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Amplitude saturation effect of a laser-driven plasma beat-wave on electron accelerations

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A large-amplitude plasma beat-wave driven by two lasers (differing in frequencies equal to the plasma frequency) can accelerate the plasma electrons to a higher energy level. As the plasma beat-wave grows, it becomes susceptible to oscillating two-stream instability. The decayed sideband plasma wave couples with the pump wave to divert its energy by the instability, and saturates it. The saturated amplitude of the plasma beat-wave traps the electrons more effectively to accelerate them to higher energy. The saturation of plasma beat-wave amplitude is shown to have a significant effect in an electron energy gain.

1. Introduction

Availability of high-power (Perry and Mourou 1994) lasers have opened new opportunities for plasma research and particle acceleration has emerged as a key point of investigation (Tajima and Dawson 1979; Esarey et al. 1996; Suk 2001; Umstadter 2001; Bingham 2004; Shukla 2009). It has been revealed that a relativistic plasma wave, having an extremely large electric field, may be utilized for the acceleration of plasma particles. Thus, large accelerating field gradient driven by a plasma wave is the basic motivation behind the acceleration mechanism. Such a plasma wave can be excited by a single laser or by two lasers from plasma interactions.

The concept proposed by Tajima and Dawson (Tajima and Dawson 1979) has also renewed the research on particle acceleration by a large-amplitude plasma wave driven by a laser. Thus, the plasma particles can be accelerated to high energies in a distance much shorter than in the conventional accelerators. In laser wakefield acceleration (LWFA), the ponderomotive force of the leading front of the laser pulse pushes out the electrons. The generating space-charge field then pulls the background electrons and a wake plasma wave is excited. Several theoretical models have been proposed to discuss the basic properties of these kinds of accelerators (Shvets and Fisch 1997; Mangles et al. 2004; Joshi 2007). Furthermore, two lasers, differing in frequencies by a plasma frequency, exert a longitudinal ponderomotive force on the electrons that resonantly drives a large amplitude plasma wave with a potential much higher than the

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ponderomotive potential. This scheme is known as the plasma beat-wave accelerators (Rosenbluth and Liu 1972; Kitagawa et al. 1992; Katsouleas and Bingham 1996). The excitation process can be most efficient at the resonant density, if the beat-frequency is comparable to the plasma frequency. Furthermore, the electrons have been externally injected into resonantly excited plasma wave and are shown to have a high energy gain. The plasma wave can also be generated through the process of stimulated Raman forward scattering in a plasma (Modena et al. 1996; Gupta et al. 2006). The plasma wave accelerates the pre-accelerated electrons to a higher energy level in a low-density plasma.

Three and four-wave parametric interactions are among the most widely studied wave-mixing processes in a plasma. It analogies to the parametric amplifier, where energy is transferred from a pump wave to the daughter waves by conserving the momentum and energy during the process (Thomson et al. 1973; Nicholson 1981; Aliev et al. 1988; Moulin et al. 1994; Shukla et al. 2010). An electromagnetic wave or an electrostatic wave (or plasma wave) can be a pump in these parametric interactions. At low amplitudes, these pump waves are mutually independent and provide a convenient description for the response of the plasma to the local perturbations. At higher amplitudes, they are coupled and can exchange energy and momentum with each other. In other words, it can be said that near resonance, the plasma wave generated by various processes discussed above attains a high amplitude and may decays parametrically into electromagnetic and electrostatic modes. Oscillating two-stream instability, by which a plasma wave decays into a zero frequency electrostatic mode and two Langmuir wave sidebands, has been known for some time and shown to be an important nonlinear process in plasmas. This process possesses a large growth rate of the instability to affect the plasma wave propagation (Liu and Tripathi 1986).

