Electron Injection for Direct Acceleration by A Gaussian Laser Field Under the Influence of Azimuth Magnetic Field

Research Article

Ravindra Singh[1,*,iD], Sandeep[2] and Jaspreet Kaur[3]

[1] Department of Physics, Shivaji College (University of Delhi), Raja Garden, New Delhi 110027, India
[2] Department of Physics, Deen Dyal Upadhyaya College (University of Delhi), Sector 3, Dwarka, Delhi 110 078, India
[3] Department of Electronics and Communication Engineering, Beant College of Engineering and Technology, Gurdaspur 143 521, Punjab, India
*Corresponding author: ravidelhi06@yahoo.com

Abstract. Electron injection for direct acceleration by a circularly polarized Gaussian laser field under the influence of azimuth magnetic field is studied. The electron energy gain, γ versus electron's injection angle δ at different values laser intensity parameters and laser spot size shows the energy enhancement on increasing the parameters. For a small change in angle of injection then there appears a significant change in electron energy gain also for the variation of energy gain and magnetic field energy gain increases when value of δ is 8.5, 8.0, 13.5 and 13, respectively. It is observed that δ should be small and optimized for appropriate momentum to maximize the electron energy gain due to a relativistic longitudinal momentum and the variation of the scattering angle of the electron θ with respect to electron's injection angle δ in the presence of magnetic field shows a relatively lower scattering is observed with optimized values of injection angle in the presence of magnetic field.

Keywords. Gaussian laser pulse; Electron's injection angle

PACS. 42.55.-f

1. Introduction

During last decade the laser driven electron acceleration mechanism has become a fast advancing area of scientific research [1, 2]. Due to its compactness and low-cost the laser acceleration of particles has been proposed the conventional acceleration schemes [3, 4]. As we know that when an electron accelerated along a specific direction (say z-direction) by a linear electrostatic plasma wave then electron is accelerated and its velocity increases which tends to the speed of light, $v_z \rightarrow c$. Suppose the phase velocity of the plasma wave is constant with $v_p < c$ then the electrons will eventually outrun the plasma wave and move into a phase region of the plasma wave that is decelerating. The relative error may be significant for some specific values of initial phase even at moderate values of laser spot sizes and it does not show initial phase dependence for a circularly laser pulse [5]. The researchers considered tight focusing of the laser pulse for electron acceleration in vacuum [6, 8] and the valuable works on the combined effect of tight focusing and frequency chirping of a laser beam on a test particle acceleration in vacuum. Direct electron acceleration in vacuum is an interesting field and by the some people it has been investigated experimentally and theoretically [9, 10]. If a laser beam is focused down to the order of laser wavelength, then a Gaussian beam description becomes inaccurate [11, 12]. Direct laser acceleration of electrons can be achieved by utilizing the axial field of a guided, radially polarized laser pulse in a density-modulated plasma waveguide [13]. Laser acceleration is less expensive than acceleration by conventional accelerators. A few years earlier the ionization-based injection schemes have attracted much attention due to their simplicity and flexibility [14, 15]. If the angle of injection is small then about the propagation axis of laser pulse definitely improves the electron energy gain during laser-electron interaction. If we inject into a single plasma wave bucket, it is necessary for both the injection pulse spot size and pulse length to be small compared to the plasma wavelength. As we are familiar that higher energy gain by the electron with a *circularly polarized* (CP) laser beam in comparison with a *linearly polarized* (LP) is indicated by the polarization characteristics of a Gaussian laser beam. An electron while interacting with CP laser pulse experiences a force due to longitudinal component of electric field of laser. Ionization injection induced by short wavelength laser pulses inside a nonlinear wakefield driven by a longer wavelength laser was investigated using multidimensional *particle-in-cell* (PIC) simulations and generation of very bright electron beams in either collinear propagating or transverse colliding geometry revealed [16]. Ultra-intense *radially polarized* (RP) laser beam has a strong longitudinal field component at the axis of the beam for accelerating electrons and among the various laser acceleration configurations it is very promising [17–19]. For direct electron acceleration in vacuum which employed by a relativistic single particle simulation, the net electron energy gain from the axicon Gaussian radially polarized laser beam is enhanced under the influence of time varying axial magnetic field [20]. The study shows that on laser driven electron acceleration use low-order Gaussian or Bessel beams [21–24]. Some parameters such as the laser parameters, pulse polarizations, beam width, initial phase, tight focusing, frequency amplifications, *chirped-pulse amplification* (CPA), and *transverse electromagnetic* (TEM) modes, these were analysed for the generation of high energy electron [7, 25–28]. Some people show that the study electron energy gain for higher modes is high, but it suffers with de-phasing of electron at shorter distance in the absence of any additional magnetic field [29], also the role of distinct mode indices under the influence of axial magnetic field can be utilized

