Axion search in the photon regeneration experiment

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1 Introduction

The aim of this work is to present a proposal for the axion search experiment of the photon-regeneration type and to discuss the theoretical predictions for the proposed setup, in order to find the optimized conditions for the experimental setup. The experiment is being prepared at CERN, where it can gain from using available dipole superconducting magnets built for the LHC. The main goal is to have a cross-check to the parallel experiment of precise optical measurements, which can study the vacuum polarizability and birefringence (for further checking QED predictions) and investigate the possibility of axion existence in the relatively high axion to photon coupling region. As we shall argue, for specific experimental conditions the coupling constant level obtained by CAST should be nearly reachable. What we would like to stress, though, is that CAST is an observation, not an laboratory experiment, so it's results indeed have to be checked separately.

At the beginning we shall discuss the origin of theoretical concept of the axion, after which we will turn to theoretical background of proposed experiment. In next sections the experimental setup and results of theoretical calculations will be presented. Finally, we shall comment on the possibilities of upgrading the setup and present the predictions for such situations. At the summary we will try to argue which experimental conditions can give the most promising results, therefore, which experimental setup should be prepared in order to probe the biggest and most interesting region of the axion parameters.

1.1 The strong CP-problem

It is a well established experimental fact that we live in a world in which P and CP are symmetries at the strong interaction level. From the other hand the QCD gauge group possess an axial part $U(1)_A$, which if it was a real symmetry, together with P would imply existence of hadronic parity doublets. However, this isn't the case in Nature, so we are forced to assume the spontaneous symmetry breaking of $U(1)_A$. The question arising is that, where is the Goldstone boson of this broken symmetry? Solution to this problem was given by 't Hooft [1] and is based on the fact that $U(1)_A$ breaking is anomalous. 't Hooft stressed the physical importance of gauge field configurations with nontrivial topology, adding $\mathcal{L}_\theta$ term to the original QCD Lagrangian having the form

$$\mathcal{L}_\theta = \theta \frac{g^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}. \tag{1.1}$$

From physical point of view it is needed to define a choice of vacuum among an infinity of possible generally inequivalent and in some sense distinct vacua. It is done by the θ parameter, which wasn't present in the original Lagrangian. Hence the lack of Goldstone boson is now automatic and the $U(1)_A$ problem seems to be fully explained. However, at the expanse of raising a new one, namely the *strong CP-problem*. The $\mathcal{L}_\theta$ term violates P and T but conserves C, so it contributes to the neutron dipole moment d_n. The experimental limits is [2]

$$|d_n| < 12 \cdot 10^{-26}\, e\, cm, \tag{1.2}$$

which yields the limit on the θ parameter $\theta \leq 10^{-10}$. The strong CP-problem can be formed in a question "Why is it so small?".

1.2 Peccei-Quinn symmetry and the Axion

To avoid fine-tunning Peccei and Quinn proposed an elegant, though yet not confirmed experimantaly, solution by introducing a new global, chiral $U(1)_{PQ}$ symmetry (called Peccei-Quinn symmetry). Since this is not an exact symmetry, a Pseudo-Goldstone boson emerges, as was pointed out by Weinberg

[3] and independently Wilczek [4], who also gave it a name *axion* . The axion mass and couplings are suppressed by high mass scale M being much larger than Λ_{QCD} for the so-called *invisible axions.* This property rises many difficulties in the experimental search for such a particle and in fact even now many theoretical models stay out of experimental range. Nevertheless, such experiments like CAST or the one proposed in this report, are getting close to confirm or rule out at least some of existing models.

2 Theoretical background of an experiment

The full Lagrangian density suitable for describing axions (or more generally pseudoscalar particles coupled to the photons using two-photon vertex) can be written as

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{1}{2}m_a^2 a^2 + \frac{g}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \mathcal{L}_{EH}, \tag{2.1}$$

where a is the axion (pseudocsalar) field, m_a its mass, $F_{\mu\nu}$ the electromagnetic field tensor and $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$ its dual. Finally the last term describes the Euler-Heisenberg effective Lagrangian arising from the vacuum polarizability (an effective way to look at the one electron loop diagram of photon-photon interactions in the limit where the photon energies are small with respect to the electron mass). The latter is needed when considering the indirect experimental methods of searching for axions using the very precise measurements of rotation of the polarization plane and arising ellipticity of initially linearly polarized laser beam (the theoretical background was firstly given by Maiani et al. [5]). However, in the experiment proposed it this paper it is irrelevant and we can leave it without writing explicitly.

