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Monoenergetic Acceleration of a Target Foil by Circularly Polarized Laser Pulse in RPA Regime without Thermal Heating

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Abstract. A kinetic model of the monoenergetic acceleration of a target foil irradiated by the circularly polarized laser pulse is developed. The target moves without thermal heating with constant acceleration which is provided by chirping the frequency of the laser pulse and correspondingly increasing its intensity. In the accelerated reference frame, bulk plasma in the target is neutral and its parameters are stationary: cold ions are immobile while nonrelativistic electrons bounce back and forth inside the potential well formed by ponderomotive and electrostatic potentials. It is shown that a positive charge left behind of the moving target in the ion tail and a negative charge in front of the target in the electron sheath form a capacitor whose constant electric field accelerates the ions of the target. The charge separation is maintained by the radiation pressure pushing electrons forward. The scalings of the target thickness and electromagnetic radiation with the electron temperature are found.

Keywords: Radiation pressure acceleration, target acceleration, Maxwellian-Juttner distribution.
PACS: 52.38.Kd, 52.40.Kh, 41.75.Jv

INTRODUCTION

With rapid advances in laser technology, laser-plasma ion accelerators have become an area of increasing interest. Laser-accelerated multi-MeV ion beams have a variety of potential applications, such as proton therapy [1, 2, 3], radiography [4], ion beam fast ignition [5], and laboratory astrophysics [6].

One of the promising schemes for producing high-energy proton beams is the radiation pressure acceleration (RPA) regime in which a thin foil is pushed forward by the pressure $P = 2I/c$ of a circularly polarized laser with high intensity $I > 10^{21} W/cm^2$. A simple one dimensional (1D) model of acceleration of the delta-like thin foil (foil with delta-function density distribution) acting as an ideally reflecting mirror [7] shows that in the RPA regime ions in the foil can be accelerated up to arbitrarily large energy, provided the laser pulse is sufficiently long. However, 1D simulations of a foil with finite thickness reveal some important features of the acceleration process: existence of the untrapped ions left behind the accelerated foil and formation of the effective potential that traps the bulk of ions in a compact phase space area [8]. These simulations show that in the acceleration process, electrons are gradually heated by the radiation that decreases the reflectivity of the plasma mirror and eventually effectiveness of the RPA regime.

In this work, we develop a self-consistent kinetic model of the interaction of the circularly polarized laser beam with the accelerated target that goes far beyond the delta-like description: in this model, the ion and electron densities n_i and n_e are continuously distributed along the direction of target acceleration z, and the target moves with constant acceleration without thermal heating.

ANALYTICAL MODEL

The laser pulse and target are assumed to be initially uniform in the transverse $x-y$ plane. Since target acceleration is constant, the radiation pressure exerted on the target [8] $P = (2I/c)(1-v/c)/(1+v/c)$, where v is the target velocity, is constant. This regime always takes place for constant laser intensity during the initial subrelativistic stage $v << c$ of the target motion. It also can be implemented during entire acceleration process by chirping the laser frequency [9] $\omega^2 = \omega_0^2(1+v/c)/(1-v/c)$ and ramping up its intensity $I = I_0\omega^2/\omega_0^2$, where ω_0 and I_0 are the initial laser frequency and intensity respectively, so that $P = P_0 = 2I_0/c$.

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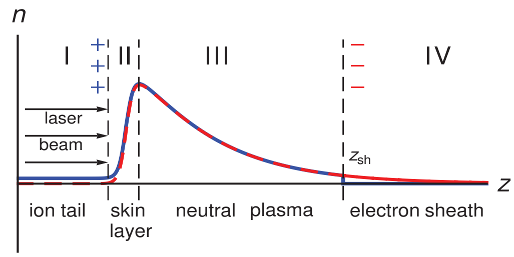

FIGURE 1. Electron (red) and ion (blue) density distribution in the accelerated target. (I) Positively charged ion tail ($n_e = 0$), (II) skin layer ($n_e = n_i$, $\vec{A} \neq 0$), (III) plasma bulk ($n_e = n_i$, $\vec{A} = 0$), and (IV) negatively charged electron sheath ($n_i = 0$). Longitudinal electric field E_z originates in the ion tail, remains constant in the skin layer and plasma bulk, and vanishes in the electron sheath.

