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Analytical Model of Ultra-intense Laser Interaction with Steep Solid Surface

超高強度レーザーと急峻な固体表面との相互作用の理論モデル

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An analytical study of the relativistic interaction of a linearly-polarized laser-field with highly overdense plasma is presented. In agreement with 1D Particle-In-Cell Simulations (PICS), the model self-consistently explains the transition between the sheath inverse bremsstrahlung (SIB) absorption regime and the J×B heating (responsible of the 2ω electron bunches), as well as the high harmonic radiations and the mean electron energy.

1.Introduction

Ultra intense (>10^{17} Wcm^{-2}) short laser pulse interaction with highly overdense plasmas offers very promising applications such as coherent and incoherent x-ray production, high harmonic generation, ion acceleration, and high-energy electron production [1-2]. In this regime, the dominant absorption mechanisms are collisionless [3]. However, even in this "simple" case of a laser pulse at normal incidence interacting with a steep plasma gradient, a plethora of absorption mechanisms exist in the literature: the ponderomotive *JXB* heating, different sort of skin effects [4], vacuum heating and many other mechanisms. Due to the complex mixing of all these processes, the basic physics is poorly understood. More recently, PIC codes have proven to be very powerful tools to study the laser plasma interaction[5-6]. Their main limitation is the persistent difficulty to distinguish between cause and consequence. Moreover, some essential physical features about the electron distribution function (EDF) are not well captured, unlike a Vlasov description. To understand the basic physics of laser interaction with overdense plasmas precisely, it is necessary to revisit the electron dynamics on a thin layer of solid target surface, where electrons are accelerated. The 1D study we present combines the results of a self-consistent cold fluid approximation, PICS, and the analysis of the EDF in a Vlasov description. The self-consistent description of the plasma surface oscillations allows us to determine the relativistic mirror equations [Eqs. (1), (2)], the laser-plasma fields scaling laws, and harmonic generation. Then, the mean electron energy and laser absorption are obtained and compared to PICS.

2. Basic Equations

We consider a half space $x \geq 0$ initially filled by neutral and homogeneous plasma of density n_0. Collisions and ion dynamics will be ignored. We assume a linearly polarized plane wave normally incident on the plasma for a long time. Let $e\vec{A}/m_e c \equiv a(x,t)\vec{e}_y$ and $e\Phi/m_e c^2 \equiv \phi(x,t)$ be the dimensionless vector and electrostatic potentials, and $a_0 \cos(\omega x/c - \omega t)$ the incident wave. Electron density, space and time coordinates are normalized as $n \rightarrow n/n_c$, $(x,y) \rightarrow (x,y)\omega/c$, $t \rightarrow \omega t$, respectively. Here, $n_c \equiv \omega^2 \varepsilon_0 m_e / e^2$ is the critical density. The plasma is assumed to be highly overdense with a plasma frequency $\omega_p = \omega\sqrt{n_0} >> \omega$. Let $H \equiv \gamma - \phi$ be the Hamiltonian of an electron test particle with

$\gamma \equiv \sqrt{1+p_x^2+(P_y+a)^2}$, and P_y $(=p_y-a)$ the conserved canonical momentum, where a , ϕ are obtained from the wave ($a_{tt}-a_{xx}=j_y$) and Poisson ($\phi_{xx}=n-n_0h(x)$) equations. Here $h(x)$ is the step function. In a cold fluid approximation, the macroscopic equations for the electrons are the continuity and momentum along x. For relativistic laser intensities ($a_0>1$), and plasmas density n_0 and temperature T_0 (in m_ec^2 units) such as the initial relativistic electron pressure (: $n_0T_0/\sqrt{1+a_0^2/n_0}$) is negligible compared to the radiation pressure (: a_0^2), electrons are pushed into the solid forming a very steep density profile. The relevant forces involved in the macroscopic motion of electrons are the ponderomotive and the longitudinal electric field caused by the strong electric charge separation effect.

