LIPSS Free-Electron Laser Searches for Dark Matter

J. R. Boyce,[1] A. Afanasev,[2] O.K. Baker,[3] K.B. Beard,[4] G. Biallas,[1] M. Minarni,[5] R. Ramdon,[2] T. Robinson,[1] M. Shinn,[1] P. Slocum[3]

[1]FEL Division, Jefferson Lab, 12000 Jefferson Ave., Newport News, VA 23606.
[2]Department of Physics, Hampton University, Hampton, VA 23668, USA
[3]Department of Physics, Yale University, PO Box 208120, New Haven CT 06520, USA
[4]Muons, Inc., 552 N. Batavia Avenue, Batavia, IL 60510, USA
[5]Department of Physics, Universitas Riau (UNRI) Pekanbaru, Riau 28293, Indonesia

E-mail: boyce@jlab.org

Abstract. A variety of Dark Matter particle candidates have been hypothesized by physics Beyond the Standard Model (BSM) in the very light (10^{-6} – 10^{-3} eV) range. In the past decade several international groups have conducted laboratory experiments designed to either produce such particles or extend the boundaries in parameter space. The **LI**ght **P**seudo-scalar and **S**calar **S**earch (**LIPSS**) Collaboration, using the "Light Shining through a Wall" (LSW) technique, pass the high average power photon beam from Jefferson Lab's Free-Electron Laser through a magnetic field upstream from a mirror and optical beam dump. Light Neutral Bosons (LNBs), generated by coupling of photons with the magnetic field, pass through the mirror ("the Wall") into an identical magnetic field where they revert to detectable photons by the same coupling process. While no evidence of LNBs was evident, new scalar coupling boundaries were established. New constraints were also determined for hypothetical para-photons and for millicharged fermions. We describe our experimental setup and results for LNBs, para-photons, and milli-charged fermions. Plans for chameleon particle searches are underway

1. Introduction

Dark matter and dark energy are postulated to explain astronomical and cosmological observations as well as strong interaction CP violations. However, these postulations are beyond the Standard Model of particle physics, a well tested model of the strong, weak, and electromagnetic interactions. [1-5] Nonetheless, by applying standard theoretical treatments (e.g., string theory) several laboratory experiments have been suggested to search for evidence of WIMPs (weakly interacting massive particles) or WISPs (weakly interacting sub-eV particles). While most of these searches are for WIMPS, a few, such as LIPSS, are exploring WISP parameter space. [6-9]

LIPSS uses the experimental technique "Light Shining through a Wall" (LSW) [10] whereby linearly polarized FEL light passes through and (very weakly) couples to a strong magnetic dipole field thus generating the dark matter candidates: pseudo-scalars if the FEL light polarization is parallel to the dipole field, or scalars if the light polarization is perpendicular to the dipole field. The light is diverted with a mirror (the wall) to a power dump but the generated particles pass on through the mirror and through a second dipole field, identical to the generating dipole field. In the second magnetic field the coupling reconverts particles back to photons that are then detected by a sensitive,

Journal of Physics: Conference Series **315** (2011) 012002 doi:10.1088/1742-6596/315/1/012002

liquid nitrogen cooled, CCD camera located inside a light tight box. Figure 1 depicts the process for (a) Light Neutral Bosons (LNBs) and (b) Para-photons.

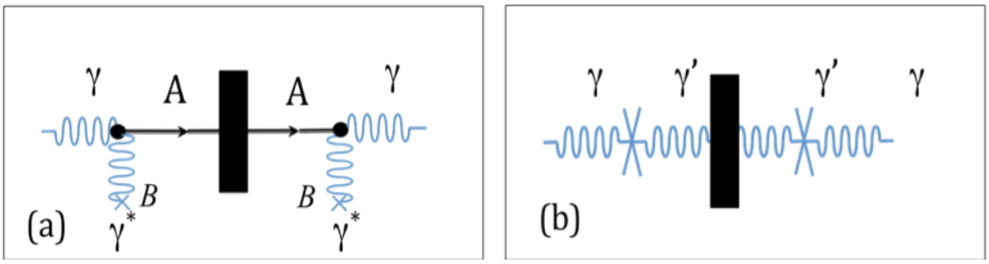

FIGURE 1. The "Light Shining through a Wall" (LSW) Technique. (a) Photons (γ) couple with a virtual photon (γ*) of the dipole's magnetic field (*B*) to produce the Light Neutral Boson (A). The photons are stopped by the wall but the LNBs pass through the wall and couple with the second dipole field thus regenerating photons which are detectable. (b) Photons couple to the hidden sector (U1), predicted by String Theory, pass through the wall and regenerate photons by the same coupling process.

