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Research on electron acceleration in interaction of intense laser and magnetized plasma by ponderomotive force

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ABSTRACT

Electron acceleration in intense laser and magnetized plasma interaction by ponderomotive force has been researched. The results are shown that, under the influence of ponderomotive force, electron give rise to transverse oscillation and obtain high energy gain, moreover, the resonance by self-generated magnetic filed enforce ponderomotive force and further accelerate electron, lead to higher energy gain. At last, electron energy trend to a steady value, and the high energy electron would be automatic ejected by the ponderomotive force. The present scheme, it can avoid making use of additional extractor of acquiring high energy electron, which may provide useful physical support for novel design of table accelerator.

1. Introduction

The interaction of laser-plasma is a fascinating field of research. There have emerged many new frontier research areas in both applied and fundamental physics [1–4]. Among these, the development of a laser-driven electron acceleration mechanism is a fast advancing area of scientific research [5]. In the process, refer to lots of nonlinear effects, such as fast electron and ion generation [6,7], indicating that ultra-strong electromagnetic fields are produced in interaction of the laser-plasma.

In many instances, magnetic field is generated by a jet of fast electrons in the direction of laser propagation [8] or by the nonlinear current of the background plasma electrons [9]. It is well known that a planar-laser pulse cannot be used for electron acceleration [10], however, an electron can gain and retain significant energy if in the influence of suitable magnetic field. During the course of laser-driven electron acceleration, one of the fundamental limitations of this acceleration scheme is the dephasing of the trapped electron with respect to the driver laser wave [11]. Resonance can be maintained for longer duration for a suitably tapered wiggler period and the electron can gain much higher energy [12]. During the interaction of the plasma electrons and the circularly polarized laser pulse, electrons absorb not only the laser energy but also the proportional amount of the total angular momentum of the laser pulse. This angular momentum transfer leads to the electron rotation and generation of the axial magnetic field by the azimuthal electron current. In the process, magnetic fields can have a significant effect on the overall nonlinear plasma dynamics. Extremely high (megagauss) magnetic fields play an essential role in the particle transport, propagation of laser pulses and laser beam self-focusing, hence, the effect of magnetic field on electron acceleration have been widely researched.

In earlier different laser-driven accelerators [13], order to overcome the wave particle dephasing, Katsouleas and Dawson proposed that a traverse static magnetic field was superimposed on the plasma wave [14]. Later, a series of research of the effect of magnetic field on particle acceleration have been widely reported. Dieckmann et al. [15] examined electron acceleration by an electrostatic plasma wave in magnetized plasma. Singh et al. [16] have shown that the duration of the interaction between plasma waves and electrons increases due to the self-generated azimuthal magnetic field and the electrons gain more energy. Recently a lot of work has been researched of the impact of magnetic field on relativistic electrons produced from intense laser plasma acceleration. The magnetic field can be self-generated or externally applied in laser plasma acceleration. Wagner et al. [17] measured azimuthal magnetic fields ∼700 MG in over dense plasmas while in under dense plasmas fields of the order of 100 MG have been reported [18]. If

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one employs circularly polarized laser with intensity $\sim 10^{19}$ W/cm^2 it can generate axial magnetic fields ~7 MG in the direction of laser propagation [19]. These self-generated magnetic fields facilitate the electron acceleration by laser plasma interaction [20–22]. Pukhov et al. [23] have in their three-dimensional (3D) particle-in-cell simulation of intense short laser pulse interaction with plasma have observed strong flows of relativistic electrons axially comoving with the laser pulse and generating 100 MG azimuthal magnetic field. Gahn et al. [24] experimentally observed generation of multi-MeV electron beam by direct laser acceleration in high-density plasma channels. Tsakiris et al. [25] developed an analytical theory and a fully relativistic 3D single particle code for direct laser acceleration of electrons in radial electrical and azimuthal magnetic fields. Tanimoto et al. [26] studied the effect of self-induced azimuthal magnetic field on the direct electron acceleration by lasers with stochastic phase disturbance. They found that apart from beam collimation electrons are accelerated to ultrahigh energies that are greater than the ponderomotive energy and that the acceleration is enhanced by increasing the strength of magnetic field. Liu et al. [27] showed that the electron acceleration depends on laser intensity and the ratio of cyclotron frequency to laser frequency. Yu et al. [28] examined similar configuration using linearly polarized laser. They have obtained electron acceleration to relativistic energies using weak magnetic field. The energy retention in this scheme is high as the energized electrons continue to execute cyclotron motion in static magnetic field. The acceleration distance is of the order of cyclotron radius. In these schemes, the phase of the laser pulse at which it interacts with electrons is important. He et al. [29] showed that the dependence of the relativistic electron dynamics on the phase of the laser is sensitive to the polarization of the laser field.

The research of laser-driven electron acceleration have achieved lots important results, but accompanying the effect of the generation of self-generated magnetic fields in intense laser-plasma interaction [30–32], there still many problems [2,4]. The Magnetic fields can have a significant effect on the overall nonlinear plasma dynamics. Extremely high magnetic fields play an essential role in the particle transport, propagation of laser pulses and laser beam self-focusing. In this paper, we have applied an intense circularly polarized Gaussian laser pulse with intensity $\sim 10^{20}$ W/cm^2 and wavelength 1 – 2 μm to examine electron acceleration in magnetized plasma. The group velocity of the laser pulse is less than the speed of light and hence electrons can resonantly interact with the pulse. The basic mechanism involves acceleration of electrons by the axial gradient in the ponderomotive potential of the laser.

