Simulation of the direct laser heating mechanisms and harmonic generation at the interaction of ultrashort laser pulses with an overdense plasma layer

A. Mihailescu, V. Stancalie and V.F. Pais

National Institute for Laser, Plasma and Radiation Physics, P.O.Box MG-36, Magurele, 077125 ROMANIA, Association EURATOM MEdC

Ultrashort and intense laser pulses with durations close to an optical cycle in the infrared and visible domains have been proven suitable in experiments looking for non-linear effects such as high harmonics generation. Focused intensities of about 10^{17} W/cm^2 from a Ti-Sapphire terawatt laser ($\lambda_0 = 0.8\mu m$ and pulse durations around 100-150 fs) allowed the experimental observation of harmonics up to 15th order [1, 2]. Using a Nd: glass laser system ($\lambda_0 = 1.05\mu m, 2.5ps$ pulses) reaching an intensity of 10^{19} W/cm^2 in relativistic regime, Norreys et al. [3] have detected harmonics as far as the 68th order.

This paper is focusing on studying the interaction of a short and intense laser beam ($I\lambda^2 = 10^{17} - 10^{19}$ Wcm$^{-2}\mu m^2$) with an overdense pre-ionized and steeply bounded plasma layer, the purpose being to give insights on the high harmonics generation mechanism. It is also the aim of this work to illustrate the contribution of direct laser heating mechanisms to electron acceleration.

We describe the laser- plasma interaction in terms of a particle-in-cell method. The plasma is treated kinetically, solving the relativistic equations of motion for a set of electrons and ions incorporated within a macroparticle. Each macroparticle obeys a distribution law that satisfies a kinetic Vlasov equation. Therefore, we make use of a 1D3V relativistic particle in cell code (LPIC++) that accounts for three components of particle velocities, the electric and the magnetic fields. The electromagnetic fields are calculated solving Maxwell's equations. The longitudinal electric field is obtained by solving Poisson's equation while the transverse electromagnetic fields yield from the corresponding current density, after tackling the wave equation. The basic algorithm for solving these equations is that of Birdsall and Langdon [4]. It includes the "leap frog" scheme for resolving particle pushing. The laser pulse is introduced as a time-dependent boundary condition for the transverse fields at the front side of the simulation box.

A 1D description of the problem might seem simplistic and limited but it has the advantage that one can force a large number of time steps per laser cycle and many particles per cell such that high orders of harmonics can be resolved. We used around 1000 time steps per laser cycle and 150 particles per cell. Inside the simulation box, the plasma was placed in the middle, the thickness of the plasma being set to one eighth of the box's length, allowing the particles to propagate without reaching the boundaries. Although the ions have little effect on the generation of harmonics and scarcely move on the time scale of short pulses, they were not kept fixed.

Various pulses with different durations- at normal and oblique incidence- have been chosen while the intensity and the polarization of the laser beam were varied. The envelope of the incident field is described by the sine function and the laser's intensity is expressed in terms of the field strength and laser wavelength as $I\lambda^2 = a_0^2 \times 1.37 \cdot 10^{18}$ Wcm$^{-2}\mu m^2$. The initial electron density, normalized to the critical density $n_c = \varepsilon_0 m \omega_0^2 / e^2$ was also changed, the values ranging from $n/n_c = 0.1$ to $n/n_c = 10$.

Simulation results reveal strong oscillations of the critical surface driven by the normal component of the laser field and by the ponderomotive force. The generation of harmonics is a consequence of the incident pulse reflected from the oscillating surface. *Figure 1* depicts such oscillating plasma surfaces, driven by a field strength of $a_0 = 0.5$ corresponding to $I\lambda^2 = 3.4 \cdot 10^{17} Wcm^{-2}\mu m^2$, with the laser either normally incident, either reaching the surface at an incidence angle of $30°$ relative to the normal. The laser is considered *p* polarized.

