown in inset 2(a), is based on developments at the Physikalisch-Technische Bundesanstalt (PTB) \cite{32,33}. The optical power of a fiber-coupled laser is strongly attenuated and measured by a calibrated powermeter. Two series-connected attenuators were previously calibrated in-situ \cite{32} and attenuate the light power to about 1000 photons per second. The so-controlled photon flux is measured by the TES and compared to the reference power of the powermeter. The ratio of the two power measurements gives the SDE. Promising SDEs of 95% ± 2% \cite{22} and above 87.7% ± 0.6% \cite{22} were detected for wavelengths of 1550 nm and 850-950 nm, respectively, in systems at PTB. The measurement of the SDE in our system, for a wavelength of 1064 nm, is again part of current investigations \cite{18,20,28}.
IV. SUMMARY AND OUTLOOK

The existence of axions and axion-like particles (ALPs) can explain mysterious phenomena in astrophysics and cosmology and they fulfill the criteria for being dark matter [34]. While haloscopes, such as ADMX [35] and MADMAX [36], look for axions and ALPs in the dark matter halo and helioscopes, like CAST [37] and IAXO [38], look for axions and ALPs emitted by the sun, ALPS II is a light shining through a wall experiment that produces ALPs in a laboratory and does therefore not rely on cosmological assumptions.

Major milestones of the ALPS II experiment, such as the installation of the magnets and clean rooms in the HERA tunnel, are completed. The operation of key technologies have been experimentally demonstrated in recent years, such as the high-power laser and the stabilization of the optical cavities, and are currently being installed in the ALPS II experiment. The heterodyne detection system will be the first of two photon detectors implemented this year to perform a first science run.

A replacement of the optical mirrors in the cavities will then increase the power buildup factor to the design values. After that, optics and laser wavelengths will be exchanged to verify the science results with the transition edge sensor. Within 20 days after the start of a measurement, first estimates for the existence of ALPs can be made. ALPS II will set in any case new limits in the parameter space of energies below 1 meV and an axion-to-photon coupling sensitivity down to $2 \times 10^{-11} \text{GeV}^{-1}$, which will exceed the boundaries from current experiments.

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