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# Electron Energy Enhancement by Comparison of Linearly and Circularly Polarized Laser Pulse in Vacuum Using Different Values of Magnetic Fields

Research Article

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**Abstract.** Energy enhancement by a comparison of circularly and linearly polarized laser pulse during acceleration of the electrons by a Gaussian laser pulses has been investigated. On comparison these two it is found that for the linearly polarized laser pulse the y-coordinate has a finite value and approximately zero for a circularly polarized laser pulse. It is noticed that there is a advantage of circularly polarized field. The comparison is done at high values of the magnetic field. The variation of electron energy with laser spot size, laser intensity, initial electron energy and initial phase has been studied. The maximum energy of the electrons gets enhanced for a circularly polarized in comparison to a linearly polarized laser pulse due to axial symmetry of the circularly polarized pulse. The y-component of the electric field of circularly polarized laser pulse contributes to the higher energy gained by the electrons.

**Keywords.** Laser acceleration; Gaussian laser pulse

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## 1. Introduction

In most materials, a specific polarization has been used to investigate the electron acceleration [1–3]. In plasma-based acceleration, a plasma wave with a phase velocity close to the speed of light is excited in acceleration schemes such as *laser wake-field acceleration* (LWFA), *plasma* *wake-field acceleration* (PWFA), plasma beatwave acceleration (PBWA), *self-modulated wake-field acceleration* (SMWFA), relatively large laser spot size effectively increases the Rayleigh range of the laser beam [4–6]. The polarization effect of the laser wave on vacuum laser acceleration by a non-chirped laser pulse has been considered by Xu *et al*. [7] and they addressed the advantage and disadvantages of employing *circular polarization* (CP) field compared to the *linear polarization* (LP) field for single electron acceleration. During the interaction of the plasma electrons with the circularly polarized laser pulse, 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 [8,9]. The generation of the axial magnetic field in the plasma by a circularly or elliptically polarized laser is generally referred to as the *inversen Faraday effect* (IFE). But the study reveals that IFE is impossible for a linearly polarized laser pulse, because it does not possess any angular momentum. IFE has been measured in several experiments [10–12]. Laser-plasma based accelerators have generated great interest recently due to 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 [13]. In the case of a linearly polarized laser pulse, the parameters of the laser pulse interaction with an electron depend upon the direction of polarization, and resonance absorption possesses an inhomogeneous distribution, which reduces the efficiency of acceleration process (Gupta *et al*. [26]; Niu *et al*. [27]; Singh *et al*. [28]). In the case of a circularly polarized laser pulse, resonance absorption possesses axial symmetry, which confines the electron near the axis. Other than this, the other laser parameters such as the laser spot size, position of the peak of pulse, initial electron energy gain play an important role in electron acceleration in vacuum. The momentum of electron increases with the magnitude of the electricfield. In this paper, electron acceleration compression of a circularly polarized and linearly polarized laser pulse in the presence of an axial magnetic field in a plasma has been studied. A vacuum as a medium for electron acceleration has some advantages over a plasma. The problems inherent in laser-plasma interaction,such as instabilities, are absent in vacuum. The group velocity of the laser pulse is higher in a vacuum than that in a plasma. This increases the duration of interaction between laser pulse and electron, thus increasing the energy gain [14]. The electrons close to the temporal peak of the laser pulse show strong initial phase dependence for a linearly polarized laser pulse. The electrons with initial phases $\phi_0 = (2n+1)\pi/2$, where $n = 0,1,2,3,\ldots$ are scattered least and retain highest energy. The electrons with initial phases $\phi_0 = n\pi$ are scattered more and retain least energy [15]. The acceleration depends on the initial laser phase for a long laser pulse and is independent for a short laser pulse [16]. If we use an axial magnetic field in the place of a transverse magnetic field, then this objective can be achieved. The electron with zero initial energy absorbs a tremendous amount of energy from the electric field of the laser when the ratio between the cyclotron frequency and the laser frequency approaches close to unity. The required value of the magnetic field for resonance is high [17]. The axial electric field of the laser is responsible for electron acceleration. The axial electric field increases with decreasing laser spot size; however, the laser pulse gets defocused sooner for smaller values and the electrons do not experience high electric field for long, reducing the energy they can reach [18]. For a tightly focused radially polarized laser pulse, the strong electric field component in the direction of propagation (longitudinal component) of the laser plays an important role in accelerating the electron [19–23]. The high-energy electrons ejected from a laser focus following the ionization of high-charge states of gases have been investigated using flat profile laser pulse [24] and radially polarized laser pulse [25], and good quality electron beams were reported.