for the formulation of desired-sized accelerators based on the accelerating distance of electron. In LWFA by a short laser pulse an electron plasma wave is driven resonantly also additional injection mechanism is required [30]. There are two types of velocity named group velocity and phase velocity these two play an important role in laser-plasma acceleration the phase velocity of the plasma wave is used to determine the minimum injection energy, the maximum energy gain, the maximum plasma wave amplitude, and the dephasing length. Plasma-based accelerators are of great interest because of their ability to sustain extremely large acceleration gradients [31]. The accelerating gradients in conventional radio-frequency, linear accelerators are currently limited. In a plasma-based accelerator the length of the accelerating wave is approximately the plasma wavelength, also the acceleration is the result of the axial field of the plasma wave and not the laser field directly and the phase velocity of the plasma wave is typically equal to the group velocity of the laser pulse and is less than the speed of light (c). Electron acceleration by laser in a vacuum by a quadratically chirped laser pulse was investigated by Salamin and Jisrawi [32] and it was found that the maximum energy gain is about half of what it would be using a linear chirp. When the electron is accelerated by an intense short pulse laser in a static magnetic field in vacuum then the optimum value of the magnetic field decreases with laser intensity and initial electron energy and the energy gain also depends upon the laser spot size and peaks for a suitable value [33]. For vacuum laser acceleration, there has been much interest in studying the acceleration of electrons by a chirped Gaussian laser pulse [34–39] and for such types of materials the electron can get considerable energy in tailored parameters such as chirp parameter and polarization state of the laser wave. Lawson-Woodward theorem says that the particle interaction with a perfectly symmetrical plane-wave pulse results in zero net energy gain [40]. This paper shows the role of electron's injection angle with respect to the propagation axis of laser pulse for effective acceleration with a CP laser pulse under the influence of external azimuth magnetic field in vacuum.

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. Also, we know that the presence of axial magnetic field improves the influence of $\boldsymbol{v} \times \boldsymbol{B}$ force and the angle of injection determines the relative dominance of transverse and longitudinal components of electron's momentum which plays an important role in early trapping of electron in laser fields. 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

$$p_0 = \hat{x} p_0 \sin\delta + \hat{z} p_0 \cos\delta, \tag{1}$$

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 ($\boldsymbol{E} = \hat{x} E_x + \hat{y} E_y$) is expressed as

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

$$\boldsymbol{B}_z(r,z,t) = -\left(\frac{1}{\omega}\right)(\nabla \times \boldsymbol{E}_L),$$

$$E_y(r,t,z) = \frac{E_0}{f(z)}\exp\left[\left(i\phi + \frac{\pi}{2}\right)\exp\left(-\left(\frac{1}{\tau^2}\left(t - \frac{z - z_L}{c}\right)^2\right) - \frac{r^2}{r_0^2 f^2}\right)\right], \tag{3}$$

where E_0 is the amplitude of electric field,
ϕ is the Gaussian beam phase, τ is the pulse duration, 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

$$f(z) = \sqrt{1 + \xi}, \tag{4}$$

where $f(z)$ is the laser beam width parameter,
$Z_R = kr_0^2/2$ is the Rayleigh length, k is the laser wave number,
$$\phi = \omega_0 t - kz + \tan^{-1}(\xi) - \frac{zr^2}{t(Z_R r_0^2 f^2)} + \phi_0$$
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 axial magnetic field along the z-axis then

$$\boldsymbol{B}_s = B_0 \hat{z}, \tag{5}$$

B_0 is the maximum value of the axial magnetic field.

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

$$E_z(r,z,t) = -\left(\frac{i}{k}\right)\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y}\right), \tag{6}$$

$$\boldsymbol{B}_z(r,z,t) = -\left(\frac{1}{\omega}\right)(\nabla \times \boldsymbol{E}_L), \tag{7}$$

where the field vectors $\boldsymbol{E}_L = E_x\hat{x} + E_y\hat{y} + E_z\hat{z}$ and $\boldsymbol{B}_L = B_x\hat{x} + B_y\hat{y} + B_z\hat{z}$ are the laser's fields.

The total magnetic field is

$$\boldsymbol{B} = \boldsymbol{B}_L + \boldsymbol{B}_s. \tag{8}$$

When a Circularly Polarized laser pulse induced electron acceleration under the influence of axial 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 azimuth 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.

$$\frac{dp_x}{dt} = -eE_x + e\beta_z B_y - e\beta_y(B_z + B_0), \tag{9}$$

$$\frac{dp_y}{dt} = -eE_y - e\beta_z B_x + e\beta_x(B_z + B_0), \tag{10}$$

$$\frac{dp_z}{dt} = -eE_z - e\left(\beta_x B_y - \beta_y B_x\right), \tag{11}$$

$$\frac{d\gamma}{dt} = -e\left(\beta_x E_x + \beta_y E_y + \beta_z E_z\right), \tag{12}$$

where $-e$ and m are the electronic charge and rest mass respectively, also the symbols have their usual meanings such as (E_x, E_y, E_z) and (B_x, B_y, B_z) are the (x, y, z) components of the electric field and magnetic field respectively. (p_x, p_y, p_z) are the (x, y, z) coordinates of the momentum $\boldsymbol{p} = \gamma m_0 \boldsymbol{v}$ and $(\beta_x, \beta_y, \beta_z)$ are the (x, y, z) coordinates of the normalized velocity, $\boldsymbol{\beta} = \frac{v}{c}$.

The Lorentz factor is $\gamma^2 = 1 + (p_x^2 + p_y^2 + p_z^2)/(m_0 c)^2$.