The term which is the most interesting for our considerations is the third one, namely the two-photon vertex interaction. It follows, that when the external field is present the mixing between axion and photon can occur (as presented on the Fig. 2). For physical reasons we will concentrate on the

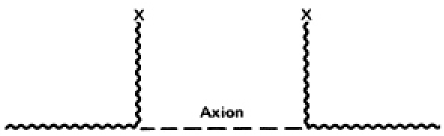

Figure 1: Diagram for photon-axion mixing.

magnetic fields only. Following K. van Bibber [6] the axion to photon transition probability in an external magnetic field is given by

$$P = \frac{1}{4}\frac{\omega}{\sqrt{\omega^2 - m_a^2}}g^2B_0^2L^2F^2(q), \tag{2.2}$$

where ω is the photon frequency (we use rationalized units throughout, so it is also its energy), B_0 the value of external magnetic field, $q = \omega - \sqrt{\omega^2 - m_a^2}$ is the momentum transfer to the magnet (or in other words the difference between the axion and the photon momenta) and $F(q)$ is the form factor for the region with magnetic field present. The latter is given by expression

$$F(q) = \int e^{-iqx}\frac{B(x)}{B_0L}\mathrm{d}x. \tag{2.3}$$

If the rectangular shape of $B(x)$ is considered (as we do in our approximation) it is easy to get

$$F(q) = \frac{sin(qL/2)}{qL/2}. \tag{2.4}$$

We expect the axion to be a very light particle (for instance models attractive to cosmology are that with axion masses between 10^{-5} and $10^{-3}\,eV$), so in comparison to the photon frequency of order 1 eV its mass can be neglected $\frac{m_a}{\omega} \ll 1$. Hence $\frac{\omega}{\sqrt{\omega^2 - m_a^2}} \approx 1$. From the same reason in this approximation we have also $q \approx \frac{m_a^2}{2\omega}$. So the expression (2.2) reduces to the following:

$$P = \frac{1}{4} g^2 B_0^2 L^2 \left(\frac{sin(qL/2)}{qL/2} \right)^2. \tag{2.5}$$

Therefore, in the experimentally most interesting case where $qL \ll 1$ we obtain very simple formula:

$$P = \frac{1}{4} g^2 B_0^2 L^2. \tag{2.6}$$

This equation is valid in the regime, where axions and photons propagate coherently. In fact, this situation is the most valuable for our purposes, even though it is also possible to acquire some information from decoherent region. We will come back to this issue when considering upgrades to the basic form of the experiment.

The basic idea of this type of experiment (sometimes called "shining through walls") is as follows. When a laser beam propagates through a region where magnetic field is present, there is a probability described by (2.2), that some of the photons will change into axions. Consequently, due to the fact, that they interact very weakly with matter, in contrary to photons they will propagate through an optical barrier. Then, the axion beam encounters another region with magnetic field, so as previously, they can change to photons, which we can easily detect. Roughly speaking, if we have a signal in the detector (apart from noise), we confirm existence of light, weakly coupled to matter particle.

To be more precise, from (2.2) we can calculate the counting rate of detector - we firstly assume that we are considering pure signal (without any noise present). Then the counting rate is given by

$$CR = \eta \frac{P_L}{\omega} \frac{N}{2} P_{\gamma \to a} P_{a \to \gamma} = \eta \frac{N P_L}{2\omega} \frac{B_0^4 g^4}{q^4} sin^2(qL_1/2) sin^2(gL_2/2), \tag{2.7}$$

where η is the detector's efficiency factor, P_L the optical power of laser beam, L_1 and L_2 lengths of magnets on the left and right side of the barrier respectively, and finally N is the number of times the beam will reflect in our cavity (the $\frac{1}{2}$ factor comes from the fact, that we detect only the axions produced when beam is propagated in one of the two directions). In the second part of Eq. (2.7) we used the fact, that the probability photon-axion transition is the same as axion-photon one. Writing this expression leaving explicitly characteristic scales yields:

$$CR = 4.07 \cdot 10^{10} \frac{GeV^4}{s} \left(\frac{\eta}{0.9} \cdot \frac{P_L}{1\,W} \cdot \frac{1\,eV}{\omega} \cdot \frac{N}{1000} \right) \left(\frac{B_0}{10\,T} \right)^4 \left(\frac{g}{10^{-6}\,Gev^{-1}} \right)^4 \frac{1}{q^4} sin^2(qL_1/2) sin^2(gL_2/2). \tag{2.8}$$

As it can be easily shown, the biggest probability of conversion and therefore counting rate is obtained when for given magnet length the cavity and regeneration regions have the same length. In the following we will assume such a configuration, with exception to the test experiment where we also consider different one (all formulas are then analogous and can be easily derived, that is why we will restrict ourselves only to giving the results).