2. Experiment

2.1. Free-Electron Laser

Photons for the experiment are produced by the Jefferson Lab Free-Electron Laser (FEL) located in an underground vault and depicted in Figure 2. An Energy Recovery Linac (ERL) produces a 110 MeV electron beam that is sent through a magnetic wiggler to generate a linearly polarized, tunable infrared (IR), high average power photon beam that is transported to the LIPSS experimental setup in a User Lab. The wavelength for the LIPSS experiment was chosen to be 935 nm since the collection efficiency of the detector and the FEL power output capability were both reasonably high. More details about the FEL facility, including a video demonstrating the tunability of the FEL, are found elsewhere. [11,12]

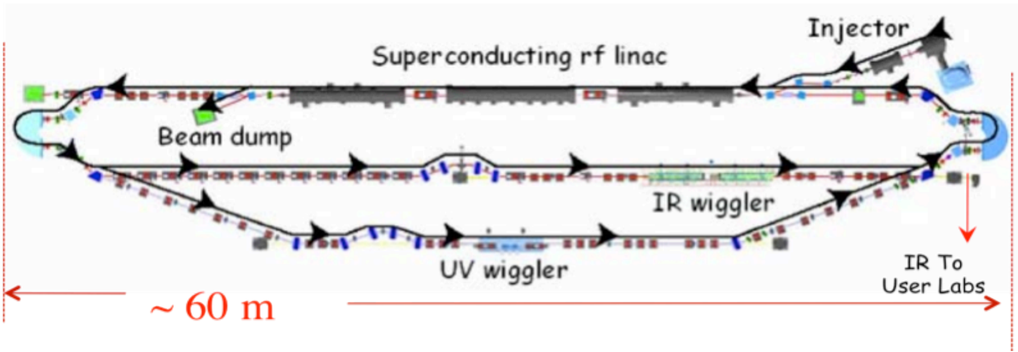

FIGURE 2. Layout of the Jefferson Lab ERL FEL. A beam of 10 MeV electrons is injected into three superconducting accelerators reaching an energy of ~110 MeV, then guided through the IR beam line, through the IR wiggler, bent back around, re-injected 180° out of phase into the SRF accelerators thus decelerating back to 10 MeV and guided to the beam dump.

2.2. Experimental Setup

Once in the User Laboratory, the 935 nm IR FEL beam is collimated to 6 mm diameter beam and sent through the LIPSS experimental setup, depicted in Figure 3, consisting of a vacuum chamber mounted inside a 1.7 T dipole. The chamber has a Brewster window at the entrance and exit. A turning mirror (TM3) deflects the IR beam to a power meter dump. Particles produced in the generating chamber pass through TM3 ("the Wall") and into a light tight regenerating vacuum chamber where the inverse reaction produces photons that enter a Light Tight Box (LTB) where they are directed by TM4 into a liquid nitrogen cooled CCD camera (Princeton Instruments ACTON 10: 400BR/LN). [12]

Journal of Physics: Conference Series **315** (2011) 012002 doi:10.1088/1742-6596/315/1/012002

