

Latest Results with the KWISP force Sensor at CAST

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The KWISP opto-mechanical force sensor has started searching for solar chameleons through their direct coupling to matter. Its sensing element, a 100 nm thick Si_3N_4 membrane, was mounted in the focal plane of the CAST X-ray telescope and several solar trackings were completed using the unique capabilities of the CAST magnet. KWISP is designed to detect, with interferometric techniques, extremely tiny membrane displacements due to the force exerted by chameleons reflecting off it, while a specially devised chameleon beam chopper provides the reference frequency necessary for detection. We will present the initial KWISP setup, discussing its status and results.

1 Introduction

The Cast Solar Axion Telescope has been probing the mysteries of the universe at CERN, in Geneva, since 2003. It has conducted several measurement campaigns searching for axions emitted by the sun, setting the current reference experimental limit on axion-photon coupling over a wide mass range[1]. The solar axion searches ended in 2015 and CAST has launched for 2016-2018 a new physics program, focused on Dark Matter (DM) and Dark Energy (DE) candidates. In particular, the program concentrates on searching for relic axions with several high-Q microwave resonant cavities inserted in the bores of the CAST magnet, and on detecting solar chameleons exploiting both their coupling to photons, and their direct coupling to matter[2]. In the latter search, CAST is pioneering the use of the novel KWISP opto-mechanical force sensor based on a thin and taut Si_3N_4 micro-membrane[3]. Under the influence of an external force, such as that resulting from the pressure exerted by a stream of solar chameleons reflecting, under certain conditions, off it [4], the membrane displaces from its initial equilibrium position in a manner that can be detected with optical interferometric techniques. KWISP also exploits two unique CAST capabilities: solar tracking and the presence of an X-ray telescope which can focus also chameleons, and provide an enhancement in expected flux of about a factor 100. We will briefly report below on the first ever solar tracking run conducted with an opto-mechanical force sensor searching for DE candidate particles, specifically for the direct coupling to matter of chameleons. The sensor was operated in an initial exploratory configuration to obtain a set of live data presently being analysed. A new, upgraded version of the KWISP sensor is now under commissioning at CAST in view of the data taking campaigns foreseen for the last part of 2016 and beyond.

2 The KWISP detector

KWISP is a novel type of particle detector exploiting the exquisite sensitivity to external forces of an opto-mechanical sensor to search for the direct interaction with matter of solar chameleons. Chameleons can be produced within the large magnetic fields present inside the sun, then stream unhindered to the earth. A flux of chameleons coming from the sun can interact directly with the sensing element of KWISP, a 100 nm thick, $5 \times 5 \text{ mm}^2$ Si_3N_4 micro-membrane. This taut and thin pellicle flexes, much like a sail under a wind, following a force acting on it. Membrane displacements are then detected with interferometric techniques, and the force acting on the membrane can be deduced (see also [3]). More specifically, if the membrane is positioned to intercept the chameleon beam at a grazing incidence angle (5° or less), a sizeable fraction of the impinging particles will reflect off the membrane, thereby exerting on it the equivalent of a radiation pressure (see [4]). In the configuration reported here, the sensing element of the detector (the membrane) is placed at the end of one of the two arms of a Michelson-type interferometer, while the other arm contains a mirror mounted on a piezoelectric linear actuator. A 532 nm, 5 mW CW laser beam is input into the interferometer and interference fringes are then observed at its output by a photodiode: membrane movements will cause a detectable fringe displacement. The piezo-actuated mirror serves for calibration purposes. Figure 1 shows a photograph of the actual interferometer with the laser beam path superimposed. The membrane can be seen at the center (also in the inset at upper right), while the piezo-actuated mirror is visible at center right.

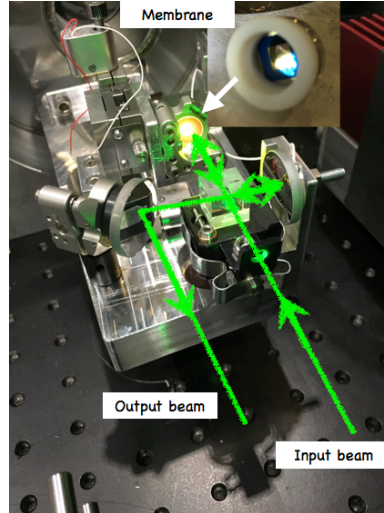


Figure 1: KWISP Michelson-type interferometer setup with the sensing membrane (see also text).

