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Electron Acceleration by a Chirped Short Intense Laser Pulse in Presence of an External Axial Magnetic Field in Vacuum With Different Phase Values

Research Article

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Abstract. We investigated electron acceleration by a chirped short intense laser pulse in presence of an external magnetic field. The retained electron energy is very high with frequency chirp on increasing the value of chirp parameter and constant value of laser intensity parameter. Also, the retained electron energy increases on increment of laser intensity parameter. A linear frequency chirp $\omega(t) = \omega_0(1-\alpha t)t$ was considered, here ω_0 is the laser frequency at $z = 0$ and α is the frequency chirp parameter. On increasing the chirp parameters corresponding to the magnetic field with phase then the retained electron energy become so high. Also, we study the variation of the relativistic factor gamma (γ)and the laser intensity parameter (a_0); also the variation of the relativistic factor gamma (γ) and the magnetic field (b_0) with different values of the phase, $\phi = 0$, $\pi/4$ and $\pi/2$, respectively. As the time duration is increased the energy gain increased.

Keywords. Chirped short intense laser pulse; Magnetic field

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1. Introduction

The technique of *chirped pulse amplification* (CPA), invented in the mid 1980's and has revolutionized laser technology [1]. We are familiar that the chirp can be generated due to dispersion of materials they propagate through. If we talk in terms of signals and frequency, the up-chirp is the signal with increasing frequency in time and down-chirp with decreasing frequency in time. Positive chirp is when leading edge of pulse is red-shifted in relation to central wavelength and trailing edge is blue-shifted but the Negative chirp happens in opposite case. A chirp breaks the symmetry and circumvents the Lawson-Woodward theorem [2]. During last few decades Particle acceleration to relativistic energies by using a high intensity laser has been originated as a developing field of research. A vacuum as a medium for electron acceleration has some advantages over plasma. Laser acceleration of particles are preferred due their compactness and low-cost alternative to the conventional acceleration schemes [3]. On chirping in laser frequency an important scheme for laser acceleration has been adopted because due to the contribution of frequency chirp to the phase synchronization of the laser pulse and the electron, also the electron can gain considerable energy in the interaction with a focused chirped laser pulse whose electric field can be simulated by low-order Gaussian field [4,5]. Chirped-pulse amplification technique has been intensively pursued for the last decade and the development of ultrahigh power, short pulse lasers based on it [6]. The few chemical reactions have been demonstrated to be better controlled using phase-controlled femtosecond pulses; chirped pulses have been shown to lead to greater molecular photodissociation than unchirped pulses [7,8]. One-dimensional nonlinear analysis of wake-field generation and electron bunch acceleration by a chirped laser pulse were investigated numerically which shows that the optimum linear chirp parameter leads to the wake-field amplitude increase by one order of magnitude and accordingly the acceleration gradient [9]. The wake-field amplitude could be increased due to the chirp effect [10,11]. Transverse electron momentum increases due to frequency chirp and the electron escapes from the laser pulse near the pulse peak. Some researchers show that the maximum electron energy gain during acceleration by a linearly polarized chirped laser pulse is higher than that of the case of unchirped laser pulse. Longitudinal momentum also increases due to increase in longitudinal force [12]. The physics of the interaction of electrons with strong fields is attracting much attention and the acceleration of electrons by a laser in a vacuum has been investigated theoretically [13–16]. Also we known that a planar-laser pulse cannot be used for electron acceleration, since when it overtakes an electron, as the electron is ponderomotively driven forward in the rising part, but no net energy gain by the electron when it backwards in the trailing part [17]. For a fixed laser output power, the tightly focused chirped laser pulse can accelerate electrons to much higher energies [18]. The electron final energy is obtained as a function of laser beam waist, laser intensity, chirp parameter, and initial phase of the laser pulse. It is shown that the electron final energy depends strongly on the chirp parameter and the initial phase of the laser pulse [19]. The electron acceleration by a tightly focused laser beam is revisited by including the effect of laser frequency chirping and when the laser is tightly then frequency chirping plays an important role to enhance the electron energy focused [20]. Chirped electromagnetic pulses can be generated using solid state laser systems, self-chirped optical pulse in a free electron laser oscillator [21] and the propagation of high intensity laser pulse through a plasma channel [22] and the reflection of electromagnetic pulses from a relativistic ionization fronts [23]. The laser pulses are modelled by finite-duration trapezoidal and $\cos^2$ pulse-shapes and the maximum energy gain from interaction with a quadratic chirp is about half of what would be gained from a linear chirp [24] For two high intensity chirped lasers having the same amplitude and frequency, crossing at an arbitrary angle in a vacuum, interfere, causing modulation of laser intensity [25]. A linear frequency chirp increases the time duration of laser-electron interaction and the magnetic wiggler is very useful in improving the strength of ponderomotive force $v \times B$, it deflects the electron periodically in order to keep it traversing in the accelerating phase up to longer distance [26].

