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Resonant acceleration of electrons by intense circularly polarized Gaussian laser pulses

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Abstract

Resonant acceleration of plasma electrons in combined circularly polarized Gaussian laser fields and self-generated quasistatic fields has been investigated theoretically and numerically. The latter includes the radial quasistatic electric field, the azimuthal quasistatic magnetic field and the axial one. The resonant condition is theoretically given and numerically testified. The results show some of the resonant electrons are accelerated to velocities larger than the laser group velocity and thus gain high energy. For peak laser intensity $I_0 = 1 \times 10^{20}$ W cm^{-2} and plasma density $n_0 = 0.1 n_{cr}$, the relativistic electron beam with energies increased from 207 MeV to 262 MeV with a relative energy width around 24% and extreme low beam divergence less than 1° has been obtained. The effect of laser intensity and plasma density on the final energy gain of resonant electrons is also investigated.

1. INTRODUCTION

Acceleration of electrons from short-pulse and high-intense laser ($\geq 10^{18}$ W/cm^2) interacting with plasmas is an important issue for electron accelerators (Hora *et al.*, 2000; Joshi & Katsouleas, 2003; Faure *et al.*, 2004; Geddes *et al.*, 2004; Borghesi *et al.*, 2007; Esarey *et al.*, 2007; Gupta & Suk, 2007; Karmakar & Pukhov, 2007; Xu *et al.*, 2007; Zhou *et al.*, 2007) and the fast ignition scheme (Tabak *et al.*, 1994; Kodama *et al.*, 2001; Nuckolls *et al.*, 2002; Hora, 2007*a*, 2007*b*) or beam fusion (Hoffmann *et al.*, 2005). Recently, different acceleration mechanisms have been investigated for laser interaction with both underdense and overdense plasmas (Gibbon, 2005; Salamin *et al.*, 2006; Stait-Gardner & Castillo, 2006; Zhou *et al.*, 2006). The idea of using the plasma wave excited by an intense laser to accelerate electrons was first suggested by Tajima and Dawson (1979) more than 20 years ago. In the so-called standard laser wakefield acceleration scheme, the wake plasma wave is most efficiently generated by the ponderomotive force of the laser pulse when its duration τ_L is close to half of the plasma wave period (Hamster *et al.*, 1993; Siders *et al.*, 1996). This is the same as acceleration of electrons in vacuum by the electromagntic laser field (Evans, 1988; Hora, 1988) where it was confirmed that the highest acceleration is achieved with half optical waves or "rectified waves" (Scheid & Hora, 1989, Hora *et al.*, 2002).

On the other hand, the nonlinear ponderomotive force also plays an important role in direct laser acceleration (Mckinstrie & Startsev, 1996; Quesnel & Mora, 1998; Stupakov & Zolotorev, 2001; Schmitz & Kull, 2002; Kong *et al.*, 2003). At high laser intensities, the relativistic motion starts to operate, causing the electron to be directed forward as well as sideways, and forming laser-plasma channels. It is known that ponderomotive expulsion of background plasma electrons from such plasma channels creates a radial quasistatic electric (QSE) field $\mathbf{E}_s$, and the current of electrons accelerated by axial ponderomotive force generates the azimuthal quasistatic magnetic (QSM) field $\mathbf{B}_{s\theta}$. For a linearly polarized (LP) laser, both fields trap a relativistic electron in the channel and result in its betatron oscillation along the laser polarization. Therefore, an electron undergoes a strong downshifted optical frequency when it is accelerated in the laser propagation direction. As a result, the transverse betatron oscillation may be in resonance with the LP laser if the downshift is strong enough (Pukhov *et al.*, 1999; Tsakiris

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et al., 2000; Yu *et al.*, 2003; Liu & Tripathi, 2005, 2006), leading to a considerable acceleration of electrons.

However, the interaction of a circularly polarized (CP) laser with plasma can additionally generate an axial QSM field $\mathbf{B}_{sz}$ due to the rotational motion of relativistic electrons, besides the radial QSE field $\mathbf{E}_s$ and the azimuthal QSM field $\mathbf{B}_{s\theta}$. The field $\mathbf{B}_{sz}$ may effectively trap and collimate the accelerated electrons. Consequently, the accelerated electrons driven by CP laser may have a smaller divergent angle than using LP laser (Sheng & Meyer-ter-vehn, 1996; Qiao *et al.*, 2005*a*). Furthermore, a sharp resonance peak is found in the interaction of a planar CP laser with a strong axial magnetic field (Liu *et al.*, 2004). To the best of our knowledge, no work has been conducted to investigate the resonant acceleration of plasma electrons in combined CP Gaussian laser fields and complete self-generated qausistatic fields so far, but it may be significant in practice. In this paper, we investigate the resonant acceleration of plasma electrons under the action of the combined laser fields and self-generated quasistatic fields. A Gaussian CP laser dependent on both space and time is introduced and the self-generated fields, including radial QSE field $\mathbf{E}_s$, azimuthal QSM field $\mathbf{B}_{s\theta}$, and axial QSM field $\mathbf{B}_{sz}$ are all taken into consideration. The resonant condition is analytically derived and numerically testified. The qualities of relativistic electron beam (REB) produced by resonant acceleration, including high energy, quasi-monoenergy, and small divergent angles, are discussed due to potential applications. The dependence of the final energy gain of accelerated electrons on laser intensity and plasma density is also investigated.

