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Effect of Laser Pulse Parameters and Initial Phase on the Acceleration of Electrons by a Circularly Polarized Gaussian Laser Beam under the Influence of Azimuth Magnetic Field

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Abstract

The effect of laser pulse parameters and initial phase on the acceleration of electrons by a circularly polarized Gaussian laser beam under the influence of azimuth magnetic field is study.The energy gained by the electron depends upon its initial position with respect to the laser pulse.The energy gained by the electrons attains a maximum value for the initial phase; normalized magnetic fields and laser spot size. Electron injected in the path of circularly polarized Gaussian laser beam, it lies between 0 and 15 and the azimuth magnetic field is applied in z direction. For small initial phases the enhancement of energy can be take place only if we vary laser parameters such as normalized magnetic field, spot size, pulse duration, electron's injection angle etc. Relationship between phase and electron's injection angle is agreed theortically.

Keywords: *Laser paramaters, energy gain, initial phase and normalized magnetic fields.*

1. Introduction

The laser-plasma accelerators have been adopted as a next generation of compact accelerators to produce relativistic electron beams. In 1980s and 1990s the plasma accelerator schemes investigated were based on a long-pulse laser. Also during last two-three decades the laser-plasma based accelerators made their unique identity and have generated more interest due to the development of super intense laser pulses and a series of experimental achievements leading to the production of quasi-monoenergetic electron beams with energies in the range of 100 MeV to 1 GeV [1-2]. These days the generation of high-quality, efficient ion beams plays an important role in the field of ultra-intense due to the compactness and cheap sources of high-energy ion beams these can be an alternative to conventional radio-frequency accelerators exhibit desirable properties such as brightness, pulse duration and emittance [3-4].Electron injected in the path of a circularly polarized Gaussian laser beam under the influence of an external axial magnetic field is accelerated with a several GeV of energy in vacuum with a small angle of injection [5]. When intense lasers interact with over-dense plasma which introduced a most powerful and efficient method ofhigh harmonic x-ray generation for the reflection of laser pulse from the over-dense plasma electrons [6]. The scheme of superposed linearly-polarized Gaussian laser pulses focused and phased in a pattern to cancel their transverse field components in vacuum and the longitudinal components accelerate the suitably-phased relativistic electrons. The study tells that the electrons energy gain is higher with a circularly polarized (CP) laser beam as compared to a linearly polarized (LP), indicated by the polarization characteristics of a Gaussian laser beam. When there is a interaction of the plasma electrons with the circularly polarized laser pulse then the electrons absorb not only the laser energy but also the proportional amount of the total angular momentum of the laser pulse, which leads to the electron rotation around the direction of the laser propagation and generation of the axial magnetic field by the azimuthal electron current [7-8]. Singh et.al. found that the energy gained by the electron depends upon its initial position with respect to the laser pulse and when the electrons are close to the pulse peak with initial phase pi/2, are scattered least and gain higher energy [9]. Generally in laser-plasma we adopt two types of magnetic fields named azimuthal magnetic field and axial magnetic field these fields generated during the interaction of the plasma electrons with the linearly and circularly polarized laser pulse which leading to betatron resonance between the electrons and the electric field of the laser, also the electrons are effectively accelerated to high energies [10-12]. The force exerted by the laser pulses accelerates the electron beam and the acceleration gradient becomes many times higher than that can be attained with RF accelerators. The study of acceleration of electrons by a circularly polarized laser pulse in the presence of a short duration intense axial magnetic field reveals that the resonance occurs between the electrons and the laser field for an optimum magnetic field leading to effective energy transfer from laser to electrons [13]. The laser intensity will be higher during the rising part than that of the falling part it is only possible when the laser intensity interacts with the electron and hence the electron gains net energy [14].