We study the nonlinear saturation of a laser-driven plasma beat-wave by a parametric instability process and consequently, observe its effect on electron accelerations. Usually, the efficiency of the acceleration scheme is strongly related to the saturation amplitude level reached by the excited plasma wave. Detuning of three-wave resonance by the relativistic effects has been important to saturate the plasma wave (Rosenbluth and Liu 1972; Divol et al. 2003). Similarly, the oscillating two-stream instability can arrest the growth of the plasma wave to saturate it at a certain level (Gupta et al. 2004). In beat-wave accelerators, initially, the amplitude of the plasma beat-wave increases due to the ponderomotive force caused by the laser beams. The growth of plasma wave could be reduced (due to the wave-breaking phenomena) and thus, the electrons cannot retain the maximum energy. To avoid this, we introduce the concept of the saturation of the plasma beat-wave via instability below the level of plasma wave-breaking. As the time goes, the oscillating two-steam instability effect overshoots the ponderomotive drivers. In this nonlinear coupling process, the sideband waves exchange energy with the pump wave via oscillating two-stream instability. In this way, the plasma wave may attain a saturated amplitude level that may maintain the maximum electron energy gain for long interaction time. Also, if the amplitude of the plasma beat-wave is not saturated, then the electrons can gain energy but cannot retain it sufficiently. This phenomenon of the saturation of plasma wave by an instability is applicable in beat-wave accelerators to retain a level of electron energy. Growth of plasma beat-wave is calculated in Sec. 2. The time-dependent equations for the interacting waves are derived and consequently, the electron acceleration is estimated in Sec. 3. Finally, the summary of the results is given in the last section.

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2. Saturation of plasma beat-wave

We consider a plasma of equilibrium density n_0 and electron temperature T_e through which two lasers co-propagate such that the frequency difference of the lasers is comparable to the plasma frequency. The lasers excite a plasma beat-wave of potential of

$$\phi_0 = \Phi_0 \exp[-i(\omega_0 t - k_0 z)], \tag{1}$$

where Φ_0 is the complex with slow space-time dependence, $\omega_0 = \omega_{01} - \omega_{02} \approx \omega_p$, $\mathbf{k}_0 = \mathbf{k}_{01} - \mathbf{k}_{02}$, $\omega_{01}, \omega_{02} > \omega_p$, ω_{01} and ω_{02} are the laser frequencies, and $\mathbf{k}_{01}$ and $\mathbf{k}_{02}$ are the wave vectors of the laser. Here, we define the plasma frequency as $\omega_p = (n_0 e^2/m\varepsilon_0)^{1/2}$, where ε_0 is the dielectric constant, and e and m are the magnitudes of the electron charge and the electron mass, respectively.

From the Poisson's equation, we obtain the dispersion relation of the plasma beat-wave as $\varepsilon_0 \Phi_0 = -\chi_{e0}\Phi_{p0}$, where $\varepsilon_0 = 1 + \chi_{e0}$, $\chi_{e0} = -(\omega_p^2 + 3k^2 v_{th}^2/2)/\omega_0^2$, $\Phi_{p0} = eA_{01}A_{02}/2\, m\omega_{01}\omega_{02}$, v_{th} is the electron thermal speed, and A_{01}, A_{02} are the laser intensity amplitudes. For resonant excitation ($\varepsilon \approx 0$), the plasma beat-wave satisfies the dispersion relation as $\omega_0^2 = \omega_p^2 + 3k_0^2 v_{th}^2/2$. We assume that this plasma beat-wave can initiate the oscillating two-stream instability process. The pump beat-wave decays into a low-frequency electrostatic wave $(\omega, \mathbf{k})$ and two Langmuir wave sidebands $(\omega_{1,2}, \mathbf{k}_{1,2})$, where $\omega_{1,2} = \omega \mp \omega_0$ and $\mathbf{k}_{1,2} = \mathbf{k} \mp \mathbf{k}_0$. We write the electrostatic potentials of the sidebands as $\phi_{1,2} = \Phi_{1,2} \exp[-i(\omega_{1,2}t - k_{1,2}z)]$. The low-frequency mode satisfies the dispersion relation, $\varepsilon\phi = -\chi_e \Phi_p$, where $\varepsilon = 1 + \chi_e + \chi_i$, χ_e ($\chi_e = 2\omega_p^2/k^2 v_{th}^2$ for $\omega \ll k v_{th}$) is the electron susceptibility at $(\omega, \mathbf{k})$, χ_i is the ion susceptibility ($\chi_i \approx 2\omega_{pi}^2/k^2 v_{thi}^2$, for $\omega \ll k v_{thi}$), ω_{pi} and v_{thi} are the ion plasma frequency and ion thermal speed, respectively, and Φ_p is the low-frequency ponderomotive potential arises due to the low-frequency ponderomotive force on the electrons by the sidebands and the pump. Similarly, the sideband waves also obey the dispersion relations, $\varepsilon_j \phi_j = -4\pi e n_j^{NL}/k^2$, where $\varepsilon_j = 1 - (\omega_p^2 + 3k^2 v_{th}^2/2)/\omega_j^2$, n_j^{NL} is the nonlinear density perturbation at $(\omega_j, \mathbf{k}_j)$ produced by the density perturbation $[n \approx n_i = (k^2 \Phi_p/4\pi e)\chi_e \chi_i/\varepsilon]$ in conjunction with the oscillatory electron velocity at $(\omega_0, \mathbf{k}_0)$, and $j = 1, 2$.