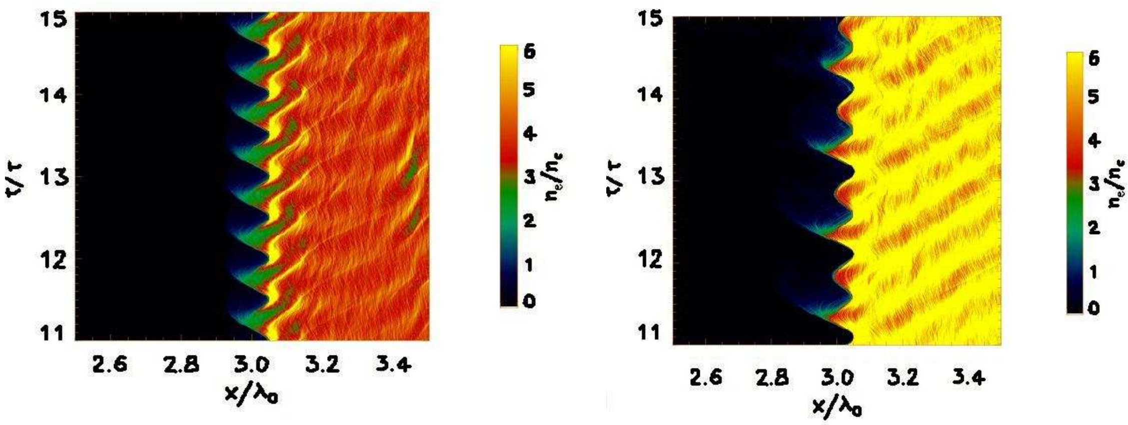


Figure 1. (left) normal incidence, laser field strength $a_0 = 0.5$, electron density relative to the critical plasma density $n/n_c = 4$; ***(right)*** oblique incidence with $a_0 = 0.5$, *p* polarized laser beam, $\alpha = 30$, $n/n_c = 4$

Figure 2 features oscillating plasma surfaces when the field strength $a_0 = 1$. At intensities above 10^{18} W/cm^2, electrons swing in the laser pulse with relativistic energies. The laser electric field is already much stronger than the atomic fields. Any material is instantaneously ionized creating plasma. Harmonics generation tends to become inefficient due to ionization.

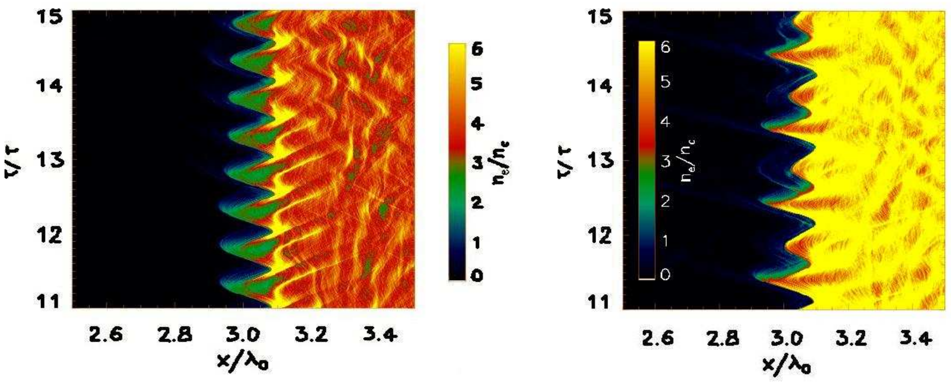


Figure 2. ***(left)*** normal incidence, laser field strength $a_0 = 1$ -- $I\lambda^2 = 1.37 \cdot 10^{18} Wcm^{-2} \mu m^2$ -- electron density relative to the critical plasma density $n/n_c = 4$; ***(right)*** oblique incidence with $\alpha = 30$, $a_0 = 1$, $n / n_c = 7$, *p* polarized beams in both cases.

Figures 3 and 4 illustrate spectra obtained from the reflection of the incident laser pulse on the oscillating plasma surface in *Figure 1 (left),* respectively *Figure 1 (right).* The obtained spectra are the power spectra of the electric field E, and include the field of the incident as well as of the reflected light. Naming $E(x_0, t)$ as the time- dependent electric field at position x_0 in the vacuum region, in front of the irradiated surface, its discrete Fourier transform, averaged over the pulse duration T is given by equation (1), where $\omega_j = j\Delta\omega$, $(j = -N/2, ...N/2)$, $\Delta\omega = 2\pi / T$, $t_k = k\Delta t$, $(k = 0,...N-1)$, $\Delta t = T / N$:

$$E(\omega_j) = \frac{1}{T}\sum_{k=0}^{N-1} \Delta t E(t_k) \exp(i\omega_j t_k) \quad (1)$$

