Põld and Spector *EPJ Techniques and Instrumentation* (2020) 7:1
https://doi.org/10.1140/epjti/s40485-020-0054-8

EPJ Techniques and Instrumentation

RESEARCH ARTICLE

Open Access

Demonstration of a length control system for ALPS II with a high finesse 9.2 m cavity

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Abstract
Light-shining-through-a-wall experiments represent a new experimental approach in the 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 9.2 m cavity resonant. The finesse of this cavity was measured to be 101,300±500 for 1064 nm light. Fluctuations in the differential cavity length as seen with 1064 nm and 532 nm light were measured. Such fluctuations are of high relevance, since 532 nm light will be used to sense the length of the ALPS II regeneration cavity. Limiting noise sources and different control strategies are discussed, in order to fulfill the length stability requirements for ALPS II.

Keywords: Lasers, Optical resonators, Precision interferometry, Axion searches

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 charge-parity conservation of Quantum chromodynamics [4]. Axions and axion-like particles are also excellent candidates to explain the dark matter in our universe [5].

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 of the axion-like particles will reconvert to photons that can be measured.

Any Light Particle Search (ALPS) II [6] 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 122 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, high finesse cavities. This is because increasing the number of photons in the PC increases the axion-like particle flux, while the finesse of the RC amplifies the probability that axion-like particles will reconvert to photons [7]. A demonstration of the optical subsystems for ALPS II is currently taking place in a 20 m test facility, referred to as ALPS IIa [8], whereas the 245 m full-scale experiment will be called ALPS IIc.

In the current ALPS IIc design, the PC will be seeded with 30 W generated from a high power laser operating at 1064 nm [9]. The cavities will be stabilized using the Pound-Drever-Hall (PDH) technique [10, 11]. With a power buildup factor of 5000 the PC will achieve a nominal circulating power of 150 kW. For the resonant enhancement of the reconversion process it is crucial that the light circulating inside the PC is simultaneously resonant in the RC. Active stabilization systems will be required to suppress the differential length noise between the cavities and maintain the dual resonance condition. Two detection methods with very different systematic uncertainties are planned for ALPS II. First a heterodyne detection scheme will be implemented [12]. Then, the optical system will be adapted to accommodate a transition edge sensor (TES) capable of measuring individual reconverted photons [13]. The two detectors cannot be operated in parallel due to the different optical systems that the experiment must employ in order to use them. For the TES 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 that is offset phase locked to the light transmitted by the PC 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 optical system must ensure that the power buildup for the regenerated photons stays within 90 % of its value on resonance [14]. This is what we refer to as the dual resonance condition. To check that this condition is satisfied, the optical barrier will be equipped with a shutter that can be opened to allow light transmitted by the PC to couple directly to the RC. By measuring the power of the PC light that is transmitted by the RC, the coupling efficiency, and hence the field overlap between the PC circulating field and RC eigenmode, can be calculated. 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, piezo controlled length actuator.

The length stability requirement calls for a differential length noise with an RMS value of less than 0.6 pm between the PC and the RC [14]. The ALPS IIc RC will have a finesse of ∼120,000 for 1064 nm light and a linewidth of 10 Hz. Circulating fields in each of the cavities will propagate through 560 Tm of magnetic field length. Considering all of the parameters given above ALPS IIc will achieve a sensitivity of $g_{\alpha\gamma\gamma}=2 \times 10^{-11}\,\mathrm{GeV}^{-1}$ for the coupling constant of photons to axion-like particles with masses up to 0.1 meV and a measurement time of 20 days [14]. While this means that ALPS II will not be sensitive to the QCD axion, it will probe an important region of the axion-like particle parameter space searching for particles related to the aforementioned astrophysical hints. A detailed overview and status report on ALPS II is given in [6] and [15]. This paper focuses on the implementation and characterization of the length stabilization system of the ALPS IIa RC.

Method

The ALPS IIa RC is being characterized with two figures of merit: finesse for 1064 nm light and differential length noise. For the characterization of the differential length noise a high bandwidth control loop with 532 nm light stabilizes the length of the RC. The error point noise of this setup can be calibrated to provide an in-loop measurement of the suppressed length noise of the cavity. Furthermore, locking a separate 1064 nm laser to the cavity revealed noise sources that were not observable with the in-loop measurement. From here on the terms infrared and green light will refer to 1064 nm and 532 nm light, respectively. The finesse of the RC for 1064 nm light is characterized by measuring the cavity storage time.

