Demonstration of the length stability requirements for ALPS II with a high finesse 10 m cavity

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Light-shining-through-a-wall experiments represent a new experimental approach to search for undiscovered elementary particles not accessible with accelerator based experiments. The next generation of these experiments, such as ALPS II, require high finesse, long baseline optical cavities with fast length control. In this paper we report on a length stabilization control loop used to keep a cavity resonant with light at a wavelength of 532 nm. It achieves a unity-gain-frequency of 4 kHz and actuates on a mirror with a diameter of 50.8 mm. This length control system was implemented on a 10 m cavity and its projected performance meets the ALPS II requirements. The finesse of this cavity was measured to be 93,800±500 for 1064 nm light, a value which is close to the design requirements for the ALPS II regeneration cavity.

1 Introduction

Axion-like particles [1] represent an extension to the standard model of particle physics that could explain a number of astrophysical phenomena including the transparency of the universe for highly energetic photons [2] as well as excesses in stellar cooling [3]. These particles are characterized by their low mass, $m < 1\,\mathrm{meV}$, and weak coupling to two photons, $g < 10^{-10}\,\mathrm{GeV}^{-1}$. The most prominent axion-like particle is the axion itself which is predicted to preserve the so called CP conservation of QCD [4]. Axions and axion-like particles are also excellent candidates to explain the dark matter in our universe.

Light shining through a wall experiments attempt to measure the interaction between axion-like particles and photons by shining a laser through a strong magnetic field at an optical barrier. This will generate a flux of axion-like particles traveling through the optical barrier to another region of strong magnetic field on the other side of the barrier. Here, some the axion-like particles will reconvert to photons that can be measured.

ALPS II [5] is a light-shining-through-a-wall experiment that is currently being set up at DESY in Hamburg. It uses strong, superconducting dipole magnets and a high power laser with 100 m cavities on either side of the optical barrier to boost the conversion probability of photons to axion-like particles and vice versa. The cavity before the barrier is called the production cavity (PC), while the cavity after the barrier is called the regeneration cavity (RC).

In order for ALPS II to reach a sensitivity necessary to probe the photon couplings predicted by the aforementioned astrophysical phenomena the experiment must employ long baseline cavities. Additionally, the PC must have a high circulating power and the RC a high finesse. This is because increasing the number of photons in the PC will increase the axion-like particle flux, while the finesse of the RC amplifies the probability that axion-like particles will reconvert to photons [6]. A demonstration of the optical subsystems for ALPS II is currently taking place in a 20 m test facility, referred to as ALPS IIa [7], whereas the 200 m full-scale experiment will be called ALPS IIc.

According to the ALPS IIc design, the production cavity will be seeded with a 30 W laser operating at 1064 nm [8]. The laser frequency will be stabilized to the PC length with the Pound-Drever-Hall (PDH) laser frequency stabilization technique [9, 10]. With a power buildup factor of 5,000 the PC will achieve a nominal circulating power of 150 kW. It is crucial that the PC and the RC are simultaneously resonant to the frequency of the input laser field for the enhancement of the axion-like particle production and photon reconversion probability. An active length stabilization system will be required to suppress the differential length noise between the cavities and maintain the dual resonance condition. The length sensing of the RC cannot use 1064 nm light to generate an error signal for the feedback control loop as this would be indistinguishable from the regenerated light. Instead 1064 nm light will be frequency doubled in front of the optical barrier and the length stabilization system will utilize 532 nm light. According to the ALPS IIc design, the length stabilization system must ensure that the power buildup for the regenerated photons stays within 95% of its value on resonance. Even though a seismically quiet environment is chosen for the ALPS II experiments, this sets challenging requirements on the bandwidth of the length control loop and requires a custom made design for the length actuator.

The ALPS II RC will have a finesse of 120,000 for 1064 nm light and the circulating fields in each of the cavities will propagate through 468 Tm of magnetic field length. Considering all of the parameters given above ALPS IIc will achieve a sensitivity of $2 \times 10^{-11}\,\mathrm{GeV}^{-1}$ for the coupling constant of photons to axion-like particles with masses up to 0.1 meV. While a detailed overview and status report on ALPS II is given in [5] and [11] this paper focuses on the characterization of the ALPS IIa RC. In section 2 the experimental setup is described. Section 3 discusses the implementation and results of the length stabilization system for the RC. The results of the finesse measurements are presented in section 4 and section 5 draws conclusions on the experimental results.