For solving above equations we will adopt such dimensionless variables. The dimensionless variables are expressed as follows:

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

$$x' \to \frac{\omega_0 x}{c}, \quad y' \to \frac{\omega_0 y}{c}, \quad z' \to \frac{\omega_0 z}{c}, \quad \beta_x \to \frac{v_x}{c}, \quad \beta_y \to \frac{v_y}{c}, \quad \beta_z \to \frac{v_z}{c},$$

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

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

Equations (8)-(11) are the coupled linear differential equations of degree 1. These equations can be solved numerically by Runge-Kutta method (RK4) for electron energy.
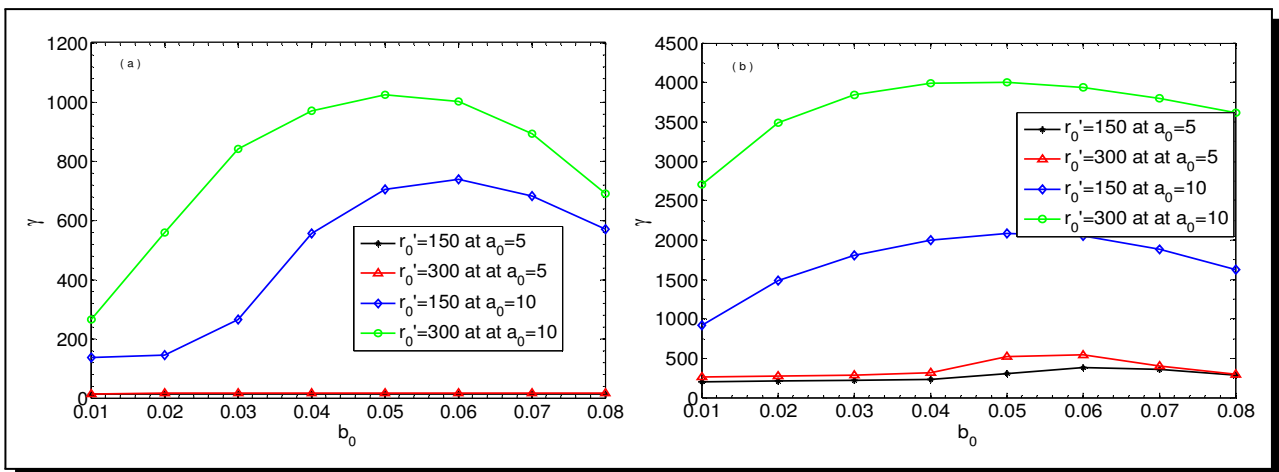
3. Results and Discussion

Figure 1 shows the electron energy gain, γ versus electron's injection angle δ. This energy gain is analysed for the normalized intensity parameters $a_0 = 5$ and 10 for Figure 1(a), $a_0 = 10$ and 15 for Figure 1(b), $a_0 = 15$ and 20 for Figure 1(c) and $a_0 = 20$ and 25 for Figure 1(d) at normalized laser spot size $r'_0 = 150$ and 300. The value of $\tau' = 150$. Electron energy gain is extremely sensitive to initial electron momentum. As the value of laser intensity parameters, a_0 is increases then the energy gain becomes higher. The electron energy gain is also sensitive to the electron's injection angle even with a small value of initial momentum. Also, the acceleration gradient increases with decrease in initial momentum so that the higher energy gain occurs at small value of initial momentum. It is notice that even for a small change in angle of injection then there appears a significant change in electron energy gain. The electron energy gain is also sensitive to the electron's injection angle δ even with a small value of initial momentum. Also, the acceleration gradient increases with decrease in initial momentum so that the higher energy gain occurs at small value of initial momentum. It is notice that even for a small change in angle of injection then there appears a significant change in electron energy gain.