We know that when an electron interacts with a laser pulse with a Gaussian radial profile in a vacuum during the rising part but in a gas during the rising part, the pulse ionizes the gas to form plasma by tunnel ionization producing a density maximum on the axis, which causes the laser pulse to defocus. Laser parameters, such as pulse polarizations, beam width, initial phase, tight focusing, frequency amplifications, chirped-pulse amplification (CPA), and transverse electromagnetic (TEM) modes, some laser parameters were analysed for the generation of high energy electron these are beam width, pulse polarizations, tight focusing, initial phase, frequency amplifications, transverse electromagnetic (TEM) modes and chirped-pulse amplification (CPA) etc. [15-19]. The interaction of a high-power laser pulse having a sharp front with a thin plasma layer which and the trajectories of the electrons of the plasma layer were calculated numerically then compared with the electron trajectories obtained in particle-in-cell simulations [20]. There are some differences between the linearly polarized (LP) and circularly polarized (CP) pulses [21-22], also the studies showed that for CP the interaction accelerates all the ions in the skin layer and the fastest ones produce a very dense bunch with a narrow energy spectrum, directed in the forward direction. One decade earlier some people found a new mechanism for laser-driven ion acceleration, where particles gain energy directly from the radiation pressure (RP) exerted onto the target by the laser beam [23-29]. If we talk about the ultrashort for which few cycle circularly polarized (CP) attosecond pulses, molecular orientation influences the generation of the induced magnetic fields as a result of preferential ionization perpendicular to the molecular axis [30]. We know that the rising edge of the laser ionizes the gas and creates a plasma, in a laser–plasma wake-field accelerator (LPWA), an intense laser pulse is focused in a light gas or in a mixture of heavy and light gases [31-34]. Plasma-based accelerators are of great interest because of their ability to sustain extremely large acceleration gradients.Group velocity and phase velocity play an important role in laser- two plasma acceleration the use of phase velocity is used to determine the minimum injection energy, the maximum energy gain, the maximum plasma wave amplitude, and the dephasing length. The study by some researchers show that on laser driven electron acceleration use low-order Gaussian or Bessel beams [35-38]. This paper shows the effect of laser pulse parameters and initial phase on the acceleration of electrons by a circularly polarized Gaussian laser beam under the influence of azimuth magnetic field.

2. Electron Dynamics

We know that when an electron interacting with CP laser pulse experiences a force due to longitudinal component of electric field of laser. As a result, it gets accelerated in the direction of propagation of the laser, but in LP laser pulse exactly same effect is not observed. In this paper we took azimuth magnetic field instead of axial magnetic field. We assume that a pre-accelerated electron is initially injected at a small angle δ with respect to the propagation axis of laser pulse with momentum having the equation $p_0 = \hat{x}p_0\sin\delta + \hat{z}p_0\cos\delta$ (P)

Where p_0 is the initial momentum of the electron. Now consider a CP laser pulse propagating along the z-direction. The transverse components of electric field $\left(\mathbf{E} = \hat{x}E_x + \hat{y}E_y\right)$ is expressed as

$$E_x(r,t,z) = \frac{E_0}{f(z)}\exp(i\phi)\exp\left(-\left(\frac{1}{\tau^2}\left(t-\frac{z-z_L}{c}\right)^2\right)-\frac{r^2}{r_0^2 f^2}\right)$$

(1)

$$\mathbf{B_z}(r,z,t) = -\left(\frac{1}{\omega}\right)\left(\nabla\times\mathbf{E_L}\right)$$

$$E_y(r,t,z) = \frac{E_0}{f(z)}\exp\left[\left(i\phi+\frac{\pi}{2}\right)\exp\left(-\left(\frac{1}{\tau^2}\left(t-\frac{z-z_L}{c}\right)^2\right)-\frac{r^2}{r_0^2 f^2}\right)\right] \quad (2)$$

where

E_0 is the amplitude of electric field,

τ is the pulse duration,

ϕ is the Gaussian beam phase,

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.

Other Gaussian beam parameters are defined as

$$f(z) = \sqrt{1+\xi} \quad (3)$$

Where $f(z)$ is the laser beam width parameter, and $Z_R = kr_0^2/2$ is the Rayleigh length, k is the laser wave number

and $$\phi = \omega_0 t - kz + \tan^{-1}(\xi) - \frac{zr^2}{\left(Z_R r_0^2 f^2\right)} + \phi_0$$

ω_0 is the laser frequency,

ϕ_0 is the initial phase,

and $\tan^{-1}(\xi)$ is the **Guoy phase**.

Suppose we applied externally an azimuth magnetic field along the z-axis then

$\mathbf{B_s} = B_0\hat{z}$ (4) B_0 is the maximum value of the azimuth magnetic field.

