Resonantly Enhanced Axion Photon Regeneration (REAPR)

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1 Goal of experiment

This experiment is a *shining light through walls* study, where photons travelling through a strong magnetic field are (in part) converted to axions; the axions can pass through an opaque wall and convert (in part) back to photons in a second region of strong magnetic field.[1] The photon regeneration is enhanced by employing matched Fabry-Perot optical cavities, with one cavity within the axion generation magnet and the second within the photon regeneration magnet. Compared to simple single-pass photon regeneration, this technique would result in a gain of $(\mathcal{F}/\pi)^2$, where $\mathcal{F}$ is the finesse of each cavity. This gain could feasibly be as high as 10^{10}, corresponding to an improvement in the sensitivity to the axion-photon coupling, $g_{a\gamma\gamma}$, of order $(\mathcal{F}/\pi)^{1/2} \sim 300$. This improvement would enable, for the first time, a purely laboratory experiment to probe axion-photon couplings at a level competitive with, or superior to, limits from stellar evolution or solar axion searches.

A two-phase approach to this experiment is envisioned. Phase I would develop the optical benches for the experiment, including the laser, the cavity injection optics, the method for actively controlling the two Fabry-Perot cavities and the laser wavelength, and the heterodyne signal detection system. As a physics deliverable, the system, including background and signal to noise, which is expected to be limited only by shot noise, will be tested by a year-long search for a regeneration signal using meter-scale cavities and 0.6 T permanent magnet fields. On account of the regeneration gain, the sensitivity of Phase I will be superior to all existing and past regeneration experiments.

Phase II is a full-scale experiment, based on a 6+6 string of Fermilab dipole magnets, and would be done in collaboration with Fermilab. A detailed design for Phase II will also be carried out during phase I.

2 Experimental setup

Figure 1a shows the photon regeneration experiment as usually conceived. It can be shown[1–3] that the photon to axion conversion probability P in

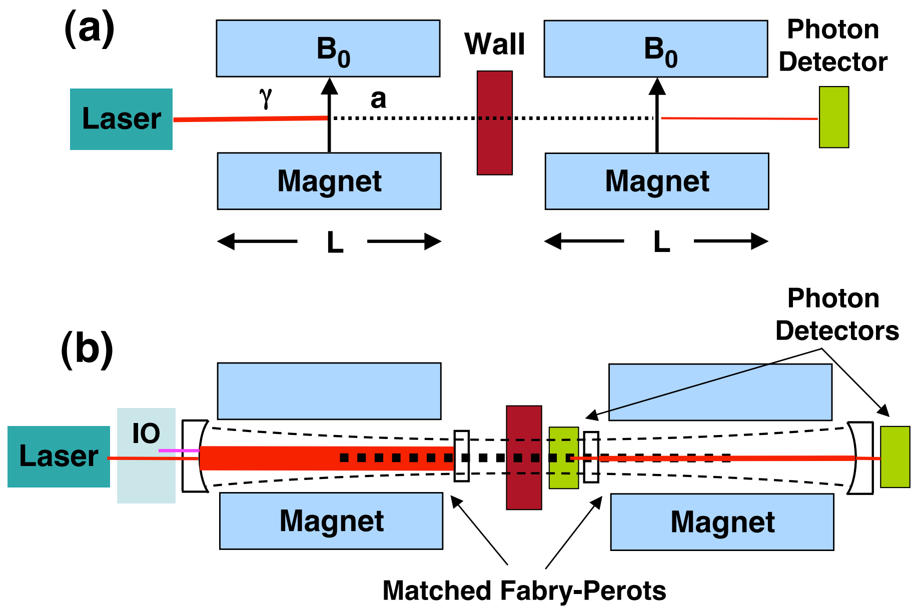

Figure 1: (a) Simple photon regeneration. (b) Resonant photon regeneration, employing matched Fabry-Perot cavities. The overall envelope schematically shown by the thin dashed lines indicates the important condition that the axion wave, and thus the Fabry-Perot mode, in the photon regeneration cavity must follow that of the hypothetically unimpeded photon wave from the Fabry-Perot mode in the axion generation magnet. Between the laser and the cavity is the injection optics (IO) which manages mode matching of the laser to the cavity, imposes RF sidebands for reflection locking of the laser to the cavity, and provides isolation for the laser. The photon detectors are also preceded by matching and beam-steering optics.