2. Electromagnetic Fields and Electron Dynamics

Now writing the equations for the propagation of a laser pulse with electric field as given below

$$E = \hat{x}E_x + \hat{z}E_z\,. \tag{2.1}$$

The electric field component E_x and E_z can be written as

$$E_x = \frac{E_0}{f}\cos(\phi)\exp\left[-\frac{(t-z/c)^2}{\tau^2} - \frac{r^2}{r_0^2 f^2}\right], \tag{2.2}$$

$$E_z = \frac{E_0}{f}\left[\frac{2x}{kr_0^2 f^2}\sin(\phi) + \frac{x}{z(1+(Z_R/z)^2)}\cos(\phi)\right]\exp\left[-\frac{(t-z/c)^2}{\tau^2} - \frac{r^2}{r_0^2 f^2}\right], \tag{2.3}$$

where

$$\phi = \omega(t)t - kz + \tan^{-1}(z/Z_R) - \frac{kr^2}{2z\left(1+\left(\frac{Z_R}{z}\right)^2\right)}, \tag{2.4}$$

$$\omega(t) = \omega_0(1-\alpha t)t \quad \text{and } f^2 = 1 + \left(\frac{z}{Z_R}\right)^2, \quad k = \frac{\omega(t)}{c},$$

$Z_R = kr_0^2/2$ is the Rayleigh length,

k is the laser wave number,

τ is the pulse duration,

r is the radial coordinate,

z_L is the initial position of the pulse peak,

$r^2 = x^2 + y^2$, r_0 is the minimum laser spot size,

and c is the velocity of light,

ω_0 is the laser frequency at $z = 0$ and α is the frequency chirp parameter.

The magneticfield related to the laser pulse is given by

$$\nabla \times E = -\frac{\partial B}{\partial t},$$

where

$$B_L = \hat{y}b_y + \hat{z}b_z\,.$$

Now specifying the symbols

$$b_z = -\frac{E_0}{f}\left[\frac{2y}{kr_0^2 f^2}\sin(\phi) + \frac{y}{z\left(1+\frac{1}{\alpha^2}\right)}\cos(\phi)\right]\exp\left[-\frac{(t-z/c)^2}{\tau^2} - \frac{r^2}{r_0^2 f^2}\right]. \tag{2.5}$$

Now consider an external axial magnetic field $B_A = (-x\hat{y})\frac{b}{r_0}\exp\left(-\frac{x^2}{2r_0^2}\right)$ is applied along y-direction to the laser pulse then the resultant field can be written as

$$B = B_L + B_A\,. \tag{2.6}$$

The equations governing electron momentum and energy has been by *Runge-Kutta* (RK4) method, initially we assume that the electron position is at origin. The electronic charge, $e = 1.6\times10^{-19}$ J and rest mass of the electron $m_0 = 9.1\times10^{-31}$ Kg. Throughout, this paper following dimensionless variables have been used.

$$a_0 \to \frac{eE_0}{m_0\omega c},\ b_0 \to \frac{eB_0}{m_0\omega},\ b_z \to \frac{eB_z}{m_0\omega_0 c},\ x \to \omega_0 x/c,\ z \to \omega_0 z/c,\ z_L \to \omega_0 z_L/c,$$
$$r_0 \to \omega_0 r_0/c,\ Z_R \to \omega_0 Z_R/c,\ t \to \omega_0 t,\ \tau \to \omega_0\tau \ \text{ and }\ \alpha \to \alpha/\omega_0\,.$$