To obtain the temporal evolution of the oscillating two-stream instability [23], we express (a) $\omega_{0,1,2} \to \omega_{0,1,2} + i\partial/\partial t$ and introduce $e\Phi_0/T_e = A_0$, $e\Phi_1/T_e = A_1$, $e\Phi_2/T_e = A_2$, $e\Phi_{p0}/T_e = A_{p0}$, and $\omega_p t = \tau$ (b) $A_0 = a_0(\tau)\exp[i\theta_0(\tau)]$, $A_1 = a_1(\tau)\exp[i\theta_1(\tau)]$, $A_2 = a_2(\tau)\exp[i\theta_2(\tau)]$, and $A_{p0} = a_{p0}\exp[i\theta_{00}]$. Then, we separate the real and imaginary parts of the resulting equations and we obtain the following equations

$$\frac{\partial a_0}{\partial \tau} = -2\alpha_0' a_1 a_2 a_0 \sin(\theta_2 - \theta_1 - 2\theta_0) - \frac{\Omega_0}{2} a_{p0} \sin(\theta_0 - \theta_{00}), \tag{2}$$

$$\frac{\partial a_1}{\partial \tau} = \alpha_1' a_2 a_0^2 \sin(\theta_2 - \theta_1 - 2\theta_0), \tag{3}$$

$$\frac{\partial a_2}{\partial \tau} = \alpha_1' a_1 a_0^2 \sin(\theta_2 - \theta_1 - 2\theta_0), \tag{4}$$

$$\frac{\partial \theta_0}{\partial \tau} = \alpha_0' a_1^2 + \alpha_0' a_2^2 + 2\alpha_0' a_1 a_2 \cos(\theta_2 - \theta_1 - 2\theta_0) - \frac{\Omega_0 a_{p0}}{2}(1/a_0)\cos(\theta_0 - \theta_{00}), \tag{5}$$

$$\frac{\partial \theta_1}{\partial \tau} = \alpha_1' a_0^2 + \alpha_1' a_0^2 (a_2/a_1)\cos(\theta_2 - \theta_1 - 2\theta_0), \tag{6}$$

$$\frac{\partial \theta_2}{\partial \tau} = \alpha_0' a_0^2 + \alpha_1' a_0^2 (a_1/a_2)\cos(\theta_2 - \theta_1 - 2\theta_0), \tag{7}$$

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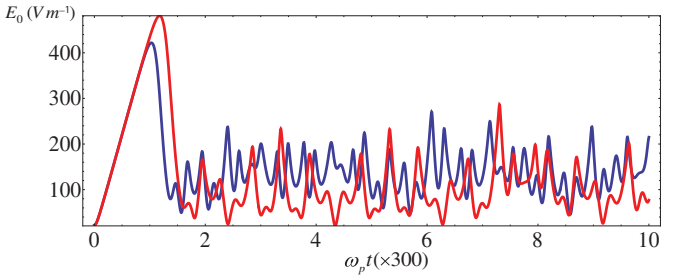


FIGURE 1. Electric field of the plasma beat-wave (E_0) with the time ($\omega_p t$) for $\omega_0 \approx \omega_p$ (red curve) and $\omega_0 \approx 0.9\ \omega_p$ (black curve). The used simulation parameters are $k_0\lambda_D = 0.16$, $k\lambda_D = 0.3$, $\omega_{pi}/\omega_p = 0.02$, $c_s/c = 10^{-5}$, $\theta_{00} = 0$, $a_{p0} = 0.2$, $a_0(\tau = 0) = 0.5$, $a_1 = a_2(\tau = 0) = 0.01$, $\theta_0 = \theta_1(\tau = 0) = 0$, and $\theta_2(\tau = 0) = \pi/2$.