2. PHYSICAL MODEL AND RESONANT CONDITION

Consider a CP laser pulse with pulse duration τ_L and spot radius r_0 propagating through a unmagnetized underdense plasma with uniform density n_0. The CP laser electric fields with Gaussian profiles both in space and time are

$$E_{Lx} = E_L \cos\phi, \tag{1}$$

$$E_{Ly} = \alpha E_L \sin\phi, \tag{2}$$

$$E_{Lz} = E_L\left(-\frac{x}{kr_0^2}sin\phi + \alpha\frac{y}{kr_0^2}cos\phi\right), \tag{3}$$

where $E_L(r,z,t) = E_0\exp\{-(r^2/2r_0^2) - (t-(z-z_0)/v_g)^2/2\tau_L^2)\}$, $\phi = \omega t - kz$, $k = \omega\eta/c$, $\eta \approx [1-\omega_{pe}^2/\omega^2\ (1+a_0^2)^{1/2}]^{1/2}$, $a_0 = eE_0/m\omega c$, $\omega_{pe} = \sqrt{4\pi n_0 e^2/m_e}$, $-e$ and m are electron charge and rest mass, c is the velocity of light in vacuum, v_g is the laser group velocity in plasma, z_0 the initial position of the laser pulse center, and $\alpha = \pm 1$, 0 represents the circular and linear polarization, respectively. In Eqs. (1)–(3), we have ensured that $\nabla\cdot\mathbf{E_L} = 0$. The magnetic field related to the laser pulse is given by $\nabla\times\mathbf{E_L} = -\partial\mathbf{B_L}/\partial t$ and can be formulated as follows:

$$B_{Lx} = -\alpha\eta E_L\left(1+\frac{1}{k^2r_0^2}\right)\sin\phi, \tag{4}$$

$$B_{Ly} = \eta E_L\left(1+\frac{1}{k^2r_0^2}\right)\cos\phi, \tag{5}$$

$$B_{Lz} = -\eta E_L\left(\alpha\frac{x}{kr_0^2}cos\phi + \frac{y}{kr_0^2}sin\phi\right). \tag{6}$$

As is well-known, when an intense laser propagates in plasma, strong QSE fields, and QSM fields are self-generated by various nonlinear effects and relativistic effects (Pukhov & Meyer-ter-vehn, 1996; Qiao *et al.*, 2005*b*). These quasistatic fields will heavily affect the electron motion and acceleration. First, the ponderomotive force $\mathbf{F}_p$ produced by laser pulse expels some electrons away from the laser axis so that a space-charge potential $\mathbf{\Phi}$ is formed, which corresponds to the QSE field $\mathbf{E}_s = -\nabla\Phi$. The longitudinal relativistic current driven by the ponderomotive force generates the azimuthal QSM field $\mathbf{B}_{s\theta}$, while the rotational current caused by the nonlinear beat interaction of the CP laser fields with relativistic electrons produces the axial QSM field $\mathbf{B}_{sz}$. Particle-in-cell (PIC) simulations (Zheng *et al.*, 2005) have shown that strong azimuthal and axial QSM fields exist in the interaction of the CP laser with dense plasma. Some of the present authors (Qiao *et al.*, 2005*b*) have put forword a self-consistent quasistatic fields model based on the relativistic Vlasov-Maxwell equations. Introducing the normalized transform $t\to\omega t$, $\mathbf{x}\to\omega\mathbf{x}/c$, $E\to eE/m_e\omega c$, $B\to eB/m_e\omega c$, the model mentioned above is given by

$$\mathbf{E}_s = k_E\frac{r}{r_0}\exp\left\{-\frac{r^2}{r_0^2} - \frac{(t-(z-z_0)/v_g)^2}{\tau_L^2}\right\}\mathbf{e}_r, \tag{7}$$

$$\mathbf{B}_{s\theta} = -k_B\frac{r_0}{r}(1-e^{-r^2/r_0^2})\exp\left\{-\frac{(t-(z-z_0)/v_g)^2}{\tau_L^2}\right\}\mathbf{e}_\theta, \tag{8}$$

$$\mathbf{B}_{sz} = -b_Z\exp\left\{-\frac{r^2}{r_0^2} - \frac{(t-(z-z_0)/v_g)^2}{\tau_L^2}\right\}\mathbf{e}_z, \tag{9}$$

where the coefficients $k_E = (1+\alpha^2)\beta_{56}I_0/r_0$, $k_B = \epsilon(\pi(1+\alpha^2)/64)n_0r_0I_0[\xi\beta_4(T_{te}) + (1-\xi)\beta_4(T_{re})]$, and $b_Z = (1/2)\alpha n_0 I_0[\xi\beta_1(T_{te}) + (1-\xi)\beta_1(T_{re})]$ are related to laser and plasma parameters such as n_0, I_0, etc, and among which other quantities β_1, β_4, β_{56}, ξ, T_{te}, T_{re}, and ϵ are defined (Qiao *et al.*, 2005*a*, 2005*b*).

