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Mode-coupling assisted electron accelerations by a plasma wave

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ABSTRACT

The acceleration of electrons by a plasma wave in the presence of density ripple in plasma has been investigated. Plasma density ripple can excite higher harmonics of different phase velocities of the fundamental plasma wave. The combined role of the different harmonics of the plasma wave contributes significantly in electrons energy gain during acceleration by the fundamental plasma wave. Our calculation shows that the plasma electrons gain considerable energy during the acceleration by the plasma waves in the presence of a density ripple in plasma. The initial electron energy and the ripple density play an important role for the acceleration of an electron.

1. Introduction

Short-pulse laser interaction with plasmas is a major area due to its relevance to laser-driven fusion, laser-driven particle accelerator, x-ray laser and other related areas [1–5]. The acceleration of electrons from laser-driven plasma waves to ultra-relativistic energies in a short distance is emerging as an attractive alternative to conventional accelerators [6,7]. The plasma wave can be driven either by beating two co-propagating lasers, differing in frequencies by a plasma frequency, or by a single short pulse laser of duration equal to plasma period [8].

In the beat-wave scheme, two lasers exert a longitudinal ponderomotive force at difference on the electrons that resonantly drives a large amplitude plasma wave with potential much higher than the ponderomotive potential. In a laser wake field accelerator (LWFA), a single short pulse laser exerts a strong longitudinal pondromotive force on electrons that excites a large amplitude plasma wave [9]. Studies with longer laser pulses [10,11] reveal that the plasma wave could be generated through the process of stimulated Raman forward scattering or self-phase modulation. In the case of a fast rising flat pulse the plasma wave is generated at the front of the pulse. It focuses/defocuses the laser periodically, causing phase modulation of the laser and in the process it acquires larger amplitude itself, giving higher acceleration gradients. The plasma wave accelerates the pre-accelerated electrons to high energy in low density plasma ($n \leq 0.1\, n_c$, where n_c is the critical density for the laser). Several experiments, however, reported highly relativistic electron generation from the plasma itself, without any external pre-acceleration. Lin et al. [12] have investigated the electron acceleration in two counter-propagating plasma waves and found that two counter-propagating plasma waves enhance the acceleration of the trapped electron.

Since a plasma wave is sensitive to density variations, which change the plasma frequency, the existence of a density ripple in the form of an ion wave excited by stimulated Brillouin scattering (SBS) could greatly affect the coupling of plasma oscillations and generate two sideband plasma waves. One sideband moves with lower phase velocity than the pump plasma wave and the other with higher phase velocity. The mode-coupling problem in this connection can be used to transfer energy to the main body of the electrons from plasma waves generated by density ripple [13,14] have studied the effect of a density ripple (same wavelength as the plasma wave) on stimulated Raman scattering (SRS) of a light wave. As per their predictions, the density ripple reduces the growth rate of SRS. Kim et al. [15] have studied laser wake field acceleration in a plasma with sharp density ramp. Their particle-in-cell (PIC) simulations reveal substantial enhancement in electron energy due to the sudden change in the phase velocity of the plasma wave. Gupta et al., [16] have studied the propagation of plasma wave in a density modulated plasma. We extend the previous work by considering the plasma inhomogeneity associated with the density ripple. Here the plasma is inhomogeneous because

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of density ripple, hence, due to the spatial inhomogeneity, the frequency of the pump wave remains constant, only wave number gets modified. Therefore, the amplitudes of the interacting waves will grow secularly with spatial parameter not with time. To find out the electron energy gain in this case, an appropriate actual interaction length has been used in the calculation.

In Section 2, we study the generation of the sideband plasma waves by a pump plasma wave in the presence of a density ripple. In Section 3, we develop the framework for numerical estimation of the electron energy during acceleration by the plasma waves with density ripple. The numerical results are discussed in Section 4 and the conclusions are summarized in the last Section.