3. Results and Discussion

Figures 1 shows relativistic factor gamma γ as a function of z. We have taken the common parameters- laser spot size $r_0 = 75$; $\phi = 0$; pulse duration $\tau = 50$, initial value of momentum $p_{z0} = 0$ and the chirp parameter $\alpha = 1.0\times10^{-5}$, 1.5×10^{-5}, 2.0×10^{-5}; but laser intensity parameters are different for Figure 1(a) $a_0 = 10$, Figure 1(b) $a_0 = 15$, Figure 1(c) $a_0 = 20$ and Figure 1(d) $a_0 = 25$, respectively. Also, the normalized magnetic field $b_0 = 0.1$, 0.2 and 0.3 corresponding to chirp parameters $\alpha = 1.0\times10^{-5}$, 1.5×10^{-5}, 2.0×10^{-5}, respectively. These figures shows the relativistic factor gamma γ as a function of z. As the laser intensity parameter increases then an increment takes place in retained energy or in other words we can say that the retained electron energy is proportional to laser intensity parameter. It is noticed that the maxima electron energy occurred at $a_0 = 10, 15, 20$ and 25 is approximately equal to $340, 550, 600$ and 700, respectively. One more important thing is also observed, at large value of chirp parameter $\alpha = 2.0\times10^{-5}$ (represented by dashed blue line) the energy gain is higher as compared the other values. We can say that the chirp parameter (α) plays important roll in energy enhancement. For all the figures there are three value of chirping parameters. Here we have applied an external axial magnetic field. The electron experiences a force by the resultant field of the lasers and during acceleration it gains high energy. For a suitable chirped frequency the electron accelerates to high energy. Also, it is assumed that the amplitude of electron oscillations is small in comparison with wavelength. Therefore, the electron is in a spatially uniform chirped electric field.