Figure 2 shows the variation of energy gain and magnetic field. In Figure 2(a) and 2(b), the electron energy gain is analysed as a function of normalized magnetic field b_0 at different values of normalized laser intensity parameters. In Figure 2(a) $a_0 = 5$ and 10; $\tau' = 100$ and $r'_0 = 150$ and 300; also for Figure 2(b) $a_0 = 20$ and 25 with $\tau' = 200$ and $r'_0 = 200$ and 300. The electron's injection angle δ having values 8.5, 8.0, 13.5 and 13. The optimization is solely a base for maximum energy gain by electron during interaction with a CP laser. It is noticed that on taking the higher values of laser intensity parameter the increment in the energy gain takes place.
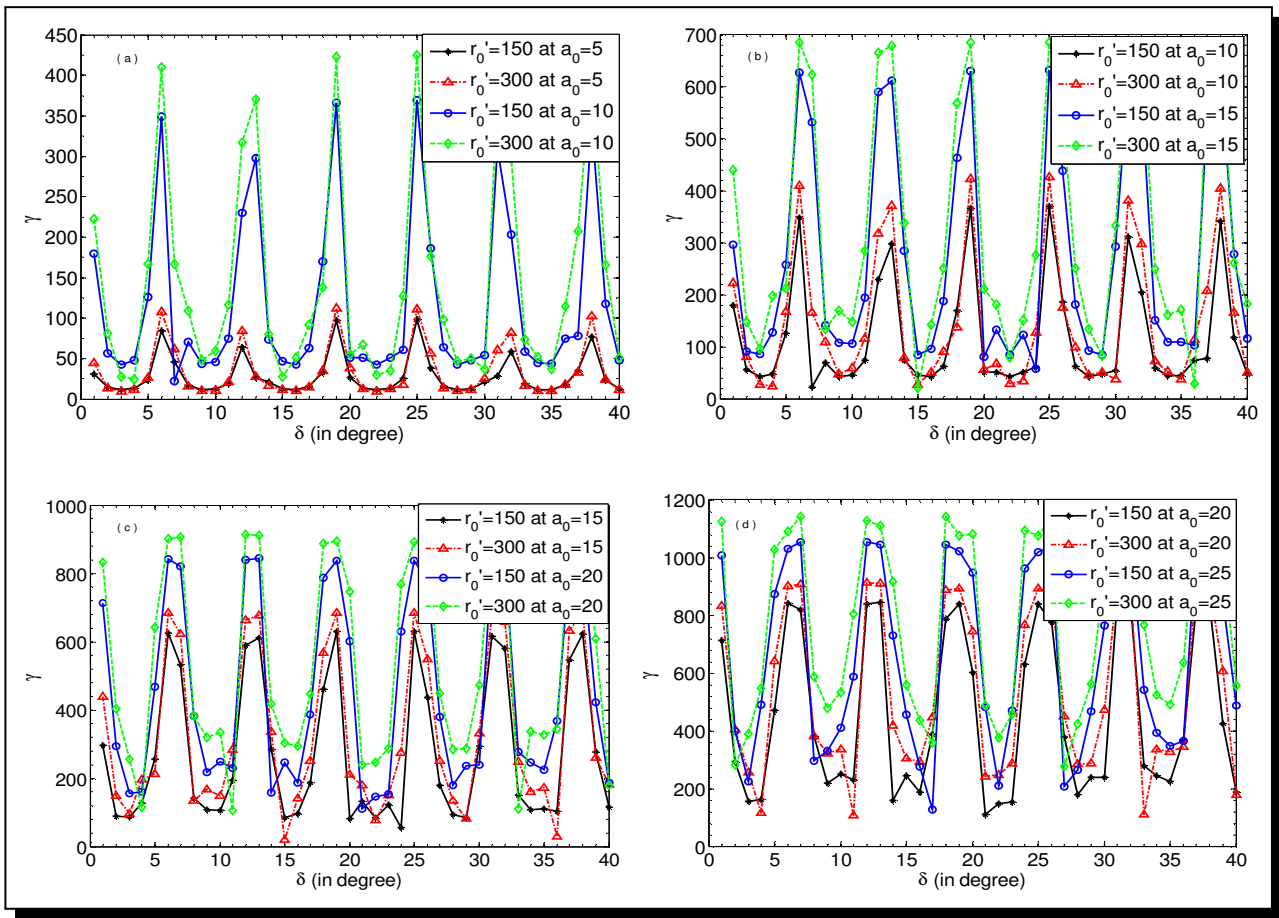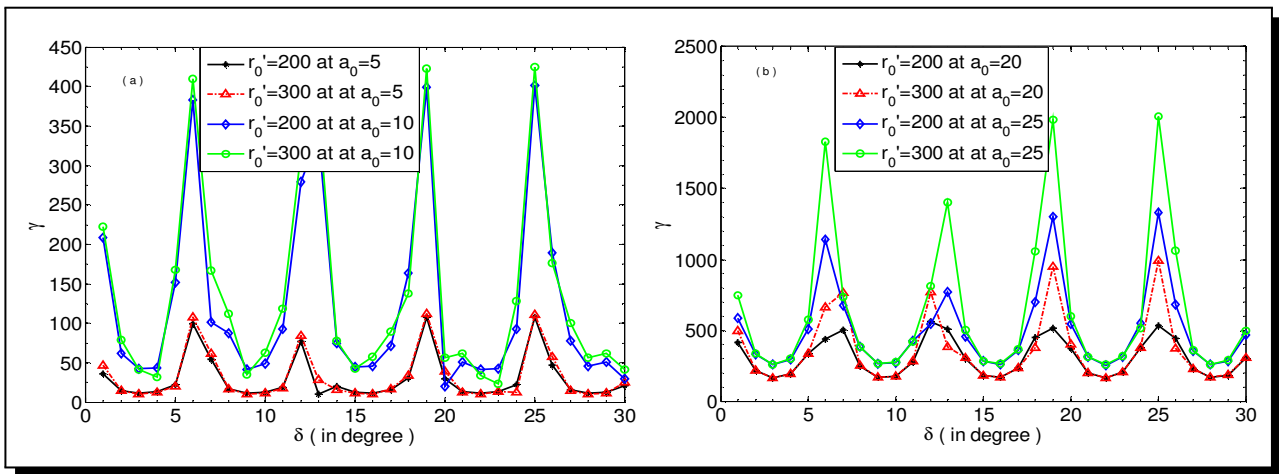
Figure 1. Electron energy gain γ variation with electron's injection angle δ for $\phi_0 = 0$, $p'_0 = 1$; $z_0 = z_L = 0$; $\tau' = 150$; $r'_0 = 150$ and 300. (a) laser intensity parameter $a_0 = 5$ and 10; (b) $a_0 = 10$ and 15; (c) $a_0 = 15$ and 20; and (d) $a_0 = 20$ and 25

Figure 2. Electron energy gain γ variations with normalized magnetic field b_0. (a) $a_0 = 5$ and 10; $r'_0 = 150$ and 300 and $\tau' = 100$; (b) $a_0 = 20$ and 25; $r'_0 = 200$ and 300, and $\tau' = 200$. The value of δ is 8.5, 8.0, 13.5 and 13, respectively

