PHY571 - Numerical Physics Final Project

Relativistic Laser - Plasma Interactions through PIC Simulations

Group Members: Christian Cabello, Arthur Bosquet

Motivation

The study of interactions between intense laser pulses and matter has been the subject of much attention since the advent of the chirped pulse amplification technique, whose inventors were awarded the 2018 Nobel Prize in Physics [1]. This technique allowed scientists to reach laser intensities that could probe nonlinear optics in the non-perturbative regime. In particular, the process of high-order harmonic generation was discovered and explained as a non-perturbative, non-linear light-matter interaction [2]. Put briefly, this process generates high frequencies of light which are integer multiples of the driving laser frequency. Physicists have found that this process can take place with all phases of matter, i.e. gas, liquid, solid, and plasma [3, 4, 5]. It has been a topic of tremendous interest because its ability to generate a spectrum which spans from the mid-infrared to XUV, or soft X-rays, has allowed the generation of isolated, attosecond pulses of light. Attosecond pulses provide the tools to study electronic motion on its natural timescale and promise revolutions in materials science and engineering, chemistry, and biomedical diagnostics. With regard to this, the scientists who enabled attosecond science were awarded the 2023 Nobel Prize in Physics [6].

For the purpose of generating isolated attosecond pulses, the medium most often chosen is a gas. This is because it can produce the broadest spectrum at the laser intensities most readily available in laser labs, compared to solids and liquids. However, there is still a hard limitation on the flux of the attosecond pulses that can be produced because the process is quite inefficient, and the only way to reasonably increase their intensity would be to increase the intensity of the driving laser. However, if the intensity is increased beyond ~ $10^{15}\ W/cm^2$, the laser will begin to noticeably ionize the gas and the efficiency of the process will become even worse. Therefore, scientists began looking for other ways to increase the intensity of the attosecond pulses. To this end, a new technique was developed involving the reflection of a laser pulse of relativistic intensity, ~ $10^{18}\ W/cm^2$, off of a plasma. In this scheme, an intense prepulse is sent to a solid target, which fully ionizes the solid into a plasma and is overdense at the frequency of the relativistic pulse. Therefore, it completely reflects the light, hence the term plasma mirror. Furthermore, since the main pulse is intense enough to induce relativistic motion of the surface electrons quasi-instantaneously, relativistic Doppler effects create high-order harmonics of the driving laser, again leading to attosecond pulses [7]. Since the plasma mirror can handle arbitrarily high intensities, this approach promises the generation of the most intense attosecond pulses possible, which would accelerate the progress of the aforementioned fields and potentially open up new fields of study. This study attempts to probe this surface high-order harmonic generation from a plasma mirror using a 1D particle-in-cell (PIC) code coupled with a 1D finite-difference time-domain (FDTD) method for the laser pulse.

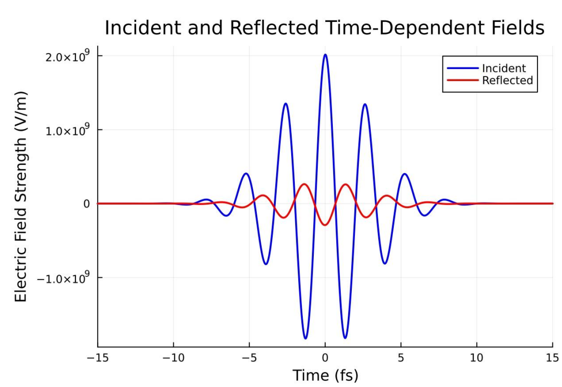
Methods and Results

The programming language Julia was chosen for this project due to its nice properties of being as easy to write and read as Python code, while being as fast as Fortran or C++ code. In the PIC scheme [8], a specific number of macro-particles are initialized in each grid cell, and they are all assigned a weight that corresponds to the density of the target and the physical situation. In our case, the surface of the plasma mirror was taken to begin at $0.9Lz$, where $Lz = 50\lambda_0$ and represents the full length of the grid. However, there is a plasma density gradient which smooths out the density from the vacuum to the surface of the plasma. The plasma consists of Si ions and electrons, with the ratio being 36 electrons and 9 ions for each grid cell. Since the grid contains 8192 cells to ensure good spatial and temporal resolution, a total of 73845 particles are created, with the initialization beginning from ~ $0.8Lz$ to prevent evolving many particles with weight ~ 0 .

