Effect of pulsed magnetic field on electron acceleration due to plasma wave generated by plane polarised laser

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Abstract:
Electron acceleration due to plasma wakefield generated by plane polarised laser field in the presence of pulsed magnetic field has been investigated. Laser propagation is considered in transverse direction to the plasma wave. The electron gets trapped in the plasma wakefield and excited in the combined effect of plasma and laser fields. The pulsed magnetic field induces a resonant effect and contributes to additional gain in the electron energy. Laser, plasma and applied magnetic field parameters are optimized to achieve high energy gain.

Keywords: Plasma wave, Pulsed magnetic field, Resonance, Electron acceleration.

1. Introduction

For effective particle acceleration, many techniques have been employed with the passage of time like plasma wakefield accelerator, laser wakefield accelerator and laser beat wave accelerator [1-3]. With the advent of laser technology, plasma wakefield is excited with involvement of ponderomotive force. It helps in the displacement of electrons in the radial direction which leads to the formation of cavity in the plasma and an electron can be accelerated in a forward direction through this cavity. It became much important to study the laser particle interaction in plasma and vacuum due to various applications like harmonic generation, self focusing, electron acceleration, etc. [4-6]. The concept of laser driven plasma wakefield was initially come up by Dawson [7]. Plasma as a medium is attractive for particle acceleration as it acts same like a waveguide for an electron to accelerate through it and to acquire higher energies, where as there are many shortcomings in case of vacuum electron accelerations, so we choose the plasma wakefield acceleration into consideration mostly. The pulse of a plane polarised laser of having pulse duration similar with the plasma period is used to excite the plasma wave. Excitation means to develop a ponderomotive force which results in formation of waveguide like structure. After formation of these exited waves, the electrons can be accelerated to higher energies and also get trapped in the resultant longitudinal field. The electron starts oscillating in this inhomogeneous oscillating electromagnetic field with the help of ponderomotive force. The ponderomotive force causes the particle to accelerate from the area of higher field strength to the lower field, as it does not restricts the oscillation of particle at a single point. The particle experiences a strong force as it is in strong field for half of the oscillation while as field strength is less in remaining half, so the magnitude of force is also low. Finally it leads the acceleration of particle (electron or ions) towards weaker field continuously.
The application of magnetic field in electron acceleration has been exciting in the field of laser plasma physics and continues to remain a hot topic and waiting to be explored. With the application of the pulsed magnetic field; which is applied in transverse direction to a plasma wave, the electron gains an extra

energy so that it can be exited to higher energies of order GeV. The applied external magnetic field also plays a role in trapping of electrons inside the plasma wave. There are many ways to make an acceleration of electron very energetic and effective through the plasma and the three of them are static magnetic field, azimuthal magnetic field and wiggler magnetic field [8-10].

On the application of static magnetic field in the transverse direction to the plasma wave, the magnetic field prevents the leakage of electrons from plasma wave. For the case of azimuthal magnetic field, it is used in combined effect with chirping, not only to enhance the energy of an electron, but also to retain this electron energy for longer distances and in case of wiggler magnetic field, a collection of magnets is taken to wiggle or in other words to deflect a beam of accelerated electrons and these magnets are known by wiggler magnets.

In the present manuscript, we present the results of a relativistic single particle code for electron acceleration due to relativistic electron plasma wave due to plane polarised laser in the influence of pulsed magnetic field. Our aim is to achieve focused and diffraction free electron beams with much higher energies. We have employed suitable axial magnetic field with plane polarised laser and observe higher energy gain as compared to in the absence of applied magnetic field. The betatron resonance is established between the plasma wave and electron in the presence of optimized axial magnetic field. The axial magnetic field helps in the alignment of electron in the direction of propagation for longer durations. Using a pre accelerated electron of 1.8 MeV of initial energy, we observed energy gain of the orders of GeV employing optimized axial magnetic field. Our work may be practically important for various medical applications related to electron acceleration.

This paper is organized as follows. In next section, the electromagnetic fields and electron dynamics is discussed. The coupled ordinary differential equations of momentum and energy are solved numerically and results are discussed. Finally, the conclusion is drawn in the last section.