A 500 mW non-planar-ring-oscillator L1 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 (SHG) (see schematic in Fig. 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 9.2 m apart from each other and within a common vacuum system. A rubber material in the feet of the optical table provides dampening above 100 Hz. For the measurements the system was pumped down to 1×10^{-5} mbar in order to minimize acoustic couplings. The entire experiment is located in a clean and temperature controlled environment which is similar to the conditions we anticipate for the ALPS IIc experiment.

The cavity input mirror RCI is flat while the cavity end mirror RCO has a radius of curvature of 19.7±0.1 m. This configuration yields a beam radius on RCI of 1.82±0.01 mm

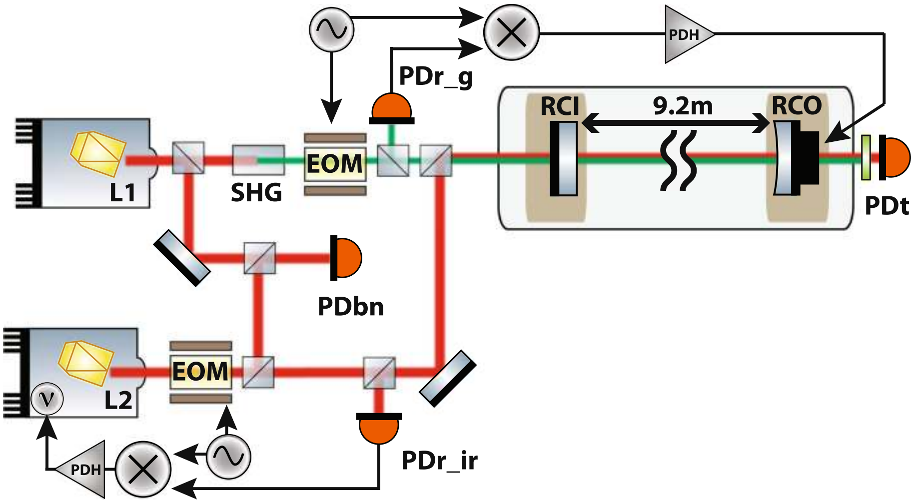

Fig. 1 Experimental setup. *Length control of the RC:* The cavity consists of the mirrors RCI and RCO as well as a PDH feedback control loop. A high bandwidth length actuator is attached to RCO. The laser beam from laser L1 is frequency doubled in a temperature controlled SHG. An EOM imprints phase modulation sidebands on the laser beam and the photodetector PDr_g is used to sense the PDH error signal. *Laser frequency feedback:* For the high finesse cavity operation with 1064 nm light the frequency of laser L2 follows the RC. The feedback control loop uses PDr_ir as a sensor and photodetector PDt in transmission of the cavity is used to measure the storage time. *Beatnote frequency measurement:* The beatnote signal between L1 and L2 is measured with a high bandwidth photodetector (PDbn)

and on RCO of 2.51±0.01 mm for 1064 nm light, 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 is 16.2 MHz.

A second laser L2 (see Fig. 1) seeds the cavity with infrared light. Photodetectors PDr_g and PDr_ir sense the beat signal between the directly reflected field of the cavity and a fraction of the circulating field that is transmitted through RCI for green and infrared light, respectively. Each signal at the output of the photodetector is demodulated, amplified in the PDH servo electronics and sent to the actuator. PDbn senses the beatnote signal of L1 and L2. In addition, photodetector PDt monitors the power in transmission of the cavity and is also used to perform a measurement of the storage time.

Results and discussion

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 [6]. 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.

Once the laser is frequency locked to the cavity the input light is blocked by suddenly closing the laser shutter. Then the exponential decay of the transmitted power is measured to determine the cavity storage time. The following function was fit to the data [16]:

$$P_{\mathrm{trans}}(t) = P_0 G T_{\mathrm{in}} T_{\mathrm{out}} \exp\left(-\frac{2t}{\tau_{\mathrm{storage}}}\right) \tag{1}$$

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

Figure 2 shows the result of one of the storage time measurements. An average of ten measurements yielded a storage time τ_{storage} of 1.99±0.01 ms. The fit considers data points 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 from reference [16] yields a finesse of 101,300±500 and the roundtrip losses are 33±1 ppm. This does not include the transmissivities of the mirrors. We believe that most of the losses are due to scattering caused by low spatial frequency surface roughness of the mirrors. The result of the measurement strongly depended on the position of the beam spot on the mirrors. To find the position with the highest finesse the position of the circulating field was scanned over the area of the mirror within the free aperture of the mount. The measurement reported here was taken at the position in which the highest finesse was measured. The 0.01 ms uncertainty is related to the statistical uncertainty of the measurements made at this position.