It is convenient to study the target plasma in the noninertial reference frame moving together with target. Since the radiation pressure is relativistically invariant [10], a stationary "gravitational" field exists in this frame, corresponding to the constant acceleration g. Note that in this frame, the frequency and the intensity of the chirped laser beam are constant in the target area.

We consider an idealized scenario, when all target characteristics are stationary in the accelerating frame: we assume that target ions are cold (immobile) and the radiation pressure of the circularly polarized laser beam is counterbalanced by the pressure of the gas of hot nonrelativistic electrons $P_e = n_e(z)T_e$, where T_e is the electron temperature ($T_e = const$, and $T_e << mc^2$, where m is the electron mass). Assuming for simplicity that electron temperature in transverse directions is zero, one can fully describe the motion of an individual electron using conservation of energy and generalized momentum in the transverse plane:

$$\varepsilon \equiv \frac{p_z^2}{2m} + \frac{e^2A^2}{2mc^2} - e\varphi = const, \tag{1}$$

$$p_x - \frac{e}{c}A_x = 0, \;\; p_y - \frac{e}{c}A_y = 0, \tag{2}$$

where $\vec{p}$, $-e$ are the electron momentum and charge, and $\vec{A} = (A_x, A_y, 0)$ and φ are the vector and electrostatic potentials. The amplitude of vector and electrostatic potentials do not depend on time and transverse coordinates x and y: $|\vec{A}| = A(z)$ and $\varphi = \varphi(z)$.

A stationary solution f of the Vlasov equation depends on the integrals of the motion, $f = F(\varepsilon)\delta(p_x - eA_x/c)\delta(p_y - eA_y/c)$, where $F(\varepsilon)$ is the electron distribution function (EDF) over energy of particles, and $\delta(x)$ is the delta function. Although $F(\varepsilon)$ can be a function of a quite general form, we limit our consideration to the Maxwellian EDF: $F = [n_0/(2\pi m T_e)^{1/2}]\exp(-\varepsilon/T_e)$, where n_0 is the electron density at the point where $\vec{A} = 0$ and $\varphi = 0$. For this EDF, the electron density is distributed by the Boltzmann law

$$n_e = \int f d^3p = n_0 \exp\Big(-\frac{\psi}{T_e} + \frac{e\varphi}{T_e}\Big), \tag{3}$$

where $\psi = mc^2a^2/2$ and $a = eA/mc^2$ are the ponderomotive and dimensionless vector potentials, respectively. The current density is given by

$$\vec{j}_\perp = -e\int \vec{v} f d^3p = -en_e c\vec{a}, \;\; j_z = 0. \tag{4}$$

STRUCTURE OF THE TARGET

In the general case, one can distinguish four different regions in the accelerated target, as shown in Fig. 1: (I) the positively charged ion tail in which ions move slower than in the target; (II) the skin layer where the radiation transfers its momentum to the target electrons; (III) the bulk of the neutral plasma where radiation does not penetrate; in this region hot electrons transfer their momentum to the target ions; and (IV) the negatively charged electron sheath ahead of the target. The ion tail and electron sheath play the role of charged capacitor plates surrounding a neutral target area (skin layer and bulk plasma).

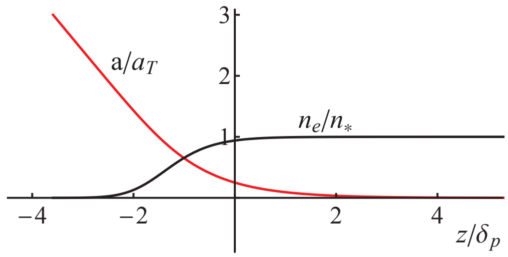

FIGURE 2. Dependence of the the vector potential and the electron density in the skin layer (region II in Fig. 1): $a_T = (2T_e/mc^2)^{1/2}$ and $\delta_p = k_0^{-1}(T_e/2mc^2)^{1/2}/a_{i0}$.

