Numerical Simulations of Ponderomotive Scattering as a Means of High Intensity Measurement

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Abstract

Developments in XFEL and optical lasers have enabled novel strong field QED experiments such as FOR, LUXE, and FACET. These experiments seek to probe processes including pair production, the trident process, and vacuum birefringence which scale with the intensity of the optical laser at the interaction point [1,2,3]. It is therefore critical to the data analysis of such experiments to have high precision measurements of the laser intensity and while various methods have been proposed and pursued to this end, no method offers direct measurement of intensity at the laser's focus to better than 10% accuracy. One potential solution is the ponderomotive scattering of electrons in rarefied gases. We use PIC simulations to define an observable feature in the angular spectra of scattered electrons, scan the dependence of the angular spectrum's rising edge on various laser parameters, and show the role of the ionization of these electrons in high-Z gases.

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Ponderomotive Scattering and Ionization

It is important to note the relationship between the peak intensity I_0 in W/cm^2 and laser strength a_0:

$$a_0 = 0.85 \times \lambda_{\mu m} \times \sqrt{I_{0,10^{18}}}. \tag{1}$$

From the relativistic particle in a plane wave, the final scattering angle relative to the laser strength is given by:

$$\theta = \arctan\left(2/a_0\right). \tag{2}$$

Laser pulses are not generally plane waves but near their focus they are planar therefore electrons scattered by the focus will have an angular dependence nearing that of the plane wave solution. In order to populate the focus of the laser pulse with electrons approximately at rest, we utilize the ionization of high-Z gases. Ionization in this regime is well characterized by ADK ionization rates which saturate at barrier suppression intensities [4].

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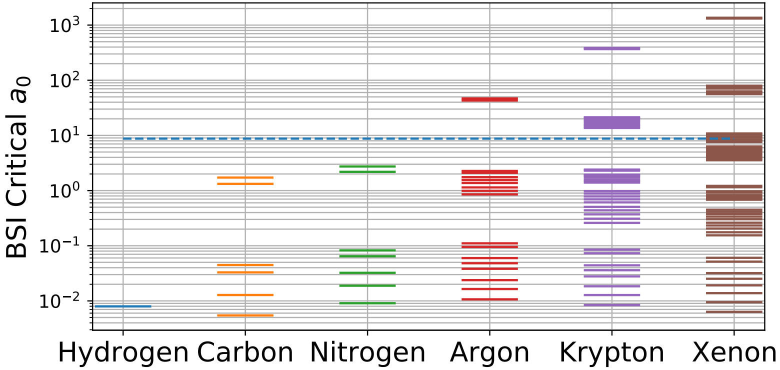
Ionization of Kyrpton and Xenon

Previous studies of ionization and ponderomotive scattering as a means to measure laser intensity focused on the ionization of lighter elements such as He, N, and Ar. As recently as 2015, Kr was chosen as a target gas for intensities above $I \approx 10^{18}$ W/cm^2 [5]. As shown below, band gaps or the absence of energy levels in these elements make them poor targets for lasers with intensities near $I \approx 10^{20}$ W/cm^2 [6]. To provide such lasers with electrons at their focus, we utilize Xe in simulations.



