Electron acceleration in a tightly focused laser beam

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Electron acceleration in a tightly focused ultra-intensity linear polarized laser beam is investigated numerically. It has been found that the acceleration is strong phase dependent and is periodic to the variety of the initial laser field phase. When optimal initial parameters are chosen, the electron can be accelerated effectively. The accelerated electrons are emitted in pulses of which the full width is less than the half period of the laser field.

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Recent advances in the technology of intense laser fields[1] motivate research efforts into the issue of electron acceleration[2−13]. As a competitive way for electron acceleration by expensive conventional means, two mechanisms have been proposed, including plasma-wave acceleration[9] and direct laser acceleration in vacuum[10,11]. Although plasma-based schemes can achieve ultra-high acceleration and offer the possibility of guiding the laser pulse (preventing pulse diffraction), they suffer from several difficulties, including laser-plasma instabilities, plasma uniformity requirements, and electron beam-plasma collisions[2]. Laser acceleration in vacuum can eliminate the difficulties associated with the plasma. In recent years, significant progress has been made theoretically[4,6,8] and experimentally[12] on laser-based particle acceleration in vacuum. Except these advances, many challenges remain.

Recently, series of papers have investigated the electron acceleration in a tightly focused intense laser beam. It has been found that for a focused laser beam propagating in free space, there exists, surrounding the laser beam axis, a subluminous wave phase velocity region. Relativistic electrons injected into this region can be trapped in the acceleration phase and remain in phase with the laser field for sufficiently long time, thereby receiving considerable energy from the field[6]. Salamin *et al.* also found that, when an electron is injected at an angle to the beam axis, reflection, capture, and transmission can be found. The largest energy gain can be found in the capture case, reflection and transmission result mostly in little gain[4]. Bahari *et al.* also showed that, when the electron propagates along the axis of the laser beam ($\theta_0 = 0$), the electron can be accelerated by a short high-intensity pulse effectively[7,8].

The time duration of high-intensity laser pulse is not always very short. Many high-power laser facilities output laser pulse in picoseconds level, which is about several hundreds to thousands optical cycles. Acceleration in these kinds of laser fields maybe different from the case of ultrashort pulse. In this letter we report the electron acceleration by a continuous wave (CW) laser during the electron propagating along the axis of the laser beam. It can be taken as an approximation of the acceleration by a long laser pulse. Numerical experiments showed that the acceleration is very effective, but is phase dependent. It is also found that the accelerated electrons are emitted in pulses in the effective acceleration direction.

Consider a relativistic electron with mass m and charge $-e$, in a linear polarized tightly focused laser beam, the vector potential of the laser fields should be described by

$$\mathbf{A} = A_0 \frac{w_0}{w} g(\eta) \exp\left(-\frac{r^2}{w^2}\right) \cos(\phi)\hat{\mathbf{x}}, \quad (1)$$

where A_0 is the constant amplitude. Schematic diagram of the Gaussian laser beam accelerator configuration is shown in Fig. 1. The beam is propagated along z axis. The beam waist at focus is w_0, and at arbitrary z is $w(z) = w_0\sqrt{1 + (z/z_r)^2}$. Furthermore, $z_r = kw_0^2/2$ is the Rayleigh length, and $r^2 = x^2 + y^2$. $g(\eta)$ is the temporal pulse shape, here $g(\eta) = 1$. The total phase of the laser field:

$$\phi = \eta - \phi_R + \phi_G, \quad (2)$$

where

$$\eta = \omega t - kz + \eta_0, \quad (3)$$

$$\phi_R = \frac{kr^2}{2R(z)}, \quad (4)$$

$$\phi_G = \tan^{-1}\left(\frac{z}{z_r}\right), \quad (5)$$

where η is the phase of plane wave with frequency ω, and η_0 is the initial value of η. ϕ_R is the phase associated with the curvature of the wave fronts, and $R(z) = z + z_r^2/z$. ϕ_G is the Guoy phase. The Gaussian vector potential

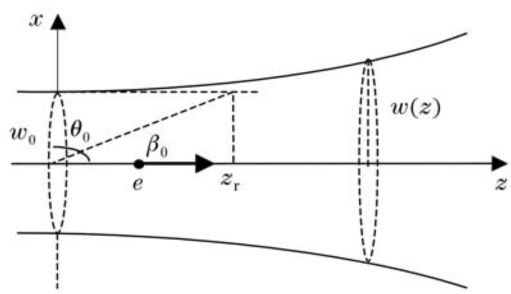

Fig. 1. Schematic diagram of the Gaussian laser beam accelerator.

is defined in the parabolic approximation[13,14], which corrects to 2nd order in the small parameter θ_0, and $\theta_0 = w/z_r$ is the diffraction angle. This is sufficient in our case, because the initial velocity of the electron is parallel to the axis of the laser beam in our model[8] .