High bandwidth cavity lock

One of the key parameter for the ALPS II sensitivity is the differential length stability between the PC and the RC. Differential length noise refers to differential length changes between the PC and the RC after the dual resonance condition has been established. The differential RMS length noise between these two cavities must be suppressed to less than

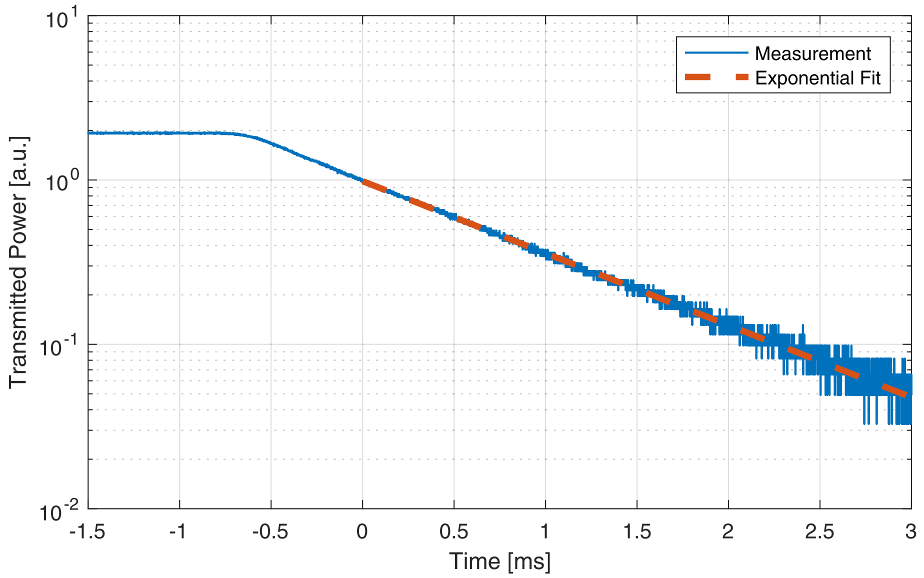

Fig. 2 Storage time measurement. The cavity storage time is a measurement of the exponential decay of the transmitted power when the laser shutter is closed

0.6 pm in order to maintain 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 158.6 kHz in ALPS IIa. The low finesse for 532 nm light was chosen such that only a minimum amount of light is circulating in the RC. A conditionally stable control loop design with two integrators is used to suppress the noise as much as possible. In order to smoothen the transfer function of the piezo actuator attached to RCO and have less impact from the piezo resonances a digital filter was inserted into the control loop. The filter coefficients were chosen such that they inverted the piezo transfer function. Consequently, this optimized the phase and gain margin of 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 (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 actuator. The result for the optimized setup contains the first resonance at 4.9 kHz.

In-loop measurement

Figure 3 shows a spectral density of the green control (solid blue trace) and error signal (solid red trace) displayed in terms of length noise of the cavity. As already mentioned in [8] 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. Electronics noise from the digital controller affected the measurement below

