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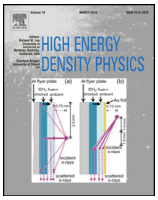

Effect of axial magnetic field on axicon laser-induced electron acceleration

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ABSTRACT

Radially polarized axicon Gaussian laser-induced electron acceleration has been studied under the influence of axial magnetic field. Employing an axicon is a significant method to generate a focused and diffraction free radially polarized laser beam. We have investigated direct electron acceleration in vacuum by employing a relativistic single particle simulation. It is observed that the net electron energy gain from the axicon Gaussian radially polarized laser beam can be enhanced under the influence of time varying axial magnetic field. This additional effect of the magnetic field reveals the fact that multi GeV energy gain can be achieved without the use of petawatt power lasers. Effect of laser initial intensity, initial spot size, initial phase, pulse duration and initial energy are taken into consideration for efficient electron acceleration up to GeV energies.

1. Introduction

The advent of high energy physics has led to the development of new possibilities in laser-driven electron acceleration. With the development of Laser-plasma accelerators, charged particles can be accelerated effectively by the tabletop high power lasers (~10 TW) of intensity $I > 10^{20}\, W/cm^2$. One of the greatest challenges faced in accelerating electrons by laser radiation is to achieve an electron beam with small energy spread for efficient acceleration [1,2]. Among the various laser acceleration configurations, the ultra-intense radially polarized (RP) laser beam in vacuum is very promising. This is due to the fact that it has a strong longitudinal field component at the axis of the beam for accelerating electrons [3–5]. Moreover, the longitudinal field component of radially polarized focused beam is dominating with respect to the field-strength of beam having any other polarization, hence, making it best suited for direct-particle acceleration in vacuum also [6–11]. From previous studies on electron acceleration by various laser polarizations, it is observed that RP laser beams can be tightly focused leading to enhanced electron acceleration. Carbajo et al. [9] recently have experimentally demonstrated a method to generate a tightly focused radially polarized laser beam by employing solenoid focussing and magnetic deflectors. This laser beam can be focused much more tightly, down to about 0.6 times the cross-sectional area of linearly polarized beam.

The results from direct laser driven electron acceleration in vacuum using low power lasers have shown that the radially polarized laser beam accelerates electrons with its axial components, whereas its radial components lead to transverse distortions and confinement of the bunch. This is the most exciting property of radially polarized beams [12]. It has been experimentally shown by Chang et al. [13] that azimuthal and radially polarized beams can be generated and tightly focused by using an intracavity large-apex angle axicon. The degrees of polarization can be up to 94% ± 3.7% and 95.4% ± 2.6% for the radially and azimuthally polarized beams respectively. The axicon fields can be achieved by using axicon optical elements [14]. The lowest-order axicon fields [15] possess nonzero radial and axial electric field components in addition to an azimuthal magnetic field component. If the tightly focused radially polarized fields have to measure accurately, then the paraxial approximation expressions of the fields require corrections in terms of associated fundamental diffraction angle ε. Salamin [16] has developed a truncated series representation of vector potentials, and calculated the fields of tightly focused radially polarized beam. His work is followed by the lines of the work of Lax et al. [17] and Davis [18]. He modelled the fields of tightly focused radially polarized Gaussian beams up to the order of ε^{15} accurately. These calculated fields are termed as axicon-Gaussian fields. The lowest order axicon fields are the one which contains axial and radial components of electric field and azimuthal component of magnetic field.

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The axial component of electric field helps in the acceleration of electrons, injected axially inside the beam and the azimuthal magnetic field component further collimates the accelerated electrons [19]. Salamin observed the electron energy gain of 3 GeV from a highly intense (10^{22} W/cm^2) axicon Gaussian laser beam, focused to beam waist radius of about 1 µm. This GeV energy gain is derived from a highly intense petawatt power laser beams focused to waist radius of microns [20]. The drawback of petawatt power laser beams is that the petawatt laser system consumes much more power than the entire electricity generating capacity of the United States and a continuous petawatt beam is not a reality yet. An atom subjected to petawatt power fields gets ionized (and its electrons scatter in all directions) quickly as long before the peak intensity is reached.

The purpose of the present study is to analyse the effect of external magnetic field of the order of few mega-Gauss on electron acceleration in vacuum by optimizing the axicon-focused radially polarized laser parameters to achieve higher electron energy gain and minimum values of radiation losses. Electron acceleration has major advantages in vacuum over plasmas. In vacuum, absence of plasma instabilities and higher value of laser group velocity, realizing it an ideal platform for laser-induced electron acceleration. Researchers have shown that external magnetic fields due to resonance give impressive consequences on electron acceleration. Recently, Ghotra and Kant [21,22] have achieved GeV energies in the presence of magnetic field with chirped pulsed circularly and linearly polarized laser. In the present paper, we investigate the effect of an external axial time varying magnetic field on the acceleration of the electron by direct laser interaction in vacuum without using high power petawatt laser beams. Direct acceleration of electrons in infinite vacuum is attractive as this scheme has no limit on the laser intensity to be used. In our scheme, the intensity requirement under the influence of external magnetic field of the orders of MG is of the order of $10^{19}\, W/cm^2$. Terawatt radially polarized laser can be focused down by an axicon optical element to much smaller spot size. Such focused radially polarized laser beam can produce a very strong longitudinal electric field. The ponderomotive force due to such intense laser field pushes the electron in the forward direction and electron gains significant energy. It has an additional advantage that, at the focused region, the radial component of the radially polarized laser vanishes and the strong longitudinal electric field accelerates the electron. The introduction of axial magnetic field not only further enhances the strength of this $\vec{v}\times\vec{B}$ force, but also retains electron energy to longer distances and hence boosts electron energy to achieve GeV energies. The values of magnetic field of the orders of few MG are experimentally available [23], and hence favour our model.

