BRIEF COMMUNICATIONS

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Electron acceleration by a laser pulse in vacuum

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The acceleration of an electron by a circularly polarized, high-intensity ultrashort laser pulse in vacuum is studied. It appears that the energy of the electron can be accelerated significantly, and the electron moves almost along the propagation direction of the laser pulse. © *1998 American Institute of Physics.* [S1070-664X(98)01501-8]

Recently, considerable progress has been achieved in the development of compact terawatt laser sources.[1] Such laser sources generate subpicosecond pulses of electromagnetic (EM) radiation with focal intensity $I>10^{18}$ W/cm^2. One of the most powerful neodymium–glass laser system, ''Vulcan'' at Rutherford Appleton Laboratory, delivers 35TW to target at an intensity of $I=10^{19}$ W/cm^2 in the short pulse mode.[2] Preliminary reports from several other centers seem quite promising, and, in the very near future, it will be possible to design petawatt facilities which will produce even higher intensity (10^{21-23} W/cm^2) pulses.[3] In the field of such strong subpicosecond pulses, it seems possible to accelerate significantly an electron.

Mckinstrie *et al.*[4] studied the electron acceleration by a high-intensity ultrashort laser pulse in a plasma recently, and the energy of a preaccelerated electron could be highly increased. In their discussion, a laser pulse of infinite transverse extent was used. When a laser pulse of infinite transverse extent propagates in vacuum and overtakes the free electron, the electron gains energy and momentum at the expense of the pulse. At the peak of an intense pulse, the electron has considerable (longitudinal) momentum in the propagation direction of the pulse, but when the laser pulse overtakes the electron completely, it regains energy from the electron and the electron is at rest.[5] But if the transverse extent of the laser pulse is finite, the situation is different.[6,7] Malka *et al.*[7] have studied the electron acceleration by a linearly polarized laser pulse, and the intensity is not so high, the free electron could be highly accelerated. In this paper, we describe the acceleration of an electron by a diffraction laser pulse with higher intensity and shorter width in vacuum, and the laser pulse is circularly polarized. For there is no plasma, this proposal is easy to realize in experiment.

The motion of an electron of mass m, in an electromagnetic field is governed by the equation

$$m\,\frac{d(\gamma\overline{\nu})}{dt}=-e\left(\overline{E}+\frac{\overline{\nu}\times\overline{B}}{c}\right) \qquad (1)$$

and the trajectory of the electron is determined by

$$\overline{r}=\overline{r_0}+\int_0^t \overline{v}\,dt, \qquad (2)$$

where $\overline{r_0}$ is the initial position of the electron.

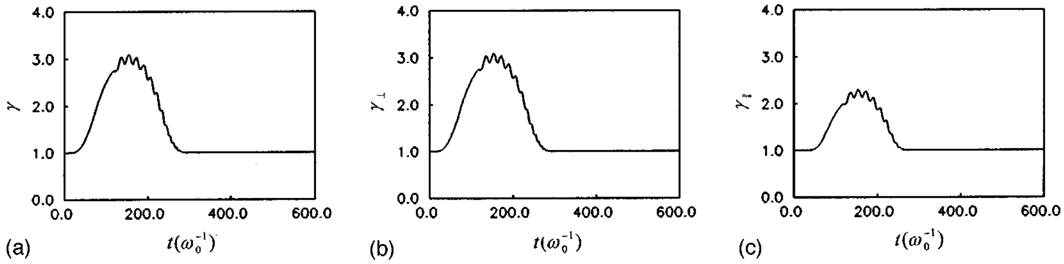

FIG. 1. The energy gain of the electron for parameters $a=2$, $L=7.5\lambda_0$, $R_0=25\lambda_0$. (a) Total energy gain γ. (b) Transverse energy gain $\gamma_\perp$. (c) Longitudinal energy gain $\gamma_\parallel$.

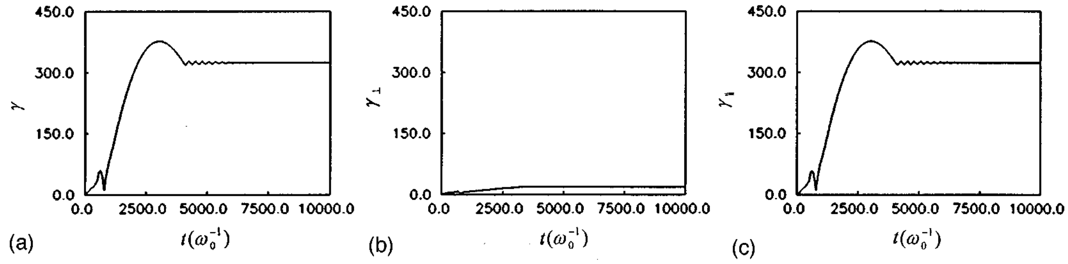

FIG. 2. The energy gain of the electron for parameters $a=6$, $L=7.5\lambda_0$, $R_0=25\lambda_0$. (a) Total energy gain γ. (b) Transverse energy gain $\gamma_\perp$. (c) Longitudinal energy gain $\gamma_\parallel$.