The corresponding electric and magnetic fields of the vector potential can be represented as

$$E_x = E_0 \frac{w_0}{w} \exp\left(-\frac{r^2}{w^2}\right) \sin(\phi), \quad (6)$$

$$E_y = 0, \quad (7)$$

$$E_z = E_0 \left(\frac{w_0}{w}\right)^2 \frac{x}{z_r} \exp\left(-\frac{r^2}{w^2}\right) \cos(\phi + \phi_G), \quad (8)$$

$$B_x = 0, \quad (9)$$

$$B_y = E_x, \quad (10)$$

$$B_z = E_0 \left(\frac{w_0}{w}\right)^2 \frac{y}{z_r} \exp\left(-\frac{r^2}{w^2}\right) \cos(\phi + \phi_G), \quad (11)$$

where $E_0 = ka_0$, $a_0 = eA_0/mc^2$ is the dimensionless intensity parameter of the laser field. A laser system is often characterized by its power P, so we take P instead of a_0. P can be calculated by integrating the time-averaged Poynting flux over a plane through the beam focus perpendicular to its axis[5]. In our case,

$$P[\text{TW}] \approx 0.0216 \left(\frac{a_0 w_0^2}{\lambda}\right)^2. \quad (12)$$

The behavior of the electron in the tightly focused laser beam is governed by the relativistic Lorentz equation:

$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = -e(\mathbf{E} + \beta \times \mathbf{B}), \quad (13)$$

and the energy equation

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = -ec\beta \cdot \mathbf{E}, \quad (14)$$

where $\varepsilon = \gamma mc^2$, $\mathbf{P} = \gamma mc\beta$, β is the electron speed normalized by c, c is the speed of light.

Equations (13) and (14) are so complicated that there is little room left for further analytic manipulation. They will be solved by the 4th-order Runge-Kutta technique.

What we interest in is whether the acceleration in this model is sensitive to the initial phase of the laser field. The initial phase that the free electron 'feels' in the tightly focused laser field is decided by the initial position of the electron z_0 and the initial phase of the laser at focus η_0. We can choose one of them as variable, and the other as a constant. It must be mentioned that the change of z_0 brings not only the variety of the initial field phase, but also the variety of the field intensity of the initial position, which can affect the acceleration too. But if the change is limited to $\delta z_0 \ll z_r$, this effect can be neglected. Figure 2(a) shows energy gain of the electron after 5000 optical cycles as a function of the initial phase of the laser at focus η_0. It is obvious that the acceleration is strong phase dependent. The curve is periodic, and the period is about π. When η_0 is confined in a small range, in which the curve of Fig. 2(a) is at its top, the electron can be accelerated effectively.

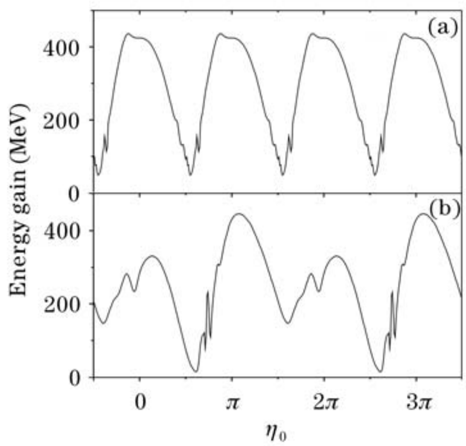

Fig. 2. Electron energy gain after 5000 optical cycles as a function of the initial phase of the laser at focus η_0. The initial speed is $\beta_0 = 0.9$. The initial position of the electron is $(0, 0, 32.55\lambda)$ for (a), and $x_0 = 2\lambda$ for (b). The parameters of laser beam is $\lambda = 1$ μm, $\eta_0 = 0$, $w_0 = 5\lambda$, and $P = 1$ PW.

It seems that the optimal initial phase for acceleration is at $\eta_0 = N\pi$, where $N = 0, 1, 2, \cdots$. When a free electron is injected into the laser field, it can 'feel' the electric force $-eE_x$ at the x direction and $-eE_z$ at the z direction. From Eqs. (6) and (8), we can get that, when the initial phase is at $N\pi$, E_z gets its maximum value and E_x gets its minimum value. Therefore the electron can be accelerated and get a considerable speed in the z direction immediately. So the electron can catch up the laser phase and be accelerated continuously. When $\eta_0 = (N + 1/2)\pi$, E_z gets its minimum value and E_x gets its maximum value, the electron cannot get enough speed along z axis to catch up the laser phase, which is scattered by $-eE_x$, so the electron cannot be accelerated effectively. The behaviors of the electrons are also affected by both the $\beta \times \mathbf{B}$ components and the ponderomotive force in the transverse direction caused by the transverse gradient of the Gaussian-beam.