## 2. Electron Dynamics

Consider the propagation of a laser pulse with electric field

$$\mathbf{E} = \hat{x}E_x + \hat{y}E_y + \hat{z}E_z \tag{1}$$

where

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

$$E_y = \alpha E_x \exp\left[i\frac{\pi}{2}\right],$$

$$E_z = -\frac{i}{k}\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y}\right).$$

Now specifying the symbols we used in equations as

- $E_0$ is the amplitude of electric field,
- $\varphi$ is the Gaussian beam phase,
- $\tau$ 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,
- $c$ is the velocity of light.
- The Gaussian beam parameters is defined as $f(z) = \sqrt{1+\xi}^2$, where $f(z)$ is the laser beam width parameter, and $\xi = z/Z_R$.
- The phase of the laser is given by $\phi = \omega t - kz + \tan^{-1}(z/Z_R) - \dfrac{kr^2}{2z(1+z/Z_R)}$.
- $f^2 = 1 + (z/Z_R)^2$,
- $Z_R = kr_0^2/2$ is the Rayleigh length.

The Rayleigh length is the distance along the propagation direction of the laser from the waist to the place where the area of the cross section is doubled, $\alpha$ can takes only two values 0 and 1. For the linearly polarized laser pulse put $\alpha = 0$ and for the circularly polarized laser pulse $\alpha = 1$. The initial position of the pulse temporal peak is taken at the origin. If we put initial coordinates of the electron in the phase of the laser then we get value of initial phase. A fundamental equation known as Maxwell's equation $\nabla \times \mathbf{E} = -\partial\mathbf{B}/\partial t$ which shows the relation between electric field and magnetic field used for finding the magnetic field. Axial magnetic field is represented by $B = \hat{z}B_0$. Also three dimensional test-particle simulation code is utilized to study the dynamics of accelerated electrons. The relativistic Newton-Lorentz equations of motion given by $d\mathbf{P}/dt = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B})$ has been solved by fourth order Runge-Kutta method with variable time step size. Following relations have been used $P_x = \gamma m_0 v_x$, $P_y = \gamma m_0 v_y$, $P_z = \gamma m_0 v_z$ and $\gamma^2 = 1 + (P_x^2 + P_y^2 + P_z^2)/m_0^2 c^2$. The kinetic energy of an electron associated is given by $\gamma m_0 c^2 = 0.51(\gamma - 1)$ MeV. Throughout this paper time, length, velocity, momentum, energy and frequency are normalized by $1/\omega$, $1/k$, $c$, $m_0 c$, $m_0 c^2$ and $k$. Following normalized parameters $a_0 = eE_0/m_0\omega c$ and $b_0 = eB_0/m_0\omega$, where $-e$ and $m_0$ are electron charge and rest mass, respectively.

## 3. Results and Discussion

We adopted the parameters for the Figure 1 which are $a_0 = 10$, $z_0 = \pi/2$, $P_{z_0} = 0$ and in Figure 1(a) the value of field $b_0$ is taken 0.0225, for Figure 1(b) $b_0 = 0.055$, for Figure 1(c) $b_0 = 0.065$ and for Figure 1(d) $b_0 = 0.0776$. The solid line is for linearly polarized and dashed green line is for circularly polarized. The variation of y-component of electromagnetic force i.e. $F_Y$ versus $t$ and the variation of electron momentum $P_Y$ versus $t$ these two figures show temporal variation of y-component of the electromagnetic force $F_y$ and the electron momentum $P_y$, respectively. Also there is no y-component of electric field for a linearly polarized laser pulse. The y-component of the electromagnetic force on the electron and electron momentum are negligible for a linearly polarized laser pulse as compared to that for a circularly polarized laser pulse. Now for figure $Y$ versus $t$ shows the temporal variation of y-coordinate of the electron. For the linearly polarized laser pulse the y-coordinate has a finite value and approximately zero for a circularly polarized laser pulse. For bottom figure in which there is a variation of energy and time shows temporal variation of electron energy $\gamma$. At starting the electron energy $\gamma$ is higher for a linearly polarized laser pulse. The electron energy is higher for a circularly polarized laser pulse for higher values of normalized time. The y-component of the electric field of circularly polarized laser pulse contributes to the higher energy gained by the electrons.