Based on the above discussion, a test electron model is investigated. The motion of the test electron in the presence of electromagnetic fields $\mathbf{E}$ and $\mathbf{B}$ is described by the Lorentz equation

$$\frac{d\mathbf{p}}{dt} = -(\mathbf{E}+\mathbf{v}\times\mathbf{B}), \tag{10}$$

together with an energy equation

$$\frac{d\gamma}{dt} = -\mathbf{E}\cdot\mathbf{v}, \tag{11}$$

where $\mathbf{p} = \gamma\mathbf{v}$ and $\gamma = (1 + p^2)^{1/2}$. Note that here the electric field $\mathbf{E}$ and magnetic field $\mathbf{B}$ include the laser fields $\mathbf{E}_L$, $\mathbf{B}_L$, and the self-generated quasistatic ones $\mathbf{E}_s$, $\mathbf{B}_s$.

As pointed out (Pukhov & Meyer-ter-vehn, 1999), the electron motion in the presence of both self-generated fields $\mathbf{E}_s$, $\mathbf{B}_s$, and laser fields $\mathbf{E}_L$, $\mathbf{B}_L$ can be seen as a driven oscillation. The electron makes betatron oscillations in the self-generated electric and magnetic fields and, the laser pulse acts as a driving source. Obviously it is difficult to obtain an exact solution of Eqs. (10)–(11) because of their nonlinearity. Nevertheless, we are interested in the condition of resonance between the electron and the laser pulse. The transverse betatron oscillation of electrons can be derived by Eqs. (10)–(11). If the magnitude of transverse displacement of an electron is much smaller than the laser spot size, i.e., $r^2 \ll r_0^2$, then E_{Lz} and B_{Lz} may have a negligible influence on the motion of electrons. Note the fact that the self-generated fields are slowly variant in laser-plasma interactions, it will be assumed to be static in the analytical discussion. The effect of time-dependence is included in the numerical calculations presented in Section 3. Under these assumptions, the equations governing p_x and p_y are

$$\frac{d^2p_x}{dt^2} + \omega_b^2 p_x = (1 - \eta v_z)E_L \sin(t - z/v_{ph}), \tag{12}$$

$$\frac{d^2p_y}{dt^2} + \omega_b^2 p_y = -\alpha(1 - \eta v_z)E_L \cos(t - z/v_{ph}), \tag{13}$$

where

$$\omega_b = \frac{1}{\sqrt{\gamma}}\left[\frac{k_E}{r_0}\left(1 - \frac{r^2}{r_0^2}\right) + \frac{k_B v_z}{r_0} + \frac{\alpha^2 b_Z^2}{\gamma}\left(1 - \frac{2r^2}{r_0^2}\right)\right]^{1/2}, \tag{14}$$

v_{ph} is the laser phase velocity. On the right-hand side of Eqs. (12) and (13), $\gamma \gg 1$ is assumed and consequently the terms E_L/γ, E_L/γ^2 are ignored in comparison with the term of E_L. The derivative of longitudinal velocity v_z is also neglected in the above derivation due to the slow variation of v_z when the electron has been pre-accelerated. In Eq. (14), we have expanded $e^{-r^2/r_0^2} \approx 1 - r^2/r_0^2$. Note that ω_b is the same for both the left-hand and the right-hand CP lasers and the b_Z-term is absent for LP lasers. It can be seen that the electron makes betatron oscillations driven by CP laser with betatron frequency $\simeq\omega_b$. When the driver frequency $\omega - kv_z$ equals the betatron frequency ω_b, i.e.,

$$\frac{1}{\sqrt{\gamma}}\left[\frac{k_E}{r_0}\left(1 - \frac{r^2}{r_0^2}\right) + \frac{k_B v_z}{r_0} + \frac{\alpha^2 b_Z^2}{\gamma}\left(1 - \frac{2r^2}{r_0^2}\right)\right]^{1/2} = 1 - \frac{v_z}{v_{ph}}, \tag{15}$$

a resonance occurs, leading to an effective energy exchange between the pulse and electrons. In fact, after the electrons are pre-accelerated, ω_b changes slowly on the time scale of one betatron oscillation. In this case, the transverse electron motion may be written

$$p_x = c(t)\cos\theta_b,\ p_y = \alpha c(t)\sin\theta_b,\ \frac{d\theta_b}{dt} = \omega_b, \tag{16}$$

where $c(t)$ is the magnitude of transverse momentum. Using this value of p_x, p_y in Eq. (11) and neglecting the rv_r-term as it averages out to be zero over one oscillation period, the electron energy equation is

$$\frac{d\gamma}{dt} = -\frac{(1+\alpha^2)c(t)}{2\gamma}E_L[\cos\psi^- + (1-\alpha^2)\cos\psi^+], \tag{17}$$

where $\psi^- = \theta_b - (t - z/v_{ph})$ and $\psi^+ = \theta_b + (t - z/v_{ph})$ are the slow ponderomotive phase and the fast ponderomotive phase, respectively. It can be seen from Eq. (17) that electrons are accelerated when their ponderomotive phase satisfies $\pi/2 < \psi^- < 3\pi/2$, and are decelerated otherwise. The maximum acceleration is attained if the betatron oscillations are exactly in counterphase with the laser electric field. In particular, if the ponderomotive phase ψ^- approximately maintains an invariable value, i.e., $d\psi^-/dt = \omega_b - (1 - v_z/v_{ph}) \simeq 0$, a resonance takes place. In this case, as displayed by the last term of Eq. (17), there exists a fast oscillation $\cos\psi^+ \simeq \cos 2\omega_b t$ in γ or p_z for the LP lasers while it is absent in the case of CP lasers.