This compact interferometer (about 15 cm by 25 cm) is placed inside a vacuum chamber, mounted on the sunrise side of the CAST magnet and aligned to place the membrane as close as possible to the focal plane of the X-ray telescope available at CAST. This instrument is able to focus chameleons much in the same way as it focuses X-rays, thanks to its cascade of grazing-incidence plates (see [5]). The focusing action increases the expected solar chameleon

flux by a factor ≈ 100 . Based on the same principle, the membrane is also tilted with respect to the incoming chameleon beam to provide a 5° grazing incidence angle for maximum chameleon reflectivity. The membrane must be under vacuum in order to ensure that it is not perturbed by the brownian motion of air. In our case, the residual pressure in the chamber was $< 10^{-5}$ mbar. Figure 2 shows the position of the KWISP vacuum chamber on the sunrise side of the CAST magnet, behind the X-ray telescope. The last key element of the setup, not visible in the image of Figure 2, is the chameleon chopper, placed in air at the exit of the X-ray telescope, before the sensing membrane. Its function is to provide an amplitude modulation of the chameleon beam in order to make it, in principle, detectable, as the instrument is not sensitive to static displacements, but rather to time-dependent ones. This modulation is imparted at a chosen frequency, which provides both a reference for data analysis, and a trigger for data acquisition. The chameleon chopper is discussed in better detail in [6].

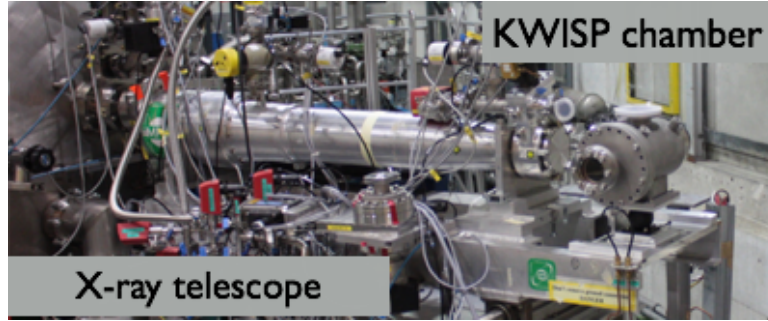


Figure 2: Placement of the KWISP chamber on the sunrise side of the CAST magnet. The chamber is aligned to position the membrane inside it in the focal plane of the X-ray telescope (see also text).

3 Preliminary results from solar tracking runs

The first ever series of measurement runs with a force sensor looking for solar chameleons was conducted at CAST, in April 2016, with the KWISP detector in the preliminary configuration briefly described above. During this campaign, the sun was observed every morning at sunrise for about 1.5 hours, over a period of one week between April 21st and April 28th, 2016. This was possible thanks to the unique sun-tracking capability of the CAST magnet assembly. The current output by the photodiode monitoring the interferometer fringes was amplified, converted to a voltage, digitised and acquired in 100 s long time records. The trigger for data acquisition was provided by the chameleon chopper, allowing for in-phase concatenation of the individual time records. Both the interferometer output and the trigger signal were acquired. At the beginning of each time record a calibration signal was briefly injected into the piezo actuated mirror in order to obtain the instantaneous sensitivity of the instrument. An example of such calibration procedure is shown in Figure 3. Here the photodiode signal (yellow trace) jumps from the dark fringe to the light fringe, corresponding to a fringe shift of $\lambda/2 = 532/2$ nm, when a voltage difference of 1.23 V is applied to the piezo-actuated mirror. This gives a transduction characteristic $C = 216$ nm/V.

LATEST RESULTS WITH THE KWISP FORCE SENSOR AT CAST

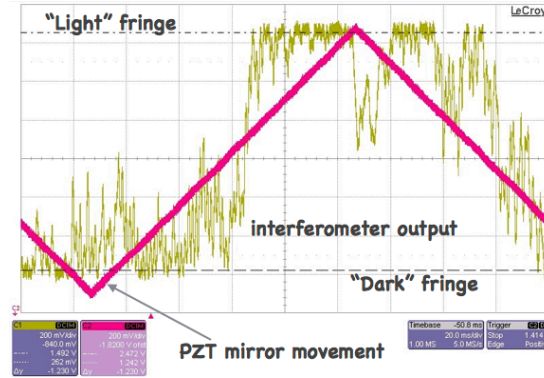


Figure 3: Sample oscilloscope screenshot illustrating interferometer calibration. The yellow trace is the photodiode signal, while the red trace is the voltage ramp applied to the piezo-actuated mirror (see also text).