3 Experiment proposition

3.1 Preliminaries and test experiment

Initially let's consider the first phase of the proposed experiment, called the test phase. It will use somewhat less sophisticated setup than the ultimately one, but still theoretical predictions for its results are worth mentioning. The reason for this is that, as we will show, it should give enough precision to check the recent PVLAS results [9], wich is absolutely needed. Furthermore, this phase can be prepared in several months time, so in rather short time it can provide us with a strong argument whether PVLAS found a new "axion-like" particle, or not.

Recently it was proposed [7] to use one $14\,m$ long superconducting magnet with the barrier after $7\,m$, the field of strength $9\,T$, laser with wavelength $\lambda = 1064\,nm$ and optical power $1\,W$. Assuming $\eta = 0.95$, 1000 reflections and 1 hour integration time we should obtain bound for the coupling

$$g > 3.6 \cdot 10^{-8}\,GeV^{-1}, \tag{3.1}$$

so two orders of magnitude better than PVLAS. However, as it was therein stated, the axion masses typically bigger than $0.4\,meV$ cannot be probed in such configuration, what prevents us from excluding whole region checked by PVLAS. One can see that some improvement is needed in the higher mass sector. It can be easily obtained by using shorter length of propagation in the magnetic field or higher frequency laser. In the first case, if instead of $7\,m$ on the both sides we use $1\,m$ long magnet, we can suspect some improvement (loosing of course in the bound for coupling g), as can be seen on Fig. 3.1. However, as we can see it still won't cover the whole PVLAS region (although almost). Using $0.5\,m$

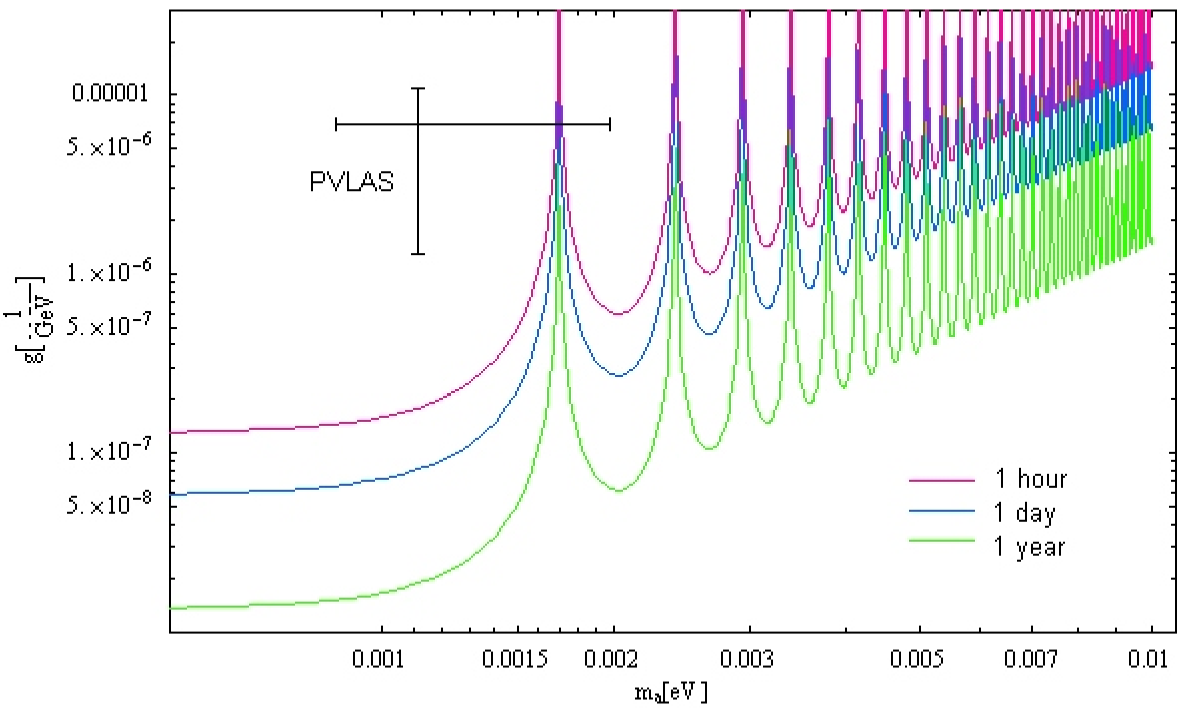

Figure 2: Plot of parameter space obtainable by test experiment for three different integration times, with the PVLAS region marked.

magnet or twice shorter wavelength (which is still experimentally accessible in the test phase) should fix the problem and PVLAS results will be therefore checked.

3.2 The parameters of experiment

The second phase will be the main experiment. The experimental setup will consist of one $14\,m$ long superconducting dipole magnet producing magnetic field up to $9.5\,T$, an optical cavity of finesse (number of reflections) of order $10^4 \div 10^5$, Nd-YAG laser of wavelength $\lambda = 1064\,nm$ and optical power up to $1\,kW$. The efficiency of photon detector for this wavelength can be brought to $\eta = 0.95$ (??). The scheme of the setup can be seen on the Fig. 3.2 and the cross-section of the magnet on Fig. 3.2.