2. Electron Dynamics and Relativistic Analysis:

The equation of electric field for plasma is defined as:

$$\vec{E}_p = \hat{z}A\exp[-\frac{x^2}{r_p^2}]\cos(\eta) + \hat{x}A(\frac{2x}{k_p r_p^2})\exp[-\frac{x^2}{r_p^2}]\sin(\eta) \tag{1}$$

where, r_p is the radius of wakefield and c is phase of the wave.

The electric field of a plane polarized laser is propagating through the plasma in transverse direction and its form is taken as:

$$\vec{E}_l = \hat{z}A_0\exp[\frac{-r^2}{r_0^2}]\exp[-i(\omega_0 t - k_0 x)] \tag{2}$$

By using Maxwell's second equation, we can derive the expression of magnetic field associated with laser propagation is as follows:

$$\vec{B}_l = -\hat{y}(\frac{k_0}{w_0})A_0\exp[\frac{-r^2}{2r_p^2}]\exp[-i(\omega_0 t - k_0 x)] \tag{3}$$

A pulsed magnetic field is applied in positive z-direction,

$$\vec{B}_{ext} = \hat{z}B_0\exp[-\frac{t^2}{\tau_b^2}] \tag{4}$$

where, τ_b is the duration of magnetic field. The electric field related to the axial magnetic field is very small as compared to the electric field of laser, and its inclusion does not make any difference.

The electrodynamics of an electron in an electromagnetic field is described by the Newton-Lorentz equation as:

$$\frac{d\vec{p}}{dt} = -e\{\vec{E}_l + \vec{v}\times(\vec{B}_l + \vec{B}_{ext})\} - e\vec{E}_p \quad (5)$$

where, $\gamma = (1 + p_x^2 + p_y^2 + p_z^2)^{1/2}$ is the Lorentz factor, p_x, p_y and p_z are the x, y and z components of momentum $p = \gamma m_0 v$ respectively, β_x, β_y and β_z are x, y and z components of normalized velocity $\beta = \vec{v}/c$, respectively. Here, $-e$ and m_0 are charge and mass of electron respectively. Throughout this paper, the set of normalized parameters are used as per the following:

$a_0 = eA_0/m_0 w_0 c$, $a_p = eA/mw_p c$, $b_0 = eB_0/mw$, $t' \to wt$, $r_0' = kr_0$, $r_p' = kr_p$, $\beta_x = v_x/c$, $\beta_y = v_y/c$, $\beta_z = v_z/c$, $x' \to k_0 x$, $and\ z' \to k_0 z, k' = kc/w$

where e and m are the electron charge and rest mass respectively.

The normalized equations governing electron velocity and energy are as follows:

$$\frac{d\beta_x}{dt'} = \frac{1}{\gamma'}\{-a_p(\frac{2x'}{k_p' r_p'^2})\exp[-\frac{x'}{r_p'^2}]\sin(\eta) - b_0\beta_y \exp[-\frac{t^2}{\tau_b^2}] - a_0\beta_z k_0' \exp[-\frac{r'^2}{2r_0'^2}]\exp[-i(t'-x')]\} \quad (6)$$

$$\frac{d\beta_y}{dt'} = \frac{1}{\gamma'}\{b_0\beta_x \exp[-\frac{t'^2}{\tau_b'^2}]\} \quad (7)$$

$$\frac{d\beta_z}{dt'} = \frac{1}{\gamma'}\{-a_p \exp[-\frac{x'^2}{r_p'^2}]\cos(\eta) - a_0 \exp[-\frac{r'^2}{2r_0'^2}]\exp[-i(t'-x')] + a_0\beta_x k_0' \exp[-\frac{r'^2}{2r_0'^2}]\exp[-i(t'-x')]\} \quad (8)$$

$$\frac{d\gamma'}{dt'} = -a_p\beta_x(\frac{2x'}{k_p' r_p'^2})\exp[-\frac{x'^2}{r_p'^2}]\sin(\eta) - b_0\beta_x\beta_y \exp[-\frac{t'^2}{\tau_b'^2}] + b_0\beta_x\beta_y \exp[-\frac{t'^2}{\tau_b'^2}] - a_p\beta_z \exp[-\frac{x'^2}{r_p'^2}\cos[\eta] - a_0\beta_z \exp[-\frac{r'^2}{2r_0'^2}]\exp[-i(t'-x')] \quad (9)$$

Equations (6) - (9) are ordinary coupled differential equations and solved numerically for electron energy. Here, the initial velocity and electron energy are taken as β_0 and γ_0 respectively. In all simulations, we set parameters as $a_p = 0.2 (I \sim 8\times10^{16}\, W/cm^2)$, b_0 =0.001 (corresponding magnetic field ~107 kG), b_0 =0.0016 (corresponding magnetic field ~171 kG) and b_0 =0.004 (corresponding magnetic field ~ 427.7 kG), τ_b' =600 (corresponding magnetic field duration $\approx$ 333 fs.