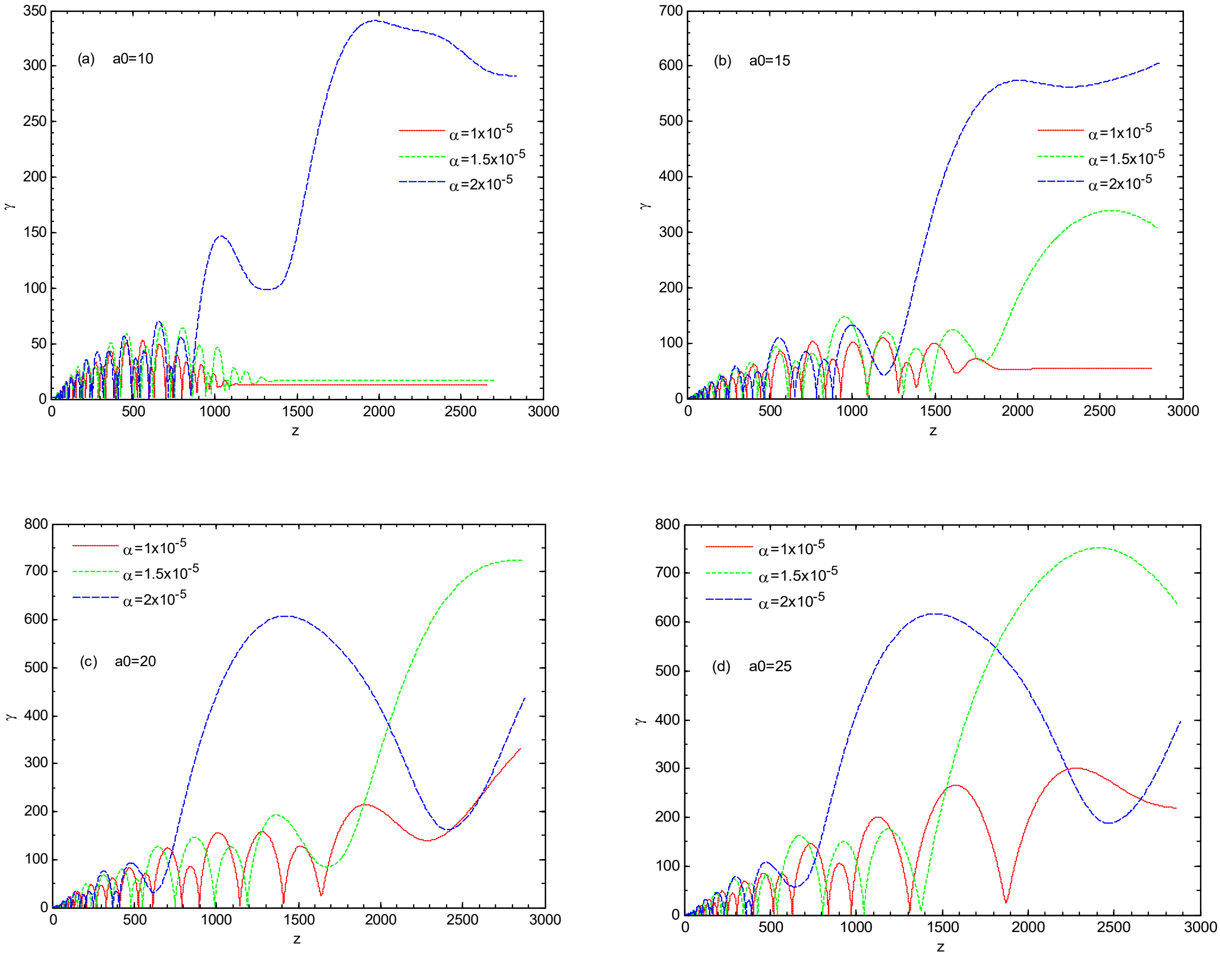

Figure 1. The variation of relativistic factor gamma γ as a function of z. $r_0 = 75$, $\phi = 0$, $\tau = 50$, $b_0 = 0.1$, 0.2 and 0.3; $p_{z0} = 0$. (a) $a_0 = 10$, (b) $a_0 = 15$, (c) $a_0 = 20$ and (d) $a_0 = 25$. Also the chirp parameter $\alpha = 1.0 \times 10^{-5}$ (for dotted red line), 1.5×10^{-5} (for dash-dotted green line) and 2.0×10^{-5} (for dashed blue line), respectively

Figure 2 shows relativistic factor gamma γ as a function of z. Here we took four values of the laser intensity parameter, $a_0 = 10, 15, 20$ and 25 with the corresponding to normalized magnetic field, b_0 are $0.1, 0.2, 0.3$ and 0.5, respectively. Also, the values of chirp parameter $\alpha = 1.0 \times 10^{-5}$, 1.5×10^{-5}, 2.0×10^{-5} and 2.5×10^{-5}. The remaining parameters are phase, $\phi = 0$, $r_0 = 75$, $p_{z0} = 0$ and the pulse duration, $\tau = 50$. When z is going on increasing corresponding to gamma then the energy gain increases and the relativistic factor for different initial energies is approximately $300, 350, 400$ and 500, respectively. The laser frequency chirping plays important role to increase the transverse momentum of the electron. Also, if there is increment in transverse momentum then there will also increment in longitudinal momentum due to the longitudinal $v \times B$ force enhancement. The energy enhancement takes place on increasing the laser intensity and chirp parameters simultaneously. The maximum value of energy takes place at $a_0 = 25$ and the chirp parameter $\alpha = 2.5 \times 10^{-5}$ represented by dashed black line in Figure 2. The energy also depends upon the chirp parameter (α). The laser frequency chirping plays important role to increase the transverse momentum of the electron. Also, if there is increment in transverse momentum then there will also increment in longitudinal momentum due to the longitudinal $v \times B$ force enhancement.

