Laser-driven plasma beat-wave propagation in a density-modulated plasma

Devki Nandan Gupta,[1,*] In Hyuk Nam,[2] and Hyyong Suk[2]

[1]*Department of Physics and Astrophysics, University of Delhi, Delhi 110 007, India*

[2]*Advanced Photonics Research Institute and Graduate Program of Photonics and Applied Physics, Gwangju Institute of Science and Technology, Gwangju 500 712, Korea*

(Received 24 December 2010; revised manuscript received 18 July 2011; published 4 November 2011)

A laser-driven plasma beat wave, propagating through a plasma with a periodic density modulation, can generate two sideband plasma waves. One sideband moves with a smaller phase velocity than the pump plasma wave and the other propagates with a larger phase velocity. The plasma beat wave with a smaller phase velocity can accelerate modest-energy electrons to gain substantial energy and the electrons are further accelerated by the main plasma wave. The large phase velocity plasma wave can accelerate these electrons to higher energies. As a result, the electrons can attain high energies during the acceleration by the plasma waves in the presence of a periodic density modulation. The analytical results are compared with particle-in-cell simulations and are found to be in reasonable agreement.

DOI: 10.1103/PhysRevE.84.056403 PACS number(s): 52.38.Ph

I. INTRODUCTION

Acceleration of electrons by laser-driven plasma waves to ultrarelativistic energies over a short distance has emerged as an attractive alternative to conventional accelerators [1–7]. There are three major types of laser-driven plasma-based accelerators: the resonantly laser-driven plasma waves for electron acceleration, the laser wake-field accelerator, and the plasma beat-wave accelerator [8–15]. An intense laser can create a plasma wave that would propagate with a phase velocity equal to the group velocity of light in a plasma. This density wave would have a sizable longitudinal electric field component that would also propagate at nearly the speed of light and be ideal for accelerating electrons over extremely short distances [16,17]. The plasma wave can be driven either by beating two copropagating lasers, differing in frequencies by the plasma frequency, or by a single short-pulse laser of duration equal to the plasma period. In the beat-wave scheme, two lasers exert a longitudinal ponderomotive force on the electrons that resonantly drives a large-amplitude plasma wave with a potential much higher than the ponderomotive potential. The plasma wave can grow significantly when the resonance condition between the plasma frequency and laser frequencies is fulfilled. The plasma wave can accelerate the preaccelerated electrons to high energy in a low-density plasma ($n \leqslant 0.1n_c$, where n_c is the critical density for the laser) [18,19]. Several experiments, however, reported highly relativistic electron generation from the plasma itself, without any external preacceleration. Koyama *et al.* [20] have performed an experiment to demonstrate the acceleration of a quasimonoenergetic electron beam by trapping electrons in a plasma wave. Fritzler *et al.* [21] have observed 55-MeV electrons from gas jet targets irradiated by 1-μm, (3×10^{18})-W/cm^2, 70-fs laser pulses at an electron density of $n \sim 2.5 \times 10^{19}$ cm^{-3}. Lin *et al.* [22] have investigated the electron acceleration in two counterpropagating plasma waves and found that two counterpropagating 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 a lower phase velocity than the pump plasma wave and the other with a higher phase velocity. Kaw *et al.* [23] treated the mode-coupling problem in this connection. This process can be used to transfer energy to the main body of the electrons from plasma waves generated by the density ripple. Darrow *et al.* [24] have presented a model for beat-wave excitation of electron plasma waves in a rippled density plasma. The temporal development of the beat wave and coupled modes was analyzed and consequently predicted the beat-wave saturation mechanism in cold as well as in warm plasmas [25]. Leemans *et al.* [26] have examined the nonlinear dynamics of the laser-driven plasma beat wave in the presence of a strong short-wavelength density ripple using the relativistic Lagrangian-oscillator model. Suk *et al.* [27] have proposed a type of density transition for plasma wake-field acceleration and found that the plasma electrons can be trapped due the proposed density transition. Kim *et al.* [28] have studied the laser wake-field acceleration in a plasma with a sharp density ramp. Their particle-in-cell simulations revealed substantial enhancement in electron energy due to the sudden change in the phase velocity of the plasma wave.