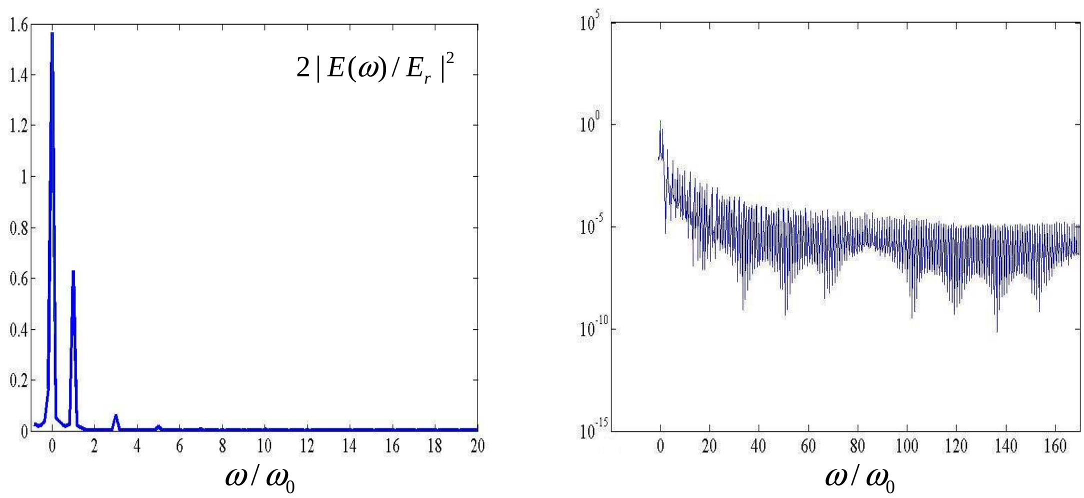


Figure 3. *(left)* Harmonics spectra obtained from the reflection of a normally incident laser pulse ($I\lambda^2 = 3.4 \cdot 10^{17} Wcm^{-2} \mu m^2$) on a surface with $n / n_c = 4$. *(right)* The same spectra on a semi-logarithmic scale. Harmonics up to order 160 can be observed with an amplitude as small as 10^{-10}.

The power spectrum $2\left|E(\omega_j)\right|^2$ is related to the average power of the signal $E(x_0,t)$ by Parseval's theorem, the final power spectrum- as shown in *Figure 3*- being normalized to relativistic units $E_r = m\omega_0 c/e$:

$$\frac{1}{T}\sum_{k=0}^{N-1}\Delta t E^2(t_k) = \left|E(\omega=0)\right|^2 + \sum_{j=1}^{N/2} 2\left|E(\omega_j)\right|^2 \qquad (2)$$

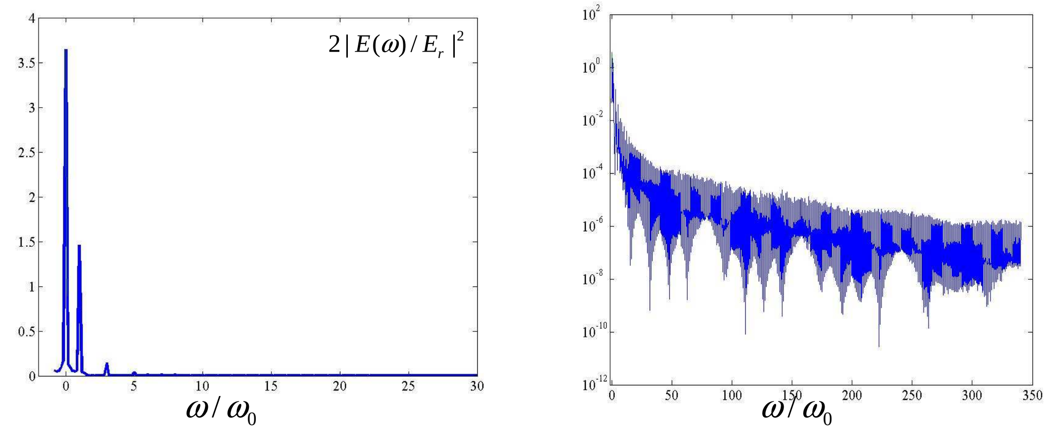
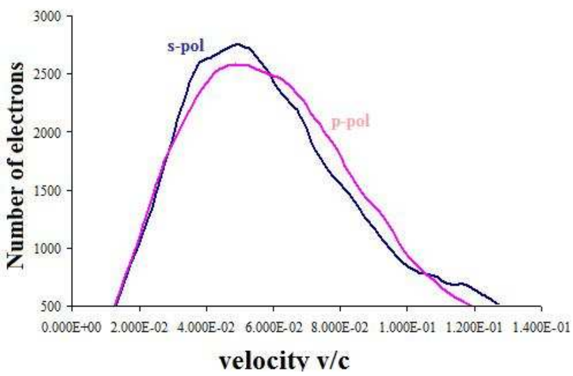


Figure 4. Harmonics spectra obtained from the reflection of a laser pulse at oblique incidence, $\alpha = 30$,with $a_0 = 0.5$, on a surface with $n/n_c = 4$.*(right)* The same spectra on a semi-logarithmic scale.

Figure 5. Electron distribution as a function of electron velocity. The laser is *s*-polarised (blue) or *p*-polarised (cyan), normaly incident. . $n/n_c = 4$



Harmonic emission increases with the laser intensity and when lowering the plasma density. In case of oblique incidence pulses, harmonics are emitted into a broad angular interval and have been found to be sensitive to the *s* or *p* polarization of the incident pulse. As a consequence of the direct laser heating, a *p*- polarized incident laser beam is far more efficient in accelerating the electrons within the plasma as illustrated in *Figure 5*.

References

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