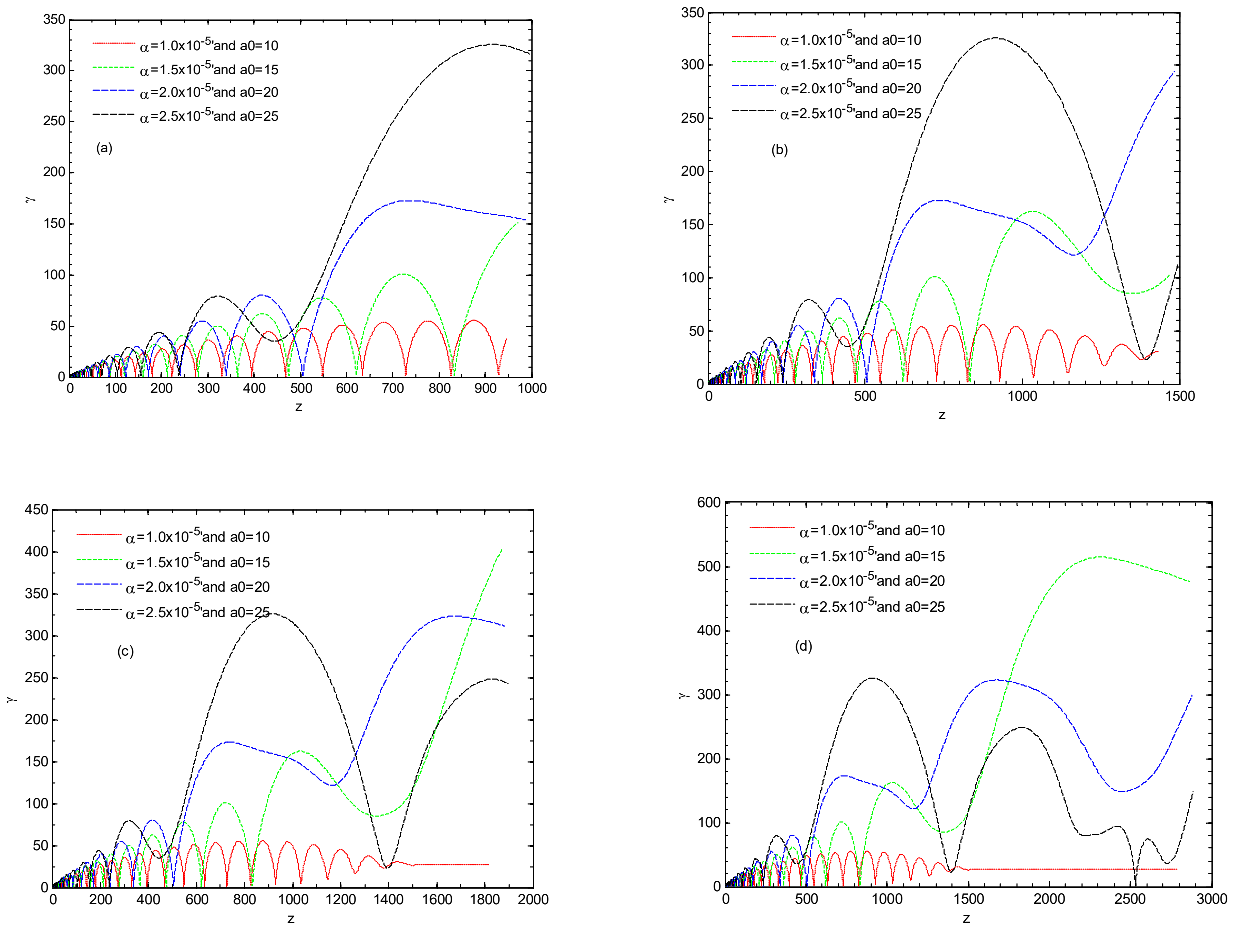

Figure 2. the variation of relativistic factor gamma γ as a function of z. $\phi = 0$, $r_0 = 75$, $p_{z0} = 0$ and $\tau = 50$. $a_0 = 10, 15, 20$ and 25 with corresponds to $\alpha = 1.0 \times 10^{-5}$, 1.5×10^{-5}, 2.0×10^{-5} and 2.5×10^{-5}, respectively. (a) $b_0 = 0.1$, (b) $b_0 = 0.2$, (c) $b_0 = 0.3$ and (d) $b_0 = 0.5$

Figure 3 shows relativistic factor gamma γ as a function of z. Here we some parameters are taken constant or fix which are $a_0 = 10$; $r_0 = 75$; $\tau = 50$; $p_{z0} = 0$ but in Figure 3(a)-3(d) only phase (ϕ) and chirp parameter (α) are varying. Again on increasing the laser intensity parameters energy enhancement is noticed. As we know that the retained electron energy depends strongly on frequency chirp parameter and initial position of the electron. Here the chirp parameters $\alpha = 1.0 \times 10^{-5}$, 1.5×10^{-5}, 2.0×10^{-5} the respective value of phase, ϕ are 0, $\pi/4$ and $\pi/2$ with $b_0 = 0.3, 0.4, 0.5$, respectively. Above figures viz. Figure 1 and Figure 2, these two are different from Figure 3 as here we are changing the values of phase (ϕ), even ϕ was taken to be zero in earlier two figures. The nature and the behaviour of all the curves is near about same excepted the energy i.e. the smoothly changing curves show the energy variation is different for every curve. With chirp parameter the energy gain increases. The electron is accelerated within a few degrees to the axial direction.