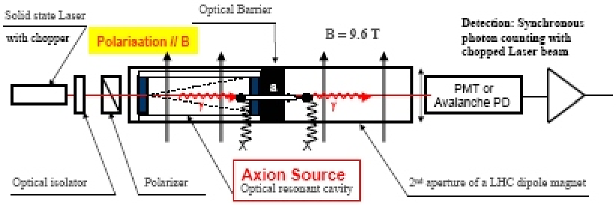

Figure 3: The scheme of an experimental setup.

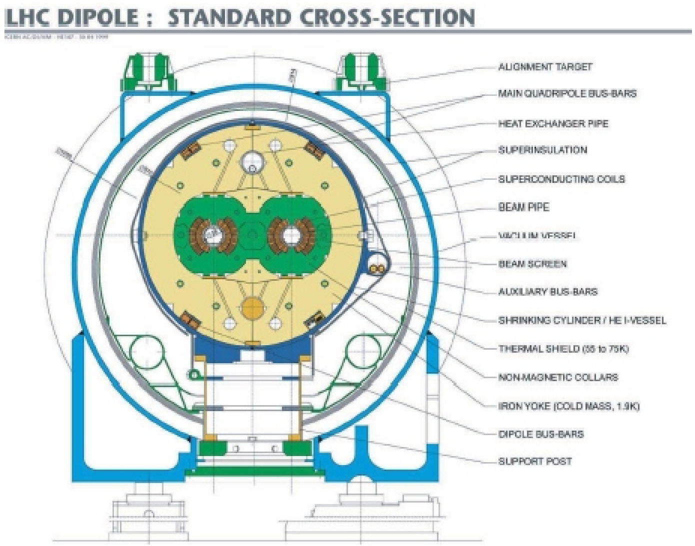

Figure 4: Cross-section of the twin aperture LHC dipole magnet.

The integration time (i.e. time of running measurements) can vary and we will present calculations for mostly 1 day, but also compare it with longer and shorter times.

3.3 Theoretical results

Using formulas above it is straightforward to get exclusion plots for the axion mass and coupling space. Assuming that we can detect a single photon (i.e. assuming counting rate for given time of integration) and plugging in the numbers for concrete parameters of the experimental setup one gets directly from formula (2.7) desired plot. For parameters as above, where we precise the finesse to be 10^4 and optical power $100\,W$, we get the prediction for our experiment for three different integration times (Fig. 3.3). That is the lower bound for the coupling constant for 1 hour, day and year experiments respectively:

$$g > 3.11 \cdot 10^{-9}, \qquad g > 1.41 \cdot 10^{-9}, \qquad g > 3.24 \cdot 10^{-10}, \tag{3.2}$$

which in the year-long measurements is very close to the CAST limit [8]. The resulting axion mass limit is the same for all cases (it does depend only on the magnet cavity and regeneration lengths and the incident beam frequency) and yields about $0.4\,meV$.

