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Progress of the Laser-based Experiment OSQAR

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OSQAR experiment at CERN is based on two laser methods for search of axions and scalar particles. The light shining through the wall experiment has been using two LHC dipole magnets with an optical barrier, argon laser, and cooled 2D CCD detector for the measuring of expected regenerated photons. The second method wants to measure the Vacuum Magnetic Birefringence. An optical set-up with electro-optical modulator has been proposed, validated and subsequently improved in collaborating institutes. Cotton-Muton effect in nitrogen was measured by this method. Prototype of a one-meter long laser cavity was developed for this experiment.

1 Introduction

The OSQAR (Optical Search for QED vacuum magnetic birefringence, Axions and photon Regeneration) is purely laboratory laser-based experiment, situated at CERN. Its aim is to explore the low energy frontier of particle and astroparticle physics by combining the simultaneous use of high magnetic fields with laser beams in two distinct experiments. In the first one, the photon regeneration effect is looked as a light shining through the wall [1], [2], whereas in the second one, ultra-fine Vacuum Magnetic Birefringence (VMB) predicted by the QED is aimed to be measured for the first time. The OSQAR activities have the preparatory phases at laboratories outside CERN, and measurement at CERN approximately 6 - 8 weeks per year. OSQAR takes advantage of the CERN two state-of-the-art superconducting spare LHC magnets, and vacuum and cooling facilities. The dipole magnets have two apertures of effective length 14.3 m, maximal magnetic field 9.5 T, perpendicular to apertures. Both magnets are placed on the same straight line, so laser beam can pass through both magnets simultaneously.

2 Experimental

2.1 Photon regeneration effect

The theory predicts photon conversion to weakly interacting axion in the magnetic field. This axion can pass through optical barrier, and can convert back to detectable photon at the second magnet field. It looks as light shining through the wall. Argon laser (3.3 W, multi-line mode 488 and 514 nm) has been used as a source of photons. The output light is linearly polarized parallel to magnetic field, so it can be used for the search of new pseudoscalar - axion particles. To look for scalar particles, a half-wave plate, oriented at 45 degrees, is inserted at the laser exit to align the polarization perpendicularly to the magnetic field. The laser beam divergence was reduced by a beam expander. The beam is attenuated and focused by additional lens to liquid nitrogen cooled CCD detector to the spot of radius around 0.1 mm. CCD chip has 1024 x 256 square pixels of 0.026 mm size. The four neighbouring pixels were binned into a 2 x 2 superpixels, so array of 512 x 128 superpixels channels was finally used. The area, where we can expect photon regeneration signal, is about 5 x 5 superpixels. The quantum efficiency of the detector is equal to 30 percent for the argon laser wavelengths, dark current is about 0.5 electrons per pixel per hour, and readout noise is typically 3.4 electrons. The laser was shining with the lower power 1.62 W due to mode stability problems. Exposure times for one 2D recorded image were 15 minutes. Total duration of data taking was 22 hours for pseudoscalar search and 24 hours for scalar search.

The analyses were performed to interpret the photon regeneration experimental runs. Cosmic noise, observed as high signal on small area of 1 - 4 superpixels, was cleaned. All data for scalar/pseudoscalar particles were added separately. The data (matrix of intensities - events on CCD superpixels) was divided to the clusters of 4 x 5 superpixels. The integrated signal of each cluster was calculated as the sum of all recorded counts of the corresponding 20 super-pixels. The integrated signal ranges between the lowest and the high signal limits due to random distribution of noise in clusters. The numbers of clusters with the same integrated signals were calculated. Histogram of these numbers was accurately fitted with Gaussian distribution function. No cluster with higher number of events was detected. We can assume from Gaussian fitting parameters that if there is a flux greater than 6.32 photons per hour, we must detect it (conservatively for the 95 percent confidence interval for both scalar/pseudoscalar particles). The values of coupling constants of possible new light scalar and pseudo-scalar particles that can couple to two photons is constrained in the massless limit to be less than $8.0 \cdot 10^{-8} \text{ GeV}^{-1}$. It confirms the present reference results obtained by the ALPS collaboration [3].

2.2 Vacuum magnetic birefringence measurement

The predicted VMB [4], [5] effect is very weak so the experiment starts with magnetic-field-induced birefringence measurement at gases (also known as a Cotton-Mouton effect), in air, in nitrogen, diluted nitrogen, helium, with final aim to measure VMB. The optical set-up based on the use of an electro-optical modulator is shown in Figure 1. A laser beam, linearly polarized by a prism (polarizer), is sent through the electro-optical modulator before propagating through the birefringence sample, where the light acquires the ellipticity to be measured. The polarization of the beam is finally analyzed by a polarizer prism (analyzer), and the modulated light intensity is detected by a photodiode. The electro-optic modulator converts the linearly polarized light into circularly polarized light oscillating between left-handed and right-handed ellipticity at 49.4 kHz

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(maximum frequency is limited by second harmonic signal for 100 kHz Lock-in amplifier, which was used for signal detection). The set of possible configurations of polarized elements was investigated. The best orientation of each successive component in the set-up is at 45 degrees rotation to its previous element [6].

