Electron capture and violent acceleration by an extra-intense laser beam

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(Received 7 April 1998; revised manuscript received 24 June 1998)

This paper reports on an interesting phenomenon in strong-field laser physics. It has been found, by numerical simulation method, that when interacting with an extraintense stationary laser beam ($Q \gtrsim 100$, where Q is the dimensionless measure of the field intensity [Y. K. Ho, Phys. Lett. A **220**, 189 (1996)], the electron can be captured and violently accelerated by the laser beam field. [S1063-651X(98)00811-3]

PACS number(s): 41.75.−i, 42.50.Vk

We have reported previously [1–3] that an electron can be scattered inelastically by an intense stationary laser beam so long as E_0, the reference electric field intensity, meets the requirement $Q_0 = eE_0/(m_e \omega c) > 0.1$, in which $-e$ and m_e are the electron's charge and rest mass, respectively, ω the laser circular frequency, and c the speed of light in vacuum. This result has not only represented an answer to the question of whether an electron can obtain net energy gain from a far-field laser field [4–6], but also provided us with a possibility to accelerate the electrons by lasers. For example, when a laser beam of Hermite-Gaussian (0,0) mode with $Q_0 = 10$ is used, the electron incident with a 5° crossing angle and initial energy of 50 MeV can obtain an energy of 400 keV from the laser field. This acquired energy is very small compared with what is obtainable from the present conventional high-energy electron accelerators, such as SLAC, which can accelerate the electrons to 50 GeV. Thus our field configuration was not thought to be an effective method for laser acceleration until recently when a breakthrough is made, which will be presented in this paper. The principal result is that the electron can be captured and violently accelerated by an extraintense laser beam with $Q_0 \gtrsim 100$. This is a new phenomenon, to our knowledge, and can be of potential interest to the far-field laser acceleration.

The configuration of electron-laser interaction is shown in Fig. 1. The field we use is the lowest-order Hermite-Gaussian mode [7], which is x polarized and propagates along the z axis. The expression for the transverse electric-field component is

$$E_x(x,y,z,t) = E_0 \frac{w_0}{w(z)} \exp\left(-\frac{x^2+y^2}{w(z)^2}\right) \times \exp\left[-i\left(\omega t - kz - \varphi(z) - \phi_0 - \frac{k(x^2+y^2)}{2R(z)}\right)\right], \quad (1)$$

where E_0 is the reference electric-field strength, w_0 the beam width at the focus center, k is the laser wave number, ϕ_0 the initial phase, and

$$w(z) = w_0\left[1+\left(\frac{2z}{kw_0^2}\right)^2\right]^{1/2}, \quad (2)$$

$$R(z) = z\left[1+\left(\frac{kw_0^2}{2z}\right)^2\right], \quad (3)$$

$$\varphi(z) = tg^{-1}\left(\frac{kw_0^2}{2z}\right). \quad (4)$$

The other electric and magnetic components can be obtained by using $E_z = (i/k)(\partial E_x/\partial x)$ and $\vec{B} = -(i/\omega)\vec{\nabla}\times\vec{E}$ [8]. The electron dynamics can be obtained by solving the Lorentz equation in the relativistic framework,

$$\frac{d\vec{P}}{dt} = -e(\vec{E}+\vec{V}\times\vec{B}). \quad (5)$$

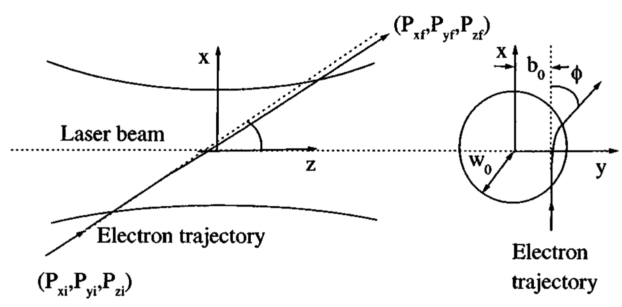

FIG. 1. Schematic geometry of electron scattering by a laser beam. The laser propagates along the z axis. w_0 is the beamwidth at the waist. Without losing generality, we assume that electrons enter from the $-x$ side, and are parallel to the x-z plane. ($\gamma_i, P_{xi}, P_{yi} = 0, P_{zi}$) denote the incoming energy and momentum of the electron, and ($\gamma_f, P_{xf}, P_{yf}, P_{zf}$) that of the outgoing state. γ is the Lorentz factor and b_0 the impact parameter. $\theta = \tan^{-1}(P_{xi}/P_{zi})$ is the electron incident angle, and $\phi = \tan^{-1}(P_{yf}/P_{xf})$ the deflection angle in the x-y plane.