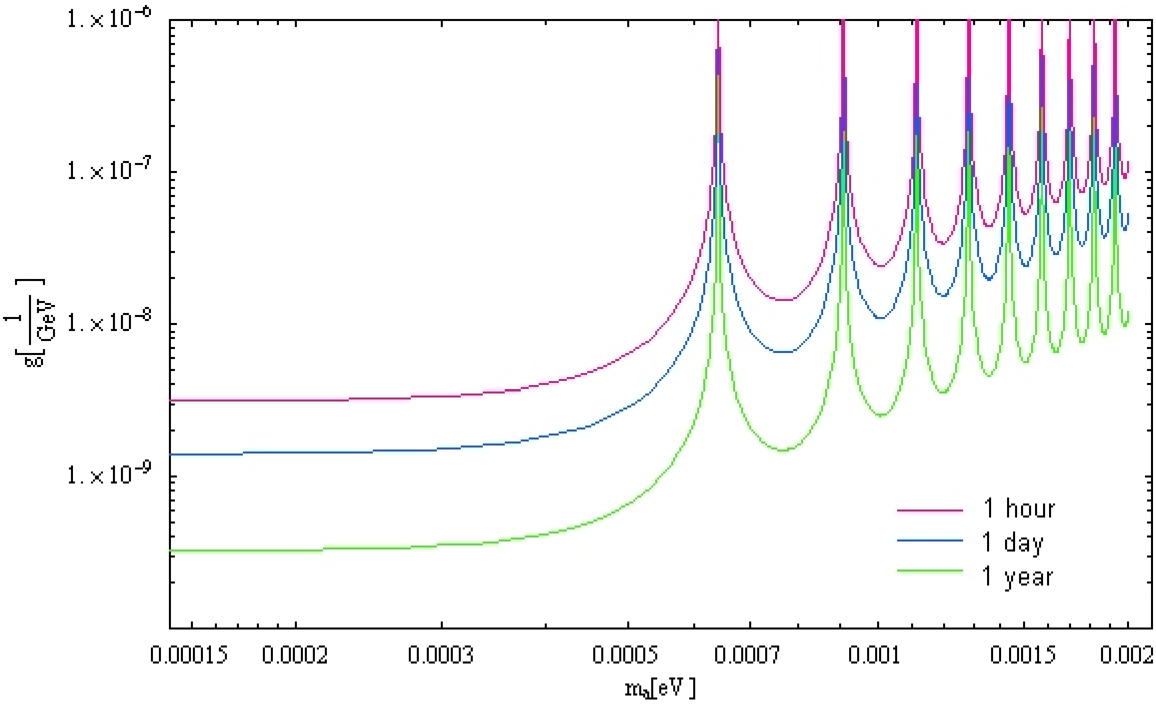

Figure 5: Exclusion plot for proposed experiment for three different integration times.

4 Possible upgrades

The first, obvious observation is that, we can reasonable lower the limits (3.2) by using

i) stronger laser (bigger optical power) or

ii) optical cavity with bigger finesse.

Both of these possibilities lay in the technical side of the experiment, so we won't discuss them, only stating that indeed the improvement in this field can be made (we would like to stress that for obtaining the results, to be cautious, we chose not the optimal paramteres given in the preccedings, when presenting our setup). The less trivial upgrades of proposed experiment we will discuss in following subsections.

4.1 Gas instead of vacuum

Till now we implicitly assumed that in the magnets we have vacuum. It isn't difficult to achieve (on experimental ground), but one can ask is it really desirable. The alternative is filling the magnet with buffer gas. The disadvantages of such an approach are that

- gas amplifies the noise,
- gas absorbs light, which weakens the laser beam and
- using gas makes the experimental setup more difficult to stabilize.

Fortunately absorption in diluted gas is negligible and the other problems also can be made not relevant by suitable setup. While the reason why to use gas is the following. The dispersion relation for photons in a ionized (???) gas

$$k_\omega = n\omega, \tag{4.1}$$

where n is the refraction index takes the well known form

$$k_\omega = \omega\Big(1 - \frac{\omega_p^2}{2\omega^2}\Big), \tag{4.2}$$

where ω_p is the plasma frequency of the medium. For vacuum $\omega_p = 0$ and we obtain the normal dispersion relation. From the other hand existence of gas do not influence the axion propagation, due to its very small couplings to matter. That is its momentum

$$k_a = \sqrt{\omega^2 - m_a^2} \approx \omega\Big(1 - \frac{m_a^2}{2\omega^2}\Big) \tag{4.3}$$

is the same as in vacuum. Now the momentum transfer to the magnet q differs from that in vacuum and takes the form

$$q = \frac{m_a^2}{2\omega} - \frac{\omega_p^2}{2\omega}. \tag{4.4}$$

Because the coherence condition yields

$$L\,|k_\omega - k_a| < \pi, \tag{4.5}$$

one can see, that with gas it can be restored for higher axion masses. The condition (4.5) reads

$$\omega_p^2 - \frac{2\pi\omega}{L} < m_a^2 < \omega_p^2 + \frac{2\pi\omega}{L}, \tag{4.6}$$

that is the gain (without losing coherence on the small mas region) for axion mass squered is $\frac{2\pi\omega}{L}$. Moreover, increasing the plasma frequency (for example by increasing the gas pressure) allows to probe even bigger masses. This of course has its limits, but still it is reasonable to extend the coherence limit for about 50% with one measurement.

In the case of our experiment $\frac{2\pi\omega}{L} \approx 3.18 \cdot 10^{-4}\, eV^2$, which is a easy obtainable value for plasma frequency for various gases. The work on concrete proposition for this matter is ongoing. For described configuration the exclusion plots for different plasma frequiences are presented on Fig. 4.1. Furthermore, if we consider multiply measurements for various plasma frequencies we can probe much bigger region, as presented for instance on Fig. 4.1, where 12 different ω_p measurements were combined (not obtaining any signal in any of them means this whole region will be excluded). Therefore, using buffer gas allows to enlarge the probed mass region more then two times!