where $\alpha_0 \cong [1/8(1+T_i/T_e)](\omega_p/\omega_{pi})$, $\alpha_1 \approx \alpha_2 \cong (k_0 \upsilon_{th}/\omega_p)(k_0/k)\alpha_0$, $\alpha_0' \approx \alpha_0'' \approx \alpha_0'''/2 \cong (k^2\upsilon_{th}^2/\omega_p^2)\alpha_0$, $\alpha_1' \approx \alpha_1'' \approx \alpha_2' \approx \alpha_2'' \cong (k^2\upsilon_{th}^2/\omega_p^2)\alpha_1$, $\Omega_0 = \omega_0/\omega_{pi}$, and θ_0, θ_1, θ_2, and θ_{00} are the phases of the interacting waves.

To observe the temporal behavior of the interacting waves, we solve (2)–(7) by computer simulation. The numerical parameters are used corresponding to the Nd-laser plasma beat-wave experiments. We take the feasible experimental parameters for deuterium plasma as follows: the intensities of lasers are $I_{1\,\max} = 1.3 \times 10^{14}\ Wcm^{-2}$ ($\lambda_1 = 1.0642\ \mu m$) and $I_{2\,\max} = 7.6 \times 10^{14}\ Wcm^{-2}$ ($\lambda_2 = 1.0530\ \mu m$). A plasma consists of electrons and deuteron ions ($Z_i = 1, m_i = 3672\,\mathrm{m}$). The initial electron temperature is 400 eV and the initial ion temperature is 100 eV. The plasma electron density is $n_e = 1.1 \times 10^{17}\,\mathrm{cm}^{-3}$. Corresponding to these experimental parameters, the normalized parameters can be approximated as follows: $k_0\lambda_D = 0.16$, $k\lambda_D = 0.3$, $\omega_{pi}/\omega_p = 0.02$, $c_s/c = 10^{-5}$, $\theta_{00} = 0$, and $a_{p0} = 0.2$. The initial conditions are $a_0(\tau = 0) = 0.5$, $a_1 = a_2(\tau = 0) = 0.01$, $\theta_0 = \theta_1(\tau = 0) = 0$, and $\theta_2(\tau = 0) = \pi/2$. The numerical results are described as below.

We show the field amplitude ($E_0, inV/m$) of the plasma beat-wave with the normalized time ($\omega_p t$) in Fig. 1 for $\omega_0 \approx \omega_p$ (red curve) and $\omega_0 \approx 0.92\ \omega_p$ (black curve) in the presence of oscillating two-stream instability. Our results show that the pump wave grows and saturates after attaining a peak. Before time $t \approx 450\ \omega_p^{-1}$, the plasma wave amplitude grows linearly due to the dominant effect of the lasers. As the amplitude grows, the large amplitude plasma wave can initiate the oscillating two-stream instability process. Thus, the energy of the plasma wave diverts to the decaying modes. Therefore, the amplitude of the plasma beat-wave starts to decay and saturates at a level. Our results show that after time $t \approx 480\ \omega_p^{-1}$, the plasma wave starts to decay and saturates at time $t \approx 510\ \omega_p^{-1}$ due to the instability. This saturated amplitude can affect the acceleration of electrons by the plasma beat-wave. To analyze this, we now propose to study the electron acceleration by the plasma beat-wave.

3. Electron acceleration

Plasma beat-wave can be employed for electron acceleration in plasmas. We examine the single particle acceleration by a plasma beat-wave of electric-field $\mathbf{E} = -\hat{z}E_0(t)\sin(\omega_0 t - k_0 z + \theta_0)$, where $E_0(\tau) = -ek_0\Phi_0(t)/T_e$ and $\Phi_0(t)$ can be

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determined by (2). The electron momentum equation can be written as follows:

$$\frac{d\mathbf{p}}{dt} = -eE_z, \tag{8}$$

where $\mathbf{p} = \gamma m\boldsymbol{v}$ is the electron momentum, $\gamma = (1 + p^2/m^2c^2)^{1/2}$ is the Lorentz factor, $\boldsymbol{v}$ is the electron velocity, and c is the speed of light in vacuum. Using the normalized parameters, (8) can be written into the following form

$$\frac{d\gamma}{d\tau} = \frac{p}{\gamma m^2c^2}\frac{dp}{d\tau} = -\frac{eE_0(\tau)}{mc}\left(1 - \frac{1}{\gamma^2}\right)^{1/2}\sin(\tau - \xi + \theta_0), \tag{9}$$

where $\xi = k_0 z$. Equations (2)–(9) are coupled differential equations. We have solved these equations numerically using a simulation code to determine the electron energy (γmc^2) by assuming the initial electron energy $\gamma_0 mc^2$.