Figure 3 shows the trajectories of the electrons for different initial phases η_0. It is obvious that the electrons are scattered in x direction. We can find that the trajectories of the electrons accelerated effectively ($\eta_0 = N\pi$) are almost symmetrical about the z axis. The trajectories of electrons which cannot be accelerated effectively depart from the trajectories of $\eta_0 = N\pi$, it is usually squiggly. In experiment, we can use a long pulse tightly focused laser beam to interact with a gas target, the free electrons can be obtained from ionization of the gas atoms. When the free electrons are born at the fixed point of z axis, due to the phase dependence of the acceleration and the trajectory, the electron pulse can be gained in the effective acceleration direction, and the full width of the electron pulse should be less than $T/2$, half period of the laser.

A rational question is why the period of Fig. 2(a) is not 2π, which is the cycle of the laser field. Figure 2(b) is for the cases similar to Fig. 2(a), but with $x_0 = 2\lambda$, the electron is not in the axis of the laser beam. It can be found that, the curve between $\eta_0 = -\pi/2$ and $\pi/2$ is not the same as that between $\eta_0 = \pi/2$ and $3\pi/2$ any more,

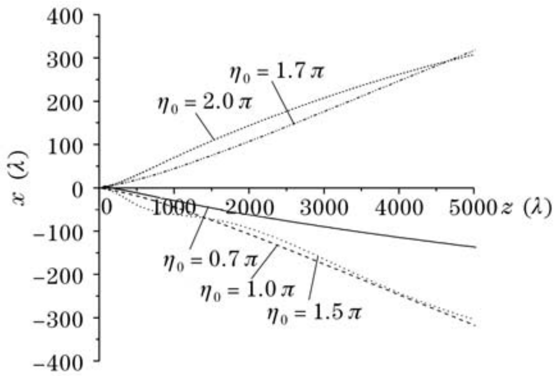

Fig. 3. Electron trajectory of different initial phases of the laser field at focus η_0. The other parameters are the same as Fig. 2(a).

so the period is 2π. When the electrons are injected into the laser field in the y-z plane, they can 'feel' the electric force of the transverse electric field in the x direction. The force can be in the $+x$ direction, and can also be in the $-x$ direction. The same energy will be gained in either of the two directions, but when $x_0 \neq 0$, the two contrary directions will not be equivalent for energy gain.

To illustrate the effectivity of the acceleration, we show the electron energy gain as a function of the axial distance in Fig. 4. We can see that, when appropriate condition is reached, the electron with initial energy less than 1 MeV can gain more than 1.4 GeV from the interaction with the 10-PW beams and over 400 MeV from the interaction with 1-PW beams. This is not less than the case of Ref. [4], in which electron must be injected at an appropriate angle.

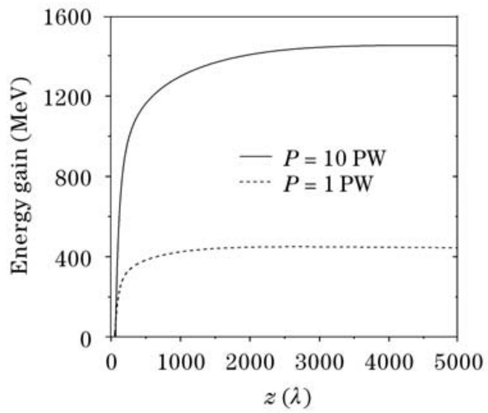

Fig. 4. Electron energy gain as a function of the axial distance. The initial position of the electron is $(0, 0, 52.65\lambda)$, and the initial speed is $\beta_0 = 0.93$. The parameters of the laser beam are the same as Fig. 2.

In conclusion, we have investigated the electron acceleration using a tightly focused ultra-intensity laser beam numerically. Strong phase dependence is found in this model. The acceleration is periodic to the variety of the initial laser field phase, and the accelerated electrons are in pulses, the full width of the electron pulse is less than $T/2$, which is the half period of the laser field. Numerical experiments showed that the acceleration is very effective. When a 10-PW intense laser beam is used, the electron with energy less than 1 MeV can be accelerated up to about 1.4 GeV.

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