Now $E_z(r,z,t)$ and $B_L(r,z,t)$ represents the longitudinal electric components and magnetic fields which can be expressed as

$$E_z(r,z,t) = -\left(\frac{i}{k}\right)\left(\frac{\partial E_x}{\partial x}+\frac{\partial E_y}{\partial y}\right) \quad (5)$$

$$\mathbf{B_z}(r,z,t) = -\left(\frac{1}{\omega}\right)\left(\nabla\times\mathbf{E_L}\right) \quad (6)$$

Where the field vectors $\mathbf{E_L} = E_x\hat{x} + E_y\hat{y} + E_z\hat{z}$ and $\mathbf{B_L} = B_x\hat{x} + B_y\hat{y} + B_z\hat{z}$ are the laser's fields

The total magnetic field is $\mathbf{B} = \mathbf{B}_L + \mathbf{B}_s$ (7)

When a Circularly Polarized laser pulse induced electron acceleration under the influence of magnetic field in vacuum then the accelerated when injected at a small angle δ about the propagation axis of laser pulse. The z-axis is aligned with the laser beam propagation direction as well as in the direction of externally applied magnetic field. We have already defined the electric and magnetic field those will be used to write the equations for the momentum and energy of electron.

$$\frac{dp_x}{dt} = -eE_x + e\beta_z B_y - e\beta_y\left(B_z + B_0\right) \quad (8)$$

$$\frac{dp_y}{dt} = -eE_y - e\beta_z B_x + e\beta_x\left(B_z + B_0\right) \quad (9)$$

$$\frac{dp_z}{dt} = -eE_z - e\left(\beta_x B_y - \beta_y B_x\right) \quad (10)$$

$$\frac{d\gamma}{dt} = -e\left(\beta_x E_x + \beta_y E_y + \beta_z E_z\right) \quad (11)$$

Where -e is the electronic charge having value 1.6 x 10^{-19} J and m_0 is the rest mass respectively, also $\left(E_x, E_y, E_z\right)$ and $\left(B_x, B_y, B_z\right)$ are the (x, y, z) components of the electric field and magnetic field respectively and $\left(p_x, p_y, p_z\right)$ are the (x, y, z) momentum coordinates of the momentum $\mathbf{p} = \gamma m_0\mathbf{v}$ and $\left(\beta_x, \beta_y, \beta_z\right)$ are the (x, y, z) coordinates of the normalized velocity, $\boldsymbol{\beta} = \frac{\mathbf{v}}{c}$. The Lorentz factor is $\gamma^2 = 1 + \left(p_x^2 + p_y^2 + p_z^2\right)/\left(m_0 c\right)^2$. For finding the solution of above equations such dimensionless

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variables used throughout. The dimensionless variables are expressed as follows:

$$\tau' \to \omega_0 \tau, \quad r'_0 \to \frac{\omega_0 r_0}{c}, \quad z'_L \to \frac{\omega_0 z_L}{c},$$

$$x' \to \frac{\omega_0 x}{c}, \quad y' \to \frac{\omega_0 y}{c}, \quad z' \to \frac{\omega_0 z}{c},$$

$$\beta_x \to \frac{v_x}{c}, \quad \beta_y \to \frac{v_y}{c}, \quad \beta_z \to \frac{v_z}{c},$$

$$t' \to \omega_0 t, \quad p'_0 \to \frac{p_0}{m_0 c}, \quad p'_x \to \frac{p_x}{m_0 c},$$

$$p'_y \to \frac{p_y}{m_0 c}, \quad p'_z \to \frac{p_z}{m_0 c}$$

$$k' \to \frac{ck}{\omega_0}, \quad a_0 \to \frac{eE_0}{m_0 \omega_0 c}, \quad b_0 \to \frac{eB_0}{m_0 \omega_0 c}.$$

The coupled linear differential equations (8)-(11) are of degree 1 and can be solved numerically by Runge-Kutta method (RK4).

