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Plasma Mirrors

Kulwinder Kaur (2021PHS7190)
Harikesh Kushwaha (2021PHS7181)

Adviser: Prof. Vikrant Saxena

Signature of student 1: ....

Signature of student 2: .... **Signature of the adviser:** ....

1 Introduction And Motivation

Interaction of relativistic and non-relativistic laser pulse is studied with underdense and overdense plasma. Underdense plasma is transparent to the laser pulse while overdense plamsa is opaque and reflects the laser back. In case of relativistic laser pulse, the plasma frequency gets shifted and hence the pulse passes through the plasma even though the plasma was underdense to start with.

When a laser pulse is incident upon plasma, it reflects if the density of plasma is large enough, forming a plasma mirror (PM). Upon reflection from the plasma the laser field drives relativistic oscillation of the PM surface due to pondermotive force that induces a periodic temporal compression of the reflected field through the Doppler effect. These oscillations results in generation of high harmonics of the incident laser frequency.[1]

2 Methodology

The simulation uses *epoch*, a parallised, second order and fully relativistic implementation of particle in cell (PIC) algorithm.[2] Though *epoch* is implemented in 3D, the current simulation is performed in 1D3V only.

2.1 PIC Algorithm

In plasma physics, the PIC method is a numerical approach that simulates a collection of charged particles that interact via external and self-induced electromagnetic fields. A spatial grid is used to describe the field while the particles move in the continuous space. The field and the particle motion are solved concurrently. In this case the simulation requires less amount of work, since each particle only interacts with the grid points of the cell where it is located.[3]

2.2 Underdense and Overdense Plasma

Plasma frequency for plasma density n_p is given by[4]

$$\omega_p = \sqrt{\frac{n_p e^2}{\epsilon_0 m_e}} \tag{1}$$

If the frequency of the incident laser pulse, ω_l, is greater than the plasma frequency, the plasma is called underdense. In this case, the plasma is transparent to the laser pulse. On the other hand, if the frequency of the incident laser pulse is less than the plasma frequency, the plasma is called overdense. In this case, the laser can not penetrate the plasma deeply and is reflected back. The case $\omega_l = \omega_p$ corresponds to critical plasma and density in this case is called critical density n_c. Using Equation 1 gives;

$$n_c = \frac{\epsilon_0 m_e \omega_l^2}{e^2} \tag{2}$$

2.3 Laser Pulse

The simulation uses ultrashort laser pulses. An ultrashort laser emitts pulse with duration of the order of pico second. Defining the laser vector potential as

$$a_0 = \frac{eE_0}{m w_l c}$$

A laser is called relativistic if $a_0 \geq 1$.

2.4 Parameters for Simulation

The simulation box extends for $20\lambda_l$ (from $-10\lambda_l$ to $10\lambda_l$), where λ_l is the laser wavelength and has total 1000 cells. The plasma is placed at $x = 0$ and with a thickess of λ_l. Number of particles per cell are 100. The plasma density n_p is defined in terms of the critical density n_c and is varied from 0.1 to 10. The vector potential a_0 of the laser pulse is also varied as 0.1, 1.0 and 10 for each set of plasma density.

The envelope of the incident laser field varies according to

$$P(t) = \begin{cases} \sin^2(\pi t/T) \text{ for } 0 \leq t \leq T \\ 0 \;\; \text{otherwise} \end{cases} \tag{3}$$