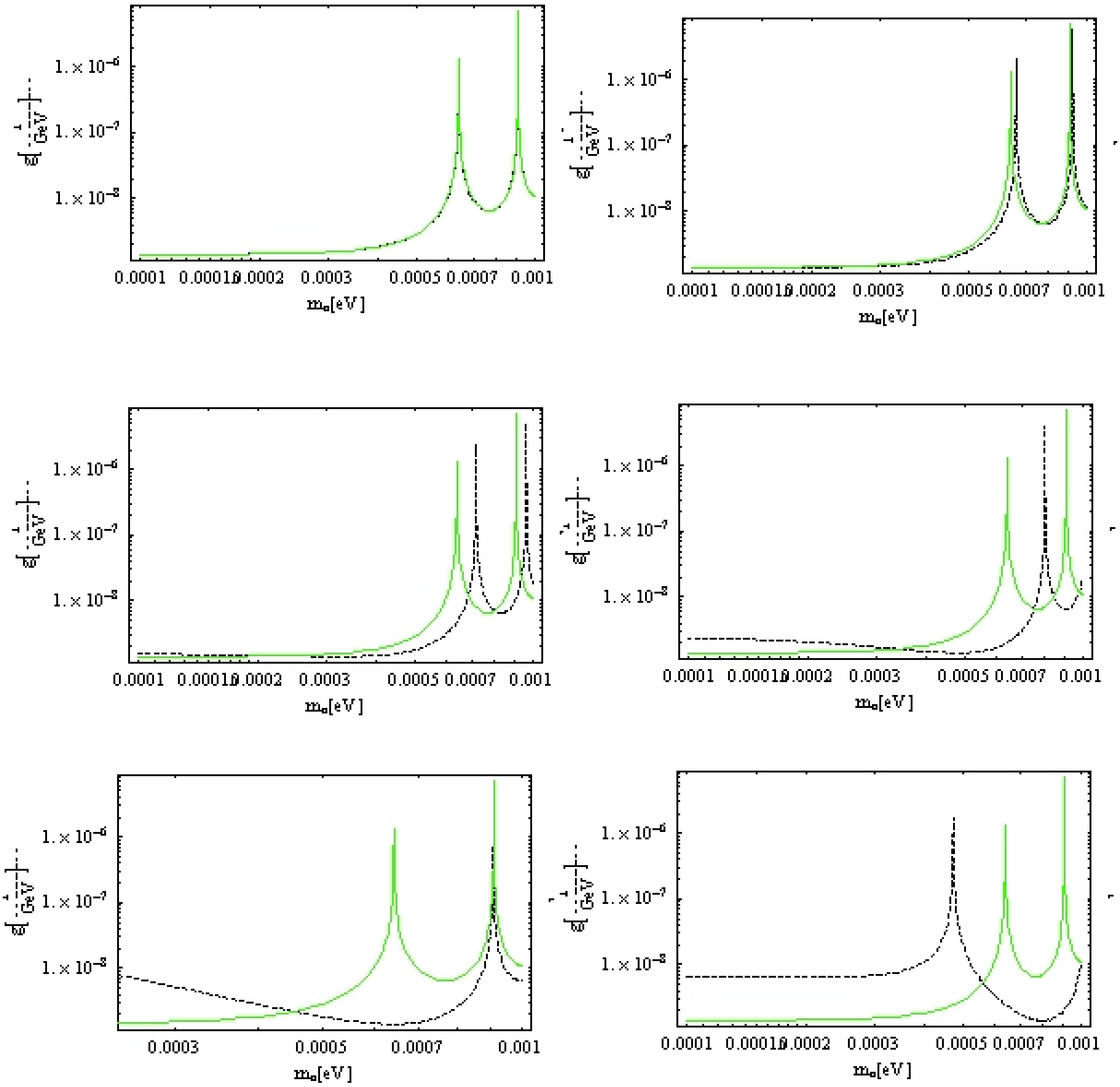

Figure 6: Comparison of exclusion plots for different plasma frequencies. Green line represents the vacuum case, while dashed one with gas.

4.2 Wigglers

Another possibility we would like to discuss is using multiply magnets with alternating polarization. The aim is similar to the previous one - restore coherence for bigger axion masses. If we consider N equal magnets of summary length L with alternating field direction, the form factor $F(q)$ can be