When the target accelerates, some of the ions gain less energy and are left behind the target, forming the ion tail (region I in Fig. 1), $N_{tail} = m_i g/4\pi e^2$, where m_i is the proton mass. This positively charged tail creates the longitudinal electric field E_z, which prevents further losses of ions from the target and pushes target ions with constant acceleration.

The fact that ions in the target are immobile in the accelerating reference frame means that the electrostatic force eE_z acting on them is balanced by the inertial force $m_i g$, and therefore the electrostatic field is constant $E_z = m_i g/e$ in regions II and III, where $n_i = n_e$ and $\varphi = -E_z z$.

The interaction between laser radiation and electrons takes place in a skin layer (region II in Fig. 1) with thickness of the order of several skin depths δ_p. When the laser radiation does not penetrate the target, the incident and reflected waves have the same amplitude $A_{r0} = A_{i0}$, and form a standing wave in which the vector potential has the following components: $A_x = A(z)\cos(\omega_0 t - \chi)$ and $A_y = -A(z)\sin(\omega_0 t - \chi)$, where $\chi = const$ is the phase of the standing wave. To proceed further, we multiply both sides of Ampere law, $\vec{A}'' = -4\pi \vec{j}_\perp/c - k_0^2 \vec{A}$ by $\vec{A}'$, where prime denotes differentiation with respect to z and $k_0 = \omega_0/c$. Taking into account the equality $\vec{A}'^2 = A'^2$ and integrating over the longitudinal coordinate from $-\infty$ to z, we obtain

$$\frac{A'^2(z) + k_0^2 A^2(z)}{8\pi} + n_e(z)T_e + eE_z N_e(z) = P_0, \tag{5}$$

$$N_e' = n_e, \tag{6}$$

where $N_e(z)$ is the number of electrons (per unit area) located between the ion tail ($z = -\infty$) and the point z, and $P_0 = k_0^2 A_{i0}^2/2\pi$ is the radiation pressure exerted on the target.

Considering Eq. (5) at $z \to +\infty$ where the electron density and vector potential vanish, we find the target acceleration, $g = eE_z/m_i = P_0/m_i N_{tot}$, where N_{tot} is the total number of electrons per unit area in the target (equal to the total number of ions), and the number of ions in the tail $N_{tail} = m_i(P_0/m_i N_{tot})/4\pi e^2 = N_{tot}[2a_{i0}^2(n_{cr}k_0^{-1}/N_{tot})^2]$, where $n_{cr} = m\omega_0^2/4\pi e^2$ is the critical electron density.

To guarantee the reflection of electrons by the laser radiation in the skin layer, the ponderomotive potential must be considerably larger than the temperature, so that $\max \psi >> T_e$ or $a_{i0} >> a_T \equiv (2T_e/mc^2)^{1/2}$, where a_T is the characteristic value of the vector potential in the skin layer. The temperature determines the magnitude of the electron density $n_* \equiv P_0/T_e = k_0^2 A_{i0}^2/2\pi T_e$ and the plasma frequency $\omega_{p*} = (4\pi e^2 n_*/m)^{1/2}$. Using these estimates, one can find that the thickness of the skin layer δ_p (that is, the skin depth) is always less than the laser wave length, so that $\delta_p = c/\omega_{p*} = k_0^{-1} a_T/2a_{i0} << k_0^{-1} = \lambda_0/2\pi$, and verify that the magnetic field in the skin layer is of the same order as in the incident wave: $a_T/\delta_p \sim k_0 a_{i0}$.

The skin depth δ_p should also be less than or of the order of the target thickness $h \equiv N_{tot}/n_* = (a_T^2/2a_{i0}^2)N_{tot}/n_{cr}$, that is, $\delta_p/h = 2(a_{i0}/a_T)(n_{cr}k_0^{-1}/N_{tot}) = (N_{tail}/N_{tot})^{1/2}(mc^2/T_e)^{1/2} < 1$. Therefore in this case when the laser wave is fully reflected by cold electrons ($T_e << mc^2$), only a small fraction of ions left in the ion tail creates an electric field accelerating a massive target, $N_{tail}/N_{tot} < T_e/mc^2 << 1$.