Figure 1 shows the electron energy gain, γ versus electron's injection angle (δ). This energy gain is analysed for the normalized intensity parameters a_0 = 15, 20 and 25. In figure 1(a), the normalized intensity parameters a_0 = 15, in figure 1(b), a_0 =20 and in figure 1(c) a_0 =25. The normalized laser spot size r'_0 = 200, 300 and 400 also the value of initial phases are $\pi/2$, π and $3\pi/2$ taken for figure 1. The value of τ' =100, 150 and 200 respectively for figures 1(a), 1(b) and 1(c). The study shows that on of increasing the laser intensity parameters the enhancement in the energy gain takes place. For higher value of laser intensity parameters the energy gain is higher. As the electron energy gain is sensitive to the electron's injection angle even with a small value of initial momentum. We are familiar about the acceleration gradient which increases with decrease in initial momentum so that the higher energy gain occurs at small value of initial momentum. A significant change in electron energy gain appears only when there is a small change in angle of injection. In figure 1 there are three values of initial phase, $\pi/2$, π and $3\pi/2$ also three values of r'_0 = 200, 300 and 400. It is noticed that for large value of initial phase as well as the normalized laser spot size, r'_0 the energy gain is maximum. The electron's injection angle (δ) lies between 0 and 15. When the electron's injection angle (δ) lies between 5 to 7 units on x-axis the energy gain is maximum. Suppose δ=0 then the contribution of transverse component of electron's momentum becomes zero and electron's injection is purely along the direction of propagation of laser pulse. A small optimized angle of electron's injection improves the electron's momentum to an appropriate value to place the electron in phase with the laser pulse for the effective acceleration.

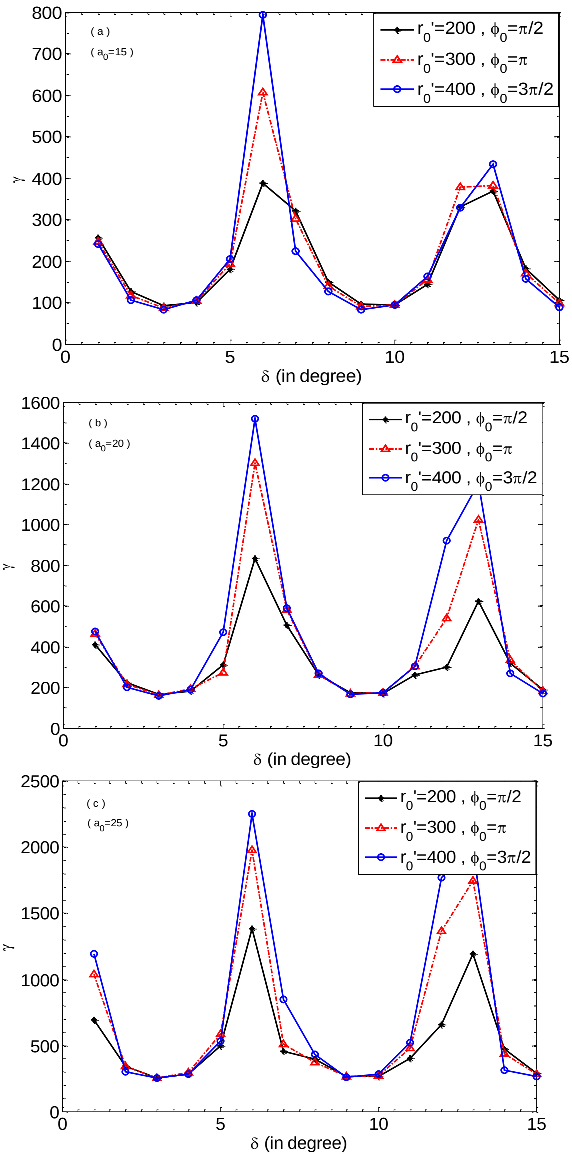

Figure 1 Electron energy gain, γ versus electron's injection angle (δ). r'_0 = 200, 300 and 400. Initial phase, $\pi/2$, π and $3\pi/2$; τ' =100 & a_0 =15, 150 & a_0 =20 and 200 & a_0 =25 respectively for figures 1(a), 1(b) and 1(c).