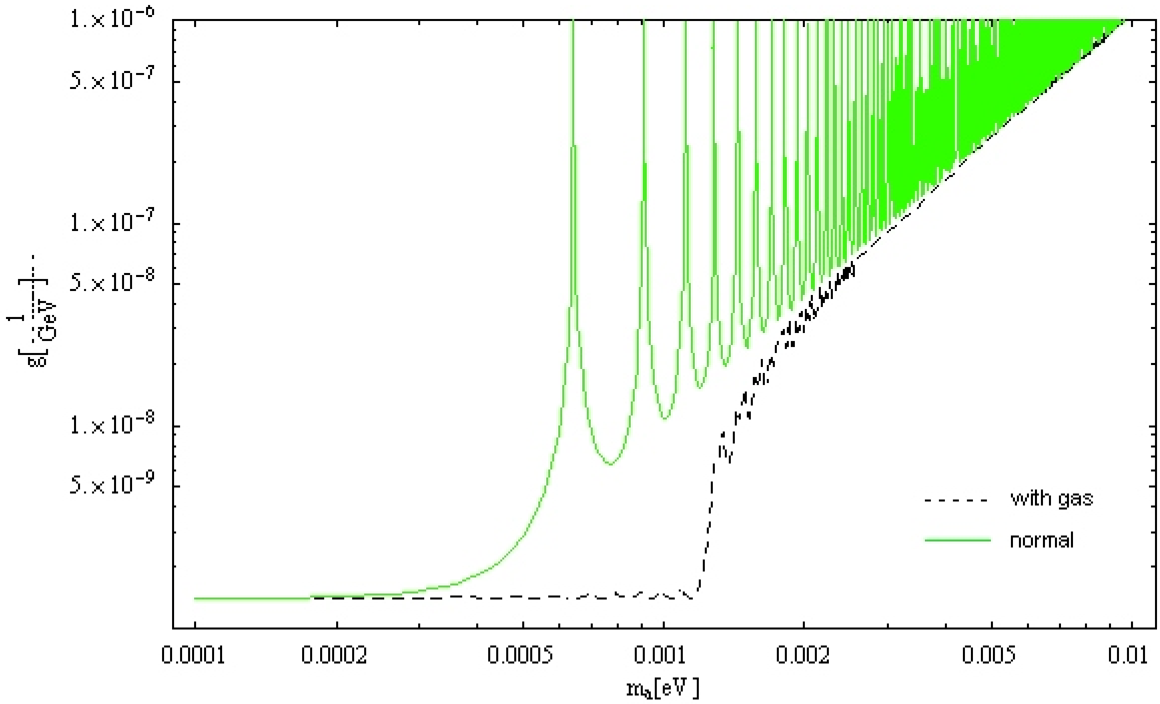

Figure 7: The exclusion plot combined from 12 measurements with buffer gas with different plasma frequencies. Green line represents the vacuum case, while dashed one with gas.

easily found to be [6]

$$F(q) = \frac{sin(qL/2)}{qL/2} tan(qL/2N). \tag{4.7}$$

This form factor has a peak in non-zero value of q as can be seen on Fig. 4.2. Consequently axions with bigger mass than in the normal case have maximum probability of mixing with photons. This

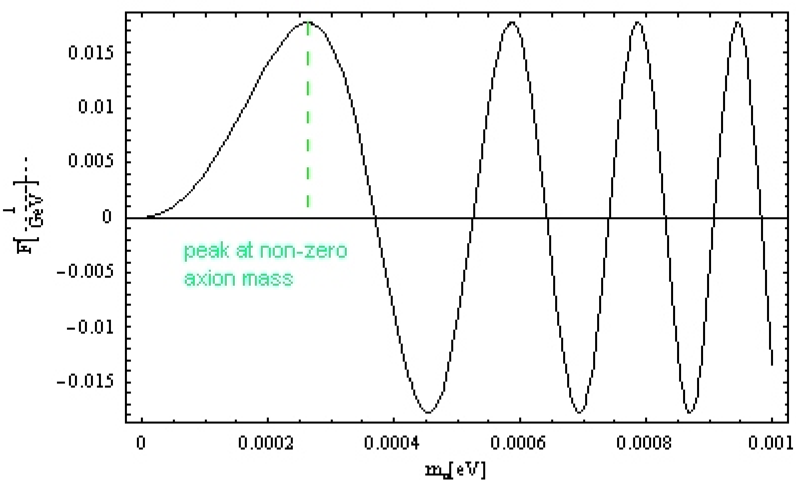

Figure 8: The form factor for three magnets with alternating polarization.

effect obviously can help to restore coherence, but unfortunately not so much. To see this let's consider comparison of the case with alternating magnets to the basic one for specific parameters, that is for three $7\,m$ long magnets in the regeneration region with alternating polarization and other parameters as previously (in vacuum), we obtain result given on Fig. 4.2. One can see that indeed there is small