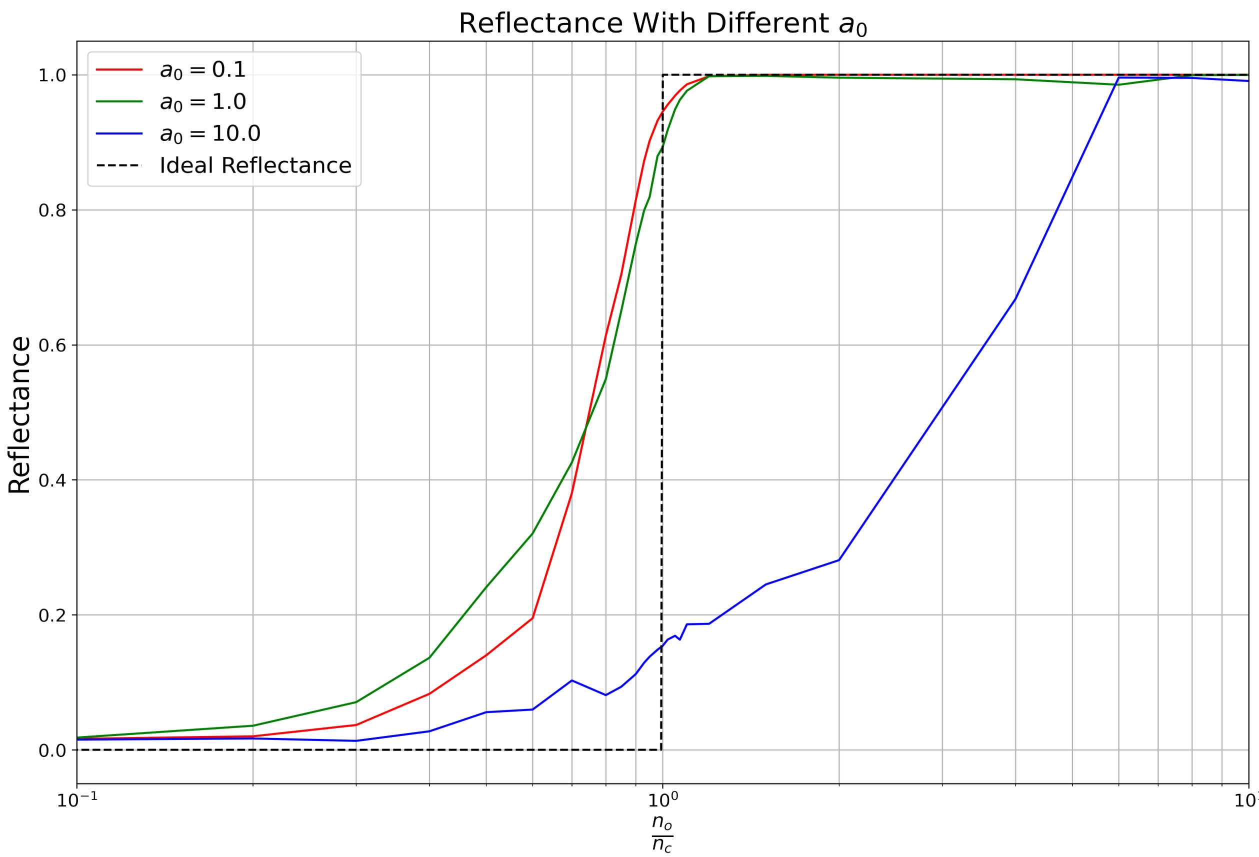
Where T is the pulse duration here taken as $T = 10\tau$ with $\tau = 2\pi/\omega_l$ is the time of one laser cycle. The simulation is performed for $t = 20\tau$.