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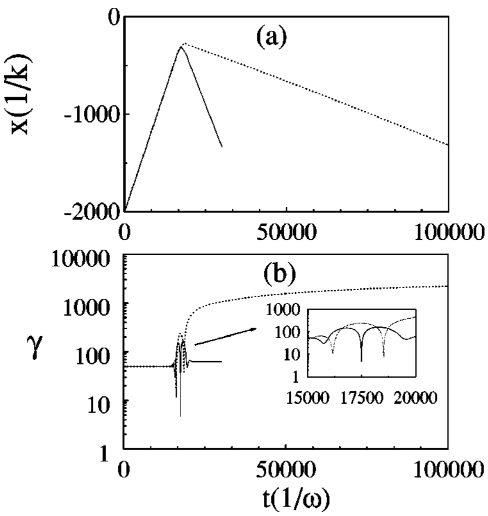

FIG. 2. Two typical cases of electron dynamics. The solid line is for ordinary electron inelastic scattering with $\phi_0=240°$, and the dotted line for electron capture with $\phi_0=0°$. A laser beam of the Hermite-Gaussian (0,0) mode, with field intensity $Q_0=100$ and beamwidth $kw_0=200$, is used. The electron incomes with momentum $P_{xi}/(m_e c)=5$, $P_{yi}/(m_e c)=0$, $P_{zi}/(m_e c)=50$, corresponding to an initial energy 26 MeV. In the electron capture case, we have terminated the calculation at $\omega t=100\,000$ when the electron is accelerated to 1.5 GeV, much greater than the final energy 32 MeV in the inelastic scattering case. The inset is an enlargement of the part denoted by the arrow.

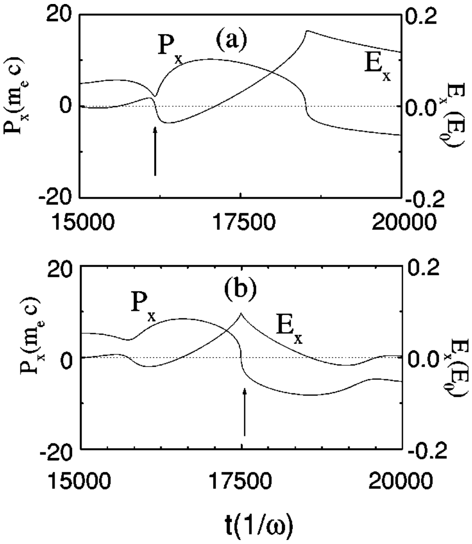

FIG. 3. Variation relationships between the electron transverse momentum P_x and the electric-field intensity E_x. All the initial conditions of the electron and the laser field are the same as those in Fig. 2. (a) is for the capture case with $\phi_0=0°$, and (b) for the scattering case with $\phi_0=240°$. The vertical arrow in (a) denotes the part responsible for the electron capture.

As usual, only the real parts of the fields are used. Because for such complicated fields, the analytical solution to Eq. (5) is almost impossible, we have to resort to numerical analysis. In our numerical simulation, Eq. (5) is solved by the fourth-order Runge-Kutta method together with Richardson's first-order extrapolation procedure [9]. For a more precise calculation, all real entities are declared to be double precision, which could hold real numbers to an accuracy of 14 digits. Test calculations against analytical results has been performed by using the plane-wave electromagnetic field over a large range of field intensity, which has shown the reliability of our numerical method. The aim of taking all the above measures is to exclude the possibility that the conclusions presented in this paper result from a numerical fluke.

In the following, we will first discuss the general electron dynamics in the extraintense laser field with $Q_0=100$, and then the characteristics of electron capture together with the electron acceleration. Finally, a conclusion is drawn.