3. Results and Discussion:

Numerical results have been calculated employing different plasma, and magnetic field parameters in order to achieve efficient higher energy electron gain. Figure 1 depicts the variation of electron energy gain γ' for different values of plasma intensity parameters as a_p =0.1, 0.2 and 0.4 respectively without external magnetic field. Here, it has been shown that as plasma intensity is incremented, the electron energy gain is enhanced as plasma wave drives the electron efficiently with increase in plasma intensity.

Also in Figure 2, we have shown the influence of external magnetic field along with the plasma wave. Here, external magnetic field also plays a crucial role in establishing resonance with plasma wave and electron energy gain is enhanced significantly upto GeV range. Hence, electron energy gain is enhanced effectively under combined effect of both plasma and magnetic fields.

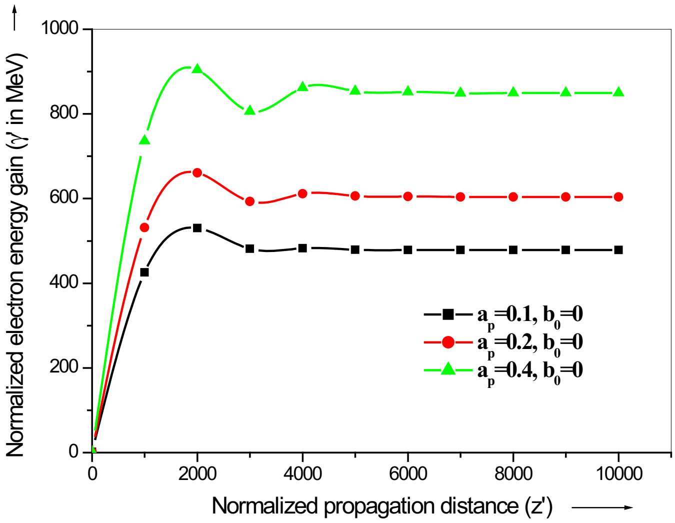

Figure 1: Variation of relativistic electron energy γ' with normalized distance z' at different plasma intensities without pulsed magnetic field. The other parameters are $r_p' = 40$, $k' = 0.96$, $\beta_z' = 0.9c$, $\gamma_0 = 1.8$

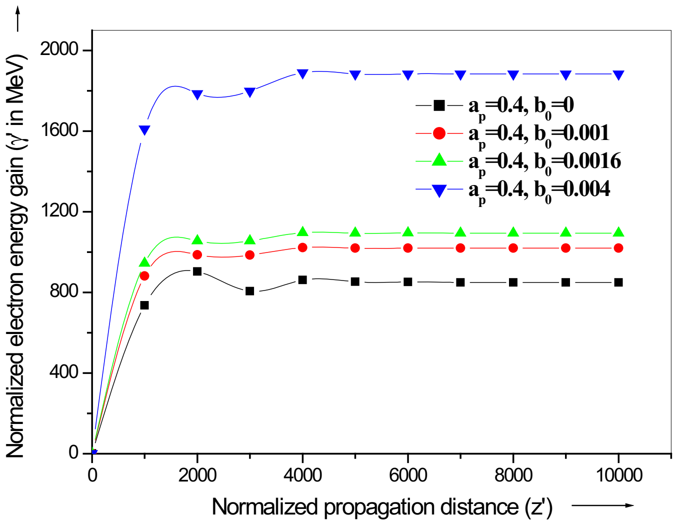

Figure 2: Variation of relativistic electron energy γ' with normalized distance z' with and without pulsed magnetic field. The other parameters are $r_p' = 40$, $k' = 0.96$, $\beta_z' = 0.9c$, $\gamma_0 = 1.8$

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4. Conclusion:

We utilize the characteristics of plasma wave, keeping the laser field constant so as to observe electron energy gain by plasma wave and shown that using the optimized parameters of plasma and axial magnetic field electron acceleration up to GeV-level is possible. We employed a single electron for simplicity.

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