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Short note

Relativistic ponderomtive force acceleration of electrons in weak inhomogenous underdense plasma

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ABSTRACT

In the paper, relativistic ponderomotive force acceleration of electrons in weak inhomogenous underdense plasma is investigated. The results shown that, in interaction of ultraintense laser and the plasma, due to the influence of relativistic ponderomotive force, laser beam presents self-focusing, and electrons are accelerated obviously. Initially, electron energy presents a fluctuation variation along the propagation distance, then the fluctuation will weaken gradually, finally it trend to a steady state and the electrons acquire a high net energy. Compared with homogeneous plasma, electron energy would increase and its vibration length becomes short in weak inhomogeneous underdense plasma. Moreover, the high-energy electrons can be easily extracted by the relativistic ponderomotive force, the results may offer some useful theoretical proof for the design of new accelerators.

1. Introduction

With the development of the chirped-pulse-amplification (CPA) technique, the high-peak power lasers have been successfully developed with light intensities as high as 10^{22} W/cm^2 [1]. Intense laser pulses are of great interest in electron acceleration through laser-plasma interactions. For laser-driven electron acceleration, there are several mechanisms, such as direct laser acceleration [2,3], laser-driven plasma wave acceleration [4–6], ponderomotive acceleration [7–10], etc. In these schemes, the ponderomotive force plays the basic roles, hence, ponderomotive acceleration has been widely investigated theoretically and experimentally.

As is well-known, the laser undergoes periodic focusing due to the relativistic mass nonlinearity in the interaction of intense laser and plasma, which can create a wake of plasma oscillations under the action of ponderomotive force. For the laser energy retention, laser acquires a minimum spot size is crucial in the axial position, based on the view, it would can accelerate electron by the focus pulse peak if one chooses laser intensity and spot size properly [11]. In this case, the electrons initially on the laser axis and at the front of the self-focusing pulse gain energy from the pulse until it is run over by the pulse peak. By the time electron gets to the tails, if pulse begins diverging, the deceleration of the electron is slower and the electron is left with net energy gain. Electrons are then trapped into the wake and can thus be accelerated to extremely high energies as high as MeV–TeV scales [8]. The idea that was presented by Tajima and Dawson [4] three decades ago has now become a reality through their experimental verifications [12,13]. In theoretical research, significant progress has been made in the field of collective plasma accelerators for attaining high electron energies [14,15]. Experiments show ultrapowerful pulses in underdense plasmas produce hot electrons with energies up to hundreds of *MeV* [16]. Recently, an

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alternative scheme has been proposed for accelerating electrons up to the TeV regime, using proton bunches for driving plasma wakefield accelerators [11].

In the theoretical and experimental research, the laser beam propagation and electron acceleration by ponderomotive force in underdense plasma has attracted much interest. Direct ponderomotive acceleration in uniform plasma was investigated [17], and it was found that there is strong electron acceleration inside the pulse with sufficiently short duration and strong intensity. In recent years, the ponderomotive acceleration of a rest electron by a laser pulse propagating through a homogeneous rarefied plasma was investigated [18]· and found the threshold laser intensity required for acceleration. Sazegari and Shokri [19] found the maximum energy of the electron grows linearly with the peak of the normalized vector potential amplitude of the laser pulse. Cao el al. [20] studied the electron acceleration process in a uniform plasma. Liu and Tripathi [7], in investigation of ponderomotive effect on various acceleration mechanisms, in this case, the electron can be trapped and accelerated by the ponderomotive force at the laser front.

However, in fact, the underdense plasma is always set up at the front of a solid target with a naturally present or deliberately created repulse, so that the preplasma has an inhomogeneous density profile in which the laser propagates with variable group velocity [21,22]. The laboratory plasma must be taken into account the influence of plasma inhomogeneity, in this paper, we investigate relativistic ponderomotive force acceleration of electrons in weak inhomogenous underdense plasma. In the current research, the laser and plasma parameters as follow: laser intensity $I \approx 3.3 \times 10^{19}$ W/cm^2, beam frequency $\omega_0 \approx 6 \times 10^{15} rad/s$, laser wavelength $\lambda \approx 0.5$ µm, the electron density of weak inhomogeneous plasma $N_e/N_{0e} = 0.3[1 + \exp(-0.5\xi)]$, here N_{0e} is equilibrium electron density and $N_{0e} \approx 1.5 \times 10^{21}$ cm^{-3}, the critical plasma density $N_c \approx 1.7 \times 10^{22}$ cm^{-3}, due to $N_e < N_c$, the plasma is an underdense plasma.

2. Basic theory of electron acceleration in underdense plasma

In an underdense plasma of equilibrium electron density N_{0e}, consider the propagation of pulsed laser of finite spot size along z. When beam self-focusing effect has been considered, the laser electric field can be written as:

$$\vec{E} = \hat{x}Ae^{-i(\omega t - kz)} \text{and} A = A_0 e^{iks} \tag{1}$$

there A is the electric intensity and a complex function of space, A_0 is the amplitude of electric field and a real function of space. Following the researched results by Sharma and Kourakis [23], applied the paraxial ray approximation, A_0 can be written as:

$$A_0^2 = \frac{A_{00}^2}{f^2}(1 + \frac{a_1 r^2}{r_0^2 f^2} + \frac{a_2 r^4}{r_0^4 f^4})e^{-r^2/r_0^2 f^2} e^{-(t-z/c)^2/\tau^2} \tag{2}$$

$$S = \frac{r^2}{2r_0^2 f}\frac{df}{dz} + \frac{S_{02} r^4}{r_0^4} \tag{3}$$

where S is eikonal function, f is the beam width parameter and r_0 is initial beam width. In the laser and underdense plasma interaction, the electron motion is governed by

$$m[\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla})\vec{v}] = -e\vec{E} - e\vec{v} \times \vec{B} \tag{4}$$

To evaluate the ponderomotive force $\vec{F}_p = -m\vec{v} \cdot \nabla\vec{v} - (e/c)\vec{v} \times \vec{B}$, we may use the complex number identity to simplify it. The ponderomotive force on electrons due to the whistler pulse is thus

$$\vec{F}_p = -\frac{m}{2}(\vec{v} \cdot \nabla)\vec{v}^* - \frac{e}{2}(\vec{v} \times \vec{B}^*) = -\frac{e}{2}(\vec{v} \times \vec{B}^*) \tag{5}$$

The laser magnetic field using Maxwell's equation

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \tag{6}$$

Equation magnetic field $\vec{B}$ can be written as

$$\vec{B} = \vec{b}e^{-i(\omega t - kz)} \tag{7}$$

There $\vec{b}$ expresses the variation of magnetic field, and is a complex function of space. Following Singh and Sharma [24], in paraxial ray approximation, and $\vec{b}$ can be written by:

$$\vec{b} = \vec{b}_0(t, z) \cdot \exp[iks - \frac{(t - z/c)^2}{2\tau^2} - \frac{r^2}{2r_0^2 f^2}] \tag{8}$$