Figure 2 shows the variation of energy gain with the normalized magnetic field (b_0). In Figures 2(a), 2(b) and 2(c) the normalized laser intensity parameter a_0 having values 15, 20 and 25 respectively. In figure the electron energy gain is analysed as a function of normalized magnetic field b_0 at different values of pulse duration, τ' and the normalized laser intensity parameter a_0. The value of pulse duration, τ' are 100, 150 and 200 respectively for figures 2(a), 2(b) and 2(c). The common parameters for figure 2 are electron's injection angle (δ), normalized laser spot size (r'_0) and initial phase; here δ =8.5, 12 and 13.5; r'_0 =200 (black line), 300 (red line) and 400 (blue line); $\phi_0 = 3\pi/2, 5\pi/2$ and $7\pi/2$. Like the figure 1 again it is noticed that when the laser intensity parameters, a_0 increases then the energy gain also increases and for higher value of laser intensity parameters a_0 the energy gain is higher. When the initial phase and laser spot size are higher, the energy gain is maximum. So the initial phase and laser spot size play an important role in energy enhancement. When thenormalized magnetic field moves in the positive direction of x then the energygain increases at every point of b_0. The optimization is solely a base for maximum energy gain by electron during interaction with a CP laser.

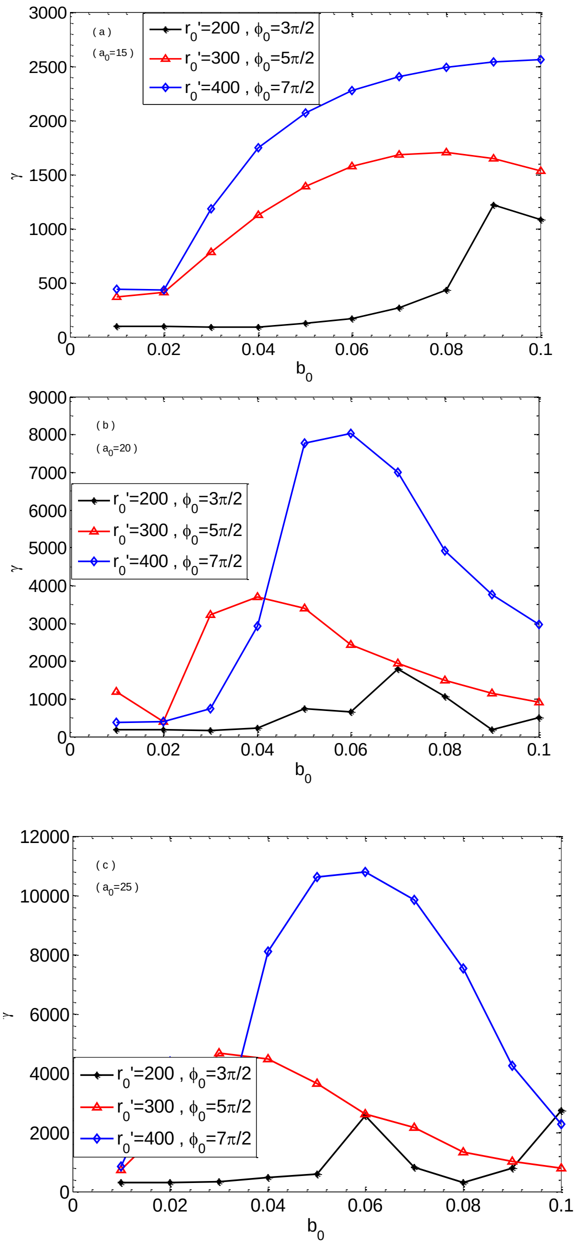

Figure 2 Variation of energy gain with the normalized magnetic field (b_0). Initial phase $\phi_0 = 3\pi/2, 5\pi/2$ and $7\pi/2$; δ =8.5, 12 and 13.5; r'_0 =200 (black line), 300 (red line) and 400 (blue line); $\phi_0 = 3\pi/2, 5\pi/2$ and $7\pi/2$. τ' =100 & a_0 =15, 150 & a_0 =20 and 200 & a_0 =25 respectively for figures 2(a), 2(b) and 2(c).

