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The Study of a Chirped Short Intense Laser Pulse In Vacuum in External Magnetic Field and The Variation of Field & Phase

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ABSTRACTS

A chirped short intense laser pulse in vacuum in external magnetic field studied as well as the variation of field & phase is studied. During the study when we fixed some parameters like laser intensity parameter, pulse duration and spot size etc. it found that the energy gain increases on increasing the phase value. In this study we took the phase values viz. $\phi = \pi/2$, $\pi/3$, $\pi/4$ and $\pi/6$. The maximum value is found at $\phi = \pi/2$, and minimum is at $\phi = \pi/6$. Also the variation of energy gain and normalized magnetic field shows that the energy gain is higher when for larger value of laser spot size and energy gain attains higher value when b_0 lies between 0 to 5.

Keywords: Laser acceleration, chirped short intense laser pulse, phase and magnetic field.

INTRODUCTION

There are many techniques for chirping the pulse, the technique of chirped pulse amplification (CPA) which was invented around 1980's and has revolutionized laser technology [1] with its effect and uniqueness on that time. The experiments show that the chirp can be generated due to dispersion of materials they propagate through. There are some advantages of a vacuum as compared to medium over plasma for electron acceleration. Laser acceleration play important role in laser-plasma because the laser acceleration of particles are preferred since they are compact and having low-cost alternative to the conventional acceleration schemes [2]. The most cases reveals that the high intensity laser pulse initially propagate through an underdense plasma before reaching the critical density surface. Particle accelerators invented in 20th century and have found applications with a wide range of fields not only in our life but also in research & development and in our society etc. The longitudinal momentum increases when there is an increment in longitudinal force [3], also some authors found that the electron energy gain during acceleration by a linearly polarized chirped laser pulse is higher than that of the case of unchirped laser pulse. Interaction of electrons with strong fields is much attracting and the acceleration of electrons by a laser in a vacuum has been investigated theoretically [4-7]. 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 $\mathbf{v}\times\mathbf{B}$, it deflects the electron periodically in order to keep it traversing in the accelerating phase up to longer distance [8]. When we apply a suitable frequency chirp in this case the energy of the electrons increases significantly and the quasimonoenergic collimated GeV electrons can be produced using a right choice of laser spot size, frequency chirp, and pulse duration [9]. It is noticed that the electrons are generated close to the rising edge of the laser pulse, trapped by the low intensity and never experience the peak of the pulse, and gain low energies. The electron can obtain net energy from a chirped electromagnetic plane wave in which the instantaneous frequency changes with the interaction time [10]. The parametric study of electron acceleration by a chirped Gaussian laser pulse was followed [11]. For the propagation distances much grater than the Rayleigh length, the modifications indicate that the temporal shape of the chirped laser beam will be changed and for propagation distances less than the Rayleigh length, the change in laser pulse shape is not considerable [12]. During last few years many views come out by the study for the tight focusing of the laser pulse for electron acceleration in vacuum [13-16]. Remarkable progress in development of high power femtosecond pulses and their applications has been achieved using chirped pulse amplification method [17-18]. The maximum electron energy gain during the acceleration by linearly polarized chirped laser pulse is higher than that of the case of unchirped laser pulse. Earlier study of vacuum electron acceleration schemes by using a chirped laser pulse, where the effect of a magnetic field was also considered and the laser field in our previous work was also linearly polarized [19-20]. The retained electron energy depends strongly on frequency chirp parameter and initial position of the electron [21]. We have more reviews on these extreme laser–matter interactions [22-23].

ELECTROMAGNETIC FIELDS AND ELECTRON DYNAMICS

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

$$\mathbf{E} = \hat{x}\,E_x + \hat{z}\,E_z \quad (1)$$

The electric field component E_x and E_z can be written as

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

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

(3)

Where

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

(4)

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

$k = \frac{\omega(t)}{c}$,

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

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

and c is the velocity of light,

k is the laser wave number,

z_L is the initial position of the pulse peak,

τ is the pulse duration,

r is the radial coordinate,

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

The magnetic field related to the laser pulse is given by

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

$\mathbf{B}_L = \hat{y}B_y + \hat{z}B_z$. Now specifying the symbols

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

(5)