It can also be implied from Eq. (17) that the main accelerating term in the z-direction is $-\mathbf{v}\times\mathbf{B}_L$. The final energy of accelerated electrons can be approximately expressed by the combination of variation of p_z and γ. Multiplying the z-product of Eq. (10) by η and subtracting from Eq. (11), we get

$$\frac{dp_z}{dt} - \eta\frac{d\gamma}{dt} = \frac{\eta k_E}{r_0}e^{-r^2/r_0^2}rv_r + \frac{k_B r_0}{r^2}(1 - e^{-r^2/r_0^2}))rv_r - \frac{\eta}{k^2 r_0^2}E_L(v_x\cos\phi + \alpha v_y \sin\phi), \tag{18}$$

where $v_r = dr/dt$. If the last term of the right-hand side of Eq. (18) (induced by the second terms of B_{Lx} and B_{Ly}) were negligible (valid for $a_0 \ll (2\pi r_0/\lambda)^2$), then Eq. (18) can be

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integrated

$$\gamma = \frac{\gamma_0(v_{0z}-\eta) + (1/2r_0)(k_E\eta + 2k_B)(r^2 - r_{in}^2) - (k_{E\eta}/4r_0^3)(r^4 - r_{in}^4)}{v_z - \eta}, \tag{19}$$

where γ_0, r_{in} and p_{0z} are the initial values of energy, radial coordinate, and z-directional momentum of electrons, respectively. This condition indicates that the final value of γ is a complicated function that relies not only on the initial and final longitudinal velocities, but also on the radial coordinates of the electron at the beginning and at the end of the interaction besides the rest of the plasma and laser parameters. However, the equation implies that a sudden increase in γ may happen when v_z approaches v_g. Furthermore, it can also be seen that if the radial QSE field and the azimuthal QSM field are absent, i.e., $k_E = k_B = 0$, then v_z is always less than v_g for an electron initially having $v_{0z} < v_g$. This demonstrates that the electron initially located in front of the pulse center is overtaken first and then is overrun by the pulse. On the contrary, if the QSE field and the azimuthal QSM field are so large as to satisfy $k_E\eta + 2k_B > 2r_0\gamma_0(\eta - v_{0z})/(r^2 - r_{in}^2)$ (here the smaller term $(k_E v_g/4r_0^3)$ $(r^4 - r_{in}^4)$ is ignored), v_z will gradually approach and may surpass v_g, thus the electron overtaken by the pulse first may always keep ahead of the pulse center until the end of the interaction, so gains more energy.

3. NUMERICAL ANALYSIS ON ELECTRON ACCELERATION

To further analyze the electron acceleration process, Eqs. (10)–(11) are numerically solved. We choose the parameters of laser beam as wavelength $\lambda = 1.06$ μm, the spot radius $r_0 = 4\lambda$ and the pulse duration $\tau_L = 100$ fs. We assume that the test electron initially locates at $z = 0$ while the laser pulse center is at $z_0 = -4c\tau_L$. We trace the motion of electron accelerated by the laser field combined with the self-generated QSE and QSM fields. For the present self-generated fields model, we have assumed the parameters are $T_{te} = 5$ KeV and $\xi = 0.5$ and consequently the coefficients k_E, k_B, and b_Z can be calculated based on the definitions in Section 2. For example, if the peak laser intensity $I_0 = 1 \times 10^{20}$ W cm^{-2} and the plasma density $n_0 = 0.1n_{cr}$ are assumed, the peak azimuthal QSM field is about 255 megagauss (MG) near r_0; The axial QSM field gets to its peak value of 90 MG at the z axis ($r = 0$) and decreases as r increases; And the self-generated QSE field reaches its maximum value of 70 CGSE at $r \simeq 0.7r_0$.

Figure 1 shows electron trajectories in three-dimensional (3D) plane and the variation of the relative distance $\Delta z = z - z_L$ and of the total energy with z. The electron rotates around the direction of the laser propagation and the direction of the rotation is such that it should generate an axial magnetic field in the negative z direction by the azimuthal current. The relative distance Δz decreases first, gets to its minimum value at $z \approx 200\lambda$. Note that the minimum distance just corresponds to $v_z = v_g$. The following increase of Δz indicates the electron has been accelerated to velocity larger than v_g. A clear sharp increase in γmc^2 occurs due to the match between the electron betatron frequency ω_b and the Doppler shifted laser frequency $\omega - kv_z$. That is to say, a resonance takes place. This can be explained in Figure 2, where a phase comparison of p_x and B_{Ly} is shown. One can see that an almost locked phase with $\psi^- \simeq \pi$ between p_x and B_{Ly} occurs from $z \approx 180\lambda$ to $z \approx 700\lambda$, i.e., $d\psi^-/\mathrm{d}t \approx 0$, which indicates the resonance condition $\omega_b \simeq \omega - kv_z$ holds. After several synchrotron rotations in the ponderomotive bucket, the phase space is mixed (about $z > 700\lambda$) and deceleration occurs. When the resonance takes place, as predicted by Eq. (17) in Section 2, the effect of polarization on the evolution of γ or p_z is apparent. In the case of LP laser, the fast oscillations at $2\omega_b$ accompanying the increase of γ or p_z are clearly seen in the p_z plot of Figure 3b. These fast oscillations are absent for CP laser because of the rotation of the CP laser electric field. In Pukhov *et al.* (1999), two-dimensional PIC simulation shows that there exists electron density modulation with two times per laser wavelength in LP laser-plasma interactions. The reason is that the transverse velocity of the resonant electrons oscillates with the laser period while the longitudinal velocity oscillating twice per laser period, leading to the electron bunching in space two times per laser wavelength. It can be seen from the resonant condition (Eq. (15)) that besides the radial QSE field $\mathbf{E}_s$ and the azimuthal QSM field $\mathbf{B}_{s\theta}$, the axial QSM field $\mathbf{B}_{sz}$ also makes partial contribution towards betatron oscillations. Furthermore, $\mathbf{B}_{s\theta}$ and $\mathbf{B}_{sz}$ play an pinch and collimation role in the acceleration process while $\mathbf{E}_s$ partly offsets the radial ponderomotive force of the pulse.