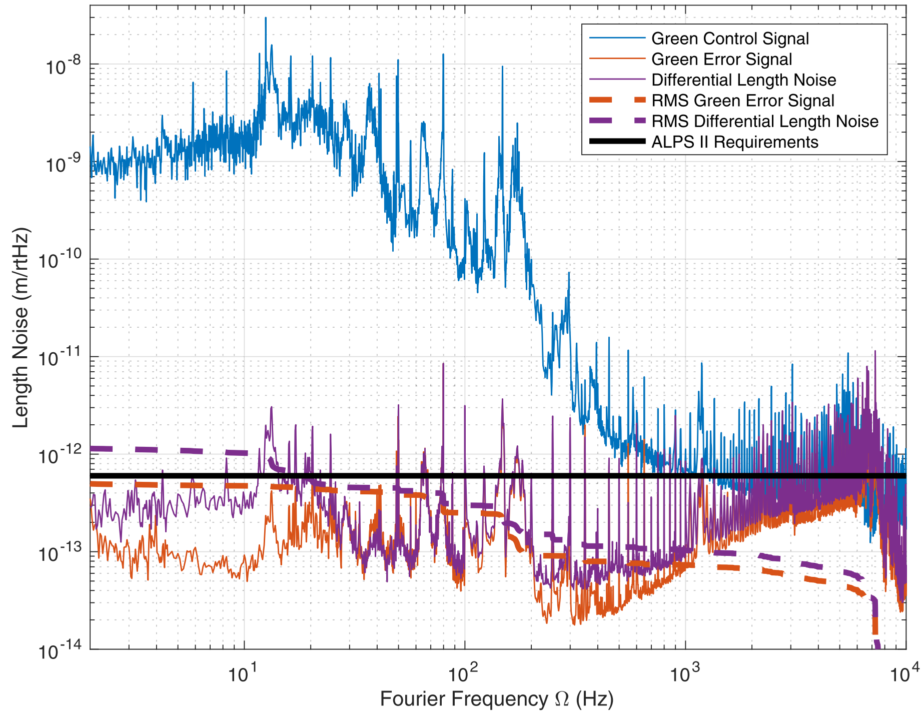

Fig. 3 Length noise measurement. Amplitude spectral densities of green control (solid blue trace) and error (solid red trace) signal of the PDH control loop calibrated in length noise as well as the beatnote frequency measurement (solid purple trace) representing the differential length noise. For a comparison with the ALPS II requirements the error signal and the beatnote frequency measurement are filtered by a cavity pole frequency of 6 Hz in post processing and its corresponding integrated RMS is shown with the dashed lines

10 Hz. This will be addressed by using a different digital control system, however this noise still does not prevent the in-loop measurements from meeting the requirements.

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 [17]. 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, assuming a Finesse of 100,000 as reported on in the previous section. The RMS projection (dashed red trace) shows that the control loop has sufficient gain to meet the length noise requirements for ALPS IIc considering similar uncontrolled length noise conditions as in the ALPS IIa lab [18].

Beatnote frequency measurement

Since the measurement in the previous section was an in-loop measurement it was important to confirm the result with an out-of-loop measurement. This was performed with a second 1064 nm laser (L2). While the cavity length is locked to the frequency doubled laser L1, the frequency of the second laser L2 is locked to the cavity in order to simulate the light that comes from the PC and is phase locked to L1. The ∼50 MHz infrared beatnote frequency is monitored with a fast photodetector PDbn and demodulated down to 100 kHz by mixing it with a stable reference. A time series of the 100 kHz signal is then recorded and its frequency noise is analyzed in post-processing.

The measurement is displayed in Fig. 3 (solid purple trace). Unexplained out-of-loop noise enters below 25 Hz and above 200 Hz. The filtered RMS noise, displayed in the corresponding dashed line, exceeds the ALPS II length noise requirements by a factor of roughly two. In order to address the out-of-loop noise below 25 Hz the control signal of the length control loop was fed back to the laser frequency of L1 instead. Thus the bandwidth of the loop could be significantly increased to 40 kHz. Electronics noise, which limited the in-loop measurement for the length lock below 10 Hz was substantially lower as the digital controller was not required for this type of control loop.

Figure 4 shows the data below 40 Hz for the length (solid blue trace) and frequency feedback (solid red trace), respectively. The measurement was loop gain limited above 40 Hz. While the length stabilization crosses the requirements at 17 Hz and increases further to an RMS value of 3.5 pm at 1 mHz, the frequency stabilization RMS meets the requirements down to 1.3 mHz.

It is apparent that the actuation on the piezo increases the out-of-loop noise. We believe this noise is due to the differential changes of the optical path length inside the cavity for 532 nm and 1064 nm light. The cause of this noise will be the subject of further investigation.