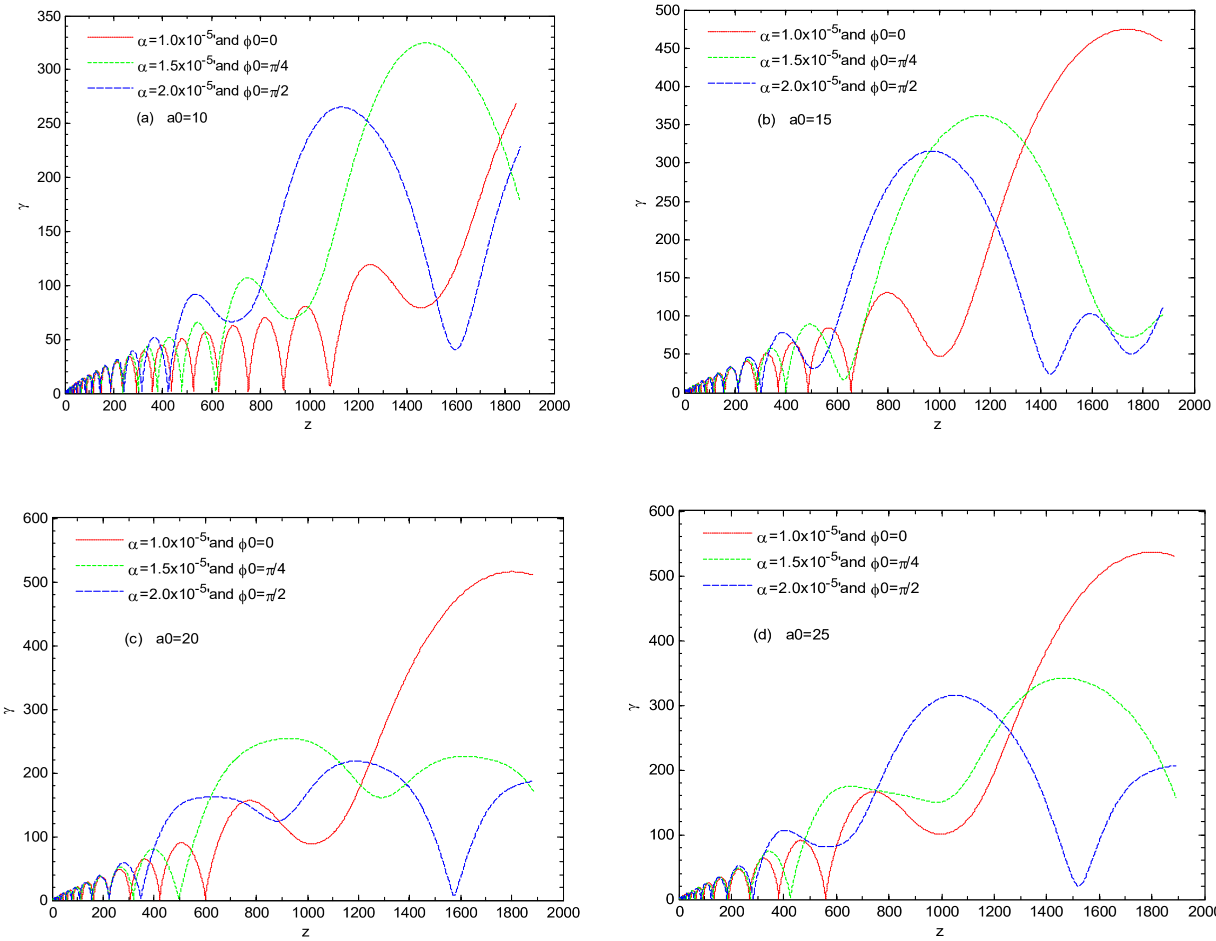

Figure 3. Relativistic factor gamma γ as a function of z. When$\alpha = 1.0 \times 10^{-5}$ then $\phi = 0$ and $b_0 = 0.3$; when $\alpha = 1.5 \times 10^{-5}$ then $\phi = \pi/4$ and $b_0 = 0.4$; when$\alpha = 2.0 \times 10^{-5}$ then $\phi = 0$ and $b_0 = 0.5$. Also $r_0 = 75$; $\tau = 50$; $p_{z0} = 0$. (a) $a_0 = 10$, (b) $a_0 = 15$, (c) $a_0 = 20$ and (d) $a_0 = 25$