Figure 3shows the electron energy gain variations γ with normalized distance z. The energy gain variations γ with normalized distance z is analysed with laser intensity parameters a_0 = 15, 20 and 25 with optimized electron injection in the presence of magnetic field. For figures 3(a), 3(b) and 3(c) the values of the laser intensity parameters are a_0 = 15, 20 and 25. For figure 3 the values of laser parameters are fixed. In figure for black curve the electron's injection angle δ=8.5; the normalized magnetic field b_0 = 0.1 and the initial phase ϕ_0 is $3\pi/2$. For red curve the electron's injection angle δ=13; thenormalized magnetic field b_0 = 0.2 and the initial phase ϕ_0 is $5\pi/2$. Last δ=13.5; b_0 = 0.3 and $\phi_0 = 7\pi/2$ for blue curve. The normalized magnetic field zero is not opted in this paper. The electron energy gain is relatively higher in the presence of magnetic field. Pulse duration, τ' takesvalues 100, 150 and 200 for figures 3(a), 3(b) and 3(c) with the respective values of r'_0 =200, 300 &400. The high energygain is depends upon the high value of laser intensity parameters; besides this it also depends on normalized magnetic fields, pulse duration and laser spot size. The energy gain also can be increased with different initial phases in this paper only three fixed values is taken. If we take small initial phases enhancement of energy can be take place only if we vary laser parameters such as normalized magnetic field, spot size, pulse duration, electron's injection angle etc. But the initial phase play important role in enhancement.

In Figure 4 shows the variation of the initial phase with respect to electron's injection angle δ when the magnetic field is applied. When electron's injection angle travels towards the positive direction change in initial phase takes place. The value of electron's injection angle lies between 0 to 15 for these values the phase values reaches and attains maximum 2.8 when τ'=100 and 4.25 when τ'=200 for figures 4 (a) and 4 (b) respectively. So the phase verifies the relationship with electron's injection angle. For both figures 4 (a) and 4 (b) the normalized laser intensity parameter a_0 having values 15 (for black line), 20 (red line) and 25 (blue line); normalized magnetic field b_0 takes values 1, 2 and 3. But laser spot size and pulse duration are different for both figures. In figure 4(a) r'_0 =200, 250 & 300; and in figure 4(b) r'_0 =200, 300 & 400; so the variation is adequate to study the behaviour of phase with the electron's injection angle.

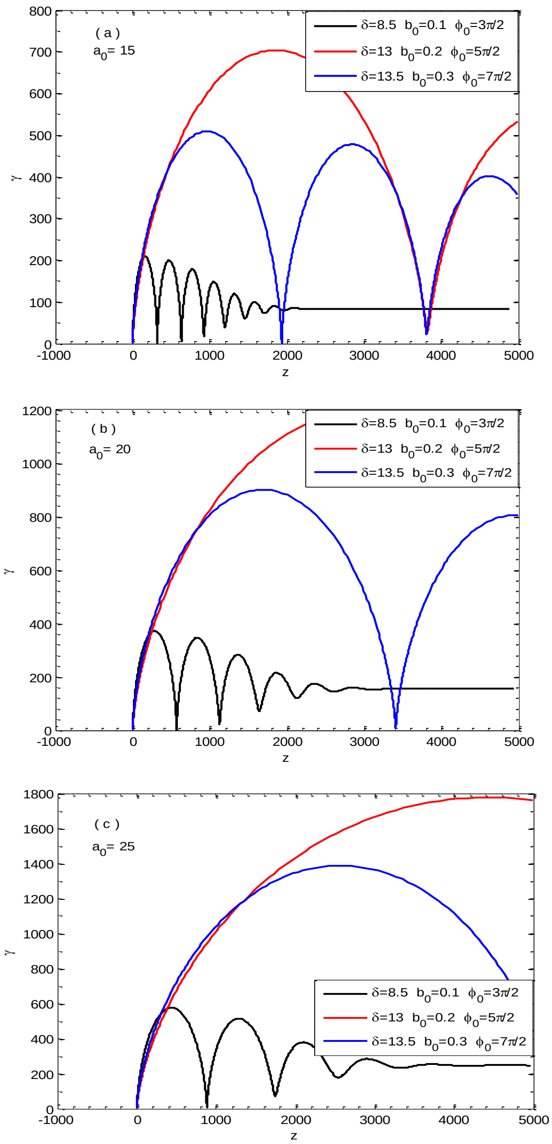

Figure 3 Electron energy gain variations γ with normalized distance z. Laser spot size r'_0 =200, 300 & 400; δ =8.5,13 & 13.5; b_0 = 0.1, 0.2 & 0.3; $\phi_0 = 3\pi/2$, $5\pi/2$ & $7\pi/2$ and τ' =100 & a_0 =15, 150 & a_0 =20 and 200 & a_0 =25 respectively for figures 3(a), 3(b) and 3(c).