In this paper we study the plasma beat-wave acceleration of electrons in the presence of a density ripple (or a sound wave or periodic density modulation). The density ripple can be in the plasma prior to launching the main laser pulse. The sound wave can be generated internally via SBS of a prepulse. The density ripple couples with the oscillatory velocity of electrons to produce nonlinear currents driving sideband plasma waves. Thus the main plasma wave $(\omega_p,\vec{k})$ generates two sideband plasma waves of the wave vectors $\vec{k}+\vec{q}$ (slow wave) and $\vec{k}-\vec{q}$ (fast wave) in the presence of a density ripple of wave vector $\vec{q}$. The plasma wave of low phase velocity accelerates the modest-energy electrons to gain substantial energies. The electrons are accelerated to high energies by the main plasma wave. They can be further

*dngupta@physics.du.ac.in

accelerated to higher energies by the plasma wave of higher phase velocity. The theoretical treatment is studied in Sec. II, where the expression for plasma-wave generation is derived in the presence of a periodic density modulation. Consequently, the formulation for electron acceleration by a plasma beat wave in the presence of two other daughter waves is given and the analytical results are discussed in Sec. III. To solve the relativistic equation of motion for a set of electrons and ions, we use a two-dimensional particle-in-cell simulation code using an object-oriented particle-in-cell method. The plasma is assumed by macroparticles that have three velocity components and contributes to charge and current density on two-dimensional spatial grids. The particles follow the equation of motion in each time step. The electron energy gain and the energy spectra are discussed in Sec. IV. A summary is given in Sec. V.

II. PLASMA-WAVE GENERATION

Let us consider a plasma with a periodic density modulation and the electron temperature T_e. The electron density in the plasma is $n_0^0 + n_q$, where $n_q = \mathrm{Re}[n_q^0 \exp(iqz)]$ is the density with a ripple and q is the propagation vector of the ripple wave. Such a density modulation or ripple can be observed in a tunnel-ionized plasma through stimulated Brillouin scattering, coincidentally with a beat excited plasma wave. Two collinear laser beams of large amplitude propagate in a plasma with electric fields

$$\vec{\mathbf{E}}_{01} = \mathrm{Re}\hat{x} A_{01} \exp[-i(\omega_{01}t - k_{01}z)], \tag{1}$$

$$\vec{\mathbf{E}}_{02} = \mathrm{Re}\hat{x} A_{02} \exp[-i(\omega_{02}t - k_{02}z)], \tag{2}$$

where $|A_{01}|^2_{x=0} = A_{01}^0 \exp(-x^2/r_{01}^2)$, $|A_{02}|^2_{x=0} = A_{02}^0 \exp(-x^2/r_{02}^2)$, $\omega_{01} - \omega_{02} \approx \omega_p, \omega_{01} \geqslant \omega_p, \omega_{02} \geqslant \omega_p$, ω_{01} and ω_{02} are the laser frequencies, $\vec{k}_{01}$ and $\vec{k}_{02}$ are the wave vectors of the laser beams, and r_{01} and r_{02} are the laser spot sizes. They produce oscillatory velocities $\vec{\upsilon}_{0j} = e\vec{E}_{0j}/mi\omega_{0j}$ $(j = 1,2)$ and exert a ponderomotive force $\vec{F}_p = -(e/2c)(\vec{\upsilon}_{01} \times \vec{B}_{02}^* + \vec{\upsilon}_{02}^* \times \vec{B}_{01}) = \hat{z}iek_0\phi_{p0}\exp[-i(\omega_0 t - k_0 z)]$ on them, where $\phi_{p0} = eA_{01}A_{02}/2m\omega_{01}\omega_{02}$, $\omega_0 = \omega_{01} - \omega_{02}$, $\vec{k}_0 = \vec{k}_{01} - \vec{k}_{02}$, $\vec{B}_{0j} = c\vec{k}_{0j} \times \vec{E}_{0j}/\omega_{0j}$, and $-e$ and m are the electron charge and mass, respectively. Because of the large mass and the slow response of the ions, we consider them immobile. The ponderomotive force drives a large-amplitude beat wave in a plasma. We write the Eulerian equation for the plasma-wave electric field driven by the ponderomotive force of the beating laser pumps as [Eq. (1) of Ref. [24]]

$$\ddot{E}_p + \omega_p^2 E_p + \upsilon_{\mathrm{th}}^2 E_p'' = \tfrac{1}{2} A_{01}A_{02}\omega_0^2 \sin(\Delta k z - \Delta\omega t), \tag{3}$$

