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Realistic laser focusing effect on electron acceleration in the presence of a pulsed magnetic field

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As we know, for a significant electron energy gain, a fast electron should be injected into the highest intensity region of the laser focus. Such intensities may be achieved in the laboratory by tight focusing of a laser. For a tight focused laser beam, it is necessary to consider all field components the arise due to the tight focusing of the laser beam, when the waist of the laser beam is of the order of the laser wavelength. By using the accurate field components of a tightly focused laser beam, we investigate the electron acceleration in the presence of a pulsed magnetic field. Our study shows that the electron energy gain during laser acceleration is found to be considerably higher. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2801392]

Tabletop terawatt lasers based on the chirped-pulse amplification technique with ultrahigh intensities and ultrashort pulses have been developed.[1] It has been possible to make electron acceleration by using these laser pulses in vacuum for the last two decades. Laser-based accelerators[2–8] are capable of producing high-energy electrons/protons in much shorter distances than conventional accelerators due to the large electric fields associated with laser. Laser acceleration in vacuum has been studied theoretically[9–14] for a long time and recently some schemes have been proposed for experimental verification.

Most theoretical treatments of the electron laser acceleration employ low-order Gaussian beams. For a significant electron energy gain, a fast electron should be injected into the highest intensity region of the laser focus. Such intensities may be achieved in the laboratory by tight focusing of the laser beam. When the waist of the laser beam is of the order of the laser wavelength, then it is necessary to consider all field components that arise due to the tight focusing of the laser beam. In our investigation, we consider all field components by the realistic focusing of the laser beam. By using the effect of tight focusing of the laser beam, it is possible to observe the real situation of the electron acceleration by a high-intensity laser. The magnetic field is also very important to enhance the electron energy gain during acceleration. An optimum static magnetic field should be applied to continuously accelerate electrons before entering the deceleration phase. As a result, the electron can gain and retain a significant energy in the form of cyclotron oscillations in the presence of a static magnetic field.[15–17] In this letter, we use a pulsed axial magnetic field of a short duration for energy enhancement. The additional effect of this kind of a magnetic field is also investigated. The duration of the magnetic field is longer than the laser pulse duration, which allows the electrons to stay in the magnetic field for the full duration of their interaction with the laser pulse. As a result, the electrons can gain a significantly higher energy during acceleration.

For a linearly polarized and tightly focused laser beam,[18,19] the electric field components can be written as

$$E_x = A_0\{1 + s^2[-\rho^2Q^2 + i\rho^4Q^3 - 2Q^2(x/w_0)^2] + s^4[2\rho^4Q^4 - 3i\rho^6Q^5 - 0.5\rho^8Q^6 + (x/w_0)^2(8\rho^2Q^4 - 2i\rho^4Q^5)]\}iQe^{-\sigma^2}e^{-i\rho^2Q}e^{i\delta}, \tag{1}$$

$$E_y = A_0\{s^2(-2Q^2xy/w_0^2) + s^4(8\rho^2Q^4 - 2i\rho^4Q^5)xy/w_0^2\}iQe^{-\sigma^2}e^{-i\rho^2Q}e^{i\delta}, \tag{2}$$

$$E_z = A_0[s(-2Qx/w_0 + s^3(6\rho^2Q^3 - 2i\rho^4Q^4)\ x/w_0 + s^5(20\rho^4Q^5 + 10i\rho^6Q^6 + \rho^8Q^7)x/w_0]iQe^{-\sigma^2}e^{-i\rho^2Q}e^{i\delta}, \tag{3}$$