Figure 3(a) and 3(b) show the electron energy gain, γ variations with electron's injection angle δ and the magnetic field b_0 is fixed with fixed values of laser intensity parameter a_0 and laser spot size, r'_0. The electron energy gain is analysed for the normalized intensity parameters $a_0 = 5, 10$ and $20, 25$, respectively for both figures. Also the normalized laser spot size $r'_0 = 200$ (for black and green lines) and 300 (for red and blue lines), respectively. Again for higher values of laser intensity parameter electron energy gain is high as compared to all lower values of a_0. Electron energy gain is extremely sensitive to initial electron momentum. Also, the acceleration gradient increases with decrease in initial momentum and the higher energy gain occurs at small value of initial momentum. The normalized initial momentum of electron to a small value $p'_0 = 1$. Also the electron energy gain is also sensitive to the electron's injection angle even with a small value of initial momentum. In Figure 3(a) and 3(b) $a_0 = 5$ and 10 (for black and red lines), and 20 and 25 (for blue and green lines) respectively with $r'_0 = 200$ and 300 the optimum values of δ for higher energy gain obtained by the equation (1), for a small change in angle of injection, a significant change in electron energy gain appears. The contribution of transverse component of electron's momentum becomes zero when $\delta = 0$ and electron's injection is purely along the direction of propagation of laser pulse. It is observed that δ should be small and optimized for appropriate momentum to maximize the electron energy gain due to a relativistic longitudinal momentum. 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 3. Electron energy gain variation with electron's injection angle $\delta \cdot r'_0 = 200$ and 300; $\tau' = 200$; and the normalized magnetic field $b_0 = 0.1, 0.2, 0.3$ and 0.4, respectively. (a) $a_0 = 5$ and 10; (b) $a_0 = 20$ and 25

Figure 4 shows the electron energy gain variations with normalized distance for distinct values of laser intensity parameters $a_0 = 5, 10, 15$, and 20 with optimized electron injection in the presence of magnetic field. For Figures 4(a) and 4(b) the values of the laser intensity parameters are $a_0 = 5, 10, 15$, and 20 with electron's injection angle $\delta = 8.5, 13, 13.5$ and 14.6, respectively. Also, for these values the respective values of the normalized magnetic fields are $b_0 = 0.1, 0.2, 0.3$ and 0.4. $\tau' = 100$ for Figures 4(a) and 4(b) with $r'_0 = 150$ and 300, respectively. Also $\tau' = 150$ for Figure 4(c) with $r'_0 = 300$. It is observed that the electron energy gain is

relatively higher in the presence of magnetic field for the same set of parametersas compared to in absence of magnetic field. The figures in absence of magnetic field is not shown in this paper. The reason of increase of magnetic field is that the magnetic field increases the duration of interaction between the laser pulse and the electron so the electron gains much energy from the laser field in the presence of magnetic field and gets accelerated. On increasing the time duration the energy gain also increases for the same parameters. For $a_0 = 25$ the energy gain is much higher.
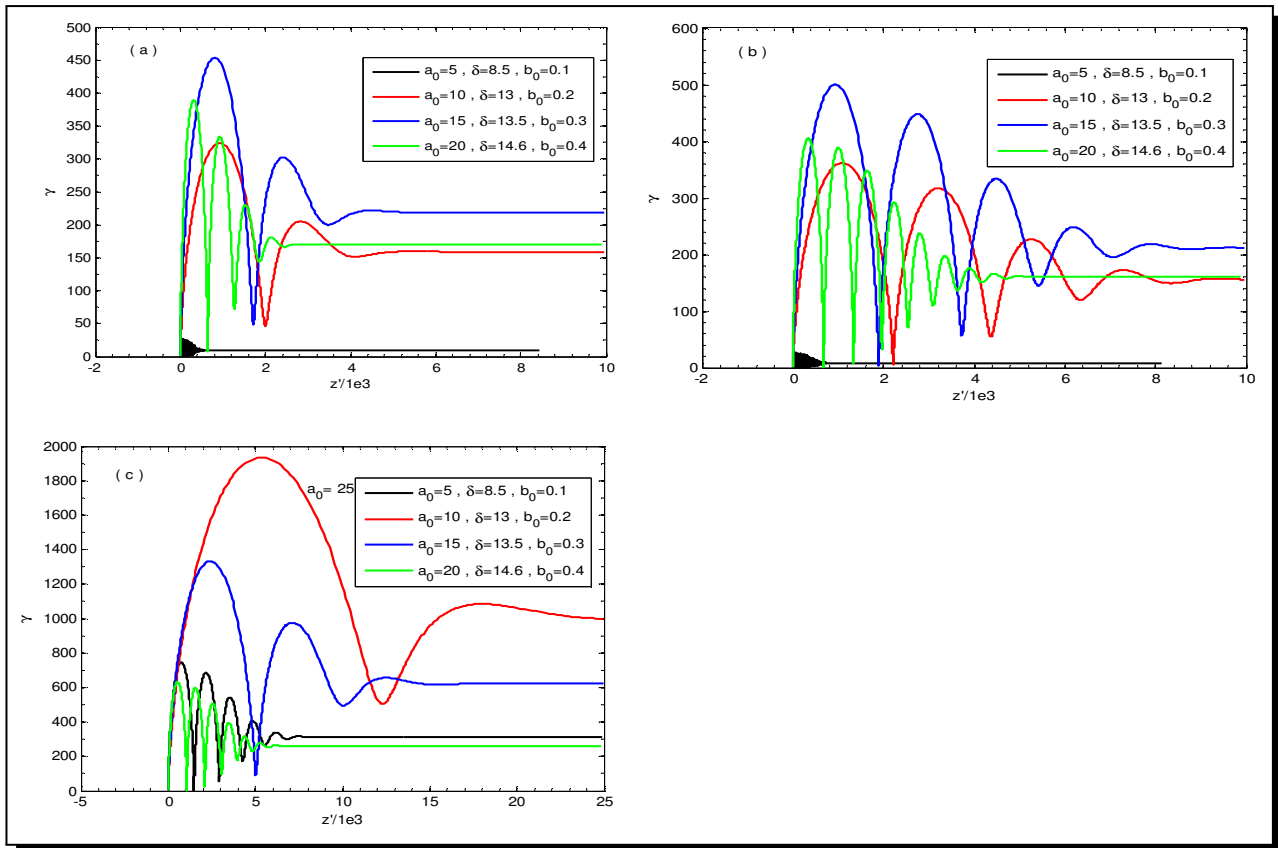
Figure 4. Electron energy gain variations with normalized distance with z' with optimized angle of electron's injection for distinct values of laser intensity parameter a_0 in the presence of normalized magnetic field b_0. $a_0 = 5$, 10, 15 and 20 at $b_0 = 0.1$, 0.2, 0.3 and 0.4 with corresponding value of $\delta = 8.5$, 13, 13.5 and 14.6, respectively. (a) $r'_0 = 150$; $\tau' = 100$; and (b) $r'_0 = 300$; $\tau' = 150$; (c) $r'_0 = 300$; $\tau' = 150$; $a_0 = 25$ and others parameters are same