For a spatially and temporally finite, circularly polarized electronmagnetic wave which propagates in vacuum, we can use following approximation for the field:[8]

$$\overline{A}=a\,\frac{R_0}{R_s}\exp\left(-\frac{R^2}{R_s^2}\right)f(\varphi)[\overline{i}\cos(\phi_p)+\overline{j}\sin(\phi_p)] \tag{3}$$

$$\phi_p(R,z,t)=\varphi+\alpha_z\,\frac{R^2}{R_s^2}-\tan^{-1}\,\alpha_z \tag{4}$$

and

$$\overline{E}=-\frac{1}{c}\,\frac{\partial\overline{A}}{\partial t},\quad \overline{B}=\nabla\times\overline{A}, \tag{5}$$

where ω_0, k_0, and λ_0 are frequency, wave number and wavelength of the laser pulse, $\varphi=k_0z-\omega_0 t$ is the phase angle, and $f(\varphi)$ the phase shape of the pulse, a and R_0 are the peak amplitude and minimum spot size of the laser pulse at focus,

$$R_s=R_0\left(1+\frac{z^2}{z_R^2}\right)^{1/2}$$

and $z_R=(k_0R_0^2)/(2)$ are, respectively, the laser spot size and Rayleigh length, $\alpha_z=(z)/(z_R)$. z is the laser propagation direction, and $R=\sqrt{x^2+y^2}$.

The equations are solved for $\lambda_0=1\,\mu$m, $R_0=25\,\mu$m, and taking for $f(\varphi)$ a Gaussian shape of half total width $L=7.5\lambda_0$.

With the magnetic field $\overline{B}$ and electric field $\overline{E}$, it is possible to describe the electron motion with a good approximation during and after its interaction with the pulse. Initially, the electron is at rest and its position is $x=0$, $y=0$, $z=2L$.

Figures 1(a), (b), (c) show total energy gain γ, transverse energy gain $\gamma_\perp$, and longitudinal energy gain $\gamma_\parallel$ of the electron for a laser pulse amplitude $a=2$. At this intensity, we find the electron gains energy with the maximum $\gamma=3$, but as the laser pulse continues to overtake the electron, the energy begins to waste, and at last the electron is almost at rest, the results conform to the suggestion by Sarachik *et al.*[5] The electron leaves the laser focus at an angle θ with respect to the propagation direction given by

$$\theta=\tan^{-1}\,\frac{P_\perp}{P_\parallel}=\tan^{-1}\,\frac{\sqrt{\gamma_\perp^2-1}}{\sqrt{\gamma_\parallel^2-1}}, \tag{6}$$

where $P_\perp$ and $P_\parallel$ are the momentums of the electron perpendicular and parallel to the propagation direction of the laser pulse. At the laser intensity $a=2$, the angle $\theta\approx 45°$.

Figures 2(a), (b), (c) show total energy gain γ, transverse energy gain $\gamma_\perp$, and longitudinal energy gain $\gamma_\parallel$ of the electron for a laser amplitude $a=6$. We can find the electron is highly accelerated with the ultimate total energy gain $\gamma=330$, and the transverse energy gain of the electron is much less than the longitudinal energy gain, here $\gamma\approx\gamma_\parallel\approx 330$ and $\gamma_\perp\approx 15$. The energy of the electron is concentrated on the longitudinal direction, and

$$\theta=\tan^{-1}\,\frac{\sqrt{\gamma_\perp^2-1}}{\sqrt{\gamma_\parallel^2-1}}\approx 2.6°.$$

Ultimately the electron moves along the direction almost parallel to the propagation axis of the laser pulse.

To further illustrate the electron acceleration by the laser pulse of different intensity, we calculate the energy gain of the electron at different intensity. In Fig. 3 the energy gain is plotted as a function of the laser amplitude, the energy gain of the electron increases monotonically. For a small intensity, the pulse overtakes the electron and the electron is almost at rest. When the peak intensity of the pulse is higher

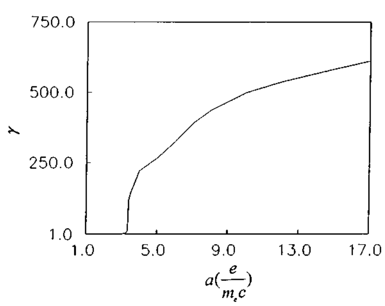

FIG. 3. The total energy gain distribution of the electron for different intensity of the laser pulse.

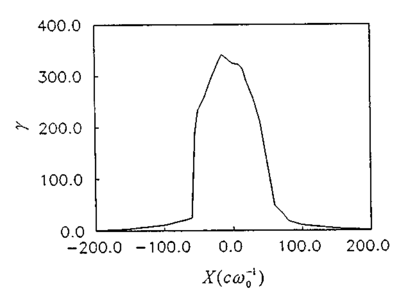

FIG. 4. The total energy gain distribution of the electron for different initial transverse position.

than the critical intensity (about 3.2), the electron is accelerated to high energy. The angle θ is inversely related to the energy gain, this is in accordance with the theoretical law[6]

$$\theta = \tan^{-1}\sqrt{\frac{2}{\gamma-1}}. \tag{7}$$

The more the electron gains energy, the smaller the angle is. When the energy gain γ is very large, the angle is very small, and the electron is accelerated at the propagation direction of the laser pulse. So if the intensity of the laser pulse is very large, the electron is accelerated significantly and moves almost along the propagation direction of the laser pulse.

The energy gain distribution of the electron for initial transverse position $X=\sqrt{x_e^2+y_e^2}$ is shown in Fig. 4. We find that the effective acceleration region is about $X < (25\lambda_0)/(\pi)$. For $\lambda_0 = 1\ \mu$m, the maximum $X_{max} \approx 4\ \mu$m.

In summary, the results show that in vacuum the free electron can be significantly accelerated by the circularly polarized, high-intensity ultrashort laser pulse of finite transverse extent, and after the laser pulse overtakes the free electron completely the electron moves almost along the propagation direction of laser pulse, which makes the free electron can be easily extracted. Finally, we should remember that our calculations have dealt with the acceleration of a single electron. In an actual experiment, an electron beam or a plasma would be used to provide the electrons. When many electrons are present, the laser pulse may be more powerful than the threshold above to accelerate the electrons. But in most experimental situations, the density would be such that the plasma frequency is far less than an optical frequency, so that plasma effects would not enter to change the conclusions of this paper.

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