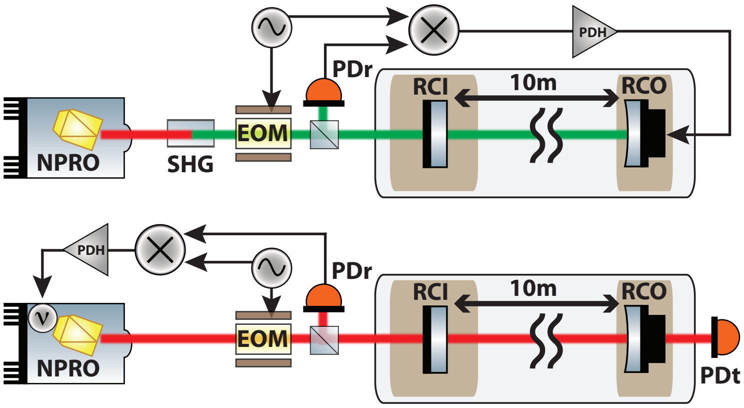

Figure 1: *Upper*: Length control of the RC consisting of the mirrors RCI and RCO with PDH feedback control loop. A high bandwidth length actuator is attached to RCO. The laser beam from the NPRO is frequency doubled. An EOM imprints phase modulation sidebands on the laser beam and the photodetector PDr is used to sense the PDH error signal. *Lower*: Laser frequency feedback for high finesse cavity operation with 1064 nm light. The photodetector PDt in transmission of the cavity is used to measure the storage time.

2 Setup

The ALPS IIa RC is being characterized with two different experiments. The first experiment uses a high bandwidth control loop with 532 nm light to stabilize the length of the RC. We are capable of measuring the error point noise of this setup and calibrating it in terms of suppressed length noise of the cavity. In the second experiment the finesse of the RC for 1064 nm light is characterized by measuring the cavity storage time.

A 500 mW non-planar-ring-oscillator (NPRO) at a wavelength of 1064 nm is used to implement the length lock of the RC. It seeds a periodically poled potassium titanyl phosphate crystal which generates 100 µW of 532 nm light in a single-pass second harmonic generation (see schematic in the upper part of figure 1). An electro-optic modulator (EOM) adds phase modulation sidebands before the light enters the optical cavity. The two cavity mirrors are mounted on separate optical tables 10 m apart from each other and the entire experiment is located in a clean and temperature controlled environment.

The cavity input mirror RCI is flat while the cavity end mirror RCO has a radius of curvature of 23.2±0.5 m. This configuration yields a beam radius on RCI of 1.97±0.02 mm and on RCO of 2.62±0.01 mm, respectively. Each mirror has a diameter of 50.8 mm with a mass of 43 g and features a dichroic coating. The mirror size was chosen to avoid diffraction losses in ALPS IIc. RCI has a nominal power transmission of 25 ppm for

1064 nm and 5 % for 532 nm light. The RCO coating has a power transmission of 3 ppm for 1064 nm and 1 % for 532 nm light. The free spectral range (FSR) is 15 MHz.

A high bandwidth photodetector PDr senses the beat signal between the directly reflected field of the cavity and a fraction of the circulating field that is transmitted through RCI. The electric signal at the output of the photodetector is demodulated and amplified in the PDH servo electronics and sent to the actuator.

In contrast to the length lock, the finesse of the cavity is measured with a setup depicted in the lower part of figure 1. The 1064 nm NPRO beam passes an EOM and is injected to the cavity. The PDH error signal is demodulated and fed back to the laser frequency in order to lock the laser to the cavity. A photodetector (PDt) monitors the power in transmission of the cavity to perform a measurement of the storage time as discussed in section 4.

3 High bandwidth length lock

One of the key parameter for the ALPS II sensitivity is the differential length stability between the PC and the RC. The differential RMS length noise between these two cavities must be suppressed to less than 0.5 pm. This will ensure that light that is resonant with the PC will experience 95 % of the maximum power buildup in the RC. This is what we refer to as the dual resonance condition. As mentioned earlier the PDH error signal for the RC is generated using 532 nm light.

Based on the transmission values of the cavity mirrors for 532 nm light the finesse is 102 and the linewidth 146.5 kHz in ALPS IIa. To suppress the noise as much as possible a conditionally stable control loop design with two integrators is used. The resonances of the piezo actuator attached to RCO were suppressed with notch filters in the control loop. A unity-gain-frequency of 4 kHz was achieved with a phase margin of 20 deg.