The continuous increase of γ leads to the decrease of ω_b and the resonant condition is violated. The electron dephases and acceleration ceases. However, since the electron has been accelerated to velocity larger than v_g, the laser electric field (seen by the electron) becomes more and more smaller. When the electron leaves the pulse, its energy gain still maintains a high level. It should be mentioned that the coincidence of ω_b with $\omega - kv_z$ just $v_z < v_g$ is a determinative condition that electron attain high energy. Some electrons make betatron oscillations but dephase just $v_z < v_g$ and consequently are run over by the pulse and only gain small energy.

The energetic electrons that attain resonance and have $v_z > v_g$ always move ahead of the pulse and emit from the plasma channel first. The final energy gain and the scattering angles of these electrons are of our concern. The numerical calculations demonstrate that the electrons originated from the vicinity of the axis are more likely to be trapped by the ponderomotive bucket and attain high energies. The final scattering angles and spatial distribution of these energetic electrons are displayed in Figure 4, where total 180 electrons are uniformly distributed within a disc with radius $r = r_0/4$

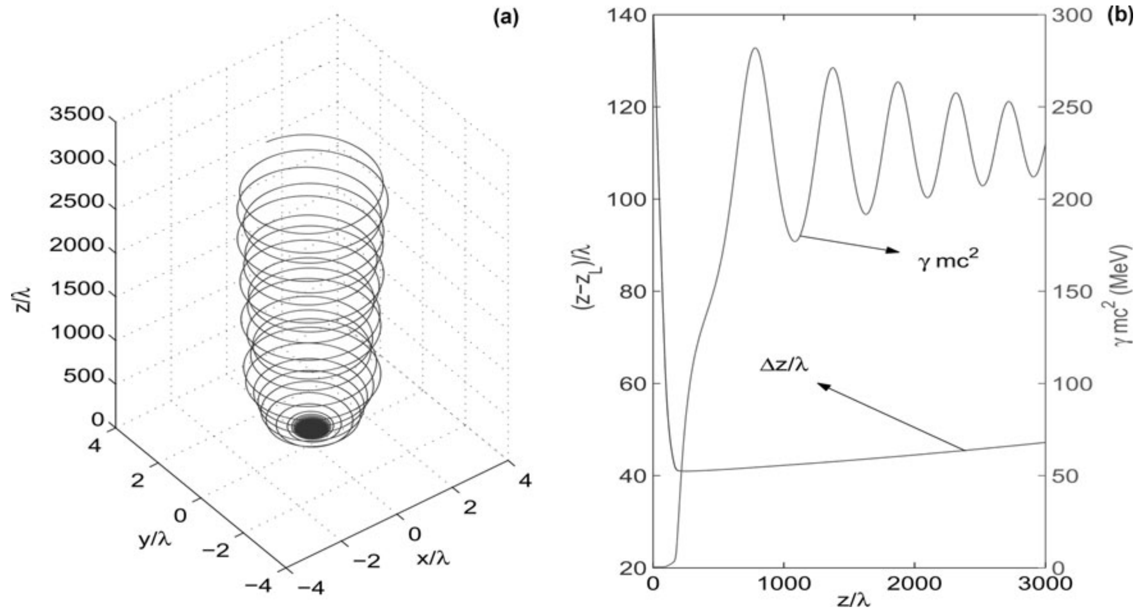

Fig. 1. (**a**) Electron trajectories in three-dimensional plane and (**b**) the electron position relative to the pulse center and the energy gain of the electron as a function of z in the interaction of an electron with a propagating laser pulse. The parameters of laser and plasma are $I_0 = 1 \times 10^{20}$ W/cm^2 and $n_0 = 0.1 n_{cr}$. The initial conditions are $p_{x0} = p_{y0} = 0$, $\gamma_0 = 1.01$, and $r_{in} = 0$. Here z_L is the position of the propagating laser pulse center.