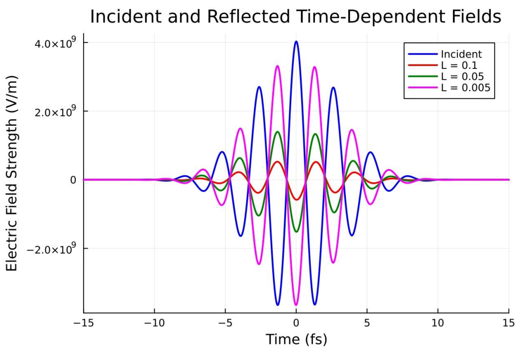
Once the particles are initialized, the charge and current densities are interpolated to the grid using linear interpolation, and the 1D Poisson equation is solved to determine the static field E_z, which has a simple solution in terms of a tridiagonal matrix in 1D [9]. For the laser pulse, a 1D FDTD method is used to simulate E_y and H_x [10]. In 1D, perfect absorbing boundary conditions can be implemented by choosing the correct Courant number. In this simulation, a Gaussian pulse is initialized on the left-side of the grid with pulse duration of ~ 5 fs FWHM and central wavelength of $\lambda_0 = 800\ nm$. A fully ionized Si target creates an electron density of $n_e = 40n_c$, with $n_c = 1.75 \times 10^{27}\ m^{-3}$ being the critical density at 800 nm. Finally, each macro-particle is evolved using Newton's law with relativistic correction:

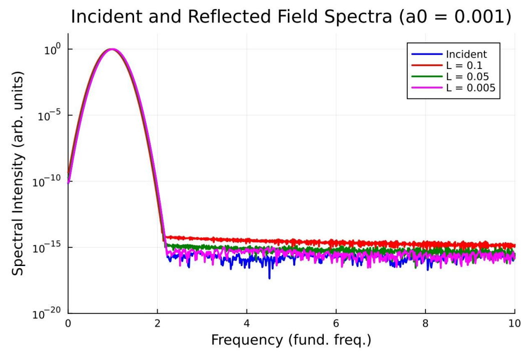
$$\frac{dx_p}{dt} = \frac{u_p}{\gamma_p} \quad ; \quad \frac{du_p}{dt} = \frac{q_s}{m_s}\left[E_p + \left(\frac{u_p}{\gamma_p} \times B_p\right)\right]$$

where, $u_p = \frac{p_p}{m_s}$ is the reduced momentum and $\gamma_p = \sqrt{1 + \frac{u_p^2}{c^2}}$ is the Lorentz factor. The velocity update is performed using the Vay method [11], which preserves Lorentz invariance, after interpolating the fields to grid. The nonlinearity is introduced via the ponderomotive force, $F = -\frac{e^2}{4m_e\omega}\nabla(E^2)$.The entire PIC loop becomes: **Interpolate Densities → Calculate Static Quantities → Perform FDTD update → Interpolate Fields → Update Particle Positions and Velocities → Repeat**. The simulation time was chosen to simulate one roundtrip of the pulse, and the electric field was recorded at $0.5Lz$ to save the incident and reflected field for later processing. A total of nine simulations were run for plasma density gradient characteristic lengths of $L = 0.1\lambda_0$, $0.05\lambda_0$, and $0.005\lambda_0$, and for incident field amplitudes of $a_0 = 0.001$, 1, and 100, with $a_0 = \frac{eE_0}{cm_e\omega}$ being the normalized field amplitude and $a_0 = 1 \rightarrow E_0 \approx 4\ TV/m$ corresponding to the field strength where relativistic electron motion begins to become important.

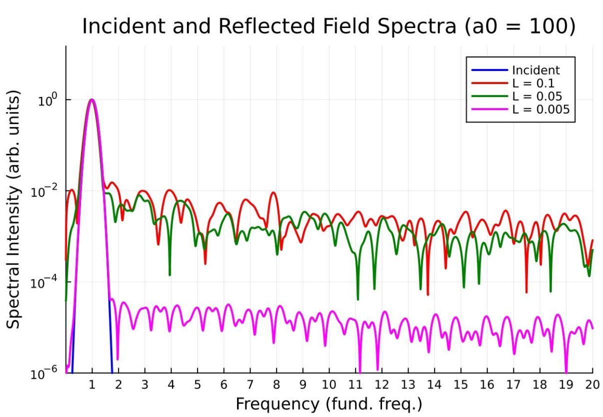


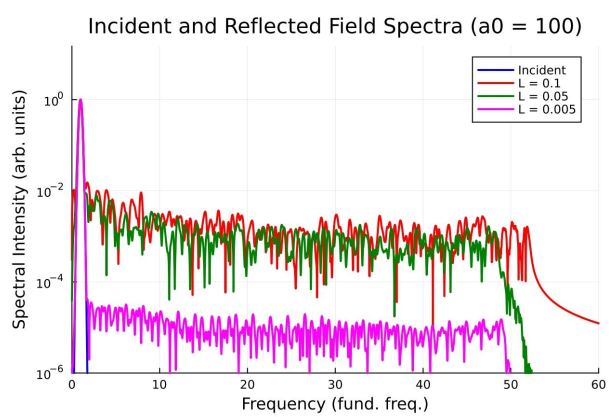
This study found that the plasma would not allow any transmission of the pulse in each simulation. However, for the largest plasma density gradient length, the plasma absorbed ~ 85.5% of the incident field. This led to the most nonlinearities since most of the pulse energy was transferred into the plasma. As the gradient became sharper, the absorption of the pulse decreased and the nonlinearities decreased, i.e. the plasma acted more like a perfect mirror.