The length actuator is a piezo ceramic from Physik Instrumente GmbH & Co. KG. We designed a custom mount to hold a stack consisting of the piezo, the cavity end mirror RCO and a wave washer. The stack is kept in place by exerting pressure on the wave washer with a retaining ring that is screwed into the mount. This also has the effect of preloading the piezo. The force exerted on the stack was optimized such that the resonances of the system were pushed as high as possible. It was also important not to over tighten the retaining ring as this reduced the performance of the length acutator. The result for the optimized setup contains the first resonance at 4.9 kHz and a phase loss of 17 deg at 4 kHz.

Figure 2 shows a spectral density of the control and error signal displayed in terms of length noise of the cavity. As already mentioned in [7] the control signal is dominated by seismic noise up to 1 kHz and by laser frequency noise above 1 kHz. The error signal represents an in-loop measurement of the suppressed length noise. A measurement of the dark noise revealed that it is not significantly contributing to the control or error signal noise.

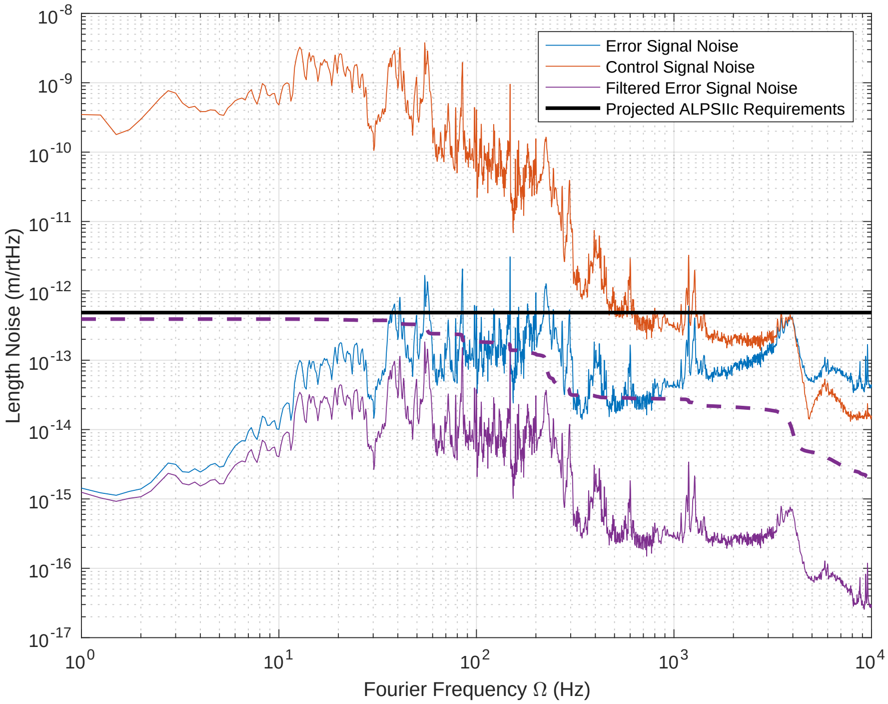

Figure 2: Amplitude spectral densities of control and error signal of the PDH control loop representing the differential length noise of the cavity with respect to the input field. For a comparison with the ALPS II requirements the error signal is filtered by the ALPS IIc RC pole frequency for 1064 nm in post processing and its corresponding integrated RMS is shown with the dotted purple line. This meets the projected ALPS II length noise requirement shown in black.

Cavities exhibit a passive low pass filter property for their circulating fields. Hence, the frequency noise of the input field is suppressed at Fourier frequencies above the cavity pole [12]. In order to predict the impact to ALPS IIc the error signal noise is therefore filtered in post processing by the expected filter property of the ALPS IIc RC. This consists of a low pass with a pole frequency of 6 Hz. If we assume identical uncontrolled length noise conditions for the ALPS IIa and ALPS IIc environments then the integrated RMS of this filtered spectrum must be less than 0.5 pm to fulfill the dual resonance condition for the ALPS IIc RC. The projection depicted in figure 2 demonstrates for the first time a measurement that is below the requirements. Achieving the ALPS II