placed at $z = 0$ initially, and their velocities approximately satisfy Maxwellian distribution with averaged temperature of 5 KeV. At the end of the interaction, we record the final energy, its radial position and its final momentum. Only electrons having energies larger than 10 MeV are shown. The scattering angle of electrons relative to the z-axis is $\theta_r = \arctan(p_\perp / p_\parallel)$. In fact, we can derive $p_\perp / p_\parallel = \sqrt{(\gamma^2 - 1)/(\gamma^2 v_\parallel^2) - 1}$ from the equation $\gamma^2 = 1 + p_\perp^2 + p_\parallel^2$. The scattering angle of the electrons obtaining

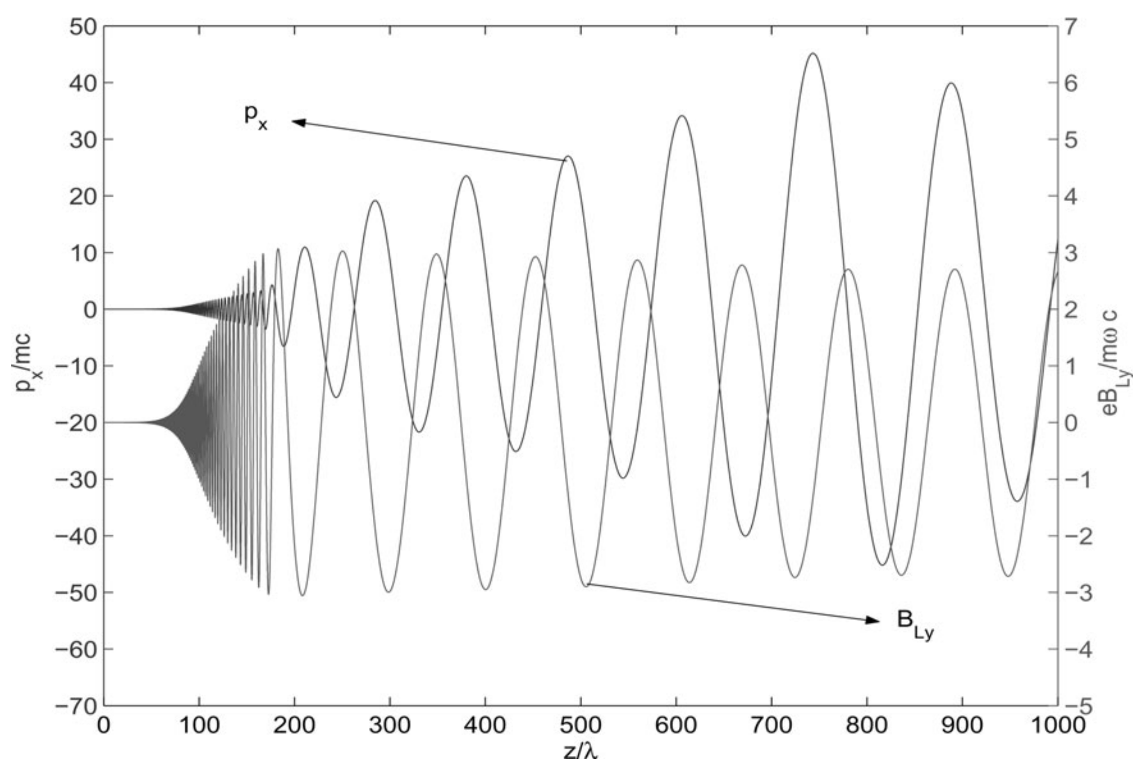

Fig. 2. Variation of p_x and B_{Ly} as a function of z for the same interaction as Fig. 1.

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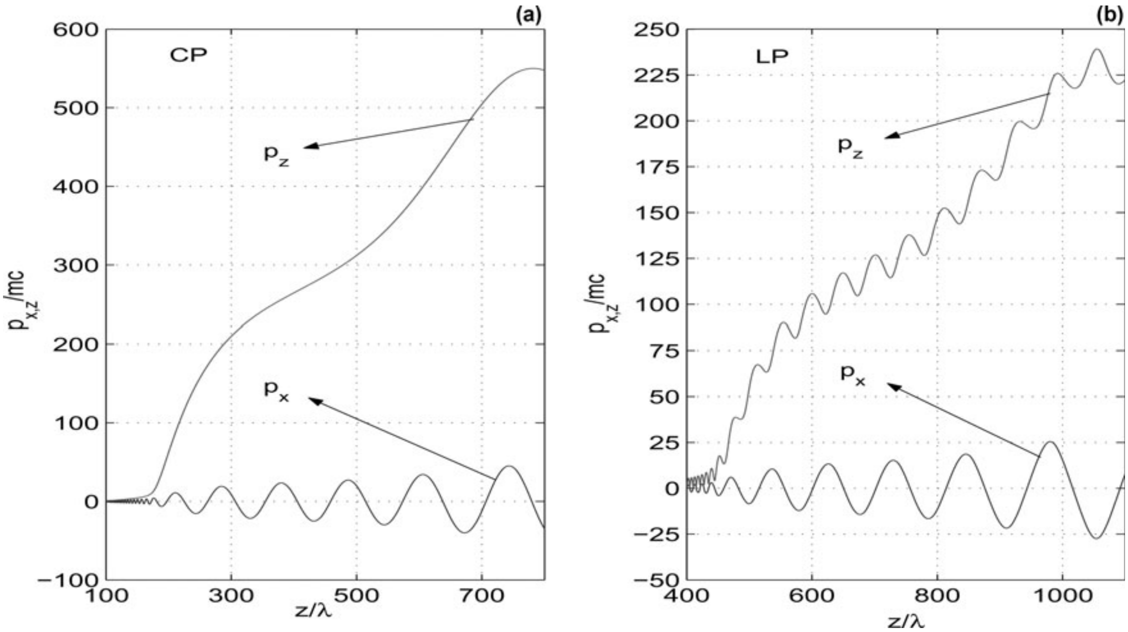

Fig. 3. The x- and z-momentum as a function of z in the interaction of an electron with a propagating laser pulse for different polarization. (**a**) CP, $\gamma_0 = 1.01$ and (**b**) LP, $\gamma_0 = 1.5$. Other parameters are the same as Fig. 1.