2. Generation of sideband waves and electron acceleration

Consider a plasma with a density ripple (inhomogeneous plasma). The electron density in the plasma is $n_0^0 + n_q$, where $n_q = n_q^0 \exp(iqz)$, q is the propagation vector of the ripple wave. A plasma wave of large amplitude propagates through it in the z-direction, $\mathbf{E_p} = \mathbf{Z}A_0 \exp[-i(\omega_p t - kz + \theta_0)]$, where θ_0 is the initial phase of the plasma wave, $\omega_p = (4\pi n_0^0 e^2/m)^{1/2}$, $k = 2\pi/\lambda$, λ is the wavelength of the plasma wave, and $-e$ and m_0 are the electronic charge and the rest mass of electron. In an inhomogeneous plasma, the frequency of pump wave remains constant, only wave number gets modified and it grows secularly with z. The pump plasma wave gives rise to an oscillatory electron velocity $\mathbf{v_p} = e\mathbf{E_p}/m_0 i\omega_p$. v_p Couples with n_q to produce two spatial harmonic with self-consistent fields (cf. Fig. 1), i.e., $\mathbf{E_{p+}} = \mathbf{z}A_1 \exp[-i(\omega_p t - \overline{k+q}z + \theta_1)]$ and $\mathbf{E_{p-}} = \mathbf{z}A_2 \exp[-i(\omega_p t - \overline{k-q}z + \theta_2)]$, where $\theta_1 = \theta_2 \approx \theta_0 + \pi/2$, and the values of θ_0 lie between $\pi/2$ to π.

If the amplitude of coupling is small, then only two significant sidebands will be survived. We treat the analysis as linear in the amplitude of oscillation. Hence, we neglect the higher harmonics and keep only lower order sidebands. The oscillatory electron velocities, $\mathbf{v_{k+q}}$ and $\mathbf{v_{k-q}}$, due to the sideband plasma wave can be deduced from given electric field of the fundamental plasma wave by replacing $\mathbf{E_p}$ by $\mathbf{E_{k+q}}$, and $\mathbf{E_{k-q}}$, respectively. Employing $\mathbf{v} = \mathbf{v_p} + \mathbf{v_{k+q}} + \mathbf{v_{k-q}}$ and $n = n_0^0 + n_q + n_{k+q} + n_{k-q}$ in the equation of continuity, $(\partial n/\partial t) + \nabla \cdot (nv) = 0$, we obtain

$$n_{k+q} = \frac{1}{\omega_p}\left(\mathbf{k} + \mathbf{q}\right) \cdot \left(n_0^0 \mathbf{v_{k+q}} + \frac{1}{2} n_q \mathbf{v_p}\right) \text{ and} \tag{1}$$

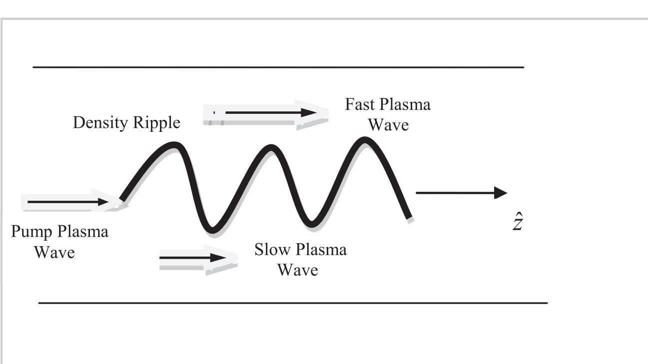

Fig. 1. The schematic of the electron acceleration by a plasma wave with a density ripple.