In Fig. 2(a), we depict the electron energy ($\gamma mc^2, inMeV$) with time ($\omega_p t$) for $\omega_0 \approx \omega_p$ (red curve) and $\omega_0 \approx 0.9\ \omega_p$ (black curve) for the amplitude of plasma beat-wave of $a_{p0} = 0.2$. The electron having the initial electron energy $\gamma_0 mc^2 = 1.5MeV$, can be accelerated to energy gain of about 70 MeV (for $\omega_0 \approx \omega_p$) and 55 MeV (for $\omega_0 \approx 0.9\ \omega_p$). To observe the effect of the saturation of plasma beat-wave on electron acceleration, we correlate these results with the results obtained in Fig. 1. Before time $t \approx 480\ \omega_p^{-1}$, the large amplitude plasma wave grows linearly. Thus, the electron energy gain is driven by the laser related ponderomotive effects. After this time, the amplitude of the plasma wave suddenly drops due to the oscillating two-stream instability. Therefore, the electron energy gain was also decreased. This means that the electron energy gain is corresponding to the beat-wave amplitude. Beyond this time, the plasma wave saturates at a level and is efficiently able to impart its energy to the interacting electrons. However, the amplitude of the plasma wave grows after saturation, but slower than that during the initial stage. The electron oscillates along the path of the plasma wave to gain energy. As a result, the electron gains considerable energy and retain it. In the absence of a saturation level, the electron energy can increase as the plasma beat-wave grows and then reduces due to the reducing amplitude of the plasma-beat wave. The instability drives the plasma wave amplitude to attain a saturation level that plays an important role for electron energy gain. Figure 2(b) shows the electron energy gain for different amplitudes of plasma beat-wave (corresponding to different laser intensities)$a_{p0} = 0.1$ (blue curve), $a_{p0} = 0.2$ (red curve) $a_{p0} = 0.3$ (black curve) with the initial electron energy $\gamma_0 mc^2 = 1.5MeV$. As we know that the strength of plasma beat-wave is the function of the intensity of the lasers ($\Phi_{p0} = eA_{01}A_{02}/2m\omega_{01}\omega_{02}$, where A_{01} and A_{02} are the laser intensity amplitudes). Thus, the results shown in Fig. 2(b) are to show the effect of laser intensity on electron energy gain. It is obvious that the electron energy gain is comparatively higher for higher laser intensities. The fact for this is the excitation of larger (stronger) amplitude plasma wave by the high power lasers.

Figure 3(a) shows the variation of maximum electron energy ($\gamma_m mc^2, inMeV$) with the initial electron energy ($\gamma_0 mc^2$) for different cases of resonance ($\omega_0 \approx \omega_p$ and $\omega_0 \approx 0.9\ \omega_p$). The maximum electron energy gain increases with the initial electron energy. If the electron is pre-accelerated (or has enough initial energy), it can extract more energy from the plasma wave. If the electron has more initial energy, the group velocity of the plasma wave is quite enough to catch up the electrons for acceleration. If the beat-wave is excited resonantly, the electron can gain more energy as estimated