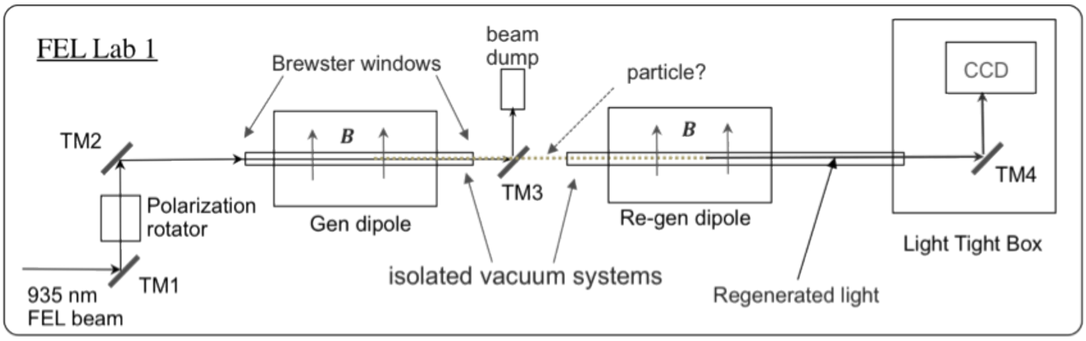

FIGURE 3. Schematic layout of the LIPSS experiment in Lab 1 of the FEL. The 935 nm FEL beam is directed by turning mirror TM1 through a polarization rotator, then by TM2 through the generating vacuum chamber in the 1.7T dipole field, and into the IR beam dump/power meter by TM3 ("the Wall"). Dark matter particles produced in the Gen dipole pass through TM3, through the Re-gen vacuum chamber where the inverse reaction regenerates photons that then enter the Light Tight Box (LTB) and be are directed by TM4 to a LN_2 cooled CCD camera.

The Light Tight Box (LTB) is depicted in Figure 4. On the left is an early photograph of the inside of the LTB. On the right is a schematic of the LTB. Great care was taken to verify that the LTB prevented photons from entering to the level of 1 photon/hour. The inside walls of the LTB were covered with black felt wall paper and the exterior was covered with three layers of Al foil sandwiched between black plastic. Hour long exposures were taken with all combinations of room lights on and off and camera shutter open and closed. With the exception of cosmic rays, there was no statistically significant variation between resulting runs.

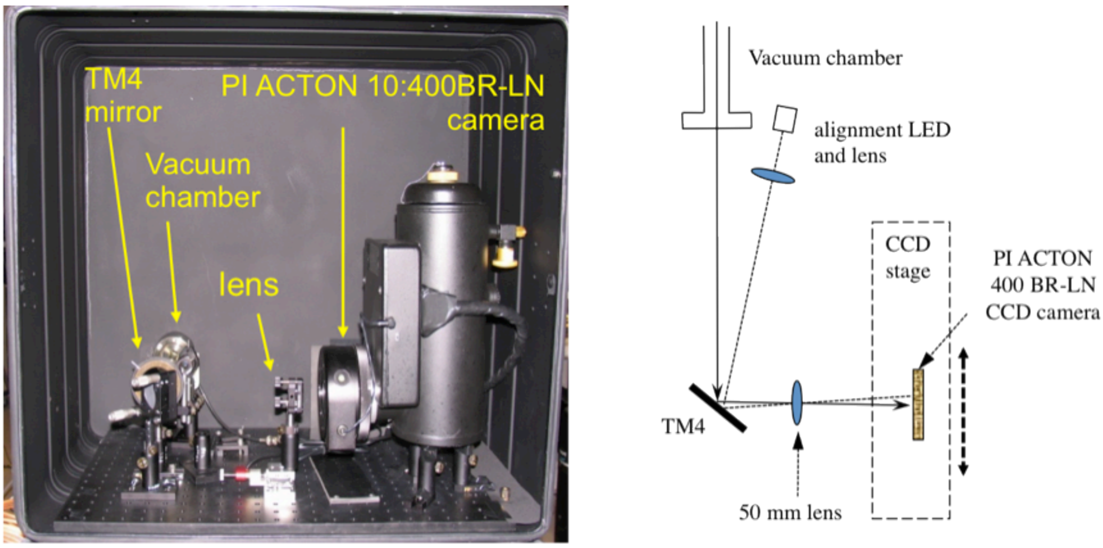

FIGURE 4. Inside layout of the Light Tight Box (LTB) and optics diagram. Regenerated photons enter the LTB through a window at the end of the regeneration vacuum chamber, reflecting off turning mirror 4 (TM4), and finally through a 50 mm lens that focuses down to one pixel in the sweet spot. All optics, window, mirror, and lens were anti-reflection coated. The camera image is 1340 x 400 pixels in size and each pixel is 20 μm x 20 μm in size. The camera was mounted on a translational stage with motion perpendicular to the incoming focused photons. The camera was moved between exposure runs in order not to depend on any one pixel. During the scalar exposure runs, alignment was verified by light from an LED. For the pseudoscalar runs, alignment was verified by pulsed low power FEL light.