where $\omega_p = \omega_p^0[1 + \mathrm{Re}\{(n_q^0/n_0^0)\exp(iqz)\}]^{1/2}$, $\omega_p^0 = (4\pi n_0^0 e^2/m)^{1/2}$ is the unperturbed plasma frequency, $\upsilon_{\mathrm{th}}^2 = 3T_e/m$, T_e is the electron temperature, and $\Delta k = k_p$ and $\Delta\omega = \omega_p$ are the frequency and wave-number differences of the two laser pumps. Under the cold plasma approximation, we set $\upsilon_{\mathrm{th}} \approx 0$ and the solution of Eq. (3) can be in the form [25]

$$\vec{E}_p = \mathrm{Re}\hat{z}A_0(t)\exp\left[-i\left(\left\{1 + \mathrm{Re}\left[\frac{n_q}{n_0^0}\exp(iqz)\right]\right\}^{1/2}\omega_p^0 t - k_p z + \theta_0\right)\right], \tag{4}$$

where θ_0 is the initial phase of the plasma beat wave. The given solution of Eq. (3) requires a small value of n_q/n_0^0. We follow the theory given by Rosenbluth and Liu [19], the large-amplitude plasma beat wave grows linearly in time as $A(t) = A(0) + (\omega_p/2)\phi_{p0}t$, where $A(0)$ is the plasma-wave amplitude at time $t = 0$ (which can be characterized by the beat-wave driver strength). However, for the other case (without density modulation), the plasma beat wave also grows secularly with time as predicted by Darrow *et al.* [25]. The early-time behavior is similar to that in the density-modulated case. However, at later times the saturation of the plasma beat-wave amplitude may be expected due to the relativistic mass detuning, but some appropriate propagation time is necessary to consider this effect. The early-time secular growth of the plasma beat wave has been adopted in the present analysis, where the main concern is to determine the role of the phase velocities of the three plasma waves that play an important role in electron energy enhancement during acceleration.

Due to the density ripple (mildly varying over the plasma period), the beat wave is frequency modulated with amplitude modulation $n_q^0/2n_0^0$ in the z space. Because of the nonlinear interaction of an electrostatic wave with the rippled plasma (if the amplitude of the modulation is small), the pump plasma wave generates two significant sidebands during the interaction with a density ripple. The self-consistent fields of the plasma-wave sideband can be obtained by considering the amplitude of the modulation as a small parameter and expanding the field $\vec{E}_p$ as

$$\vec{E}_p = \hat{z}A_0(t)\left(2\cos\left(\omega_p^0 t - k_p z + \theta_0\right) - \frac{n_q^0}{2n_0^0}\omega_p^0 t\left\{\sin\left[\omega_p^0 t - z(k_p - q) + \theta_1\right] - \sin\left[\omega_p^0 t - z(k_p + q) + \theta_2\right]\right\}\right), \tag{5}$$

where $\theta_1 = \theta_2 \approx \theta_0 + \pi/2$ and the values of θ_0 lie between 0 and $\pi/2$. We neglect the higher-order harmonics and keep only lower-order sidebands because of the small modulation amplitude. The amplitude of the lowest-order sideband is seen to grow in time as in a parametric oscillator.

III. ELECTRON ACCELERATION

The electron momentum in the presence of the plasma beat wave and the sidebands is governed by the equation