It has been found [1] that when scattered by a laser beam of Hermite-Gaussian(0,0) mode with $Q_0 \lesssim 10$, the electron can either be reflected by the field or pass through the field, depending upon the electron incident transverse momentum P_{xi} and the field intensity Q_0. The delimiting P_{xi} can be estimated, from the traditional repulsive ponderomotive potential [10], to be about $Q_0/\sqrt{2}$. But when Q_0 is increased to around 100, things begin to change and a new electron behavior emerges, i.e., the electron can be captured. In Fig. 2, we present two typical cases with $Q_0=100$, one for ordinary inelastic scattering and the other for capture of the electron by a laser field. It is interesting to note, that the captured electron can be accelerated to an energy as high as 1.5 GeV, much greater than the keV energy gain from the inelastic effect. It seems that the electron capture turns out to be an effective laser acceleration mechanism. Thus, in the following, we will focus on the electron capture characteristics, leaving aside the inelastic scattering, which has been discussed in detail before [1–3]. By comprehensive numerical research, it is found that there are at least three conditions under which the electron capture phenomenon may emerge.

First, an extraintense laser field with $Q_0 \gtrsim 100$ is necessary, viz. $I\lambda^2 \gtrsim 10^{22}\ \mu\mathrm{m}^2\ \mathrm{W/cm}^2$, which should be achievable in the near future [11].

Second, the electron should be incident with a small crossing angle relative to the laser beam propagation direction, and its transverse momentum P_{xi} must not be too large, namely $P_{xi} \ll Q_0/\sqrt{2}$. The latter condition is totally contrast to the conventional idea about the electron scattering, which claims that when $P_{xi} \leq Q_0/\sqrt{2}$, the electron cannot overcome the repulsive ponderomotive potential barrier and will be reflected by the laser field. The physics of this condition is still not very clear at this moment. But its usefulness is obvious, since unlike most previous laser acceleration mechanisms [12] the electron is not required to be preaccelerated to high energy before final acceleration.

When the above two conditions are satisfied, the electron can still not be assured to be captured because the capture effect is very sensitive to the third factor, namely, the initial phase ϕ_0 of the laser field, which has been embodied in Fig. 2, where the 240°-phase difference leads to quite different electron dynamics. To see in detail the role played by ϕ_0, we present in Fig. 3 the variational relationship between the transverse electric field E_x and the momentum P_{xi}. It can be seen from Fig. 3 that the conspicuous difference between the electron scattering and capture takes place when P_{xi} approaches zero; that is, the electron begins to be reflected by the laser field. At this time, in the transverse direction, the electron is mainly influenced by the electric field E_x. For

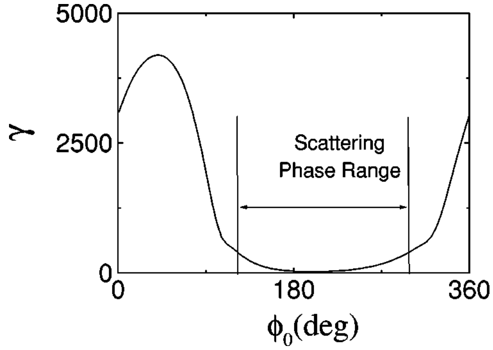

FIG. 4. Demonstration of the phase range of the electron capture. All the initial conditions of the electron and the laser field are the same as those in Fig. 2. In the electron capture cases, the calculation are terminated at $\omega t = 100\,000$.

ordinary scattering, the force exerted by E_x will pull the electron outside of the laser field in the $-x$ direction. But, as opposed to the electron capture case, it is just the opposite. Hence the electron will further approach the beam axis, where the field intensity is extra strong, leading to capture and violent acceleration afterwards. Similar situation can also be found in other capture cases. Since the direction of E_x at the electron reflection point is dependent upon ϕ_0, we can now see why the electron capture is so sensitive to the initial phase. The capture phase range corresponding to Fig. 3 is presented in Fig. 4, from which it can be seen that about 50% of electrons can be captured when the initial electrons are uniformly distributed in the 360°-phase range.