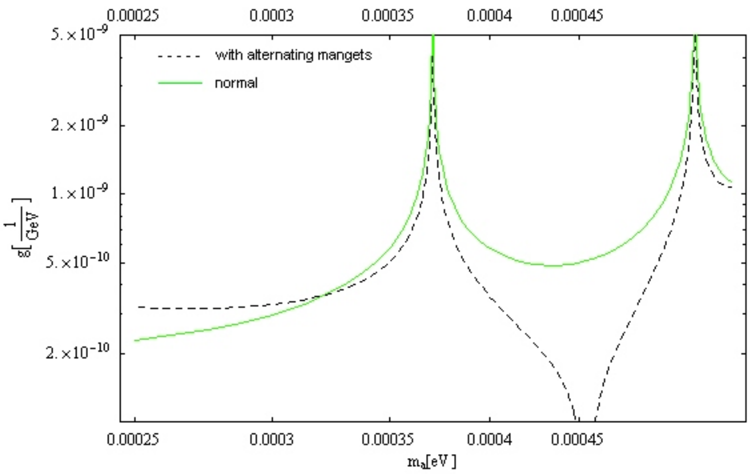

Figure 9: Plot of parameter space obtainable by experiment using in the regeneration region three magnets with alternating polarization, compared to the vacuum one.

improvement and second small window for axion parameters can be viewed. However, if compared to the previous case with gas it becomes useless. The reason is mainly the fact, that in summary longer magnet length are needed to build the setup. Also if we combine these two methods, i.e. multiply magnets with alternating polarization and filling with buffer gas, the result occur to be unsatisfactionry (see Fig. 4.2). Again the loss of coherence due to enlarging the magnet length outweighed the gain of

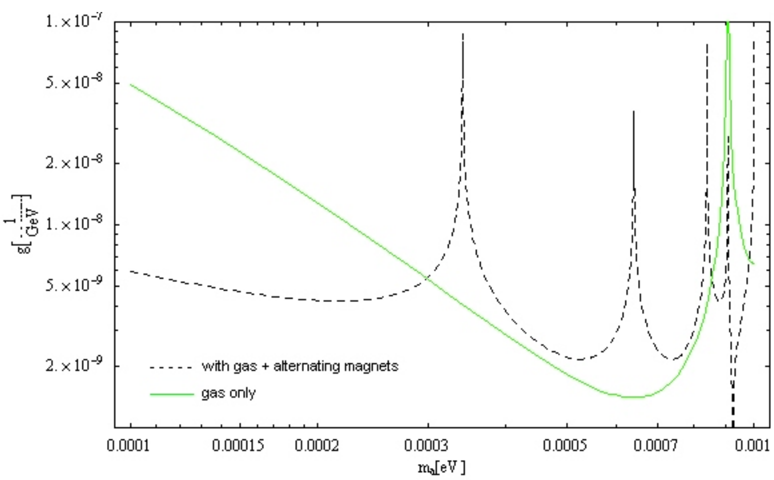

Figure 10: Plot of parameter space obtainable by experiment using in the regeneration region three magnets with alternating polarization with buffer gas, compared to the case, where only gas was used.

the form factor effect.

5 Summary

We have presented a proposition for an experiment designed to search for axion-like particles using photon regeneration method. The theoretical predictions for the result of the experiment were discussed. For the presented experimental configuration the best results should be obtained by making multiply $1\,m$ day (or even longer) measurements for several different gas plasma frequencies (i.e. different pressures). The best obtained exclusion plot was presented on Fig. 4.1. The minimum value of coupling constant yields

$$g > 1.41 \cdot 10^{-9}, \tag{5.1}$$

for corresponding axion masses typically $m_a < 1.2\,meV$. This limit can be further enhanced by using cavity with bigger finesse and laser with stronger optical power. Assuming finesse to be 10^5 and optical power $1\,kW$ for other parameters the same we would improve to:

$$g > 4.45 \cdot 10^{-10}. \tag{5.2}$$

Finally we would like to present the plot from CAST experiment with marked expected results of our proposition, which in our opinion sounds very promising.

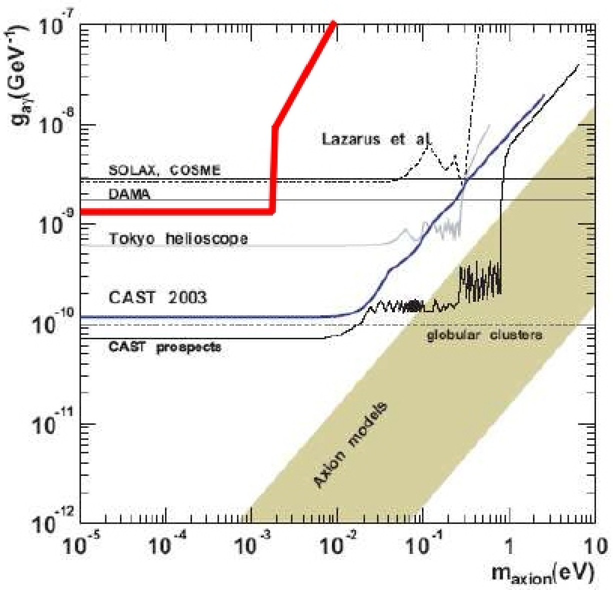

Figure 11: CAST results with expected exclusion region for our proposition.

6 Acknowledgments

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