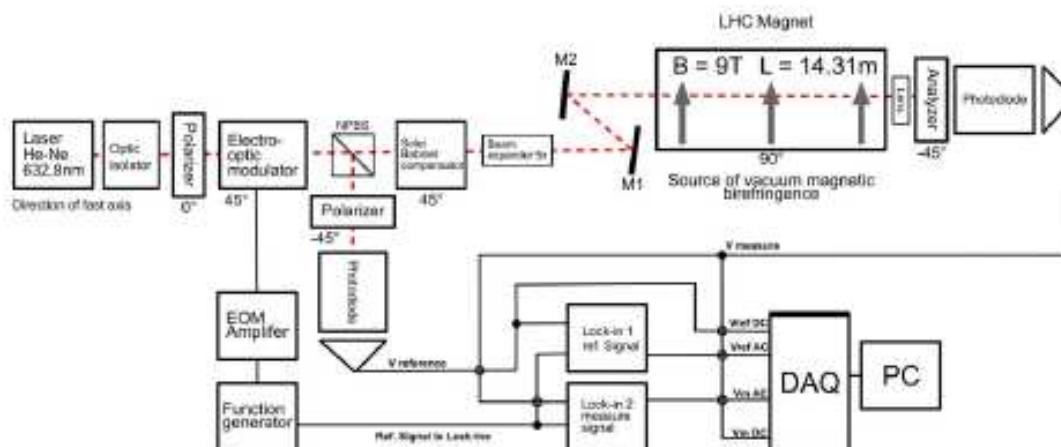


Figure 1: Set-up for the measurement of the Gas Magnetic Birefringence.

Stabilised He-Ne laser 632.8 nm and corresponding optical components were chosen. The optical set-up was installed with one LHC dipole dedicated to OSQAR. The Cotton-Mouton effect was measured in N_2 gas with pressure in the dipole aperture ranging from 1000 to 2000 mbars. The measured optical retardance was found to increase with the square of magnetic field as expected. The constant of the Cotton-Mouton effect for N_2 at 1 bar was found to be equal to $-3.6 \cdot 10^{-7} \text{ rad T}^{-2} \text{m}^{-1}$. The difference in refractive indices for $\lambda = 632.8 \text{ nm}$, and $L = 14.3 \text{ m}$ effective LHC dipole magnetic length was $n - 2.28 \cdot 10^{-13}$ for N_2 at atmospheric pressure in 1 T field. This result is in good agreement with published values [7].

2.3 Development of high finesse optical cavity

Application of resonant cavities will increase the optical path of the laser beam passing within strong magnetic field and it can increase sensitivity of the both laser experiments. A prototype of an one-meter long plano-concave resonator cavity was built in the laboratory of CTU Prague. The cavity is constructed to be used with He-Ne laser, wavelength 632.8 nm. The optical cavity is build using two circular mirrors: one semi-permeable planar 2 - inch mirror and one highly reflective concave 2 - inch mirror with radius of 1 m. Distance between the mirrors is 980 mm. Mirrors are mounted in kinematic holders. Planar 2-inch mirror is used for locking the cavity resonance frequency. The mount of this mirror has 5 degrees of freedom (two rotations and three translations) tuned by piezoelectric actuators and controled by a close loop controller.

Concave 2-inch mirror has 4 degrees of freedom (two rotations and three translations) and its mount can be also positioned by piezoelectric actuators too.

Obviously all components should be compatible with ultra-high vacuum ($< 10^{-9}$ mbar). The light will be locked inside the cavity using the Pound-Drever-Hall lock-in technique [8]. The prototype was successfully tested at the laboratory. Two full length (19.6 m) cavities are now built on the base of these experiences. The first one for VMB experiment, using 632 nm He-Ne laser, the second one for photon regeneration experiment, using second-harmonic of solid state laser 532 nm used at present. Both with different optics, but with the same mechanics and piezoelectronics control.

3 Conclusion

The results of the photon regeneration experimental runs for pseudoscalar/axion and scalar particle search were deeply analyzed. They confirm the results published by the ALPs collaboration. Progress towards the measurement of the VMB has been achieved. Cotton-Mouton effect for N_2 at 1 bar was used to confirm sensitivity of apparatus. The constant of the C-M effect was found to be equal to $-3.6 \cdot 10^{-7}$ rad $T^{-2}m^{-1}$. The one-meter long prototype of the cavity was built and tested. New full length cavities for VMB and PR experiments were designed and constructed too.

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