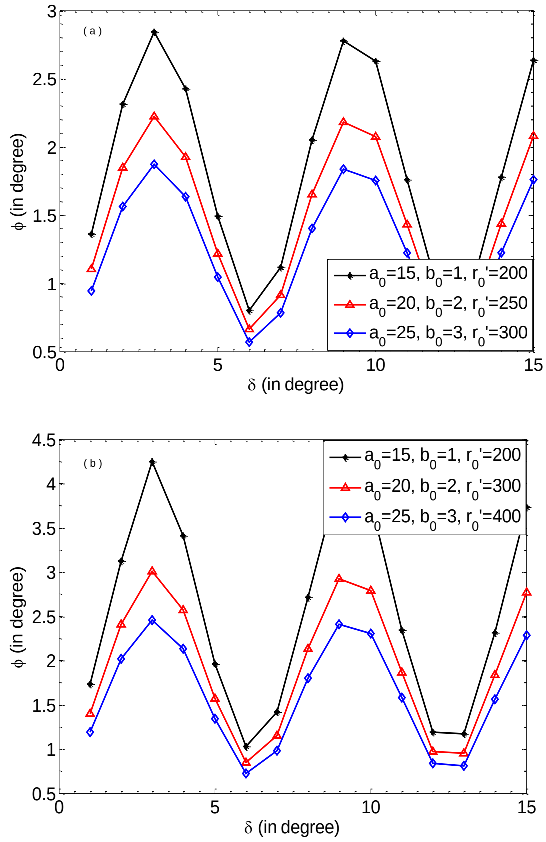

Figure 4 Variation of the initial phase with respect to electron's injection angle (δ) when the magnetic field is applied. (a) r'_0 =200, 250 & 300; τ' =100 and (b) r'_0 =200, 300 & 400; τ' =200; b_0 =1, 2 & 3.

3. Conclusions

The variation of laser pulse parameters and initial phase is discussed. We took the acceleration of electrons by a circularly polarized Gaussian laser beam under the influence of azimuth magnetic field which is is applied along z-direction. It is found that the energy gained by the electron depends upon its initial position with respect to the laser pulse. Also the energy gained by the electrons reaches at a maximum value on taking the suitable laser parameters such as initial phase; normalized magnetic fields and laser spot size etc. For small initial phases the enhancement of energy can be take place only if we vary laser parameters such as normalized magnetic field, spot size, pulse duration, electron's injection angle etc. Relationship between phase and electron's injection angle is studied.

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References

[1] Singh K.P., Sajal V. & Gupta D.N., Quasi-monoenergeticGeV electrons from the interaction of two laser pulses with a gas, Laser Part. Beams **26**, 597–604 (2008).

[2] Esarey E., Sprangle P., Krall, J. & Ting, A., Overview of plasma-based accelerator concepts. IEEE Trans. Plasma Sci. **24**, 252–288. (1996).

[3] Snavely R. A., Key M. H., Hatchett S. P., Cowan T. E., Roth M., Phillips T. W., Stoyer M. A., E. A. Henry E. A., T. C. Sangster T. C., Singh M. S., Wilks S. C., MacKinnon A., Offenberger A., Pennington D. M., Yasuike K., Langdon A.B., Lasinski B. F., Johnson, Perry J.D., and Campbell E. M., Phys. Rev. Lett. **85**, 2945 (2000).

[4] E. L. Clark E. L., Krushelnick K., Zepf M., Beg F. N., Tatarakis M., Machacek A., Santala M. I.K, Watts I., P. A. Norreys P. A., and Dangor A. E., Phys. Rev. Lett. **85**, 1654 (2000).

[5] Ghotra H.S. and Kant N., Electron injection for direct acceleration to multi-GeV energy by a Gaussian laser field under the influence of axial magnetic field, Phys. Plamsas**23**, 053115 (2016).

[6] Thaury C., Quéré F., Geindre J.P., Levy A., Ceccotti T., Monot P., Bougeard M., Réau F., D'oliveira P., Audebert P., Marjoribanks R. & Martin P.H. Plasma mirrors for ultrahigh-intensity optics. Nat. Phys. **3**, 424–429 (2007).