Figure 5 show the variation of the scattering angle of the electron θ with respect to electron's injection angle δ in the presence of magnetic field. For Figure 5(a) $\tau' = 25$, the laser intensity parameters $a_0 = 5$, 10, 15 and 20 with $b_0 = 0.1$, 0.2, 0.3 and 0.4, respectively. $r'_0 = 150$ (for black and blue lines) and 200 (for red and green lines). Also, for Figure 5(b) the laser intensity parameter a_0 and the normalized magnetic field b_0 is same but $\tau' = 50$ and $r'_0 = 200$ (for black and blue lines) and 300 (for red and green lines). Both the figures shows that as the field is increasing the electron's injection angle δ is decreasing. It means the value of the scattering angle of the electron θ is least for higher field. A relatively lower scattering is observed with optimized values of injection angle in the presence of magnetic field.
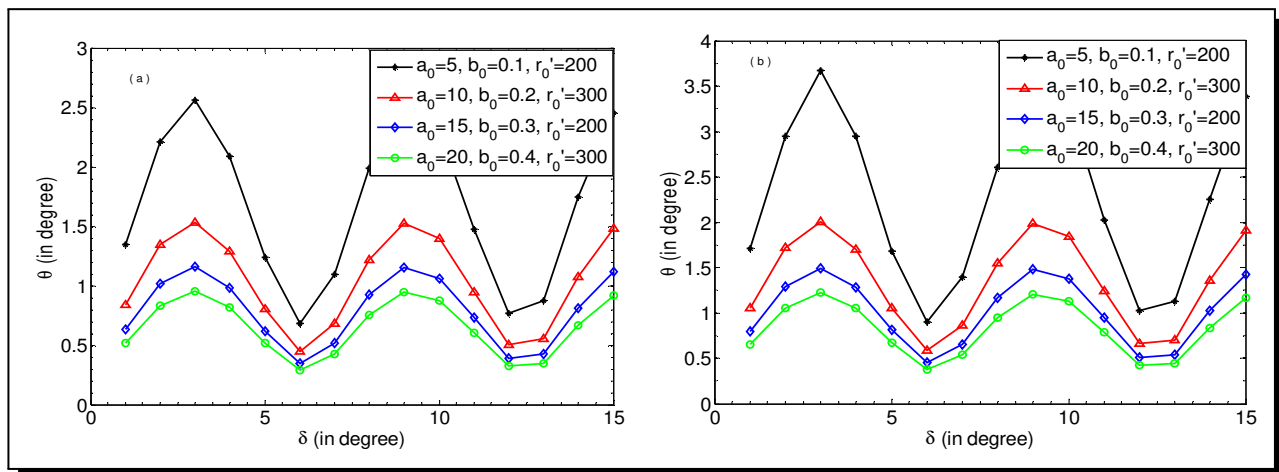
Figure 5. The variation of angle of scattering (θ) with the angle of scattering (δ) of the electron. The laser intensity parameter $a_0 = 5$, 10, 15 and 20 with the normalized magnetic field $b_0 = 0.1$, 0.2, 0.3 and 0.4, respectively. (a) $\tau' = 25$; $r_0' = 150$ and 200 and (b) $\tau' = 50$ and $r_0' = 200$ and 300

4. Conclusions

The electron injection for direct acceleration by a Gaussian laser field under the influence of azimuth magnetic field is studied. It is found the value of laser intensity parameters a_0 is increases then the energy gain becomes higher. The electron energy gain is also sensitive to the electron's injection angle even with a small value of initial momentum. Also, the acceleration gradient increases with decrease in initial momentum so that the higher energy gain occurs at small value of initial momentum. It is notice that even for a small change in angle of injection then there appears a significant change in electron energy gain. There is increment in magnetic field because the duration of interaction between the laser pulse and the electron so the electron gains much energy from the laser field in the presence of magnetic field and gets accelerated. The value of the scattering angle of the electron θ is least for higher field. A relatively lower scattering is observed with optimized values of injection angle in the presence of magnetic field. The optimization is solely a base for maximum energy gain by electron during interaction with a CP laser. It is noticed that on taking the higher values of laser intensity parameter the increment in the energy gain takes place.

Acknowledgement

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.

References

[1] A. Modena, Z. Najmudin, A. E. Dangor, C. E. Clayton, K. A. Marsh, C. Joshi, V. Malka, C. B. Darrow, C. Danson, D. Neely and F. N. Walsh, Electron acceleration from the breaking of relativistic plasma waves, *Nature* **377**, 606 (1995), DOI: 10.1038/377606a0.

[2] E. Esarey, P. Sprangle, J. Krall and A. Ting, Overview of plasma-based accelerator concepts, *IEEE Trans. Plasma Sci.* **24**, 252 (1996), DOI: 10.1109/27.509991.