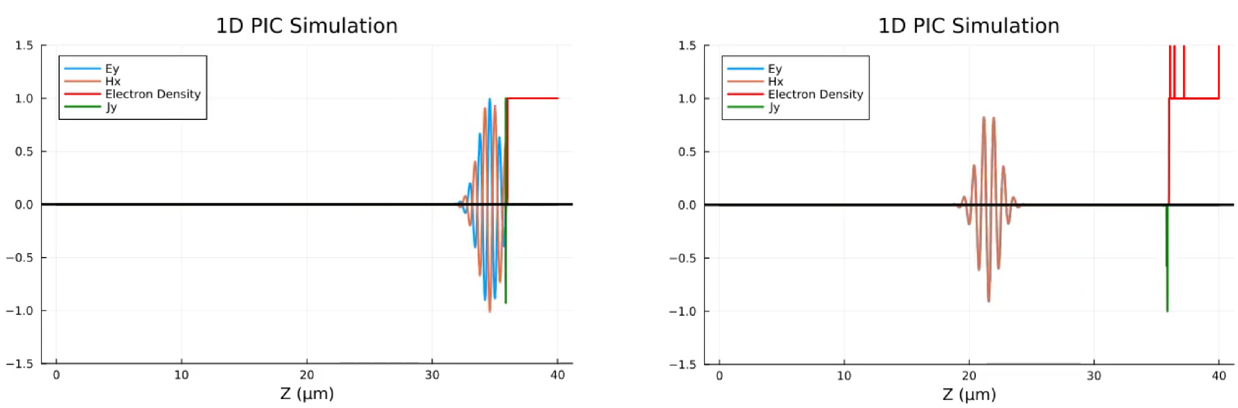
However, for the lowest incident field amplitudes, these nonlinearities are still barely above the noise floor of the incident pulse and are practically irrelevant. The same absorbing behavior was observed for the three different incident amplitudes. However, as the intensity was increased, the nonlinear behavior became more apparent. For the highest incident field amplitude, high-order harmonic generation as well as optical rectification were observed, both of which have been observed in the literature [12, 13].





Discussion and Conclusion

It can be noted that the high-order harmonics generated from the simulation are consistent with operation in the relativistic regime because the cutoff extends past the plasma frequency, $\omega_p = 40f_0$, with f_0 being the fundamental frequency of the driving pulse. This is the so-called relativistic oscillating mirror regime [7], which was outlined previously. Before reaching the relativistic regime, the high-order harmonics are generated from the coherent-wake emission process [5]. This process consists of accelerating electrons out of the plasma, which creates a large charge separation. Then, with the aid of the laser sign flip, the electrons are accelerated up and into the critical density surface, creating electron density spikes which are no longer under the influence of the driving pulse. These spikes excite waves in the plasma at the local plasma frequency, which then becomes the cutoff of the generated spectrum. These spikes were indeed observed in the simulation.



In conclusion, this study shows that PIC simulations can be a useful tool in accessing ultra-high intensity laser-plasma interactions, since these intensities are not easily available for many labs. The scheme could be improved tremendously by extending this simulation to two spatial dimensions, but this often requires supercomputing power. However, even a simple 1D scheme as presented here can capture many of the important features of the high-order harmonic generation process from plasma mirrors.

References

[1] D. Strickland and G. Mourou, “Compression of Amplified Chirped Optical Pulses,” Optics Comm. 56, 219 (1985).

[2] P. B. Corkum. “Plasma perspective on strong field multiphoton ionization.” Phys. Rev. Lett., 71 (1993).

[3] Li, J., Lu, J., Chew, A. et al. “Attosecond science based on high harmonic generation from gases and solids.” Nat Commun 11, 2748 (2020).

[4] Luu, T.T., Yin, Z., Jain, A. et al.” Extreme–ultraviolet high–harmonic generation in liquids.” Nat Commun 9, 3723 (2018).

[5] Marie Ouillé. “Génération d’impulsions laser proches du cycle optique en durée pour l’interaction lasermatière relativiste à haute cadence.” Plasmas. Institut Polytechnique de Paris, (2022).

[6] Press release. NobelPrize.org. Nobel Prize Outreach AB (2023). <https://www.nobelprize.org/prizes/physics/2023/press-release/>

[7] Quéré F, Vincenti H. “Reflecting petawatt lasers off relativistic plasma mirrors: a realistic path to the Schwinger limit.” High Power Laser Science and Engineering (2021).

[8] “PIC Algorithms — Smilei 5.0 Documentation.” Smileipic.github.io, smileipic.github.io/Smilei/Understand/algorithms.html.

[9] The Steady 1D Poisson Equation MATH1091: ODE Methods for a Reaction Diffusion Equation.

[10] Schneider, John. “Understanding the Finite-Difference Time-Domain Method” (2020).

[11] J.-L. Vay; “Simulation of beams or plasmas crossing at relativistic velocity.” Phys. Plasmas 1 (2008).

[12] Hamster H, Sullivan A, Gordon S, White W, Falcone RW. “Subpicosecond, electromagnetic pulses from intense laser-plasma interaction.” Phys Rev Lett. (1993).

[13] Haessler, Stefan, et al. “High-Harmonic Generation and Correlated Electron Emission from Relativistic Plasma Mirrors at 1 kHz Repetition Rate.” Ultrafast Science (2022).