It is noticed that there is a advantage of circularly polarized field it was found that its acceleration channel occupies a relatively larger phase space, stemming from the distribution of the longitudinal electric component. Also it gives rise to greater acceleration efficiency. Laser is not very tightly focused in our study and capture and acceleration scenario scheme is not playing a role in the acceleration process. The role of longitudinal laser fields may be different for a tightly focused laser pulse. Also we are familiar that the ponderomotive force $\mathbf{v} \times \mathbf{B} \propto \mathbf{E} \times \mathbf{B}$ of the laser light pushes electrons in the direction opposite to the gradient and is main contributor to the longitudinal acceleration. Even though the electrons with initial position at origin interact with the falling edge of the pulse, the ponder motive force $\mathbf{v} \times \mathbf{B} \propto \mathbf{E} \times \mathbf{B}$ is always in the forward direction. This is because the direction of magnetic and electric fields remains same irrespective of rising or trailing edge of the pulse. The electrons are always accelerated in the forward direction and do not slip back with respect to the pulse.

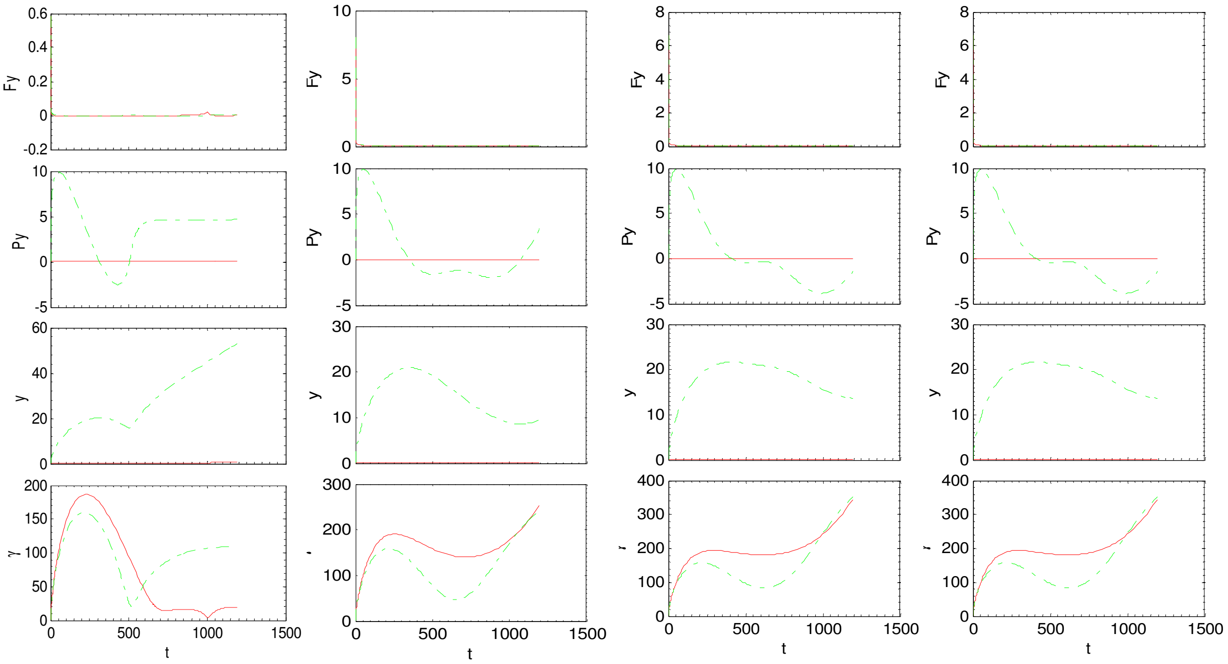
Sazegari and Shokri [5] shows that the trapping and acceleration of an electron by forward ponderomotive force associated with intense short laser pulses, propagating in homogeneous rarefied plasmas. One-dimensional plane wave laser pulse propagating in a homogeneous plasma was considered. It was shown that the gain of acceleration increases linearly with the field strength of the laser and the relativistic factor of the group velocity of the laser in the plasma. The energy gain is proportional to laser intensity in our study and proportional to electric field in their study.