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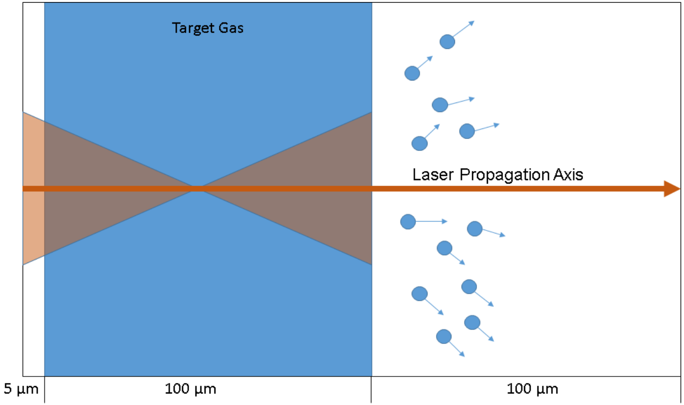
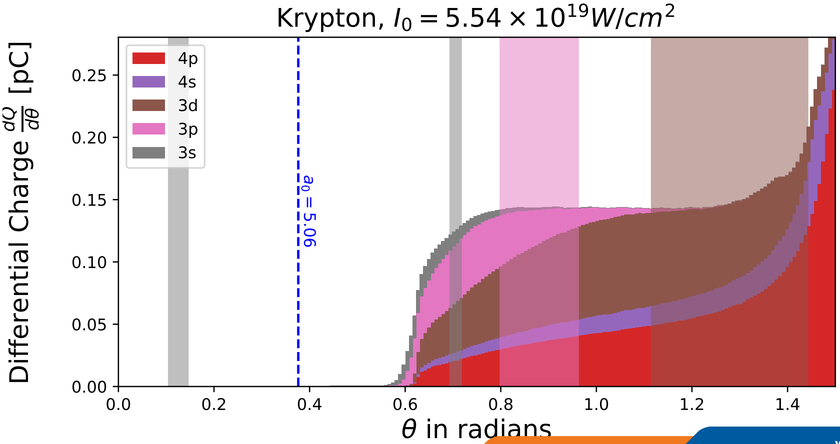
Simulation



Simulations were conducted using the 3D PIC code EPOCH which includes ADK ionization [7]. The laser propagates through 100 μm of the target gas at a density of $n = 10^{10}$/cc and is focused at the center of the gas. Between runs, peak laser intensity and target gas have been permuted. Laser wavelength and spotsize are fixed at 800 nm and 8 μm.

Angular Spectra of Ionized Electrons

From the simulated electrons final momenta, we construct the spectrum of final electron scattering angle relative to the laser propagation axis. Contributions to the spectrum are separated by the principle quantum number of the electron's original energy level. Shaded regions indicate the range of angles one would expect from each electron group from plane wave scattering and the blue line is the plane wave scattering angle.



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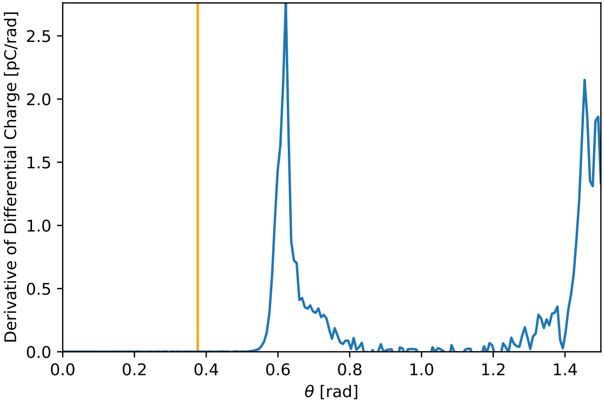
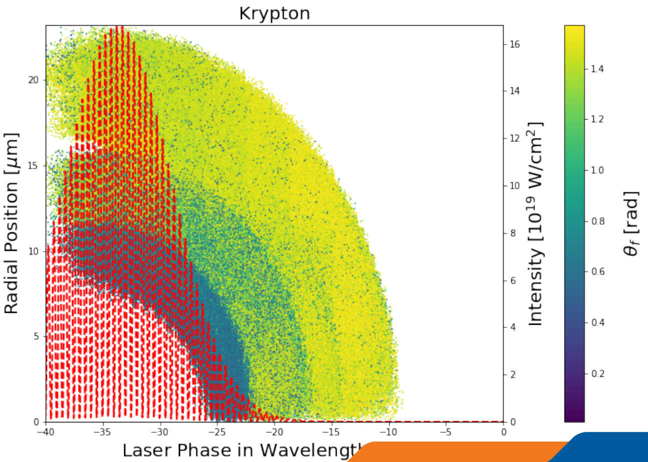
The Rising Edge

The angular spectra of electrons ionized and scattered by strong laser pulses contain contributions from each energy level the laser is capable of ionizing. It is crucial to define a distinct spectral feature which depends on laser intensity. This role is served by the rising edge of the angular distribution which we define as the maximum of the angular distribution's derivative with respect to scattering angle.