The structure of the paper is as follows: In section 2, we have discussed the momentum and energy equations governing the motion and acceleration of electron, numerical results are discussed in section 3 and conclusion is drawn in section 4.

2. Electron dynamics

Consider the lowest order axicon fields with electric field $\left(\vec{E} = \hat{r}\vec{E}_r + \hat{z}\vec{E}_z\right)$;

$$\vec{E}_r = \varepsilon E_0 \left(\frac{w_0}{w}\right)^2 \left(\frac{r}{w_0}\right) e^{-r^2/w^2} \cos\psi \tag{1}$$

$$\vec{E}_\theta = 0 \tag{2}$$

$$\vec{E}_z = \varepsilon^2 E_0 \left(\frac{w_0}{w}\right)^2 e^{-r^2/w^2} \left[\left(1-\frac{r^2}{w^2}\right)\sin\psi - \left(\frac{z}{z_r}\right)\left(\frac{r}{w}\right)^2 \cos\psi\right] \tag{3}$$

The magnetic field related to laser pulse is given by Maxwell's equation $\nabla\times\vec{E} = -\partial\vec{B}/\partial t$, so,

$$\vec{B}_r = 0 \tag{4}$$

$$\vec{B}_\theta = \frac{\vec{E}_r}{c} \tag{5}$$

$$\vec{B}_z = 0 \tag{6}$$

where, r, θ and z are the radial, azimuthal and axial coordinates of the cylindrical system respectively, $w = w_0\sqrt{1+(z/z_r)^2}$, w_0 is the beam waist radius, $z_r = k_0 r_0^2/2$ is the Rayleigh length, $k_0 = \omega_0/c$ is the wave number, ω_0 is the laser frequency, r_0 is the spot size of laser which is equal to the waist diameter $2w_0$.

$$\psi = \psi_0 + \omega t - kz - \left(\frac{z}{z_r}\right)\left(\frac{r}{w}\right)^2 + 2\tan^{-1}\zeta \tag{7}$$

where, $\zeta = z/z_r$, $r = \sqrt{r_\perp^2 + z^2}$, $r_\perp$ is the radial distance perpendicular to z axis and ψ_0 is the initial phase.

So, an axicon Gaussian pulse laser is characterized by important parameters such as beam wavelength λ, beam waist parameter w_0, laser initial intensity parameter a_0, and phase constant ψ_0. The minimum laser spot size r_0 is assumed to be the same for all frequency components. A schematic of axicon focusing is shown in Fig. 1. It is noteworthy to discuss that the radial component $\vec{E}_r$ vanishes at the z-axis and the longitudinal component $\vec{E}_z$ is dominating at the points on z-axis, which enables electron acceleration along the axis.

The externally applied short duration intense axial magnetic field is given by

$$\vec{B}_z = -B_0 \exp\left[-\frac{t^2}{\tau_b^2}\right] \tag{8}$$

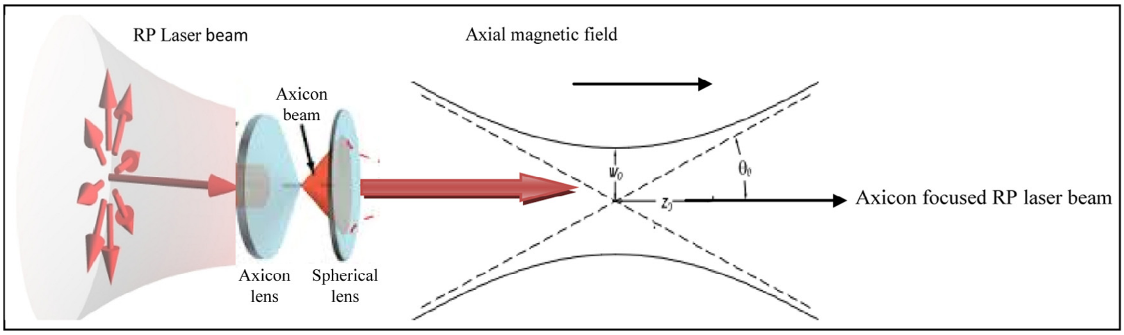

Fig. 1. A schematic showing the radially polarized beam focused by using an axicon.