A series of exposures were taken with a 0.5 mW red alignment laser to simulate one-hour-long runs with a few counts above background per hour. Neutral density (ND) filters were stacked in front of the entrance to the regeneration vacuum chamber where the solid stainless steel blank-off flange was replaced with a quartz window. Figure 5 shows the attenuation of the laser light as a function of ND filter value. To obtain a photon rate of a few per hour, the rate anticipated based on the PVLAS claim (later withdrawn), the laser had to be attenuated by fifteen (15) orders of magnitude.

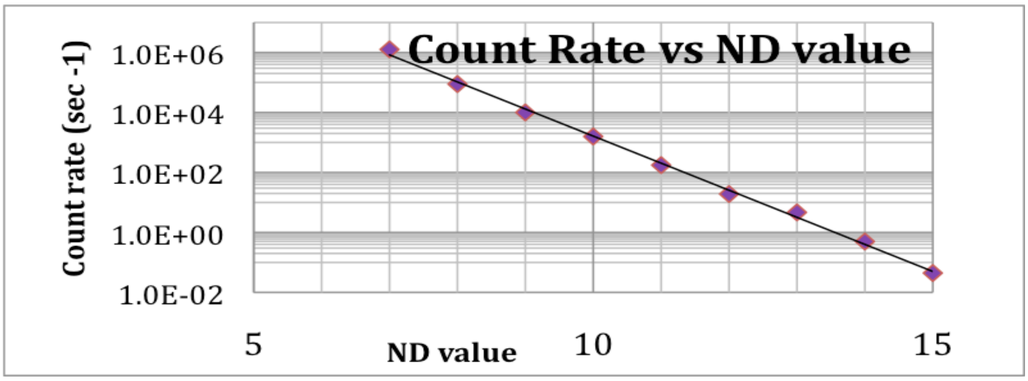

FIGURE 5. System check out and simulation results using a 0.5mW red alignment laser with Neutral Density (ND) filters directly in front of the entrance to the re-generation vacuum chamber. In order to simulate the anticipated WISPS count rate (~ few/hour) the laser needed to be attenuated by fifteen orders of magnitude.

Figure 6 is a typical image resulting from a 1-hour-long simulation using a 0.5 mW red alignment laser and a ND filter value of 15. These data were used not only to illustrate a positive result but also to verify the analysis algorithms were working properly.

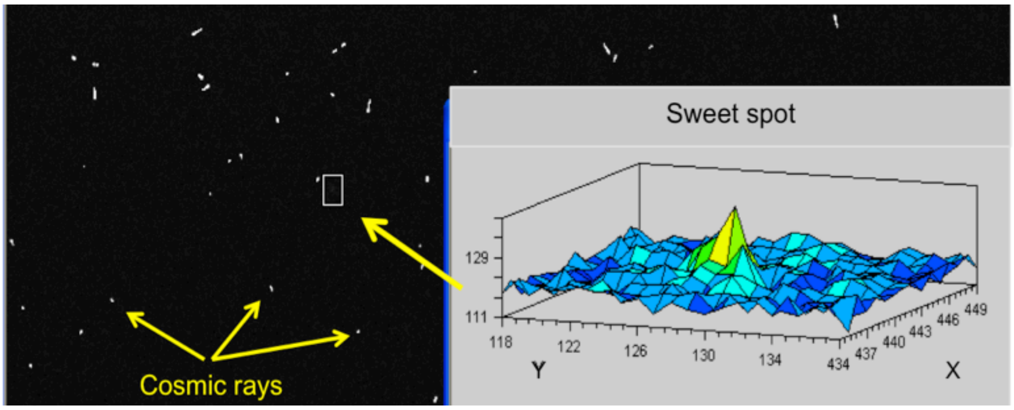

FIGURE 6. Typical 1-hr simulation image from the CCD camera. The white spots are cosmic rays. The "Sweet spot" region is magnified and shown in the inset. Since pixels can "go bad" the camera was moved between each run to remove any dependence on any one pixel. Any image with a cosmic ray near the Sweet spot region was discarded. An algorithm removed cosmic rays from remaining images. The resulting image was examined for deviations from background and readout noise.