where $\delta=\omega t-kz$, $\rho^2=(x^2+y^2)/w_0^2$, $Q=b/(ib+2z)$, $\sigma^2=\tau^2/c^2\tau_0^2$, $b=2\pi w_0^2/\lambda_0$, $\tau=z-ct$, $s=1/kw_0$, $k=\omega/c$, A_0 is the laser intensity amplitude, w_0 is the laser spot size, λ_0 is the laser wavelength, and τ_0 is the laser pulse duration. Here, we would like to mention that the higher order terms of the fields arise due to the tight focusing of the laser. To realize the focusing effect (when the beam size approaches the order of magnitude of the beam wavelength), it is necessary to include these focusing-induced field components that may have significant effect on the electron scattering in vacuum. In addition, it is worth discussing the longitudinal component of the laser field. The longitudinal field component is important especially near the focus of the beam in vacuum. The longitudinal field component arising from the focusing of the beam is always one order of magnitude smaller than the incident field. Hence, the longitudinal field may be neglected. However, the laser field without longitudinal component does not satisfy the free-space Maxwell equation $\nabla\cdot\mathbf{E}=0$, which gives the overestimated electron energy gain during laser acceleration in vacuum. In our case, we consider the field that satisfies the Helmhotz equation up to fifth-order

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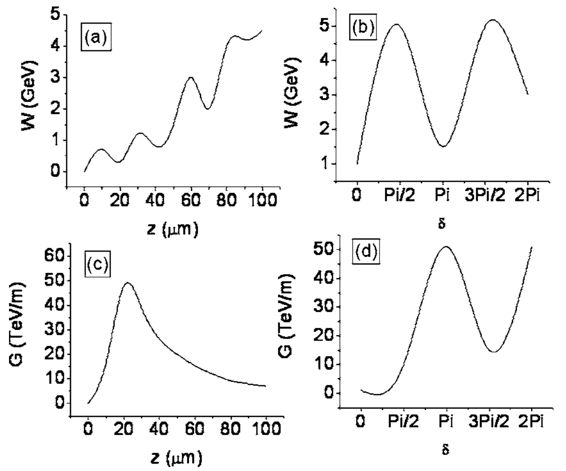

FIG. 1. (a) Electron energy gain with the propagation distance, (b) electron energy gain with phase of the field during a field cycle, (c) energy gradient with the propagation distance, and (d) energy gradient with phase of the field during a field cycle. The used laser parameters are $I_0 \sim 5\times10^{21}$ W/cm^2 ($a_0=10$), $\lambda_0 \sim 1$ μm, $w_0=4$ μm, and $\tau_0=25$ fs. In all plots, the used initial electron energy is $\gamma_0=5$ and the used peak magnetic field is 60 T of the duration of 100 ms.

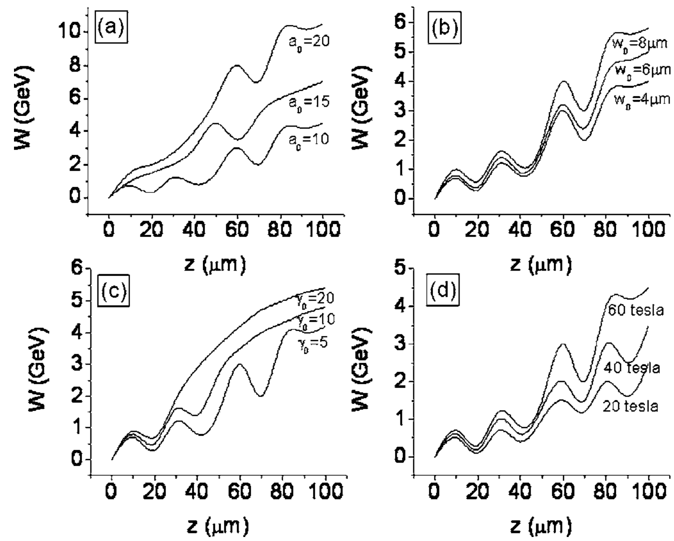

FIG. 2. Electron energy gain with the propagation distance (a) for different laser intensity parameters of $a_0=20,15,10$, (b) for different laser spot sizes of $w_0=8,6,4$ μm, (c) for different initial electron energies of $\gamma_0=20,10,5$, and (d) for different strengths of the pulsed magnetic fields of 60, 40, 20 T. The other numerical parameters are the same as those in Fig. 1.

terms. This implies survival of the finite longitudinal electric field component that can accelerate electrons traveling in the longitudinal direction. The magnetic field components related to the tightly focused laser beam can be easily deduced from Maxwell's equations.