Figures 2(a)-2(d) show electron energy $\gamma$ as a function of $z_0$ at $P_{z_0} = 0$ and $r_0 = 7a_0$ for $a_0 = 5$, $a_0 = 10$ and $a_0 = 20$, respectively. We compare for the different values of $b_0$. For Figure 2(a), Figure 2(b), Figure 2(c) and Figure 2(d) the values of $b_0$ are 0.0776, 0.065,0.055 and 0.0776, respectively. For these figures the energy of the electrons increases with laser intensity parameter $a_0$. For a circularly polarized laser pulse the electrons gain higher energy than that for a linearly polarized laser pulse for all the three values of $a_0$. Also the energy of the electrons decreases with $z_0$ that is the electrons close to temporal peak of the pulse gain higher energy and the electrons close to the leading edge of the laser pulse gain small energy for all the values of laser intensity.

Figures 3(a)-3(d) for all sets show electron energy $\gamma$ as a function of $z_0$ at $a_0 = 10$ for $P_{z_0} = 1$, $P_{z_0} = 3$, and $P_{z_0} = 5$, respectively. We compare for the different values of $b_0$. For Figure 3(a), Figure 3(b), Figure 3(c) and Figure 3(d) the values of $b_0$ are 0.0225, 0.055, 0.065 and 0.0776, respectively. For all case of Figure 3 the energy of electrons increases with initial electron momentum $P_{z_0}$. For a circularly polarized laser pulse the electrons gain higher energy than that for a linearly polarized laser pulse for different values of $P_{z_0}$ as mentioned above. Also the energy trend with $z_0$ nearly same for all the values of $P_{z_0}$.

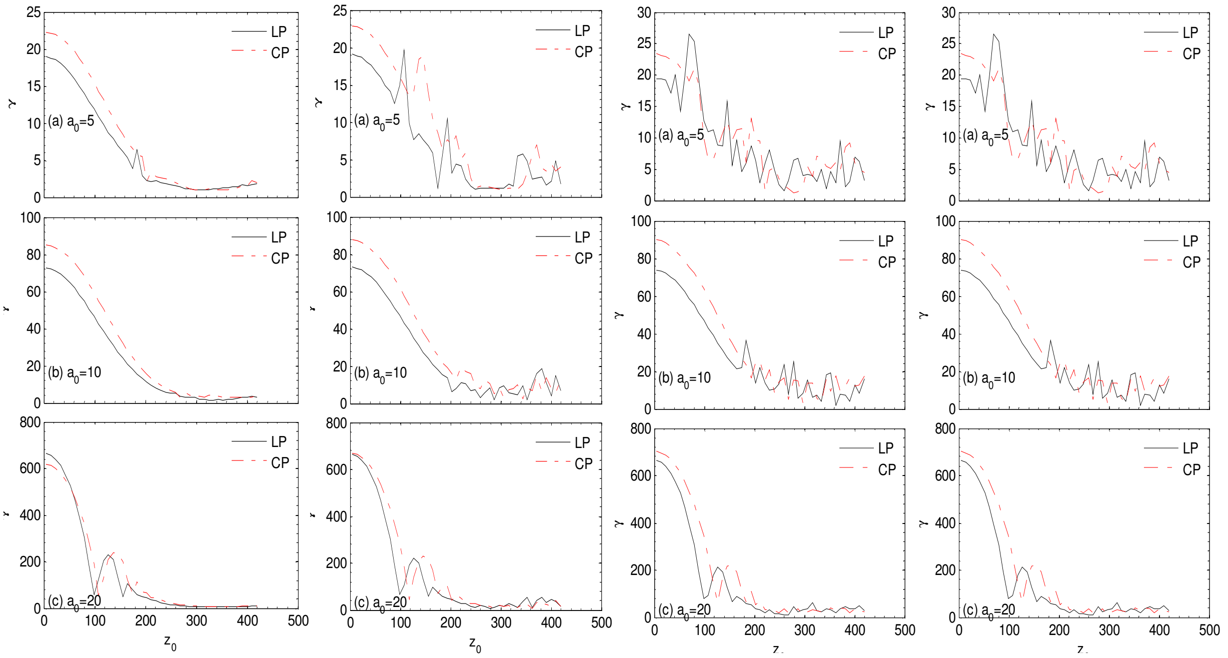
Figure 4 (variation of energy with $Z$ at different values magnetic field for linearly polarized) shows how the energy of electrons $\gamma$ varies with $z$ for $P_{z_0} = 0$, $a_0 = 10$, $z_0 = \pi/2$ and $r_0 = 70$. The values of $b_0 = 0.0225$, 0.055, 0.065 and 0.0776, respectively. For these values the colour of the lines are red, green, blue and black, respectively. The electrons close to the temporal peak of the laser pulse show strong initial phase dependence for a linearly polarized laser pulse. The pattern for different values of magnetic field is complicated to distinguished them. If we take very high values then there is possibility to distinguished them which is not presented in this paper.