3. Results

Table 1 summarizes the relevant parameters for the LIPSS runs with the FEL. Analysis of all the runs did not show any significant deviations from background and readout noise. Thus upper limits were set by these experiments consistent with other LSW results as shown in Figures 7, and 8. [9]. Regions above the curves are excluded by the experimental results.

TABLE 1). LIPSS parameter sets for both scalar and pseudoscalar experiments with the FEL.

Parameter	**Scalar Runs (2007)**	**Pseudoscalar Runs (2009)**
B-field	1.7 T	1.7 T
Magnet length	1.0 m	1.0 m
IR FEL power	0.2 kW	0.4 kW
IR FEL wavelength	935 nm (1.3 eV)	935 nm (1.3 eV)
Quantum efficiency	0.4	0.4
Linear polarization	100%	100%
Acceptance	100%	100%
experimental efficiency	~ 90%	~90%
Background rates (all sources)	< 1count/hr/pixel	< 1count/hr/pixel

4. Conclusions

The Jefferson Lab FEL was successfully used to search for three families of dark matter candidate particles: Pseudoscalar and Scalar Light Neutral Bosons, Paraphotons, and Milli-charged fermions. Although no positive evidence was detected, new exclusionary boundaries were established consistent with more recent LSW experiments by other Collaborative Teams. Plans for chameleon particle [14, 15] searches are underway.

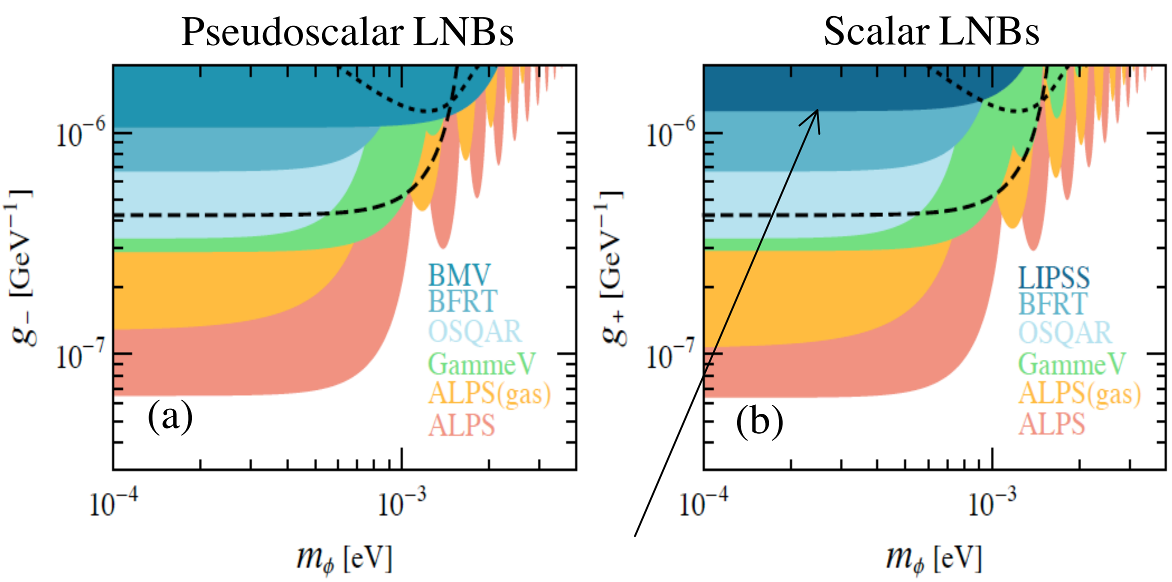

FIGURE 7. LIPSS results compared to results of other LSW experiments. (a) Pseudoscalar Light Neutral Bosons, (b) Scalar Light Neutral Bosons compiled in Reference [9]. Note: these plots from Reference [9] were generated prior to LIPSS pseudoscalar experiment.