[7] Kostyukov I. Yu.,Shvets G., Frisch N. J., and Rax J. M., Laser Part. Beams **19**, 133 (2001); Bull. Am. Phys. Soc. **47**, 39 (2000).

[8] Steiger A.D. and Woods C.H., Phys. Rev. D **6**, 1468 (1972).

[9] Singh K.P., Gupta D.N. and Malik H.K., The effect of laser pulse parameters and initial phase on the acceleration of electrons in a vacuum, Phys. Scr. **77** 045401 (6pp) (2008)

[10] Zeng G., Phys. Rev. E **60**, 5950 (1999).

[11] Kostyukov I. Yu., Shvets G., Fisch N. J., and Rax J. M., Phys. Plasmas **9**, 636 (2002).

[12] Gahn C., Tsakiris G.D., Pukhov A., Meyer-ter-Vehn J., Pretzler G., Thirolf P, Habs D and Witte K. J., Phys. Rev. Lett. **83**, 4772 (1999).

[13] Singh K.P., J. Appl. Phys. **100**, 044907 (2006).

[14] Singh K. P., Gupta D. N., Tripathi V. K. and Gupta V. L. , *Phys. Rev.* E **69,** 046406 (2004).

[15] Ghotra H. S. and Kant N., Opt. Commun. **356**, 118 (2015).

[16] Salamin Y. I., Phys. Rev. A **82**, 013823 (2010); Ghotra H. S. and Kant N., Laser Phys. Lett. **13**, 065402 (2016).

[17] Ghotra H. S. and Kant N., Laser Part. Beams **34**(2), 9 (2016).

[18] Hu S. X. and Starace A. F., Phys. Rev. E **73**, 066502 (2006).

[19] Ghotra H. S. and Kant N, Opt. Rev. **22**, 539 (2015).

[20] Victor V. Kulagin, Vladimir A. Cherepenin, Min Sup Hur and Hyyong Suk, Flying mirror model for interaction of a super-intense nonadiabatic laser pulse with a thin plasma layer: Dynamics of electrons in a linearly polarized external field Phys. Plasmas **14**, 113101 (2007).

[21] Liseikina T. V. and Macchi A., Features of ion acceleration by circularly polarized laser pulses. Appl. Phys. Lett., **91**(17):171502, (2007).

[22] Macchi A., Cattani F, Liseykina Tatiana V., and FulvioCornoltiFulvio, Laser acceleration of ion bunches at the front surface of overdense plasmas. Phys. Rev. Lett., **94**(16):165003, (2005).

[23] Liseikina T. V. et.al., Appl. Phys. Lett. **91**, 171502 (2007).

[24] Zhang X. et. al., Phys. Plasmas **14**, 073101 (2007).

[25] Rykovanov S. G. et al., New J. Phys. **10**, 113005 (2008).

[26] Robinson A. P. L. et al., New J. Phys. **10**, 013021 (2008).

[27] Yan X. Q. et. al., Phys. Rev. Lett. **100**, 135003 (2008).

[28] Klimo O. et. al., Phys. Rev. ST Accel. Beams **11**, 031301 (2008).

[29] Qiao B. et. al., Phys. Rev. Lett. **102**, 145002 (2009).

[30] Yuan Kai-Jun and Andr´e D. Bandrauk, Attosecond Magnetic Field Pulse Generation by Intense Few Cycle Circularly Polarized UV Pulses, J1K 2R1 January 13, 2018 arXiv:1306.2209v2 [physics.optics] 10 Jul 2013.

[31] Geddes C G R et. al., *Nature* **431** 538–41(2004).

[32] Mangles S. et. al.,*Nature* **431** 535 (2004).

[33] Faure J et. al., *Nature* **431** 541 (2004).

[34] Chen M, Sheng Z-M, Ma Y-Y and Zhang J, *J. Appl. Phys.* **99** 056109 (2006).

[35] B. Hafizi, A. Ting, E. Esarey, P. Sprangle, and J. Krall, Phys. Rev. E **55**,5924 (1997).

[36] Hartemann F.V., et al, Phys. Rev. E **58**, 5001 (1998).

[37] Lax M., Louisell W.H., and McKnight W.H., Phys. Rev. A **11**, 1365 (1975).

[38] Hafizi B., Ganguly A. K., Ting A., Moore C. I., and Sprangle P., Phys.Rev. E **60**, 4779 (1999).