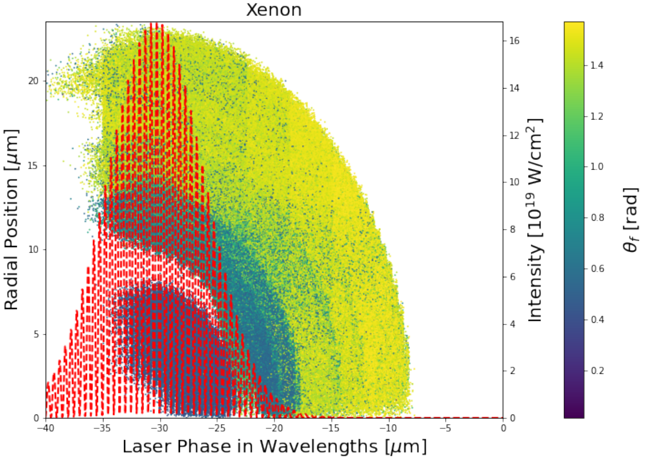
Ionization within the Laser Pulse

This plot shows the initial position of ionized electrons in terms of radial position and laser phase and their final scattering angle is shown by color. On the right axis, the intensity of the laser is plotted against its phase. For a $I_0 = 1.66 \times 10^{20}$ W/cm^2 laser incident on Kr, electrons are scattered in the region surrounding the focus.



Ionization within the Laser Pulse

Under the same laser conditions but using Xe as the target, electrons from the deeper ionization shells originate within only a few microns of the focus and scatter over a small range of angles.



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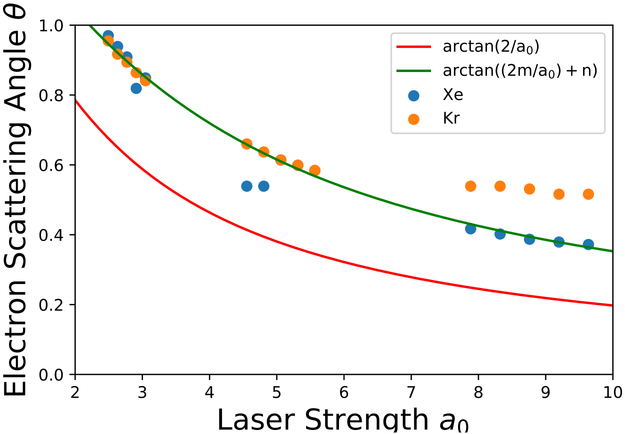
Scattering Angle vs. Laser Strength



The final scattering angle as found through the rising edge for Kr and Xe under lasers with $a_0 = 2.77, 5.06, 8.76$ permuted by 5% and 10%. The plane wave scattering angle predicted by Eqn. 2 is shown in red. When Xe data points are used for the highest laser amplitudes, an arctangent fit where $m = 1.693$ and $n = 0.03$ can be found.

Conclusion and Outlook

Our numerical simulations show the relation between the final scattering angle of ionized electrons and peak laser strength. In considering the ionization energies of high-Z gases, we have found appropriate inert gas targets for intensities between 10^{19} and 10^{20} W/cm^2 with electrons ionized into the focal region of the laser. The rising edge of the angular distribution of electrons serves as a detectable signal of ponderomotive scattering. We have found an arctangent relation between the ponderomotive scattering angle and the laser strength sensitive to 10% shifts in a_0, however, this relation is offset from the plane wave solution. This work is being expanded to examine this relationship for tighter laser focusing and probe the origin of the offset from the plane wave scattering solution.

Bibliography

1. A. Blinne, *et al.* Phys. Rev. D **99**, 17 (2019).
2. H. Abramowicz, *et al.* arXiv:2102.02032.
3. Technical Design Report for the FACET-II Project at SLAC National Accelerator Laboratory (SLAC-R–1072), (2016).
4. Delone, N. B. and Krainov, V. P. J. Opt. Soc. Am. B **8**, 1207 (1991).
5. M. Kalashnikov, *et al.* Laser Part. Beams **33**, 361 (2015).
6. A. Kramida, *et al.* NIST Atomic Spectra Database (ver. 5.8), [Online]
7. Arber, T D, *et al.* Plasma Phys. Control. Fusion **57**, 11 (2015).