a region of length L, permeated by a constant magnetic field B_0 transverse to the direction of propagation, is given by ($\hbar = c = 1$)

$$P = \frac{1}{4}\frac{1}{\beta_a}\left(g_{a\gamma\gamma}B_0 L\right)^2\left(\frac{2}{qL}\sin\frac{qL}{2}\right)^2, \tag{1}$$

where β_a is the axion speed, $g_{a\gamma\gamma} \equiv \alpha|g_\gamma|/\pi f_a$ is the axion-photon coupling, with f_a some large energy scale where PQ symmetry is spontaneously broken and g_γ, a model-dependent parameter of the theory. Note that $g_{a\gamma\gamma} \propto m_a$ and limited explorations of axion models find that for a given mass, $g_{a\gamma\gamma}$ only varies over about an order of magnitude. Finally, $q = k_a - k_\gamma \approx -m_a^2/2\omega$ is the momentum transfer.

If E_0 is the amplitude of the laser field propagating to the right, the amplitude of the axion field traversing the wall is $E_0\sqrt{P}$ where P is the conversion probability in the magnet on the LHS of Figure 1a. Let P' be the conversion probability in the magnet on the RHS. The field generated on that side is then $E_S = E_0\sqrt{P'P}$ and the number of regenerated photons is $N_S = P'PN_0$ where N_0 is the number of photons in the initial laser beam.

Figure 1b shows the two improvements[4–6] we propose for the experiment. The first is to build up the electric field on the left hand side of the experiment using a Fabry-Perot cavity, as illustrated. We will call this cavity the axion generation cavity. Assuming an amplitude transmissivity of t_{1a} of the input mirror, amplitude reflectivities of the two cavity mirrors r_{1a} and $r_{2a} \approx 1$, and a cavity length such that the multiple reflections between the mirrors interfere constructively, then the right-propagating field inside the cavity, E_a, will be:

$$E_a = \frac{2t_{1a}}{t_{1a}^2 + V_a}E_{in} \tag{2}$$

where E_{in} is the amplitude of the laser field going into the cavity and V_a is the round-trip fractional power loss from power absorption in both mirrors, scattering due to mirror defects, diffraction from the finite mirror size, etc. Note that the power build-up is the square of the field, so that the ratio of the power in the cavity to the incident power is $\mathcal{F}_a/\pi$ with $\mathcal{F}_a = 4\pi T_{1a}/(T_{1a} + V_a)^2$ the finesse of the cavity.

The circulating light in the cavity creates an axion field of amplitude

$$a = \sqrt{P}E_a = \sqrt{P}\frac{2t_{1a}}{t_{1a}^2 + V_a}E_{in} \tag{3}$$

The optimum power transmissivity $T_a = t_a^2$ of the input mirror for given losses V_a inside the cavity is equal to V_a; this is the impedance matched case. As long as $\omega \gg m_a$, the spatial distribution of the axion field is identical to the spatial distribution of the electric field. Assuming the lasers in Figure 1a and Figure 1b have the same power, the flux is increased by the factor $4t_a^2/(t_{1a}^2 + V_a)^2$ compared to the case without generation cavity. These axions propagate through the "wall" and reconvert into photons in the regeneration region.

The second improvement[4–6] is to install also a second Fabry-Perot cavity, the photon regeneration cavity, on the other side of the experiment, making a symmetric arrangement, as illustrated on the right-hand side of Figure 1b. In this setup, the axion field acts as a source field similar to a gain medium in a laser resonator. The intra-cavity field can be calculated using the equilibrium condition:

$$E_\gamma = \frac{1}{1 - r_{1\gamma} r_{2\gamma} e^{i\phi_{RT}}} \eta \sqrt{P} a e^{ik_a d} \tag{4}$$

where ϕ_{RT} is the round trip phase of the field, d is the distance between the two cavities and $r_{1\gamma}$ and $r_{2\gamma}$ are the amplitude reflectivities of the two cavity mirrors. η is the spatial overlap integral between the axion mode and the electric field mode. This overlap will be identical to unity (up to corrections of order m_a/ω_0) if the spatial eigenmodes of the two cavities are extensions of each other, e.g. when the Gaussian eigenmode in one cavity propagated to the other cavity is identical to the Gaussian eigenmode of that cavity.