Suppose an external axial magnetic field writing in vector form,

$\mathbf{B}_A = (-x\hat{y})\frac{B}{r_0}\exp\left(-\frac{x^2}{2r_0^2}\right)$ is applied along y-direction to the laser pulse then the resultant field can be written as

$$\mathbf{B} = \mathbf{B}_L + \mathbf{B}_A$$

(6)

The above equations governing electron momentum and energy has been solved by Runge-Kutta (RK4) method, we took into account initially the electron takes position at origin. Here e is the electronic charge having value 1.6 x 10^{-19} J and the value of rest mass of the electron (m_0) is 9.1 x 10^{-31} Kg. In this paper we introduced following dimensionless variables.

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

RESULTS AND DISCUSSION

Figure 1 shows relativistic factor gamma γ as a function of z. Here we fixed some parameters for figure 1(a)-1(d), laser spot size r_0 = 100; pulse duration τ = 60, initial value of momentum p_{z0} = 0 and the chirp parameter (α) takes values α =1.0x10^{-5}, 1.5x10^{-5}, 2.0x10^{-5}; also the magnetic field b_0 =0.1, 0.2 and 0.3. Here the value of phase (ϕ) is different for figure 1(a)-1(d). For figure 1(a)-1(d) α =1.0x10^{-5}& b_0 =0.1 (shown by red dotted line), when α =1.5x10^{-5}& b_0 =0.2 (shown by green dotted line) and when α =2.0x10^{-5}& b_0 =0.3 (shown by blue dotted line). We observed that the chirp parameter (α) as well as phase plays important roll in energy enhancement. There are three value of chirping parameters and an external axial magnetic field ids applied. 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 and here the amplitude of electron oscillations is small in comparison with wavelength. Therefore, the electron is in a spatially uniform chirped electric field. The laser frequency chirping plays important role to increase the transverse momentum of the electron. When the transverse momentum increases then longitudinal momentum also increases due to the longitudinal $\mathbf{v}\times\mathbf{B}$ force enhancement. The energy enhancement takes place on increasing the laser intensity and chirp parameters simultaneously. Figures 1(a)-1(d) show that the nature and the behaviour of curves are approximately same 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. Here we observe that the energy gain going on increasing with phase. The maximum values of energy gain is when phase ϕ is π /2 and minimum for ϕ = π /6. On increasing the phase the energy gain increases.