Data were taken continuously both while tracking the sun, and with the magnet stationary, to provide background levels. In 7 days of running, 9000 s of sun-tracking data (90 time records) and 121400 s of background data (1214 time records) were accumulated. A chameleon signature should appear as a peak at the chopper frequency in the spectrum of the interferometer output photodiode signal. A full data analysis is still in progress, however Figure 4 shows a preliminary example of the type of result that can be expected.

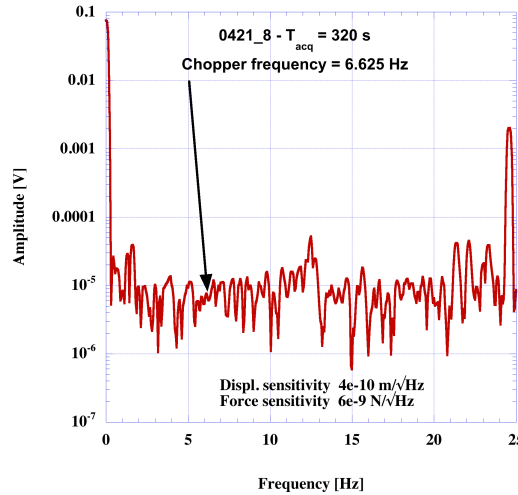


Figure 4: Preliminary sample sun tracking spectrum (see text).

In the case of Figure 4 the chopper frequency was 6.625 Hz, and an arrow indicates the position in the spectrum where a positive chameleon signal should appear. Here the force sensitivity was $6 \cdot 10^{-9} \text{ N}/\sqrt{\text{Hz}}$.

4 Conclusions

The first ever search for the direct interaction with matter of solar chameleons, with a force sensor, was conducted at CAST in April 2016. The opto-mechanical KWISP sensor, in a preliminary Michelson-type configuration, was placed in the focal plane of the X-ray telescope mounted on the sunrise side of the CAST magnet and used for a week long data taking campaign. The sensor took data stably with a force sensitivity of the order of 10^{-9} N/ $\sqrt{\text{Hz}}$. A chameleon chopper, originally invented, was used to provide the necessary reference frequency. Thanks to the dependence of the energy of the reflected chameleon on the chopper angular position, in case of a positive signature there is also the possibility of particle identification. A full data analysis is in progress. Presently, the KWISP sensor is being upgraded to a Fabry-Perot interferometer configuration, where the sensitivity will be amplified proportionally to the Fabry-Perot finesse. With a nominal finesse of ≈ 60000 , we project an initial sensitivity of the order of $6 \cdot 10^{-13}$ N/ $\sqrt{\text{Hz}}$, or better, at room temperature.

References

- [1] M. Arik *et al.* [CAST Collaboration], “New solar axion search in CAST with ^4He filling”, Phys. Rev. D **92**, 021101 (2015). doi:10.1103/PhysRevD.92.021101
- [2] V. Anastassopoulos *et al.*, “Search for chameleons with CAST”, Phys. Lett. B **749**, 172-180 (2015). doi:10.1016/j.physletb.2015.07.049
- [3] M. Karuza *et al.*, “KWISP: An ultra-sensitive force sensor for the Dark Energy sector”, Physics of the Dark Universe **12**, 100-104 (2016). doi:10.1016/j.dark.2016.02.004
- [4] S. Baum *et al.*, “Detecting solar chameleons through radiation pressure”, Phys. Lett. B **739**, 167-173 (2014). doi:10.1016/j.physletb.2014.10.055
- [5] O. K. Baker *et al.*, “Detection of radiation pressure from solar chameleons”, (2012) [arXiv:1201.0079 [astro-ph]].
- [6] G. Cantatore *et al.*, “Recent Progress with the KWISP Force Sensor”, (2015) [arXiv:1510.06312 [physics.ins-det]], Proceedings of the 11th “Patras ” Workshop on Axions, WIMPs and WISPs (Patras2015).