When the ratio δ_p/h is small, the electric field does not affect the skin layer structure and the electric potential in the skin layer can be set to zero (because its variation is small- $E_z\delta_p = (T_e/eh)\delta_p = (\delta_p/h)T_e/e << T_e/e$). Also, the electrostatic force pulling back electrons can be neglected here because the number of particles in the skin layer $(\delta_p/h)N_{tot}$ is small compared to the total number of particles N_{tot}. The radiation pressure is balanced only by the

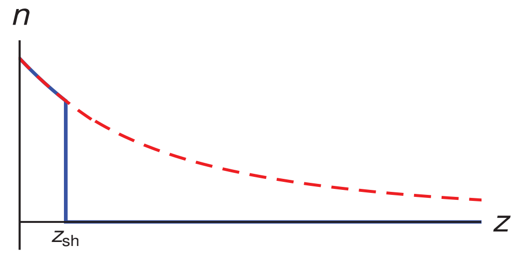

FIGURE 3. Distribution of the electron (red) and ion (blue) densities in the electron sheath (region IV in Fig. 1).

pressure of electron gas. Introducing these simplifications and using $k_0^2 A^2 << A'^2$, one can integrate Eq (5) and obtain:

$$\frac{z}{\delta_p} = -\int \frac{da/a_T}{[1-\exp(-a^2/a_T^2)]^{1/2}}, \tag{7}$$

In the skin layer, the ponderomotive potential changes by several electron temperatures, $\psi \sim T_e$, so that the vector potential a scales here as a_T while the coordinate scales as δ_p, see Fig. (2).

In the bulk of the plasma (region III in Fig. 1) where $A_\perp = 0$ and $E_z = const$ ($\varphi = -E_z z$), the ion and electron density decreases exponentially $n_i = n_e = n_* \exp(-z/h)$, which obviously satisfies Eqs. (5) and (6). In this region, electrons are reflected by the electrostatic potential transferring the momentum to the target ions.

Lastly, in the electron sheath there is only a negative charge that quenches the electric field (the ion density $n_i = 0$ in the region IV in Fig. 1). Solving the Poisson equation at $z > z_{sh}$,

$$e\varphi'' = 4\pi e n_e, \;\; n_e = n_* \exp(e\varphi/T_e), \tag{8}$$

with the boundary condition $e\varphi'|_{z=z_{sh}} = -eE_z = -m_i g$, we find the electron density and the electrostatic potential in the sheath:

$$n_e = (N_{tail}/2h)[1+(z-z_{sh})/2h]^{-2}, \tag{9}$$
$$e\varphi = e\varphi(z_{sh}) - 2T_e \ln[1+(z-z_{sh})/2h]. \tag{10}$$

where $\varphi_{sh} = -E_z z_{sh}$ and $z_{sh} = 2h\ln(2N_{tot}/N_{tail})$ and $N_{tail}/N_{tot} = 2a_{i0}^2(n_{cr}k_0^{-1}/N_{tot})^2$. As it is always the case for the sheath when the electron distribution has a Maxwellian tail, $\varphi(z) \to -\infty$ when $z \to \infty$ (when the distribution tail is cut off, φ is finite everywhere).

CONCLUSION

In summary, an analytical self-consistent model of the target with distributed density pushed by the circularly polarized laser beam with chirped frequency and increasing intensity has been developed. Since there is no thermal heating of electrons, all laser energy goes into kinetic energy of ions in the target, which always reflects the laser beam as an ideal mirror. In the model, there are four different regions in the target: the positively charged ion tail (where $n_e = 0$), the skin layer (where electrons of the neutral plasma interact with radiation), the plasma bulk (where the neutral plasma is distributed by the Boltzmann law), and the negatively charged electron sheath (where $n_i = 0$). A small fraction of the particles $N_{tail}/N_{tot} < T_e/mc^2 << 1$ in the ion tail and the electron sheath form a capacitor whose electric field accelerates the target while laser radiation sustains the charge separation.

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