We use test particle simulations to study the electron dynamics in the field of a tightly focused laser. The equations governing the electron momentum and energy are

$$\frac{d\mathbf{p}}{dt} = -e[(\mathbf{E}+\mathbf{E}_p) + \boldsymbol{\beta}\times(\mathbf{B}+\mathbf{B}_p)], \tag{4}$$

$$\frac{d\gamma}{dt} = -e\boldsymbol{\beta}\cdot(\mathbf{E}+\mathbf{E}_p), \tag{5}$$

where the momentum $\mathbf{p}=\gamma\boldsymbol{\beta}$ is normalized in the unit of m_0c, the energy is normalized in the unit of m_0c^2, $\gamma=(1-\beta^2)^{-1/2}$ is the Lorentz factor, $\boldsymbol{\beta}(\beta_x,\beta_y,\beta_z)$ is the electron velocity in the unit of c, $-e$ and m_0 are the electron's charge and mass, respectively, and c is the velocity of light in vacuum. Here, $\mathbf{B}_p=\mathbf{z}b_p\exp(-t^2/t_p^2)$ is the pulsed magnetic field of the duration of t_p, where b_p is the amplitude of the magnetic field. From Maxwell's equations, the electric field related to the pulsed magnetic field can be estimated as $\mathbf{E}_p=(-\mathbf{x}y+\mathbf{y}x)(t/t_p^2)b_p\exp(-t^2/t_p^2)$.

Simulations are carried out by solving the momentum and energy equations by using the relativistic single-particle computer program. The electron energy γ as a function of the propagation distance is obtained for different parameters by assuming the initial electron energy γ_0 at the origin. The normalized laser intensity parameter is expressed as $a_0=eA_0/m_0\omega c$. From Eqs. (4) and (5), we can obtain the electron energy gain, $W=m_0c^2(\gamma-\gamma_0)$, in terms of the propagation distance and the phase of the laser. In Fig. 1(a), the dependence of the electron energy gain (W in GeV) has been presented as a function of the propagation distance (z in micrometers). For this calculation, we take the value of laser intensity parameter $a_0=10$ with the peak laser intensity of $I_0\sim5\times10^{21}$ W/cm^2. These parameters correspond to the laser wavelength $\lambda_0\sim1$ μm and the laser pulse duration $\tau_0=25$ fs. To realize the realistic focusing of the laser beam, we choose the laser waist size $w_0=4$ μm. About 60 T peak magnetic field of the duration of 100 ms is chosen. Here, we fix the value $\gamma_0=5$ in our numerical derivations of the electron motion according to Eqs. (4) and (5). The tight focusing of the laser beam provides the extremely intense fields. The intense ponderomotive force driven by the tightly focused laser beam pushes the electron in the forward direction and the electron can be accelerated to a GeV energy. The magnetic field plays an important role in resonance energy absorption by the electron from the electric field of the laser. When the cyclotron frequency of the electron motion in the uniform magnetic field approaches the Doppler-shifted laser frequency, the energy transfer from the laser to the electron will be maximum. The duration of the magnetic field is longer than the laser pulse duration, which allows the electron to stay in the magnetic pulse for the full duration of its interaction with the laser pulse. As a result, the electron can gain a very high energy up to the 10 GeV level for $a_0=10$. Figure 1(b) shows the electron energy gain with the phase of the laser field for the same parameters mentioned above. The electron energy gain is sensitive to the phase of the laser field. In a single cycle of the laser pulse, the electron energy gain approaches the maximum and minimum values. The magnetic field bends the electron out of the laser path. Hence, the electron leaves the interaction region and it does not lose its energy. In the absence of the magnetic field, the electron will get a maximum energy in the acceleration region and loses it energy in the deceleration region. The energy gradient can be estimated by $G=dW/dz$. The variation of energy gradient with the propagation distance is shown in Fig. 1(c) for $a_0=10$. The energy gradient has a peak and decreases with the propagation distance. In the same way, the energy gradient with phase of the field is shown in Fig. 1(d) for the same parameters as before. One can see that the energy gradient reaches a maximum for a particular phase of the field.