Conclusion

In ALPS IIa we demonstrated a control loop actuating on the length of a 9.2 m cavity. This system will be capable of maintaining the length stability to a level below the requirements in the ALPS IIc environment. A customized, high bandwidth length actuator that

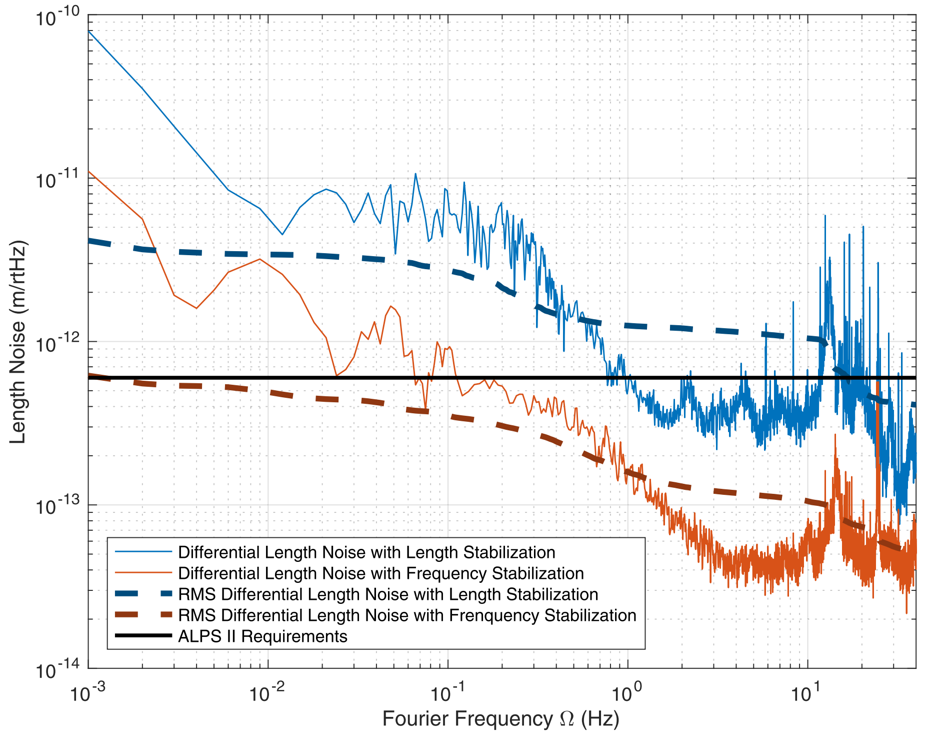

Fig. 4 Out-of-loop measurement. Beatnote frequency measurement for the length (solid blue trace) and frequency (solid red trace) feedback and corresponding RMS filtered by the infrared RC cavity pole for ALPS IIc

moves a 50.8 mm mirror with a control bandwidth of 4 kHz was an essential component of this work. The discovery of the additional out-of-loop noise indicates that it might be necessary to change the control concept for ALPS II such that the PC length will be actuated on. The PC length sensing will be done with infrared light which avoids differential effects for the green and infrared eigenmodes.

Furthermore, an out-of-loop measurement of the differential length noise of the RC with feedback to the laser frequency confirmed that the length stability requirements of ALPS IIc should be maintained over time scales of at least 1000 s. If the out-of-loop noise is not reduced in the future, it is an option to open a shutter in the light tight wall roughly every 1000 s to ensure that the resonance condition for infrared light is still met. This would of course require a thorough characterization of the ALPS IIc RC with the shutter open, to ensure that over the time scales that the shutter is closed we can be confident that the cavities are dually resonant. In this case ALPS IIc could be set up without a dedicated seismic isolation system for the cavity mirrors, as measurements of the seismic noise environment in ALPS IIc are similar to those taken in ALPS IIa [18].

In addition, the finesse of the ALPS IIa RC was measured to be 101,300±500 with a storage time of 1.99±0.01 ms. These results are comparable to experiments that employ long baseline, high finesse optical cavities such as gravitational wave detectors [19, 20], filter cavities for non-classical light [21] and vacuum magnetic birefringence experiments [22].

These results represent a major milestone for ALPS II from the previous work [8]. The next steps will be towards the identification of the out-of-loop noise sources and their mitigation.

Abbreviations

ALPS: Any light particle search; EOM: electro-optic modulator; PC: production cavity; PDH: Pound-Drever-Hall; RC: Regeneration cavity; SHG: Second harmonic generation

Acknowledgements

The authors would like to thank the other members of the ALPS collaboration for valuable discussions and support, especially Axel Lindner and Benno Willke. This work would not have been possible without the wealth of expertise and hands-on support of the technical infrastructure groups at DESY.

Author's contributions

JP and AS designed and conducted the experiment. Both authors read and approved the final manuscript.

Funding

Deutsche Forschungsgemeinschaft (DFG) (SFB 676) Volkswagen Stiftung

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Received: 27 June 2019 Accepted: 27 January 2020

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