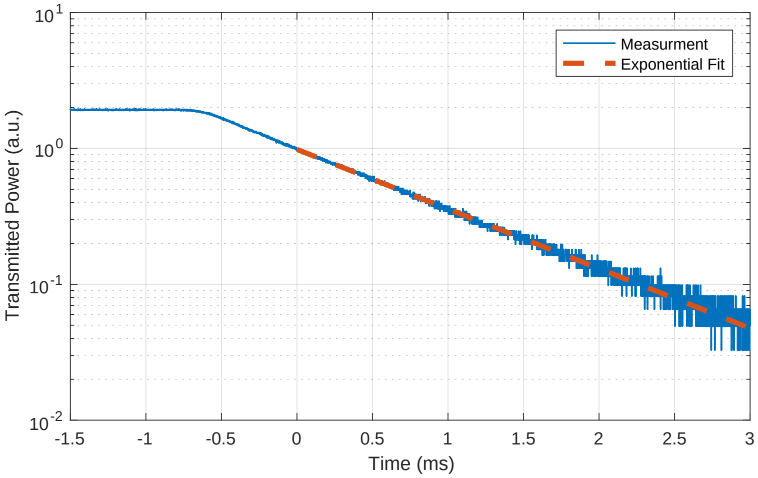

Figure 3: The cavity storage time is a measurement of the exponential decay of the transmitted power when the laser shutter is closed.

requirements with a piezo length actuator shows that the optical system for ALPS II does not require active or passive seismic isolation systems for the cavity mirrors. The characterization of the out-of-loop noise in this system must take place before the length stability requirements can be demonstrated with 1064 nm light.

4 High finesse cavity characterization

State-of-the-art optics with ultra low losses are required to construct a cavity with a finesse of 120,000 for the ALPS II RC [5]. These types of cavities must be set up in vacuum to avoid any kind of dust particles contaminating the mirror surfaces and avoid scattering of the intra-cavity light. Hence, for this measurement we set up the ALPS IIa RC in vacuum and environmental conditions similar to the one that we anticipate for the ALPS IIc experiment.

The cavity storage time can be used to characterize the intra-cavity losses and finesse of the cavity [13]. Equation 1 gives the relation between storage time and finesse for high finesse cavities.

$$\tau_{\text{storage}} = \frac{\mathcal{F}}{\pi \cdot f_{\text{FSR}}} \simeq \frac{g}{f_{\text{FSR}}} \tag{1}$$

In this equation $\mathcal{F}$ is the finesse and f_{FSR} represents the FSR. The cavity gain factor g^2

is defined by the following equation.

$$g^2 = \frac{1}{\left(1 - \sqrt{R_{\text{in}} R_{\text{out}} (1 - L)}\right)^2} \tag{2}$$

This contains the input and output mirror power reflectivites R_{in} and R_{out} as well as the roundtrip power losses L.

For a cavity storage time measurement the power injected to the cavity is set to 10 mW. The cavity storage time is determined by measuring the exponential decay of the transmitted power once the input light has been blocked. To do this a laser was stabilized to the cavity by feeding back to its frequency and then the laser shutter was suddenly closed. The power in transmission was then measured and the following function was fit to the data [13]:

$$P_{\text{trans}}(t) = P_0 g^2 T_{\text{in}} T_{\text{out}} \exp\left(-\frac{2t}{\tau_{\text{storage}}}\right) \tag{3}$$

In this equation P_0 is the initial power, T_{in} and T_{out} are the power reflectivities of the input and output mirror, respectively.

Figure 3 shows the result of one of the storage time measurements. An average of ten measurements yielded a storage time of 1.99±0.01 ms. The fit considers datapoints when the power in the cavity dropped by a factor of two since it takes some time until the shutter has blocked the entire input beam. Applying equations (1) and (2) yield a finesse of 93,800±500 and the roundtrip losses are 39±1 ppm. We believe that most of the losses are due to low spatial frequency surface roughness of the mirrors. While the result strongly depends on the beam spot position on the mirrors, the measurements were performed at a position that gave the longest storage time.

5 Conclusion

The development of a customized, high bandwidth length actuator led to a successful demonstration of the ALPS IIc length noise requirements in the ALPS IIa environment. This will allow us to set up ALPS IIc without a dedicated seismic isolation system for the cavity mirrors if we assume that the seismic noise environment is similar to ALPS IIa. A length actuator that moves a 50.8 mm mirror with a cavity feedback control loop and a unity-gain-frequency of 4 kHz has been successfully demonstrated. In addition the finesse of the ALPS IIa RC was measured to be 93,800±500 with a storage time of 1.99±0.01 ms. However, in order to reach the ALPS IIc design value the losses must be cut in half. Still, the current results are comparable to experiments that employ long baseline, high finesse optical cavities such as gravitational wave detectors [14, 15], filter cavities for non-classical light [16] and vacuum magnetic birefringence experiments [17].