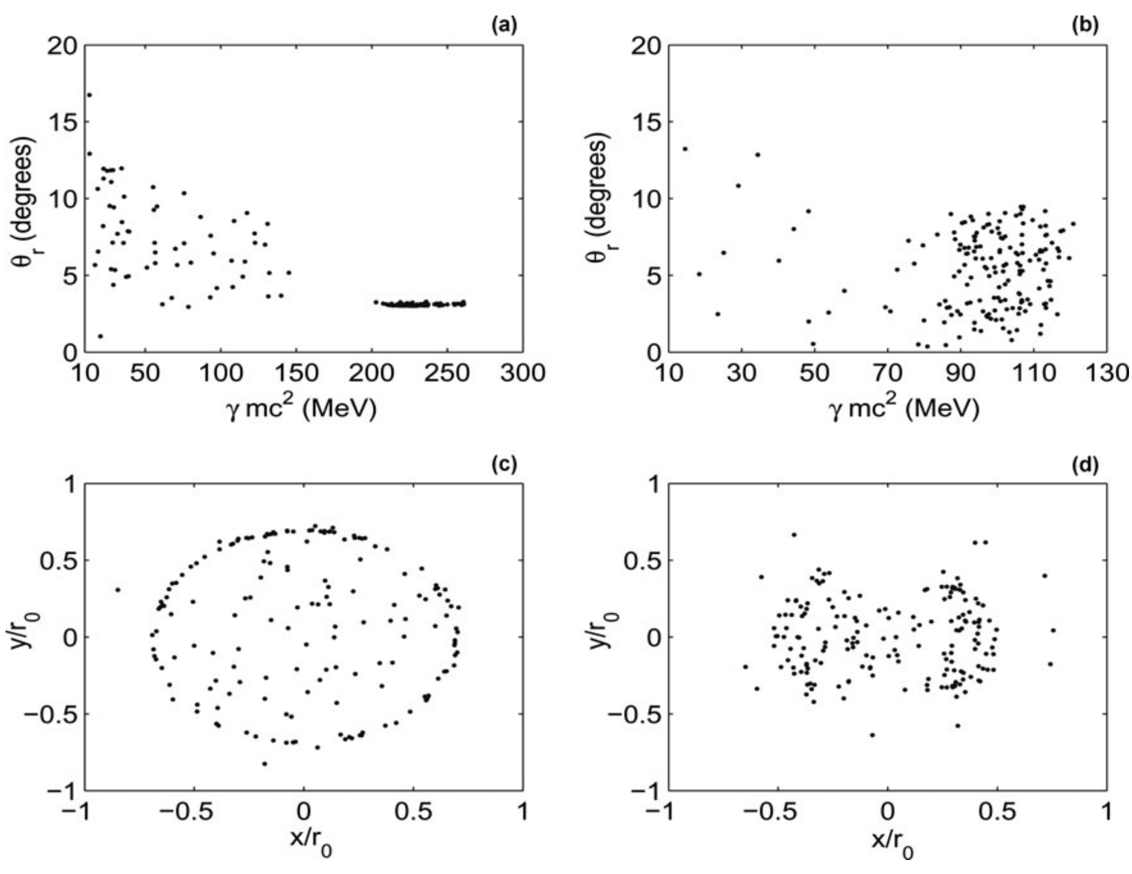

Fig. 4. (**a**) and (**b**) The distribution in $\gamma - \theta_r$ space, and (**c**) and (**d**) the spatial distribution of the energetic electrons in the $x - y$ plane for different polarization when the interaction of electrons with the laser pulse is over. The total 180 electrons are initially ($t = 0$) located uniformly within a disc with radius $r = r_0/4$ placed at $z = 0$. Their initial velocities approximately yield Maxwellian distribution with averaged temperature 5 KeV. Here the plasma density $n_0 = 0.1n_{cr}$ is assumed. The peak laser intensity $I_0 = 1 \times 10^{20}$ $\mathrm{W/cm^2}$ and $I_0 = 6 \times 10^{19}$ $\mathrm{W/cm^2}$ are chosen for CP and LP, respectively.