The field will be resonantly enhanced if $\phi_{RT} = N2\pi$, i.e., if the second cavity is resonant at the frequency of the converted photons. To detect the regenerated field, a small part is allowed to transmit through one of the cavity mirrors, say mirror 1, with an amplitude transmissivity of $t_{1\gamma}$:

$$E_S = t_{1\gamma} E_\gamma \approx \frac{2t_{1\gamma}}{t_{1\gamma}^2 + V_\gamma} \eta \sqrt{P} a e^{ik_a d} \tag{5}$$

where V_γ are the roundtrip losses inside the cavity excluding the power transmissivity $T_{1\gamma} = t_{1\gamma}^2$ of mirror 1. The final regenerated electric field is:

$$E_S = \left(\frac{2t_{1\gamma}}{t_{2\gamma}^2 + V_\gamma} \right) \left(\frac{2t_{1a}}{t_{1a}^2 + V_a} \right) \eta P E_{in} e^{ik_a d} \tag{6}$$

Or in terms of regenerated photons:

$$N_S = \left(\frac{4T_{1\gamma}}{(T_{1\gamma} + V_\gamma)^2} \right) \left(\frac{4T_{1a}}{(T_{1a} + V_a)^2} \right) \eta^2 P^2 N_{in} \tag{7}$$

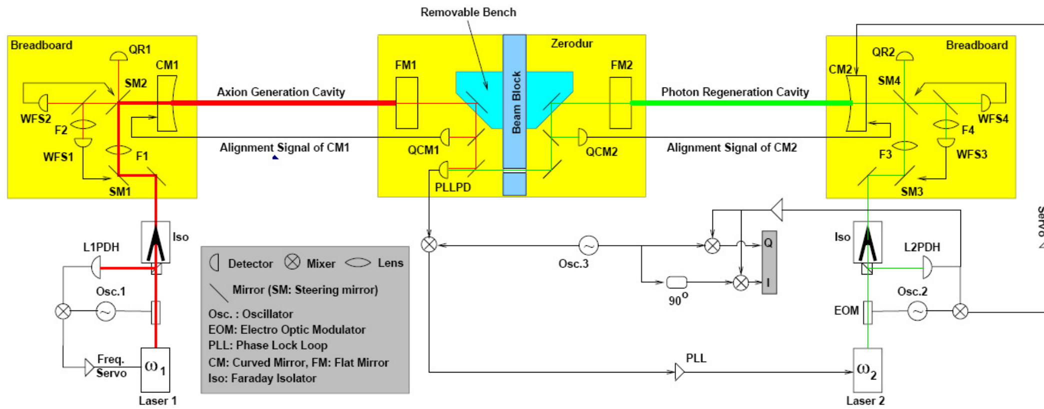

Figure 2: Experimental Layout: The left cavity formed between CM1 and FM2 produces axions from the electric field of Laser 1. The right cavity is used to regenerate the electric field from the axions which enter it. The layout shows the detectors and sensors needed for length, frequency, and alignment control. The components which will be placed inside the vacuum enclosure are CM1,2, SM1-4, F1, F3, and the entire optical bench (yellow), including all optical components and detectors on that bench.

The final signal depends on the laser power build-up in the axion generation cavity and the signal build-up in the photon regeneration cavity. The build-up in the regeneration cavity is limited by the losses V_γ and the transmissivity $T_{1\gamma}$. As always, the field outside the cavity is maximum when the cavity is impedance matched ($T = V$). The losses include coating absorption and scattering from imperfections in the polished surface, mainly small angle scattering. Current state-of-the-art mirrors have coating absorption of $< 1\,\mathrm{ppm}$ and scatter of $< 5\,\mathrm{ppm}$ or total losses in the order of $V \approx 10\,\mathrm{ppm}$ for both mirrors combined. For the impedance-matched case, it is convenient to express equation Equation (7) in terms of the finesse $\mathcal{F}_{\gamma,a}$ of the cavities:

$$N_S = \eta^2 \frac{\mathcal{F}_\gamma}{\pi} \frac{\mathcal{F}_a}{\pi} P^2 N_{in} \tag{8}$$

Note that resonant regeneration gives an enhancement factor of $\sim (\mathcal{F}/\pi)^2$ over simple photon regeneration. This factor may feasibly be 10^{10}, corresponding to an improvement in sensitivity to $g_{a\gamma\gamma}$ of ≈ 300.