[3] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J. P. Rousseau, F. Burgy and V. Malka, A laser-plasma accelerator producing monoenergetic electron beams, *Nature* (London) **431**, 541 (2004), DOI: 10.1038/nature02963.

[4] S. P. D. Mangles, C. D. Murphy, Z. Najmudin, A. G. R. Thomas, J. L. Collier, A. E. Dangor, E. J. Divall, P. S. Foster, J. G. Gallacher, C. J. Hooker, D. A. Jaroszynski, A. J. Langley, W. B. Mori, P. A. Norreys, F. S. Tsung, R. Viskup, B. R. Walton and K. Krushelnick, Monoenergetic beams of relativistic electrons from intense laser-plasma interactions, *Nature* (London) **431**, 535 (2004), DOI: 10.1038/nature02939.

[5] K. P. Singh, R. Arya and A. K. Malik, Effect of initial phase on error in electron energy obtained using paraxial approximation for a focused laser pulse in vacuum, *J. Appl. Phys.* **118**, 104902 (2015), DOI: 10.1063/1.4930291.

[6] S. G. Bochkarev and V. Yu. Bychenkov, Acceleration of electrons by tightly focused femtosecond laser, *Quantum Electron.* **37**, 273 (2007), DOI: 10.1070/QE2007v037n03ABEH013462.

[7] S. X. Hu and A. F. Starace, Laser acceleration of electrons to giga-electron-volt energies using highly charged ions, *Phys. Rev. E* **73**, 066502 (2006), DOI: 10.1103/PhysRevE.73.066502.

[8] Y. I. Salamin, Electron acceleration in a tightly-focused vacuum laser beat wave, *Phys. Lett. A* **335**, 289 (2005), DOI: 10.1016/j.physleta.2004.12.049.

[9] B. Hafizi, A. K. Ganguly, A. Ting, C. I. Moore and P. Sprangle, Analysis of Gaussian beam and Bessel beam driven laser accelerators, *Phys. Rev. E* **60**, 4779 (1999), DOI: 10.1103/PhysRevE.60.4779.

[10] H. Hora, M. Hoelss, W. Scheid, J. Wang, Y. Ho, F. Osman and R. Castillo, Principle of high accuracy for the nonlinear theory of the acceleration of electrons in a vacuum by lasers at relativistic intensities, *Laser Part. Beams* **18**, 135 (2000), DOI: 10.1017/S0263034600181169.

[11] Y. I. Salamin, G. R. Mocken and C. H. Keitel, Electron scattering and acceleration by a tightly focused laser beam, *Phys. Rev. Spec. Top. Accel. Beams* **5**, 101301 (2002), DOI: 10.1103/PhysRevSTAB.5.101301.

[12] Y. I. Salamin and C. H. Keitel, Electron acceleration by a tightly focused laser beam, *Phys. Rev. Lett.* **88**, 095005 (2002), DOI: 10.1103/PhysRevLett.88.095005.

[13] M. W. Lin, B. W. Morgan and I. Jovanovic, Progress on the *Study of Direct Laser Electron Acceleration in Density-Modulated Plasma Waveguides*, Proceedings of IPAC, Richmond, VA, USA WEPJE024 (2015).

[14] A. Pak, K. A. Marsh, S. F. Martins, W. Lu, W. B. Mori, and C. Joshi, Injection and trapping of tunnel-ionized electrons into laser-produced wakes, *Phys. Rev. Lett.* **104**, 025003 (2010), DOI: 10.1103/PhysRevLett.104.025003.

[15] E. Oz, S. Deng, T. Katsouleas, P. Muggli, C. D. Barnes, I. Blumenfeld, F. J. Decker, P. Emma, M. J. Hogan, R. Ischebeck, R. H. Iverson, N. Kirby, P. Krejcik, C. O'Connell, R. H. Siemann, D. Walz, D. Auerbach, C. E. Clayton, C. Huang, D. K. Johnson, C. Joshi, W. Lu, K. A. Marsh, W. B. Mori and M. Zhou, Ionization-induced electron trapping in ultrarelativistic plasma wakes, *Phys. Rev. Lett.* **98**, 084801 (2007), DOI: 10.1103/PhysRevLett.98.084801.

[16] X. L. Xu, Y. P. Wu, C. J. Zhang, F. Li, Y. Wan, J. F. Hua, C. H. Pai, W. Lu, P. Yu, C. Joshi and W. B. Mori, Low emittance electron beam generation from a laser wakefield accelerator using two laser pulses with different wavelengths, *Phys. Rev. Spec. Top. Accel. Beams* **17**, 061301 (2014), DOI: 10.1103/PhysRevSTAB.17.061301.

[17] A. Sell and F. X. Kartner, Attosecond electron bunches accelerated and compressed by radially polarized laser pulses and soft-x-ray pulses from optical undulators, *J. Phys. B At. Mol. Opt. Phys.* **47**, 015601 (2014), DOI: 10.1088/0953-4075/47/1/015601.

[18] A. F. Lifshitz, J. Faure, Y. Glinec, V. Malka and P. Mora, Proposed scheme for compact GeV laser plasma accelerator, *Laser Part. Beams* **24**, 255 (2010), DOI: 10.1017/S026303460606037X.

[19] L. J. Wong and F. X. Kartner, Direct acceleration of an electron in infinite vacuum by a pulsed radially-polarized laser beam, *Opt. Express* **18**, 25035 (2010), DOI: 10.1364/OE.18.025035.