Figure 5 (variation of energy with $Z$ at different values magnetic field for circularly polarized) shows how the energy of electrons $\gamma$ varies with $Z$ for $P_{z_0} = 0$, $a_0 = 10$, $z_0 = \pi/2$ and $r_0 = 70$. The values of $b_0 = 0.0225$, 0.055, 0.065 and 0.0776, respectively. For these values the colour of the lines are red, green, blue and black, respectively. For circularly polarized the energy values are not superimposed and can be distinguished. Bahari and Taranukhin reported that the electron acceleration is not dependent on the initial laser phase for a short laser pulse.



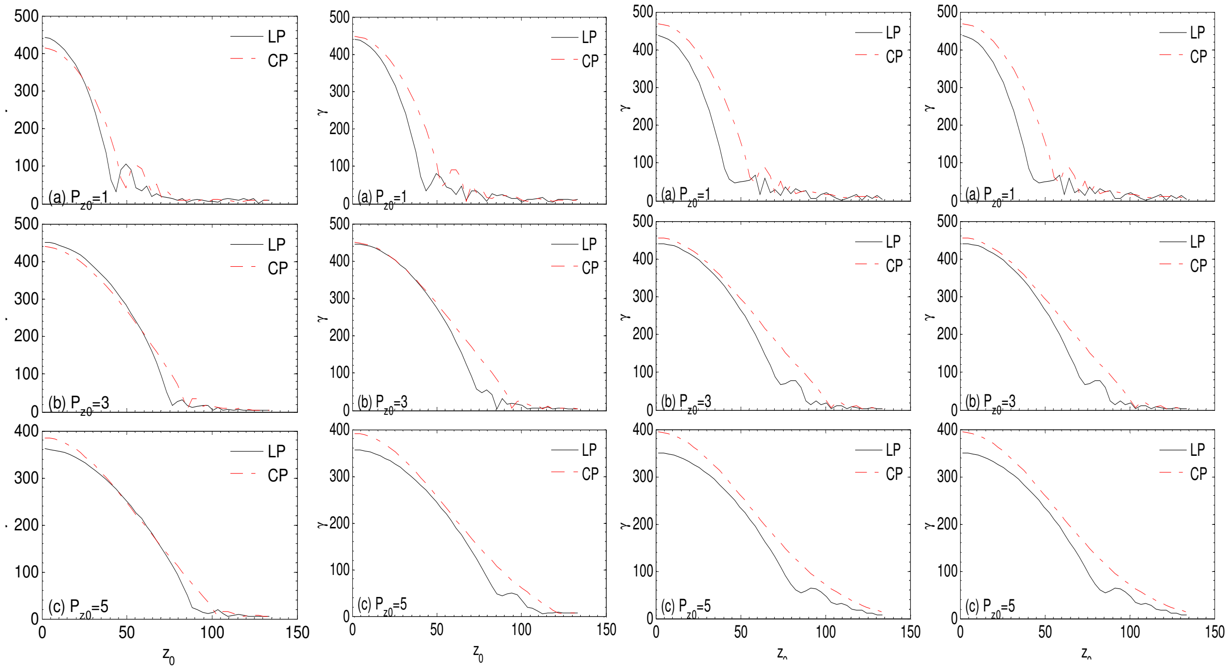
(a) (b) (c) (d)

**Figure 1.** Figures1(a)-1(d) are the comparison of Linearly polarized and Circularly polarized for the temporal variation (i) y-component of electromagnetic force ($F_Y$) (ii) the electron momentum ($P_Y$) (iii) the y-coordinate of electron and (iv) the electron energy $\gamma$ for $a_0 = 10$, $z_0 = \pi/2$, $P_{z_0} = 0$ and in Figure 1(a) $b_0$ is 0.0225, for Figure 1(b) $b_0 = 0.055$, for Figure 1(c) $b_0 = 0.065$ and for Figure 1(d) $b_0 = 0.0776$. The solid line is for linearly polarized and dashed green line is for circularly polarized.