Intrinsic to resonantly enhanced photon regeneration is the requirement that the axion generation and photon regeneration cavities are both on resonance and are aligned with the axion generating laser field E_{in}. The proposed experimental setup to achieve these conditions is shown in Fig. 2. The layout is complex, but the basic idea is that Laser 1 (shown with red light in the diagram) is locked to a resonance of the axion generation cavity. Laser 2 (shown with green light) is "offset locked" to laser one, with the offset, determined by Oscillator 3, equal to one or more free spectral ranges of the cavities (58 MHz in Phase I and 3.4 MHz in Phase II). This offset locking ensures that both cavities have common resonances while at the same time having the light used to lock the detection cavity be at a different frequency than the regenerated photons.[6]

3 Accelerator or Lab Facility

The Phase I research will be take place at the University of Florida. The Phase I magnets would come from Fermilab. These would be permanent magnets with 0.6 T field and 2.5 m length. A strawman design has been performed by James Volk of Fermilab. The magnet would be built from existing strontium ferrite magnets, with a design similar to the dipoles used in the MI-8 transfer line. The pole spacing is 10.2 mm and the pole pieces are 101.6 mm by 152.4 mm, made from low-carbon steel. The central field has been calculated using PANDRIA (a two dimensional magnet modeling program) to be 0.62 T. Double stacks of strontium ferrite magnets are used on the top and bottom of the poles and on each side of the poles. A total of 240 pieces of ferrite would be needed for each magnet.

Phase II, much more sensitive than Phase I, would be built at Fermilab. The Phase II design utilizes a total of 12 Tevatron superconducting dipoles (each 5 T field, 6 m length, and 48 mm diameter bore), 6 for the axion generation cavity (total magnetic length of 36 m) and 6 for the photon regeneration cavity (the "TeV 6+6" configuration). There is a large infrastructure and experience base for the Tevatron dipoles, and an adequate number are available.

Phase I and Phase II would of course use different optical cavities. The injection and detection benches would be the same for both experiments. (A few lenses would have to be changed.) The bench would be built, tested, and used for phase I at Florida and then would be brought to Fermilab to be installed with the magnets.

4 Physics Reach

4.1 Phase I

For a baseline of 2.5 m length 0.6 T magnets, an input power of 1 W, a cavity finesse of $\mathcal{F} \sim 1.5 \times 10^5$ ($T = 20\,\text{ppm} = V$) for both cavities, and 10 days of operation, we find at signal-to-noise ratio of unity,

$$g_{a\gamma\gamma}^{min} = \frac{6 \times 10^{-9}}{\text{GeV}} \left[\frac{0.95}{\eta}\right] \left[\frac{1.6\,\text{Tm}}{BL}\right] \left[\frac{T}{20\,\text{ppm}}\right]^{1/2} \left[\frac{1\,\text{W}}{P_{in}}\right]^{1/4} \left[\frac{10\,\text{days}}{\tau}\right]^{1/4}. \tag{9}$$

This equation translates into a 95% exclusion limit (3σ) for axions or generalized pseudo scalars with $g_{a\gamma\gamma}^{min} < 6 \times 10^{-9}\text{GeV}^{-1}$ after 90 days cumulative running, well below the best photon regeneration limit set to the present. The short cavity means that the zeros of the $\text{sinc}(qL/2)$ function, which modulates the conversion probability in Equation (1), are above 5 meV in the Phase I experiment.

4.2 Phase II

For a baseline of a TeV 6+6 setup, an input power of 10 W, a cavity finesse of $\mathcal{F} \sim \pi \times 10^5$ ($T = 10\,\text{ppm} = V$) for both cavities, and 10 days of operation, we find at signal-to-noise ratio of unity,

$$g_{a\gamma\gamma}^{min} = \frac{2 \times 10^{-11}}{\text{GeV}} \left[\frac{0.95}{\eta}\right] \left[\frac{180\,\text{Tm}}{BL}\right] \left[\frac{T}{10\,\text{ppm}}\right]^{1/2} \left[\frac{10\,\text{W}}{P_{in}}\right]^{1/4} \left[\frac{10\,\text{days}}{\tau}\right]^{1/4}. \tag{10}$$

