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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 that 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.

Tabletop terawatt lasers based on the chirped-pulse amplification technique with ultrahigh intensities and ultrashort pulses have been developed.\textsuperscript{1} It has been possible to make electron acceleration by using these laser pulses in vacuum for the last two decades. Laser-based accelerators\textsuperscript{2–8} are capable of producing high-energy electrons/protons in much shorter distances than conventional accelerators due to the 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.\textsuperscript{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,\textsuperscript{18,19} the electric field components can be written as

\begin{align*}
E_x &= A_0(1 + s^2)\left[-\rho^2 Q_4 + i\rho^3 Q_5 - 2Q^2(x/w_0)^2\right] + s^2\left[2\rho^4 Q_6 - 3i\rho^5 Q_7 - 0.5\rho^6 Q_8 + (x/w_0)^2(8\rho^8 Q_4 - 2i\rho^9 Q_5)\right]|Qe^{-\sigma^2 - i\rho Q_0}e^{i\delta}, \tag{1}
\end{align*}

\begin{align*}
E_y &= A_0\left[2Q^3 x y / w_0^3 + s^4(8\rho^7 Q_4 - 2i\rho^8 Q_5)\right]|Qe^{-\sigma^2 - i\rho Q_0}e^{i\delta}, \tag{2}
\end{align*}

\begin{align*}
E_z &= A_0\left[2\rho^4 Q_5 x y / w_0^3 + 5(2\rho^5 Q_5 + 10i\rho^6 Q_6 + \rho^7 Q_7) x / w_0\right]|Qe^{-\sigma^2 - i\rho Q_0}e^{i\delta}, \tag{3}
\end{align*}

where \(\delta = \omega t - k z, \quad \rho^2 = (x^2 + y^2) / w_0^2, \quad Q = b / (ib + 2z), \quad \sigma^2 = \tau^2 / c^2 \tau_0^2, \quad b = 2\pi w_0^2 / \lambda_0, \quad \tau = z - ct, \quad s = 1 / kw_0, \quad k = \omega / c, \quad A_0\) is the laser intensity amplitude, \(w_0\) is the laser spot size, \(\lambda_0\) is the laser wavelength, and \(\tau_0\) 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 Helmholtz equation up to fifth-order...
tron velocity in the unit of \( e_0 \cdot c \). For this calculation, we take the value of laser intensity parameter \( a_0 = 4 \), \( w_0 = 4 \mu m \). 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 \( G = G/dz \). 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 energies, and magnetic fields. For a particular intensity parameter, we choose the laser waist size \( w_0 = 4 \mu m \). 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 \( G = G/dz \). 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.

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tial 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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