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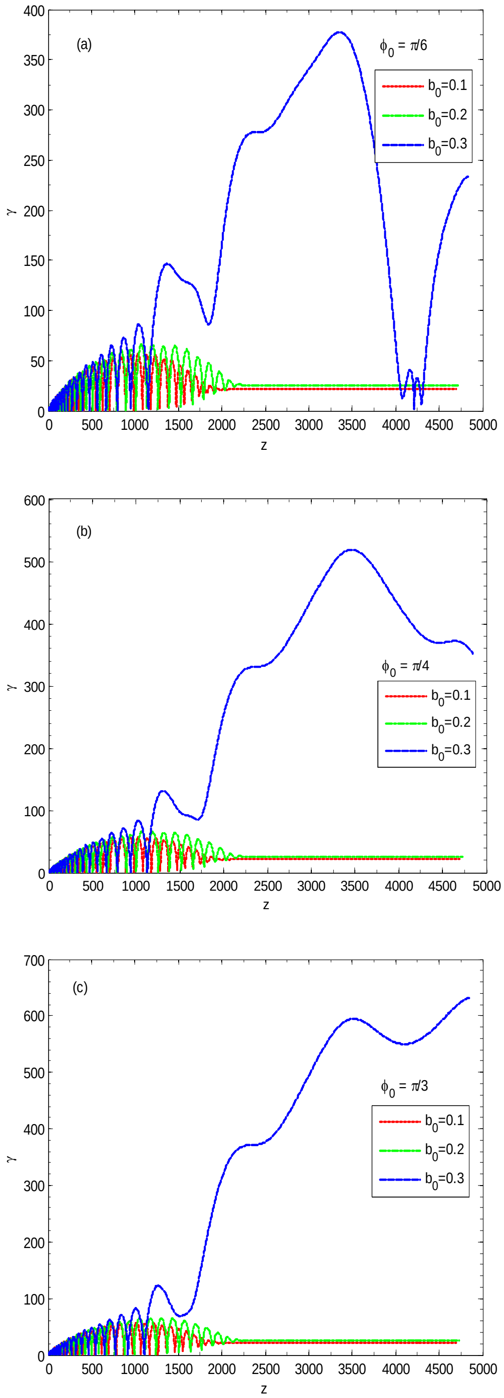
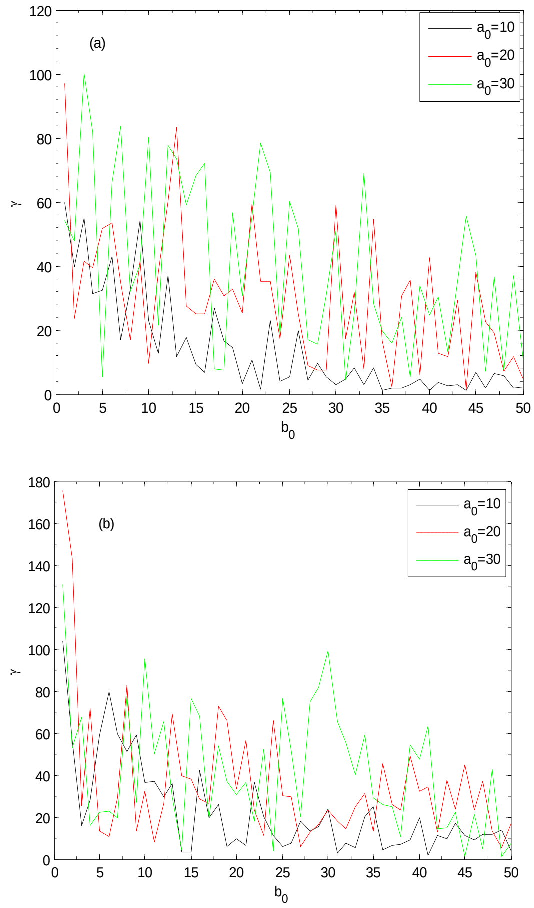


Figure 1 relativistic factor gamma γ as a function of z. Here α takes values α =1.0x10^{-5}, 1.5x10^{-5}, 2.0x10^{-5}; and b_0 =0.1, 0.2, 0.3. Also a_0 =10; r_0 =100; p_{z0} =0 and τ =50].

Figure 2 shows the relativistic factor gamma γ as a function of normalized magnetic field b_0 . For figures 2(a)-2(b) we took some common parameters like, pulse duration τ =50; laser intensity parameter, a_0 =10, 15 and 20; Here the chirp parameter α =3.0x10^{-5}, 4.0x10^{-5} and 5.0x10^{-5}.The value of phase (ϕ) is π /3, π /4 and π /2 respectively corresponding to laser intensity parameter. But for figure 2(a) r_0 =75 and 100 for figure 2(b).

We don't 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. 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. From these two figures we observe that the

energy gain is higher for figure 2(b) and this higher value is only when the normalized magnetic field lies between 0 and 5. The behaviour for both is same but not identical.



[Figure 2 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, 20 and 30 with corresponding values of $\phi = \pi/4$, $\pi/3$ and $\pi/2$; τ =50; α =3.0x10^{-5}, 4.0x10^{-5} and 5.0x10^{-5}].

CONCLUSIONS

The study of a chirped short intense laser pulse in vacuum in external magnetic field shows the variation of energy gain with normalized distance as well as with normalized magnetic field. When we take some fixed values of laser intensity parameter, pulse duration and spot size etc. then the energy gain increases on increasing the phase value. Here we take only four values of the phase values i.e. $\phi = \pi/2$, $\pi/3$, $\pi/4$ and $\pi/6$. The behaviour and nature of the curves of figure 1 are near about same but energy gain is different. The maximum value of it is observed at $\phi = \pi/2$, and minimum is at $\phi = \pi/6$. For each curve magnetic field is different. Also the observation for variation of energy gain with normalized magnetic field reveals that the energy gain is higher when for larger value of laser spot size only when we took fixed values of other parameters, and energy gain attains higher value when b_0 lies between 0 to 5

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