3 Result and Discussion

Reflecatance here is define as

$$R = \frac{E_{300}^2 - E_{600}^2}{E_{300}^2} \tag{4}$$

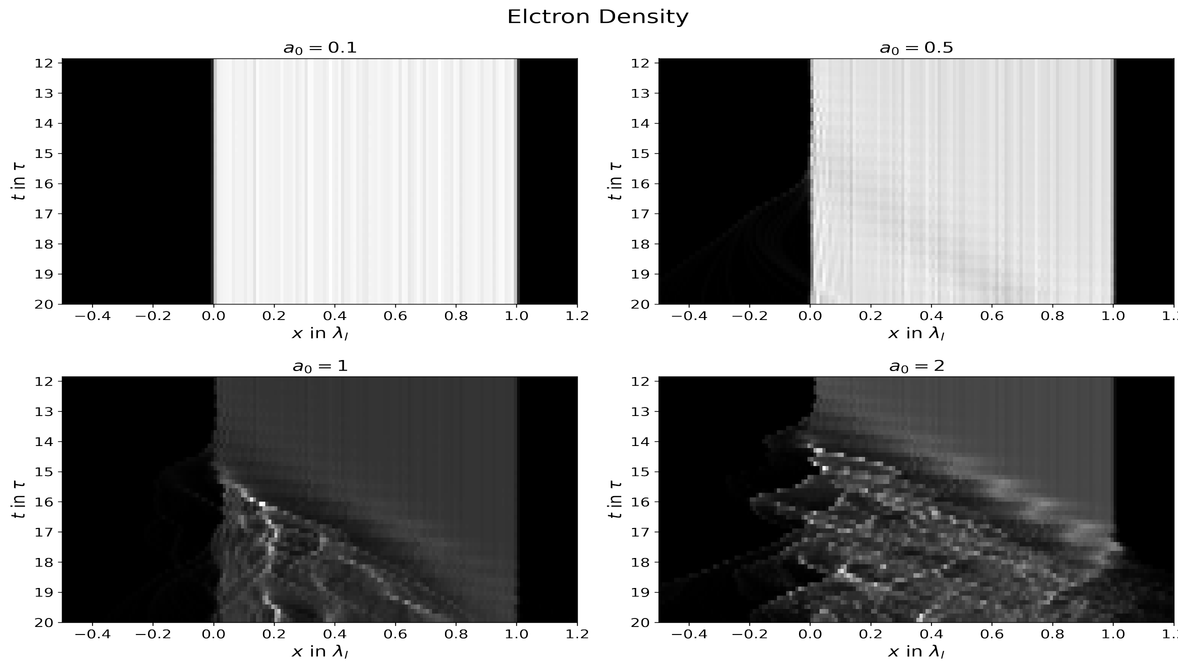
where E_{300} is the sum of y component of the electric field at 300^{th} node and E_{600} is the sum of y component of the electric field at 600^{th} node for all the simulation time. The plot of reflectance with different ratio of n_c and n_0 is shown in the figure below for different values of vector potential a_0.



Plot of reflectance (see 4) with different ratio of n_c and n_0 for different values of vector potential a_0.

The ideal curve for the interaction of laser pulse with underdense and overdense plasma is shown in the figure with black dotted line. Ideally, when the ration $r = \frac{n_0}{n_c}$ becomes 1, the reflectance should also become 1. However, when the laser becomes relativistic for $a_0 \geq 1$, the particles inside plasma starts to oscillate with relativistic velocity, gaining mass. This results in change in the plasma frequency and hence the laser does not get reflected even for density greater than the critical density corresponding to the non-relativistic case. So, there is a shift in the critical density due to relativistic laser pulse.

Next, the plot of the oscillation of plasma surface with time is shown for different values of vector potential. The laser pulse, after interacting with electrons, makes them oscillate. If the pulse becomes relativistic, the oscillations becomes strong and hence the plasma surface oscillates with relativistic velocity. The figure below shows that for $a_0 = 0.1$, the oscillation is very weak. As a_0 increases, the oscillation becomes stronger.



4 Current Status and Future Plan of Work

Study of interaction of relativistic and non-relativistic laser pulse is studied with underdense and overdense plasma. Future plan is simulation of harmonic generation in 1D using ultrashort intense laser pulse.

5 Acknowledgement

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References

[1] R. Lichters Et al. Physics of Plasmas 3, pp. 3425-3437 (1996)

[2] Arber, T D Et al. Plasma Physics and Controlled Fusion 57 1-26 (2015)

[3] Alin Suciu Et al. 2020 15th Conference on Computer Science and Information Systems (FedCSIS), pp.381-385, 2020

[4] Francis F. Chen Introduction to Plasma Physics and Controlled Fusion 3^{rd} Ed.