Figures 4 shows the relativistic factor gamma γ as a function of laser intensity parameter a_0. In this figure we have taken the laser spot size $r_0 = 75$, the pulse duration $\tau = 50$ and the chirp parameter $\alpha = 3.0 \times 10^{-5}$, 5.5×10^{-5}, 7.5×10^{-5} the values of phases are same as in Figure 3. Only difference is that here is we took the different values of the normalized magnetic field for Figure 4(a) and 4(b). For Figure 4(a) $b_0 = 0.01, 0.03, 0.05$ and $b_0 = 0.1, 0.3, 0.5$ for Figure 4(b). As the time duration is increased the energy gain increased. High energy gain can be achieved when the laser intensity becomes high and electrons pre-accelerate it is only desirable; high energy gain also can be achieved when we change the some parameters like laser intensity parameter, laser spot size, pulse duration and chirp parameter etc. The energy in Figure 4(a) is smaller than Figure 4(b) because the normalized magnetic field is 10 times smaller as compared to Figure 4(b); so the normalized magnetic field plays important role in energy gain. The tight focussing effect of the beam can be ignored when the beam waist size is larger than laser wavelength. For tightly focussed laser the energy gain becomes maximum when adopted a suitable frequency chirp.

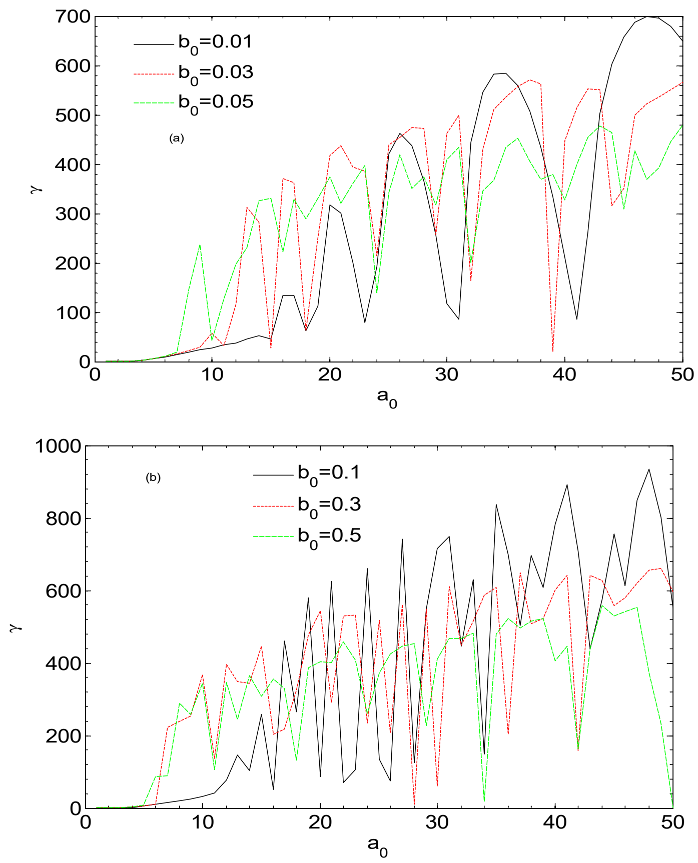

Figure 4. The relativistic factor gamma γ as a function of laser intensity parameter a_0. $r_0 = 75$; $\tau = 50$; $p_{z0} = 0$. When $\alpha = 3.0 \times 10^{-5}$ then $\phi = 0$; $\alpha = 5.5 \times 10^{-5}$ then $\phi = \pi/4$; $\alpha = 7.5 \times 10^{-5}$ then $\phi = \pi/2$. (a) $b_0 = 0.01, 0.03, 0.05$ (b) $b_0 = 0.1, 0.3, 0.5$

Figures 5 shows the relativistic factor gamma γ as a function of normalized magnetic field b_0. The common values taken for both the figures are the values of the phase which are used in Figure 3. In Figure 5(a) we have taken $r_0 = 75$; $\tau = 100$ and the chirp parameter $\alpha = 3.5 \times 10^{-5}$, 6.5×10^{-5} and 7.5×10^{-5}. But the different values of r_0 is used in Figure 5(b) which is $r_0 = 150$. Also the values of the laser intensity parameter, a_0 are 10, 15 and 20, respectively. We do not consider the tight focussing effect of the beam when the beam waist size is large compared to laser wavelength. We know that the higher value of frequency chirp parameter reduces the electron energy gain during acceleration because the rate of frequency chirp of laser pulse decreases and reduces the rate of frequency chirp. But by changing some parameters like laser intensity parameter, laser spot size, pulse duration and chirp parameter etc. the energy gain can be increased. As the time duration is increased the energy gain also increased. In some situations a high electron energy can be achieved if the electron is injected with finite kinetic energy between ultra-high intensity chirped lasers.