$$\frac{d\vec{p}}{dt} = -e\vec{E}_p. \tag{6}$$

Equation (6) is an ordinary differential equation. We solve this numerically by the Runge-Kutta method to have the electron energy $\gamma = (1 + p_z^2/m^2c^2)^{1/2}$ as a function of the propagation distance z for optimum value of the initial phase θ by assuming the initial electron energy to be γ_0 and the electron to have the momentum $p_{z0} = m\upsilon_{z0}$, where υ_{z0} is the initial electron velocity in the z direction and c is the speed of light in vacuum. Throughout this paper, time and distance are normalized by $1/\omega_p^0$ and c/ω_p^0, respectively. Velocity, momentum, and energy are normalized by c, mc, and mc^2, respectively, and the field amplitudes are normalized as $a_{02} \to eA_{02}/m\omega_{02}c$, $a_{01} \to eA_{01}/m\omega_{01}c$, and $a_0 \to eA_0/m\omega_p^0 c$. The laser parameters are as follows: $a_{01} = a_{02} = 1$ (corresponding to the peak laser intensity $I_{01} \approx I_{02} \approx 1.37 \times 10^{18}$ W/cm^2), the wavelength of the first laser considered is $\lambda_{01} \sim 1$ μm, the wavelength of the second laser has been chosen according to the resonant condition for beat-wave excitation, and the initial waist size is $r_{01} \approx r_{02} \sim 8.2$ μm. The uniform component density is $n_0^0 \approx 10^{19}$ cm^{-3}. The amplitude of periodic modulation is 5% ($n_q^0/n_0^0 = 0.05$) and 10% ($n_q^0/n_0^0 = 0.1$) of the uniform plasma density. The ripple wave vector is chosen as $q = 0.2k_p, 0.5k_p$ and $p_{z0} = 1.125mc, 3mc$. We examine these numerical parameters for an optimum value of the initial phase of the pump wave to solve the above differential equation. The analytical and simulations results are presented in the following.

IV. NUMERICAL RESULTS

A. Analytical results

Figure 1 shows the maximum electron energy as a function of the initial phase of the pump plasma beat wave for $a_{01} = a_{02} = 1$, $n_0^0 \approx 10^{19}$ cm^{-3}, $n_q^0 = 0.1n_0^0$ (with density ripple), $n_q^0 = 0$ (without density ripple), $q = 0.2k_p$, and $p_{z0} = 1.125mc$.

The maximum electron gain during acceleration is sensitive to the initial phase of the plasma beat wave. For a certain initial phase of the beat wave, the electrons enters the accelerating phase and gain sufficient energy and hence attains the maximum energy for an optimum value of the initial phase of the plasma beat wave. The electron energy gain is much larger in the presence of a density ripple for a certain initial phase of the plasma beat wave. Our results show that the electron energy is maximized for particular values of the initial phase of the beat wave (0, 2π) for both cases. The change in the initial electron phase decreases the electron energy due to wave-particle dephasing. The energy of the electrons over time may be further change because electrons have varying initial phases and speeds relative to the wave.

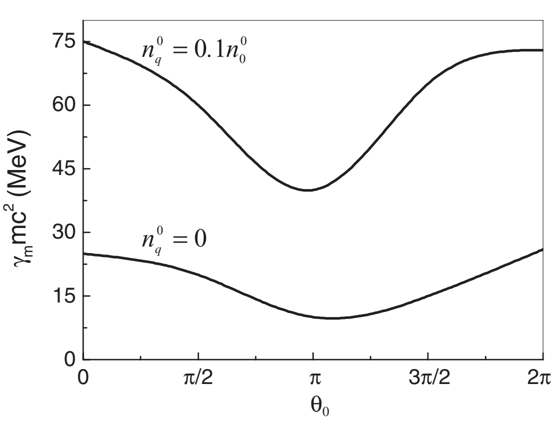

FIG. 1. Maximum electron energy $\gamma_m mc^2$ (MeV) as a function of the initial phase of the plasma beat wave θ_0 (rad) at a propagation time of $16/\omega_p^0$. The numerical parameters are $a_{01} = a_{02} = 1$ and $\lambda_{01} \sim 1$ μm, the wavelength of the second laser has been chosen according to the resonant condition for beat-wave excitation, $r_{01} \sim 8.2$ μm, $n_0^0 \approx 10^{19}$ cm^{-3}, $n_q^0 = 0.1n_0^0$ (with density ripple), $n_q^0 = 0$ (without density ripple), $q = 0.2k_p$, and $p_{z0} = 1.125mc$.

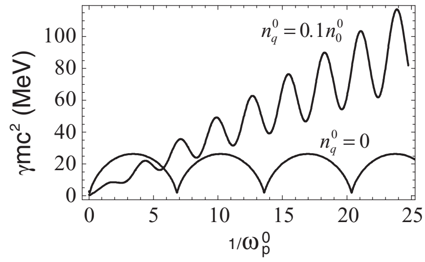

FIG. 2. Electron energy γmc^2 (MeV) as a function of the propagation time $1/\omega_p^0$ with plasma density ripple ($n_q^0 = 0.1n_0^0$, top curve) and without density ripple ($n_q^0 = 0$, bottom curve) for $a_{01} = a_{02} = 1$, $n_0^0 \approx 10^{19}$ cm^{-3}, $q = 0.2k_p$, and $p_{z0} = 1.125mc$.