2. Electron acceleration by ponderomotive force

In magnetized plasmas, consider the propagation of a right circularly polarized laser pulse in the direction of static axial magnetic field $B_s\hat{z}$. According to the previous work by Singh and Sharma [33], the laser electric and magnetic field can be expressed by

$$\vec{E} = \hat{x}E_x + \hat{y}E_y = A\left(\frac{t-z}{\eta_g c}\right)\exp\left[-i\omega\left(\frac{t-\eta z}{c}\right)\right]\left(\hat{x}+i\hat{y}\right) \quad (1)$$

$$\vec{B} = \hat{x}B_x + \hat{y}B_y = \left[\eta A + i\frac{(1-\eta_g\eta)}{\eta_g\omega}\frac{\partial A}{\partial t}\right]\exp\left[-i\omega\left(\frac{t-\eta z}{c}\right)\right]\left(-i\hat{x}+\hat{y}\right) \quad (2)$$

here ω is the laser pulse beam frequency, c is the light velocity. Ac for a Gaussian pulse is given by

$$A^2 = A_0^2\exp\left[-\frac{(t-z/\eta_g-t_0)^2}{\tau^2}\right] \quad (3)$$

here A_0 is the amplitude of laser pulse beam, τ is the laser pulse duration. η_g the group velocity of the laser pulse and can be written

$$\eta_g = \frac{\eta}{\left[1+\omega_p^2\omega_c/2\omega(\omega-\omega_c)^2\right]} \quad (4)$$

here η is the refractive index and can be expressed by

$$\eta = \left[1-\frac{\omega_p^2\omega_c}{\omega(\omega-\omega_c)^2}\right]^{1/2} \quad (5)$$

here ω_p is the electron plasma frequency, $\omega_c = eB_s/mc$ is the electron cyclotron frequency, $-e$ is the electronic charge, and m is the rest mass of the electron. One may note that the refractive index has a sensitive dependence on dc magnetic field through a resonant denominator $(\omega-\omega_c)$. Physically this dependence arises due to the inherent nature of the magnetic field to rotate the electrons about the lines of force in the right handed sense at the cyclotron frequency. The right circularly polarized wave also rotates the electrons in the right handed sense at frequency ω. Hence at $\omega=\omega_c$ the two are resonant and one obtains a resonant enhancement in electron response, hence the refractive index.

In the interaction of laser and magnetized plasmas, the equations governing the x, y, and z components of electron momentum are given by

$$\frac{dp_x}{dt} = -eE_x + \frac{ep_zB_y}{m\gamma c} - \frac{p_y\omega_c}{\gamma} \quad (6)$$

$$\frac{dp_y}{dt} = -eE_y - \frac{ep_zB_x}{m\gamma c} + \frac{p_x\omega_c}{\gamma} \quad (7)$$

$$\frac{dp_z}{dt} = -\frac{e(p_xB_y-p_yB_x)}{m\gamma c} \quad (8)$$

where γ is the relativistic factor, and can be written as $\gamma = \left[1+(p_x^2+p_y^2+p_z^2)/m^2c^2\right]^{1/2}$. In fact, which γ express the electron energy. Introduce the variation into $P_z = p_z/mc$, $P_y = p_y/mc$, $P_x = p_x/mc$, and the axial ponderomotive force is given by

$$F_{pz} = \frac{dp_z}{dt} = \frac{e^2\eta\partial\left|A^2\right|/\partial t}{2m\gamma c\left[\omega(1-P_z\eta/\gamma)-\omega_c/\gamma\right]^2} \times\left[\left(1-\frac{P_z\eta}{\gamma}\right)^2-\frac{\omega_cP_z(1-\eta\eta_g)}{\gamma^2\eta_g\omega}\right] + \frac{e^2(1-P_z\eta/\gamma)(1-\eta\eta_g)}{2m\gamma\omega c\eta_g[\omega(1-P_z\eta/\gamma)-\omega_c/\gamma]}\frac{\partial\left|A^2\right|}{\partial t} - \frac{e^2\eta\omega_c(1-P_z\eta/\gamma)\left|A^2\right|}{m\gamma^3c[\omega(1-P_z\eta/\gamma)-\omega_c/\gamma]^3}\frac{d\gamma}{dt} \quad (9)$$

From Eq. (9) it can be seen that the ponderomotive force is a sensitive function of η, η_g, and Doppler shifted cyclotron resonance $[\omega(1-P_z\eta/\gamma)-\omega_c/\gamma]$, moreover, it is noted that, the ponderomotive force have tight connection with the electron energy gain γ. Near resonance an approximate study of acceleration process can be done by choosing $\Delta = [\omega(1-P_z\eta/\gamma)-\omega_c/\gamma]$.

In order to solve Eq. (6), we assume the initial $p_x = p_{0x}(t-z/\eta_gc)\exp[-i\omega(t-z\eta/c)]$ and $p_y = ip_x$. Applying iteration method, and solve Eq. (6) iteratively. On substituting for p_x in Eq. (6) we get

$$\left[1-\frac{p_z}{m\gamma c\eta_g}\right]\frac{\partial p_{0x}}{\partial t} - i\left[\omega\left(1-\frac{p_z\eta}{m\gamma c}\right)-\frac{\omega_c}{\gamma}\right]p_{0x} = -eA\left(1-\frac{p_z\eta}{m\gamma c}\right)+\frac{iep_z(1-\eta\eta_g)}{m\gamma c\eta_g\omega}\frac{\partial A}{\partial t} \quad (10)$$