Let $\lambda_s(t)$ be the position of the electron plasma boundary (EPB), then $E_x=n_0xh(x)$ for $x\le\lambda_s$. Let $x(x_0,t)$ be the trajectory of a fluid particle such that $x(x_0,t_0)=$ $x_0\ge\lambda_s(t_0)$. Using Poisson and continuity equations, the momentum equation reads $dp/dt=$ $n_0(x_0h(x_0)-xh(x))+\phi_{x_0}-\gamma_m^{-1}aa_x$, Taking $x_0=\lambda_s(t_0)$ we get the equation for $\lambda_s(t)$:

$$\frac{d}{dt}\left(v_s\sqrt{\frac{1+v_s^2}{1-\lambda_s^2}}\right)+n_0\lambda_sh(\lambda_s)+a_sa_{xs}\sqrt{\frac{1-v_s^2}{1+a_s^2}}-0 \quad (1)$$

, where $a_s\equiv a(\lambda_s,t)$ and $a_{xs}\equiv a_x(\lambda_s,t)$. The second term is the electrostatic force (: ω_p oscillations), and the right one the ponderomotive (: 2ω frequency). In $x<\lambda_s$ the EM wave contains the incident plus the reflected wave, $a_r(x+t)$. The continuity of both a and a_x at $x=\lambda_s$, yield the equation governing $a_s(t)$,

$$d^2a_s/dt^2=(dl_s/dt+1)a_{xs}+2a_0\sin(l_s-t) \quad (2)$$

and $a_r(\tau\equiv x+t)=a_s(t')-a_0\cos(\lambda_s(t')-t')$

4. Results

In Fig. 1a, we are plotting $\lambda_s(t)\sqrt{n_0}$ keeping $a_0n_0^{-1/2}=1$, and the equivalent PIC-EPB. Concerning PICS, the laser pulse is a 2 cycle linear ramp + 11 cycles at constant intensity, with a plasma temperature of 500 eV. All comparisons are done during the thirteenth cycle. A weak but fast oscillation is superimposed (: ω_p) with the 2ω oscillations. This is a consequence of the electron-inertia together with the electrostatic force. This local fast oscillation becomes stronger when decreasing n_0 .

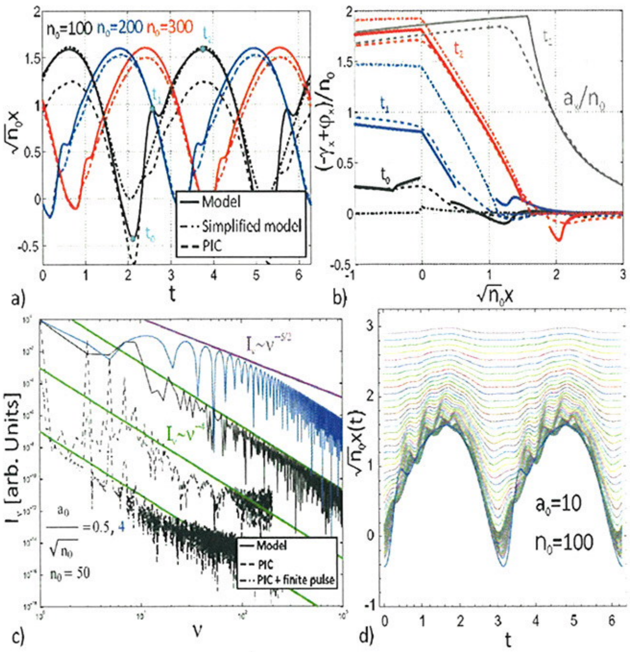

FIG. 1.

a) EPB $\lambda_s(t)$ against time for 3 different cases of the density n_0=100. b) Total ponderomotive force $-\gamma_{0x}+\phi_x$ at different times and magnetic field for ($a_0=10$, n_0=100). c) High harmonic spectrum calculated from the model and from PICS. d) Electron fluid trajectories $x(x_0,t)$ for the same as Fig. 1b.

3. In conclusion

we have developed a self-consistent model of laser/plasma interaction. The model foresees a non-monotonic behavior of the laser absorption, and the high harmonic spectrum has been self-consistently derived.

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