This equation translates into a 95% exclusion limit (3σ) for axions or generalized pseudo scalars with $g_{a\gamma\gamma}^{min} < 2.0 \times 10^{-11}\text{GeV}^{-1}$ after 90 days cumulative running, well into territory unexplored by stellar evolution bounds or direct solar searches. Note that the exclusion sensitivity follows the inverse of $\text{sinc}(qL/2)$, for the case of the TeV 6+6 configuration, the first null sensitivity occurring at 2.8×10^{-4}eV. The momentum mismatch between a massless photon and a massive axion defines the oscillation length of the process to be $L_{osc} = 2\pi/q$. (As pointed out in Ref. [1] however, there is a practical strategy to extend the mass range upwards if the total magnetic length L is comprised of a string of N individual identical dipoles of length l. In this case, one may configure the magnet string as a "wiggler" to cover higher regions of mass, up to values corresponding to the oscillation length determined by a single dipole, i.e., $q \sim l^{-1}$.)

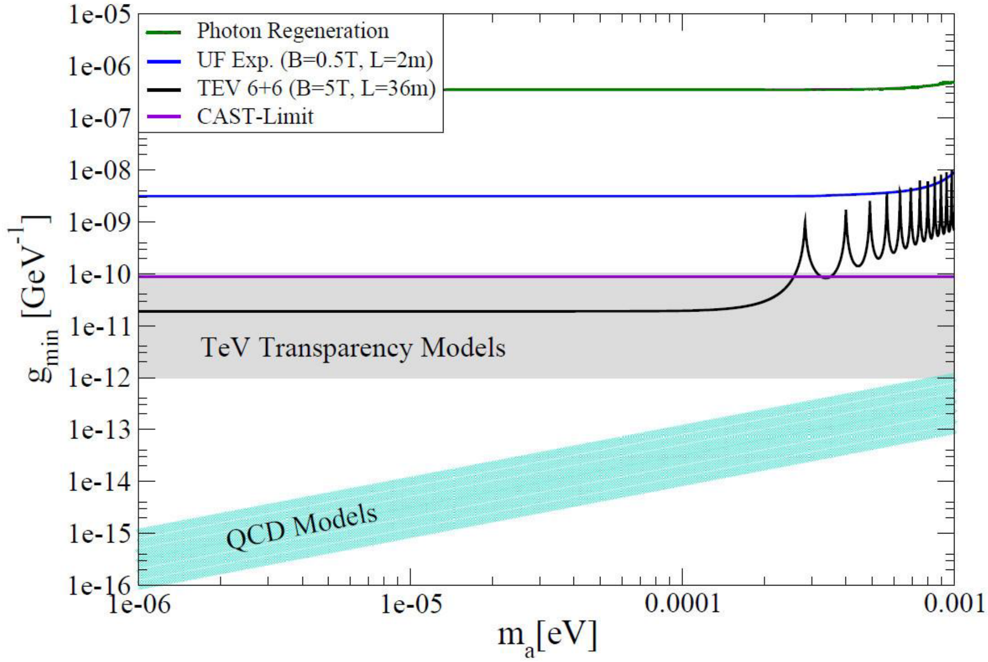

Figure 3: Exclusion plot of mass and photon coupling $(m_a, g_{a\gamma\gamma})$ for the axion, and the 95% CL exclusion limit for the resonantly enhanced photon regeneration experiment calculated for Phase I ("UF experiment," in blue), Phase II (the "TeV 6+6" configuration, in black). The existing exclusion limits indicated on the plot include the best direct solar axion search (CAST collaboration, in purple),[7] the Horizontal Branch Star limit (gray shaded area),[8] and previous regeneration experiments (in green).[9–12]

5 Status and Schedule

This experiment has been described in two papers. See Refs. [5, 6]. A proposal is planned for FY2012.

6 Future Plans

Future plans and upgrades are discussed above, as phase II. Beyond this, one could extend the cavity length to 500 m and the field to 13 T using technology from CERN, giving a limit in g of 8×10^{-13} GeV^{-1}, about 25 times better than the Phase 2 limit of Figure 3.

7 Collaborating Institutions and Collaborators

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4. University of Michigan (Dick Gustafson)

8 Written Materials (e.g., references)

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