(a) (b) (c) (d)

**Figure 2.** The electron energy $\gamma$ fas a function of $z_0$ at $P_{z_0} = 0$ and $r_0 = 7a_0$ for $a_0 = 5$, $a_0 = 10$ and $a_0 = 20$, respectively. In Figure 2(a) $b_0$ is 0.0225, in Figure 2(b) $b_0 = 0.055$ in Figure 2(c) $b_0 = 0.065$ and in Figure 2(d) $b_0 = 0.0776$. The solid line is for linearly polarized and dashed red line is for circularly polarized.



**(a)** **(b)** **(c)** **(d)**

**Figure 3.** The electron energy $\gamma$ fas a function of $z_0$ at $a_0 = 10$ for $P_{z_0} = 1$, $P_{z_0} = 3$, and $P_{z_0} = 5$, respectively. In Figure 3(a) $b_0$ is 0.0225, in Figure 3(b) $b_0 = 0.055$ in Figure 3(c) $b_0 = 0.065$ and in Figure 3(d) $b_0 = 0.0776$. The solid line is for linearly polarized and dashed red line is for circularly polarized.

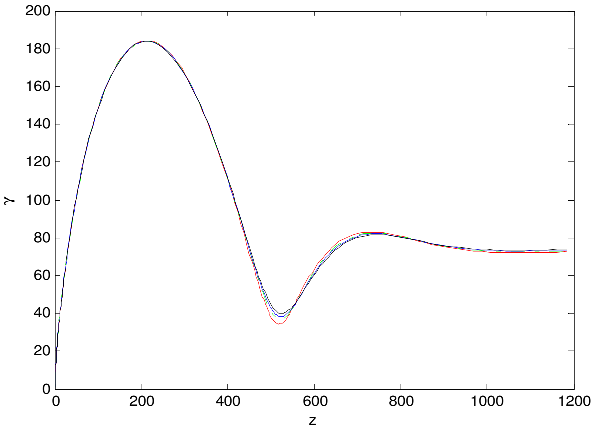


**Figure 4.** The electron energy of electrons $\gamma$ with $z$ for $P_{z_0} = 0$, $a_0 = 10$, $z_0 = \pi/2$ and $r_0 = 70$. The values of $b_0 = 0.0225$ (red line), 0.055 (green line), 0.065 (blue line) and 0.0776 (black line) respectively for linearly polarized.

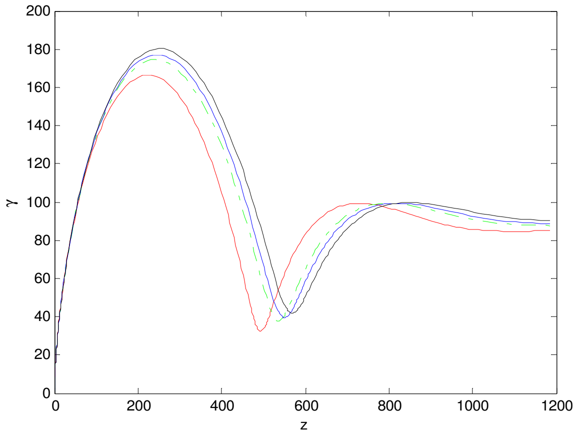


**Figure 5.** The electron energy of electrons $\gamma$ with $z$ for $P_{z_0} = 0$, $a_0 = 10$, $z_0 = \pi/2$ and $r_0 = 70$. The values of $b_0 = 0.0225$ (red line), 0.055 (green line), 0.065 (blue line) and 0.0776 (black line) respectively for circularly polarized.

## 4. Conclusions

The comparison of electron acceleration by the linearly and circularly polarized laser pulses has been invested in this paper. For the linearly polarized laser pulse the y-coordinate has a finite value and approximately zero for a circularly polarized laser pulse. For a circularly polarized laser pulse the electrons gain higher energy than that for a linearly polarized laser pulse for all values of $a_0$. The electron energy is higher for a circularly polarized laser pulse for higher values of normalized time. The y-component of the electric field of circularly polarized laser pulse contributes to the higher energy gained by the electrons. The electrons close to the temporal peak of the laser pulse show strong initial phase dependence for a linearly polarized laser pulse. For circularly polarized the energy values are not superimposed and can be distinguished.

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### Competing Interests

The author declares that he has no competing interests.

### Authors' Contributions

The author wrote, read and approved the final manuscript.

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