These results represent a major milestone for ALPS II from the previous work [7]. The next steps will involve coupling 1064 nm light transmitted from the ALPS IIa PC to the RC and directly measuring the dual resonance condition using the length stabilization system detailed in this paper.

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References

[1] C. Patrignani et al (Particle Data Group). “Review of Particle Physics”, Chin. Phys. C, 2016, **40** (10): 100001

[2] 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, **5**, 035027, (2013).

[3] M. Giannotti, I. Irastorza, J. Redondo and A. Ringwald, “Cool WISPs for stellar cooling excesses”, J. Cosmol. Astrop. Phys., **5**, 57 (2016).

[4] R. D. Peccei and H. R. Quinn, “CP Conservation in the Presence of Pseudoparticles” Phys. Rev. Lett. **38**, 1440 (1977).

[5] R. Bähre, B. Döbrich, J. Dreyling-Eschweiler, S. Ghazaryan, R. Hodajerdi, D. Horns, F. Januschek, E. -A. Knabbe, A. Lindner, D. Notz, A. Ringwald, J. E. von Seggern, R. Stromhagen, D. Trines and B. Willke, “Any light particle search II - Technical Design Report,” J. Inst. **8** (9),T09001 (2013).

[6] F. Hoogeveen and T. Ziegenhagen, “Production and detection of light bosons using optical resonators,” Nucl.Phys. B 358, 3–26 (1991).

[7] A. D. Spector, J. H. Põld, Robin Bähre, A. Lindner, and B. Willke, “Characterization of optical systems for the ALPS II experiment,” Opt. Express 24, 29237–29245 (2016).

[8] M. Frede, B. Schulz, R. Wilhelm, P. Kwee, F. Seifert, B. Willke and D. Kracht, “Fundamental mode, single-frequency laser amplifier for gravitational wave detectors,” Opt. Express 15 **2**, 459–465 (2007).

[9] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G.M. Ford, A. J. Munley and H. Ward, “Laser phase and frequency stabilization using an optical resonator,” Appl. Phys. B 31 **2**, 97–105 (1983).

[10] E. D. Black, “An introduction to Pound-Drever-Hall laser frequency stabilization,” Am. J. Phys **69**, 79 (2001).

[11] A. D. Spector, “ALPS II technical overview and status report”, arXiv:1611.05863 (2016).

[12] C. L. Mueller, M. A. Arain, G. Ciani, R. T. DeRosa, A. Effler, D. Feldbaum, V. V. Frolov, P. Fulda, J. Gleason, M. Heintze, K. Kawabe, E. J. King, K. Kokeyama, W. Z. Korth, R. M. Martin, A. Mullavey, J. Peold, V. Quetschke, D. H. Reitze, D. B. Tanner, C. Vorvick, L. F. Williams, and G. Mueller, “The advanced LIGO input optics,” Rev. Sci. Instrum. **87**, 014502 (2016).

[13] T. Isogai, J. Miller, P. Kwee, L. Barsotti and M. Evans, “Loss in long-storage-time optical cavities,” Opt. Express 21, 30114–30125 (2013).

[14] The LIGO Scientific Collaboration, “Advanced LIGO,” Classical Quant. Grav. **32**, 074001 (2015).

[15] S. Sato, S. Miyoki, M. Ohashi, M. Fujimoto, T. Yamazaki, M. Fukushima, A. Ueda, K. Ueda, K. Watanabe, K. Nakamura, K. Etoh, N. Kitajima, K. Ito, and I. Kataoka, “Loss factors of mirrors for a gravitational wave antenna,” Appl. Opt. 38, 2880-2885 (1999).

[16] M. Evans, L. Barsotti, P. Kwee, J. Harms and H. Miao, “Realistic filter cavities for advanced gravitational wave detectors,” Phys. Rev. D 88 **2**, 022002 (2013).

[17] F. Della Valle, E. Milotti, A. Ejlli, U. Gastaldi, G. Messineo, L. Piemontese, G. Zavattini, R. Pengo, and G. Ruoso,“Extremely long decay time optical cavity,” Opt. Express 22, 11570-11577 (2014).