[20] N. Kant, J. Rajput, P. Giri and A. Singh, Effect of axial magnetic field on axicon laser-induced electron acceleration, *High Energy Density Phys.* **18**, 20 – 25 (2016), DOI: 10.1016/j.hedp.2015.12.002.

[21] F. V. Hartemann, J. R. VanMeter, A. L. Troha, E. C. Landahl, N. C. Luhmann, H. A. Baldis, A. Gupta and A. K. Kerman, *Three-dimensional relativistic electron scattering in an ultrahigh-intensity laser focus*, *Phys. Rev. E* **58** 5001 (1998), DOI: 10.1103/PhysRevE.58.5001.

[22] B. Hafizi, A. Ting, E. Esarey, P. Sprangle and J. Krall, Vacuum beat wave acceleration, *Phys. Rev. E* **55**, 5924 (1997), DOI: 10.1103/PhysRevE.55.5924.

[23] B. Hafizi, A. K. Ganguly, A. Ting, C. I. Moore and P. Sprangle, *Analysis of Gaussian beam and Bessel beam driven laser accelerators*, *Phys. Rev. E* **60**, 4779 (1999), DOI: 10.1103/Phys-RevE.60.4779.

[24] M. Lax, W. H. Louisell and W. B. McKnight, From Maxwell to paraxial wave optics, *Phys. Rev. A* **11**, 1365 (1975), DOI: 10.1103/PhysRevA.11.1365.

[25] Y. I. Salamin, Direct particle acceleration by two identical crossed radially polarized laser beams, *Phys. Rev. A* **82**, 013823 (2010), DOI: 10.1103/PhysRevA.82.013823.

[26] H. S. Ghotra and N. Kant, Sensitiveness of axial magnetic field on electron acceleration by a radially polarized laser pulse in vacuum, *Opt. Commun.* **356**, 118 (2015), DOI: 10.1016/j.optcom.2015.07.058.

[27] H. S. Ghotra and N. Kant, TEM modes influenced electron acceleration by Hermite–Gaussian laser beam in plasma, *Laser Part. Beams* **34**, 385 (2016), DOI: 10.1017/S0263034616000239.

[28] J. X. Li, W. P. Zang and J. G. Tian, Electron acceleration in vacuum induced by a tightly focused chirped laser pulse, *Appl. Phys. Lett.* **96**, 031103 (2010), DOI: 10.1063/1.3294634.

[29] H. S. Ghotra, D. Jaroszynski, B. Ersfeld, N. S. Saini, S. Yoffe and N. Kant, Transverse electromagnetic Hermite–Gaussian mode-driven direct laser acceleration of electron under the influence of axial magnetic field, *Laser Part. Beams* **36**, 154 – 161 (2018), DOI: 10.1017/S0263034618000083.

[30] E. Esarey, R. F. Hubbard, W. P. Leemans, A. Ting and P. Sprangle, Electron injection into plasma wakefields by colliding laser pulses, *Phys. Rev. Lett.* **79**, 2682 (1997), DOI: 10.1103/PhysRevLett.79.2682.

[31] E. Esarey, C. B. Schroeder and W. P. Leemans, Physics of laser-driven plasma-based electron accelerators, *Rev. Mod. Phys.* **81**, 1229 (2009), DOI: 10.1103/RevModPhys.81.1229.

[32] Y. I. Salamin and N. M. Jisrawi, Electron laser acceleration in vacuum by a quadratically chirped laser pulse, *J. Phys. B At. Mol. Opt. Phys.* **47**, 025601 (2014), DOI: 10.1088/0953-4075/47/2/025601.

[33] K. P. Singh, Electron acceleration by an intense short pulse laser in a static magnetic field in vacuum, *Phys. Rev. E* **69**, 056410 (2004), DOI: 10.1103/PhysRevE.69.056410.

[34] S. Kumar and M. Yoon, Electron acceleration by a chirped circularly polarized laser pulse in vacuum in the presence of a planar magnetic wiggler, *Phys. Scr.* **77**, 025404 (2008), DOI: 10.1088/0031-8949/77/02/025404.

[35] F. Sohbatzadeh, S. Mirzanejhad and M. Ghasemi, Electron acceleration by a chirped Gaussian laser pulse in vacuum, *Phys. Plasmas*. **13**, 123108 (2006), DOI: 10.1063/1.2405345.

[36] F. V. Hartemann, E. C. Landahl, A. L. Troha, J. R. Van Meter and H. A. Baldis, The chirped-pulse inverse free-electron laser: A high-gradient vacuum laser accelerator, *Phys. Plasmas* **6**, 4104 (1999), DOI: 10.1063/1.873718.

[37] F. Sohbatzadeh, S. Mirzanejhad and H. Aku, Synchronization scheme in electron vacuum acceleration by a chirped Gaussian laser pulse, *Phys. Plasmas* **16**, 023106 (2009), DOI: 10.1063/1.3077666.

[38] K. P. Singh and V. Sajal, Quasimonoenergic collimated electrons from the ionization of nitrogen by a chirped intense laser pulse, *Phys. Plasmas* **16**, 043113 (2009), DOI: 10.1063/1.3116646.

[39] A. G. Khachatryan, F. A. Van Goor and K. J. Boller, Interaction of free charged particles with a chirped electromagnetic pulse, *Phys. Rev. E* **70**, 067601 (2004), DOI: 10.1103/PhysRevE.70.067601.

[40] J. D. Lawson, Lasers and accelerators, *IEEE Trans. Nucl. Sci.* **26**, 4217 (1979), DOI: 10.1109/TNS.1979.4330749.