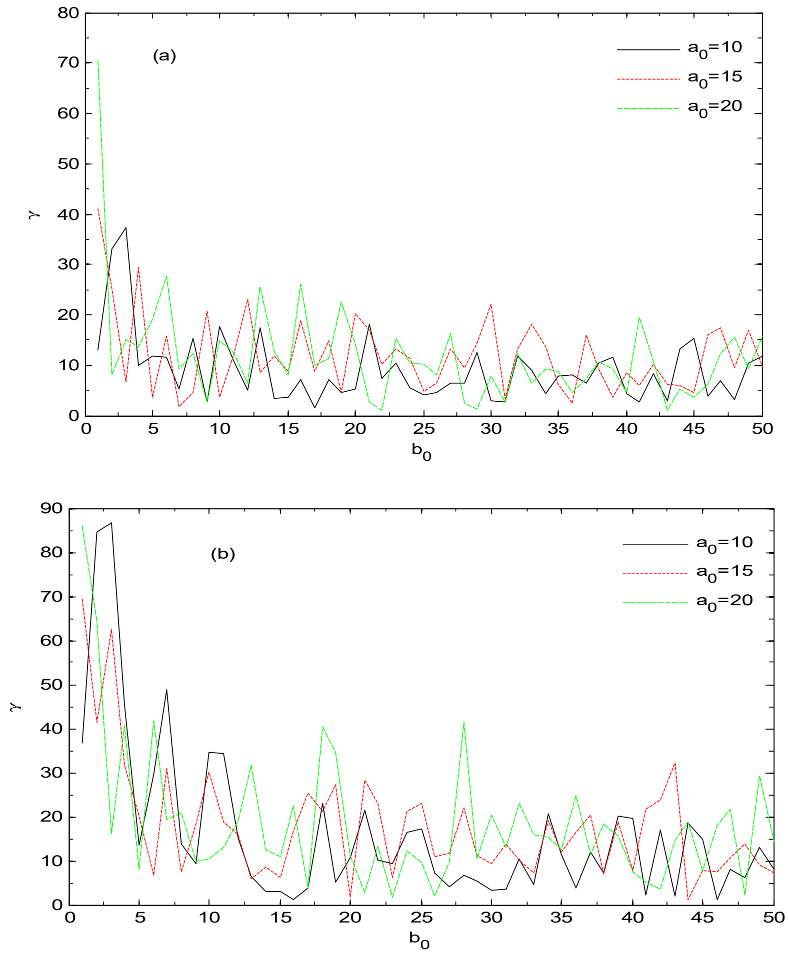

Figure 5. The relativistic factor gamma γ as a function of normalized magnetic field b_0. (a) $r_0 = 75$; and (b) $r_0 = 150$. Also $a_0 = 10, 15$ and 20; $\tau = 100$; $\alpha = 3.5 \times 10^{-5}$, 6.5×10^{-5} and 7.5×10^{-5}

4. Conclusions

The study of this paper is based on field variation and electron acceleration by a chirped short intense laser pulse in presence of an external magnetic field in vacuum. It is found that the following parameters- laser spot size, laser pulse duration, phase, and the relative position of the electrons with respect to laser pulse and chirp parameters affect electron acceleration. Chirp parameter and phase play important role for energy enhancement. On varying the chirp parameter with corresponding values of electric and magnetic field as well as phase the maximum energy gain can be achieved. We investigated electron acceleration by a chirped short intense laser pulse when an external magnetic field is applied along y-direction. The retained electron energy is very high with frequency chirp when we increase the value of chirp parameter and take the constant value of laser intensity parameter. Also the retained electron energy increases on increment of laser intensity parameter. A linear frequency chirp $\omega(t) = \omega_0(1 - \alpha t)t$ was considered, here ω_0 is the laser frequency at $z = 0$ and α is the frequency chirp parameter. On increasing the chirp parameters as well as magnetic field with phase then the retained electron energy become so high. Also we study the variation of the relativistic factor gamma γ and the laser intensity parameter, a_0. As the time duration is increased the energy gain increased.

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Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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