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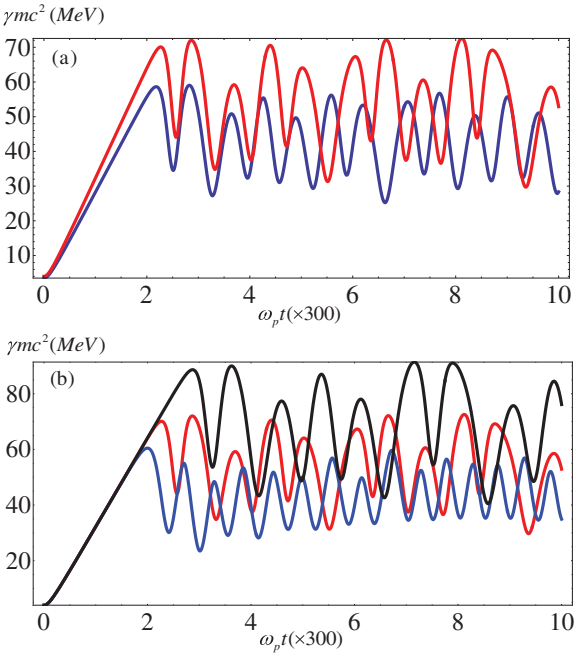


FIGURE 2. (a) Electron energy ($\gamma mc^2, inMeV$) with the time ($\omega_p t$) for $\omega_0 \approx \omega_p$ (red curve) and $\omega_0 \approx 0.9\ \omega_p$ for the amplitude of plasma beat-wave of $a_{p0} = 0.2$ and (b) electron energy with the time ($\omega_0 \approx \omega_p$) for different amplitude of plasma beat-wave (corresponding to different intensities of lasers)$a_{p0} = 0.1$ (blue curve), $a_{p0} = 0.2$ (red curve), and $a_{p0} = 0.3$ (black curve) with the initial electron energy $\gamma_0 mc^2 = 1.5\,\text{MeV}$. Other simulation parameters are the same as those of Fig. 1.

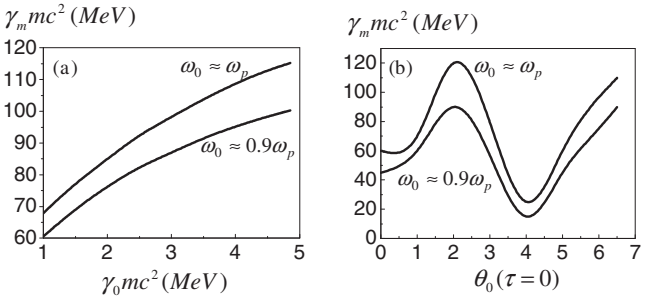


FIGURE 3. Maximum electron energy ($\gamma_m mc^2, inMeV$) with (a) the initial electron energy ($\gamma_0 mc^2$) and (b) the initial phase [$\theta_0(\tau = 0)$] of the plasma beat-wave (with $\gamma_0 mc^2 = 5\,\text{MeV}$) for $\omega_0 \approx \omega_p$ and $\omega_0 \approx 0.9\ \omega_p$.

by our calculations. The deviation from the resonance condition reduces the electron energy gain.

In Fig. 3(b), finally, we show the maximum electron energy gain with the initial phase [$\theta_0(\tau = 0)$] of the plasma beat-wave for different cases of resonance ($\omega_0 \approx \omega_p$ and $\omega_0 \approx 0.9\ \omega_p$). The maximum electron gain in acceleration is sensitive to the initial phase of the plasma beat-wave. For a certain initial phase of the beat-wave, the electron enters in accelerating phase and gains sufficient energy. Changing in initial

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phase of the electron affects the electron energy due to wave–particle dephasing. The energy of the electron is also modified with the variation of the initial phases and speeds related to the wave.

4. Conclusions

Large amplitude plasma beat-wave appears to be susceptible to the oscillating two-stream instability. As the plasma beat-wave attains a large amplitude, it decays into two sidebands plus a low-frequency electrostatic mode. The amplitude of the beat-wave starts to decrease after attaining a peak due to energy transportation into the decaying modes. This saturation process is crucial in electron acceleration the plasma beat-wave. At a time, when the amplitude of the plasma wave just starts to decrease, the electron energy is reduced. Beyond this time, the beat-wave amplitude saturates at a certain level, and electron acceleration process is seen to be more efficient. Our results show that the electrons gain enough kinetic energy as they were seriously influenced by the saturated amplitude of the beat-wave. If the plasma wave is excited resonantly, this effect can be more pronounced. The electrons velocity can be comparable to the phase velocity of the saturated plasma beat-wave, if they have considerable initial energy. Thus, the electron can gain more energy in this case. The electron energy can also be maximized by optimizing the initial phase of the plasma beat-wave.

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