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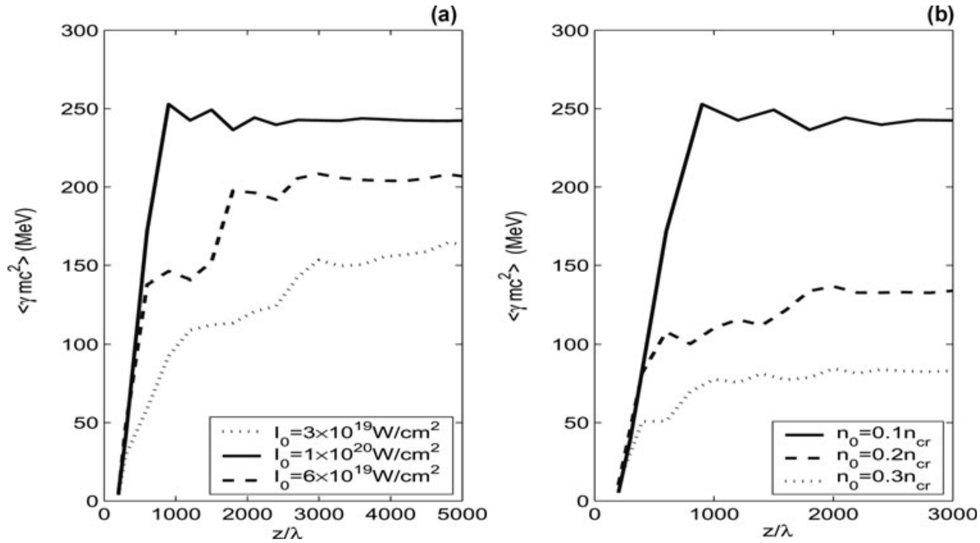

Fig. 5. Variation of the averaged energy gain $\langle \gamma mc^2 \rangle$ over several betatron oscillations as a function of z for (**a**) different laser intensities, $n_0 = 0.1n_{cr}$ and (**b**) different plasma densities, $I_0 = 1 \times 10^{20}$ W/cm^2. The initial conditions of the electron are $r_{in} = 0$ and $\gamma_0 = 1.0$.

$\gamma \gg 1$ and $v_z > v_g$ is doomed to be small. The numerical results show that most of the electrons attain resonance and the energy gain spreads from 207 MeV to 262 MeV with an relative energy width $\Delta E/\langle E \rangle \simeq 24\%$. These resonant electrons separate from the pulse with scattering angle around 3° with respect to z axis (see Fig. 4a). Moreover, the beam divergence of REB is less than 1° after the interaction is over. For comparison, The corresponding results in the case of LP laser are shown in Figure 4b. It can be seen that the REB driven by the LP laser has a larger beam divergence around $10^\circ - 1^\circ = 9^\circ$. The attainment of such REB is relevant to the motion of electrons. The electrons driven by the CP laser helically move within a Larmor radius induced by the axial QSM field until leaving the pulse. The spatial distribution of these electrons is almost circular (see Fig. 4c). While the motion of electrons driven by the LP pulse is about elliptical and predominantly along the direction of laser polarization (see Fig. 4d). By comparison, the REB produced by CP laser-plasma interaction with good qualities of high energy, quasi-monoenergy, and extreme low beam divergence may be a better candidate in future laser-plasma accelerator.

We turn to the dependence of the energy gain of the energetic electrons on laser intensity and plasma density. The different laser intensities $I_0 = 30,\ 60,\ 100\ (\times 10^{18}\ \text{W cm}^{-2})$ and different plasma densities $n_0 = 0.1n_{cr},\ 0.2n_{cr},\ 0.3n_{cr}$ are chosen. The self-generated fields are correspondingly changed by Eqs. (7)–(9). Figure 5 shows that the final energy gain of accelerated electrons increases with laser intensity but decreases with plasma density. In fact, in terms of Eq. (17), the electron energy gain is proportional to the laser electric field E_0. At higher plasma density, the laser pulse travels with a lower group velocity v_g and the electrons are earlier to be accelerated to reach v_g and then are pushed away from the pulse. As a result, the duration of interaction between the electron and the laser pulse decreases, leading to the reduction of the energy gain.

A quantity that is often quoted in discussions of particle accelerators is the energy gradient, defined as the energy gained by the particle per unit of distance along its trajectory. It is usually expressed in units of MeV m^{-1}. For example, the maximum energy gradient achievable in radio-frequency (rf) conventional accelerators is 100 MeV m^{-1}. In our case, the energy gain in general is about tens or hundreds of MeV with acceleration length around several millimeters. So we can attain the energy gradient about tens or hundreds of GeV m^{-1}, which is 2~3 orders larger than the rf accelerators.

4. CONCLUSION

In conclusion, the resonance acceleration of plasma electrons in interaction of an intense short laser with underdense plasma is theoretically and numerically studied by using a test particle model, where the joint effect of the CP Gaussian laser fields and the self-generated quasistatic fields, including the radial QSE field, the azimuthal QSM field, and the axial QSM field, is included. It is found that the resonance takes place when the betatron oscillation frequency of electrons in self-generated quasistatic fields coincides with the Doppler shifted laser frequency. Due to resonant acceleration, some electrons attain energy directly from the laser pulse and thus form a well qualified REB with high energy, quasi-monoenergy and extreme low divergent angle. It is also found that the final energy of the REB increases with laser intensity but decreases with plasma density. Our results show that the REB produced by CP laser-plasma interaction has better collimation comparing to the LP case for the resonant electrons move helically within a

Larmor radius induced by the axial QSM field. We believe that our results can give some enlightenment on the future laser-plasma based accelerators.

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