$$n_{k-q} = \frac{1}{\omega_p}\left(\mathbf{k} - \mathbf{q}\right) \cdot \left(n_0^0 \mathbf{v_{k-q}} + \frac{1}{2} n_q^* \mathbf{v_p}\right), \tag{2}$$

where, we have used the complex number identity, Re $\mathbf{A} \cdot$ Re $\mathbf{B} \equiv$ Re$(\mathbf{AB} + \mathbf{A} \cdot \mathbf{B}^*)/2$, with * denoting the complex conjugate and Re the real part of the quantity. Using Poisson's equation $\nabla \cdot \mathbf{E} = -4\pi e(n - n_0^0)$, we obtain

$$\frac{\partial A_1}{\partial z} = i\left(k + q\right)\frac{n_q^0}{2n_0^0} A_0, \text{ and} \tag{3}$$

$$\frac{\partial A_2}{\partial z} = i\left(k - q\right)\frac{n_q^{0*}}{2n_0^0} A_0. \tag{4}$$

Over an interaction length L, A_1 and A_2 acquire the values as $A_1 = i(k+q)\,L(n_q^0/2n_0^0)A_0$ and $A_2 = i(k-q)\,L(n_q^0/2n_0^0)A_0$.The interaction length L may be the actual length of the region on which ripple exists or it may be the characteristic length over which phase mismatch due to finite thermal effects or relativistic effects occurs. The electron motion in the presence of the pump plasma wave and the sidebands is governed by the equations

$$\frac{dp_z}{d\tau} = a_0\left[\sin\left(\tau - z + \theta_0\right) + \frac{a_1}{a_0}\sin\left(\tau - \overline{1 + q/k}z + \theta_1\right) + \frac{a_2}{a_0}\sin\left(\tau - \overline{1 - q/k}z + \theta_2\right)\right], \tag{5}$$

$$\frac{d\gamma}{d\tau} = k_1 \frac{p_z}{\left(1 + p_z^2\right)^{1/2}}, \tag{6}$$

where $a_1 = 2\pi(1 + q/k)\,\xi(n_q^0/2n_0^0)a_0$, $a_2 = 2\pi(1 - q/k)\,\xi(n_q^0/2n_0^0)a_0$, and $\gamma = (1 + p_z^2/m^2c^2)^{1/2}$. In this calculation, we have used the dimensionless quantities as follows:$p_z \to p_z/m_0 c$, $a_0 \to eA_0/m\omega_p c$, $a_1 \to eA_1/m\omega_p c$, $a_2 \to eA_2/m\omega_p c$, $\tau \to \omega_p t$, $z \to kz$, $v_z \to v_z/c$, $\xi \to L/\lambda$, $k_1 \to kc/\omega_p$.

Eqs. (5) and (6) are coupled differential equations. We solve them numerically by using a computer simulation program to find the electron velocities (v_z) and the corresponding electron energy (γ) as a function of normalized distance z for optimum value of initial phase θ by assuming the initial electron energy to be γ_0 and electron to have the momentum $p_{z0} = m_0 v_{z0}$, where v_{z0} is the initial electron velocity in the z-direction. This mechanism is related to the laser beat-wave acceleration, where two low-intensity lasers can excite a large amplitude plasma wave. And as we know the phase velocity of the plasma beat-wave can approach to the velocity of the light. Therefore, the selection of such arbitrary initial electron velocity is just to estimate the electron energy gain in this mechanism. Our results are as follows:

3. Numerical results

The electron velocity v_z and the electron energy γ as a function of normalized distance z for different normalized parameters have been obtained. We choose the dimensionless parameters as follows: $a_0 = 0.4,\ 0.6$ (corresponding to electric field gradient$A_0 \approx 0.97 \times (n_0^0[\text{cm}^{-3}])^{1/2}$ V/cm), $n_q^0/n_0^0 = 0.01$(corresponding to plasma electron density $n_0^0 \approx 10^{19}$ cm^{-3}), $q/k = 0.2$(corresponding to wavelength of pump plasma wave $\lambda \sim 10$ μm), $k_1 = kc/\omega_p = 1.02,\ 1.05$, $\xi = 25$(corresponding to the interaction length $L \sim 250$ μm), initial electron energies $v_{z0}/c = 0.9,\ 0.95$, $\theta_0 = \pi/2$, and $\theta_1 = \theta_2 = \theta_0 + \pi/2$. We examine these parameters for an optimum value of initial phase of the pump