After being captured, the electron will run along the laser propagation direction, and be accelerated by the extraintense laser field. According to our numerical analysis, the acceleration is mainly due to the nonlinear longitudinal force $V_x B_y$, where V_x and B_y are the velocity and magnetic field in the x and y directions, respectively. After some transition time following capture, the electron energy can increase monotonously until reaching a limiting energy $E_{\max} = m_e c^2 \gamma_{\max}$, where $\gamma_{\max}$ is about $Q_0^2/2$ in magnitude. To give a physical picture to such a phenomenon, we can resort to the linearly polarized plane-wave field. In this field, the energy of an electron initially at rest will oscillate with an amplitude of $Q_0^2/2$ [13], which is just the maximum energy an electron can obtain from the laser beam. Because the electron energy increases quickly due to the ultraintense laser field, the phase slippage between the laser field and the electron becomes very slow, which almost disappears in Fig. 2(b) over a very long time, leading to a total failure of the ponderomotive-potential model to describe the electron–laser-beam interaction. Furthermore, we have also observed that accelerated electrons can be extracted from the laser beam without losing much of the gained energy by applying a static magnetic field of intensity available with present technology.

From all the results and discussion above, we can summarize as follows. When the laser intensity is strong enough ($Q \gtrsim 100$ for a Nd:glass laser; this value corresponds to a laser intensity about 10^{22} W/cm^2, which is expected to be available in the next couple of years), the electron-laser interaction enters a regime where the conventional ponderomotive potential model can no longer be used either quantitatively or qualitatively. One of the features of the electron dynamics in this regime is that relatively lower-energy electrons with small crossing angles to the laser propagation direction and with proper phases relative to the field can be captured by the laser beam, thus entering the near-axis region where the field intensity is extrastrong, and moving along the wave propagation direction without quivering motion, and being violently accelerated longitudinally by the laser electric magnetic field.

It is worthwhile to indicate that the above electron dynamics characteristics have also been found in the electron–extraintense-laser-pulse interaction, except those effects stemming from the leading and trailing edges of the pulse [14]. Thus it is hoped that our predictions can be submitted to experimental tests in the near future.

The authors would like to thank Professor Z. M. Fu for a careful reading of this manuscript, and for enlightening discussion. This work was partially supported by the National Natural Science Foundation of China under Contract No. 10684001, the National High-Tech ICP Committee in China, and the Science and Technology Foundation of CAEP.

[1] Y. K. Ho, J. X. Wang, L. Feng, W. Scheid, and H. Hora, Phys. Lett. A **220**, 189 (1996).
[2] J. X. Wang, Y. K. Ho, W. Scheid, and H. Hora, Phys. Lett. A **231**, 139 (1997).
[3] J. X. Wang, Y. K. Ho, and W. Scheid, Phys. Lett. A **234**, 415 (1997).
[4] T. C. Katsouleas, Proc. SPIE **664**, 2 (1986), and references therein.
[5] A. M. Sessler, Am. J. Phys. **54**, 505 (1984), Phys. Today **1**, 26 (1988).
[6] Y. K. Ho and L. Feng, Phys. Lett. A **184**, 440 (1994).
[7] Orazio Svelto and David C. Hanna, *Principles of Lasers*, 3rd ed. (Plenum, New York, 1989).
[8] Melvin Lax, Phys. Rev. A **11**, 1365 (1975); L. W. Davis, *ibid.* **19**, 1177 (1979).
[9] M. L. James, G. M. Smith and J. C. Wolfford, *Applied Numerical Method for Digital Computation* 3rd ed. (Harper and Row, New York, 1985).
[10] T. W. B. Kibble, Phys. Rev. Lett. **16**, 1054 (1966); Phys. Rev. **150**, 1060 (1966).
[11] G. Mourou, C. P. J. Barty, and M. D. Perry, Phys. Today **51** (1), 22 (1998); M. D. Perry and G. Mourou, Science **264**, 917 (1994).
[12] W. D. Kimura, R. D. Romea, and L. C. Steinhauer, Part. World **4**, 22 (1995).
[13] Y. I. Salamin and F. H. M. Faisal, Phys. Rev. A **54**, 4383 (1996); Phys. Lett. A **55**, 3678 (1997).
[14] P. H. Bucksbaum, M. Bashvansky, and T. J. McIlrath, Phys. Rev. Lett. **58**, 349 (1987).