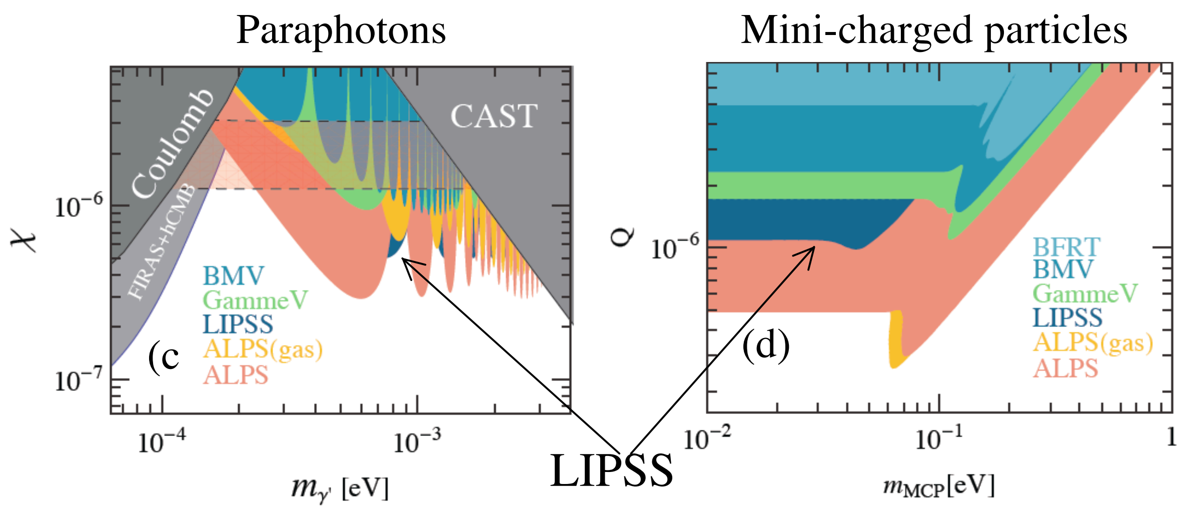

FIGURE 8. LIPSS results compared to results of other LSW experiments: (c) Paraphotons, and (d) Mini-charged particles, compiled in Ref. [9]. Note that the LIPSS Paraphoton data are behind the other results.

Acknowlegements
The authors thank the technical staff of the Jefferson Lab Free-Electron Laser Facility, especially F. Dylla, G. Neil, G. Williams, R. Walker, D. Douglas, S. Benson, K. Jordan, C. Hernandez-Garcia, J. Gubeli, summer 2009 interns Jon Evans, Jennifer Caldwell, and Joe Amma, as well as M.C. Long of Hampton University for their excellent support of the experimental program.

This work was supported by the Office of Naval Research Award N00014-06-1-1168, the Joint Technology Office, the Commonwealth of Virginia, the Air Force Research Laboratory, and by DOE under contract DE-AC05-06OR23177. Notice: Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

References

[1] S. Glashow, Nucl. Phys. **22,** 579 (1961).
[2] S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967).
[3] A. Salam. In: W. Swatholm (Ed.) *Elementary Particle Theory*, Almquist and Wiksell, Stocholm, 1968.
[4] H.D. Politzer, Phys. Rev. Lett. **30**, 1346 (1973).
[5] D. Gross, F. Wilczek, Phys. Rev. Lett. **30**, 1343 (1973).
[6] E. Zavattini, et al., Phys. Rev. Lett. **96**, 110406 (2006); arXiv:0706.3419 [hep-ex].
[7] A. Afanasev, et al., Phys. Rev. Lett. **101**, 120401 (2008).
[8] A. Chou, et al., Phys. Rev. Lett. **100**, 080402 (2008).
[9] K. Ehret, et al., Phys. Lett. B. **149**, 689 (2010).
[10] K.V. Bibber, et al., Phys. Rev. Lett. **59**, 759 (1987).
[11] S. Benson, et al., "The 4th Generation Light Source at Jefferson Lab", Nucl. Instr. Methods **A582**, 14-17 (2007).
[12] http://www.jlab.org/FEL/
[13] http://www.princetoninstruments.com/products/speccam/spec10/dsheet.aspx
[14] J. Khoury and A. Weltman, Phys. Rev. Lett. **93**, 171104 (2004).
[15] A.S. Chou, et al., arXiv:0806.2438v1 [hep-ex] 15 June (2008).