Figure 2 shows the electron energy gain with the distance for different laser intensity amplitudes, spot sizes, initial electron energies, and magnetic fields. As the electron velocity approaches the velocity of light, it moves from the focus due to the ponderomotive scattering. Because of the tight focusing effect, enhancement in energy of the electron is observed for higher laser intensity as seen in Fig. 2(a). As a result of high intensity of the laser, the energetic electron is pushed beyond the Rayleigh distance. Far from the Rayleigh length, the electron moves freely with a speed close to the speed of light, because the laser intensity is weak due to a large beam size far from the focus. From Fig. 2(b), it can be observed that the electron energy gain increases with spot size of the laser. The reason for this is that the increased spot size lengthens the interaction time of the electron in the acceleration region. In the same way, effects of the initial electron energy and the magnetic field strength on electron energy gain for laser intensity $a_0=10$ are represented in Figs. 2(c) and 2(d). From the results, it is seen that higher energy gain can be obtained if the electron has enough initial kinetic energy because the duration of the interaction between the laser and the electron increases with the initial electron energy. Furthermore, the electron is guided by the magnetic field so that it can stay in the interaction region to absorb more energy from the laser field. The resonance between the electron and the electric field of the laser becomes stronger at higher magnetic field. Therefore, the electron energy gain increases for higher magnetic field.

In conclusion, we studied the electron acceleration to GeV energies with a high power laser including the effect of tight focusing and the pulsed magnetic field. When the waist of the laser beam is of the order of the laser wavelength, then it is necessary to consider all field components that arise due to the tight focusing of the laser beam. In our investigation, we considered all field components from the realistic focusing of the laser beam. Additional effect of the pulsed magnetic field was also observed. The duration of the magnetic field should be longer than the laser pulse duration, which allows the electron to stay in the magnetic field for the full duration of its interaction with the laser pulse. As a result, the electron can gain a much higher energy during the acceleration. From our calculations, it is shown that achieving about 10 GeV energy is possible with a suitable laser intensity of proper spot size and magnetic field.

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[1] M. D. Perry and G. A. Mourou, Science **264**, 917 (1994).
[2] H. Hora, Nature (London) **333**, 337 (1988).
[3] T. Hauser, W. Scheid, and H. Hora, Phys. Lett. A **186**, 189 (1994).
[4] H. Hora, *Laser Plasma Physics: Force and the Nonlinearity Principle* (SPIE, Bellingham, WA, 2000), PM75, p. 144.
[5] J. Zawadzka, D. A. Jaroszynaki, J. J. Carey, and K. Wynne, Appl. Phys. Lett. **79**, 2130 (2001).
[6] D. Umstadter, Phys. Plasmas **8**, 1774 (2001).
[7] C. Joshi and T. Katsouleas, Phys. Today **56**(6), 47 (2003).
[8] D. N. Gupta and H. Suk, J. Appl. Phys. **101**, 114908 (2007).
[9] P. Sprangle, E. Esarey, and J. Krall, Phys. Plasmas **3**, 2183 (1996).
[10] D. N. Gupta and H. Suk, Laser Part. Beams **25**, 31 (2007).
[11] F. V. Hertemann, J. R. Van Meter, A. L. Troha, E. C. Landahl, N. C. LuhmannJr., H. A. Baldis, A. Gupta, and A. K. Kerman, Phys. Rev. E **58**, 5001 (1998).
[12] D. N. Gupta and H. Suk, Phys. Plasmas **13**, 044507 (2006).
[13] G. Malka, E. Lefebvre, and J. L. Miquel, Phys. Rev. Lett. **78**, 3314 (1997).
[14] Y. Cheng and Z. Zu, Appl. Phys. Lett. **74**, 2116 (1999).
[15] H. Liu, X. T. He, and H. Hora, Appl. Phys. B: Lasers Opt. **82**, 93 (2005).
[16] D. N. Gupta and H. Suk, Phys. Plasmas **13**, 013105 (2006).
[17] K. P. Singh, J. Opt. Soc. Am. B **23**, 1650 (2006).
[18] M. O. Scully and M. S. Zubairy, Phys. Rev. A **44**, 2656 (1991).
[19] S. M. Sepke and D. P. Umstadter, Opt. Lett. **31**, 2589 (2006).