The electron energy gains are presented in Fig. 2 for numerical parameters that are different from those given above. The effect of a density ripple could be seen from these results. The electron experiences a force by the plasma waves and moves toward the axis of the wave. Initially, the electrons are accelerated by the main plasma wave. As time passes, the slow plasma wave traps the energetic electrons and accelerates them further. The fast plasma wave accelerates the energetic electrons to higher energies.

In the given example, the electron gains about 75 MeV of energy (at a propagation time of $16/\omega_p^0$) in the presence of a density ripple (top curve) and about 25 MeV of energy (at a propagation time of $16/\omega_p^0$) without a density ripple (bottom curve), which implies that the density ripple effect is significant. This is because there is only one pump plasma wave that is responsible for acceleration of the electron in the absence of a density ripple, while if a density ripple exists in the plasma, the pump plasma wave generates two sideband plasma waves that can increase the electron energy further. Hence the electron can attain higher energy during acceleration by the plasma wave in the presence of a density ripple.

The effect of the wave number of the ripple wave in the presence of a density modulation could be seen in Fig. 3(a). We have plotted the electron energy gain for different wave numbers of the ripple wave ($q = 0.2k_p, 0.5k_p$). The electron gains less energy for a larger wave number of the ripple wave ($q/k = 0.5$, top curve). The electron can gain higher energy by increasing the ripple spacing to speed up the wave. The initial energy of the electrons can also affect the electron energy gain during acceleration. Figure 3(b) shows the electron energies for different initial electron energies ($p_{z0} = 2mc, 3mc$) in the presence of a density ripple. In this mechanism, the electron energy also increases with the initial electron energy. It is shown that if the electron has a sufficient initial energy to interact with the plasma waves, it can gain a large amount of energy during acceleration. The analytical result shows that the electron gains about 100 MeV of energy (at a propagation time of $16/\omega_p^0$) for an initial electron energy of $p_{z0} = 3$ (top curve).

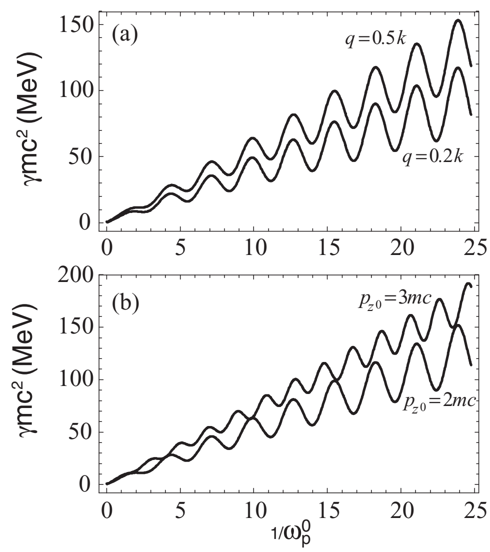

FIG. 3. Electron energy γmc^2 (MeV) as a function of the propagation time $1/\omega_p^0$ in the presence of a plasma density ripple for (a) different wave numbers of the ripple wave, $q/k = 0.5$ (top curve) and $q/k = 0.2$ (bottom curve), and (b) different initial energies of the electrons, $p_{z0} = 3mc$ (top curve) and $p_{z0} = 2mc$ (bottom curve). Other numerical parameters are $a_{01} = a_{02} = 1$, $n_0^0 \approx 10^{19}$ cm^{-3}, $n_q^0 = 0.1n_0^0$, and $q = 0.2k_p$.

B. Two-dimensional particle-in-cell simulations

To validate the theoretical model we perform two-dimensional (2D) simulations using a 2D particle-in-cell (PIC) code. The simulation parameters are the same as those used previously for the analytical calculation. Two lasers are launched from the left boundary and propagate in a preformed plasma. A moving window is used to simulate a 50-μm-long plasma system to observe the simulation results. The physical dimension of the simulation is 50×50 μm^2, where the grid size $\Delta x = \lambda_{01}/20$ and $\Delta y = \lambda_{01}/4$ is chosen for the number of grids in a 2D simulation box (N_x, N_y) = (1000, 200). The number of particles per cell is $N = 4$ in 2D simulations. The time step dt is calculated by the correlation using the Courant theorem during the simulations. The amplitudes of the periodic

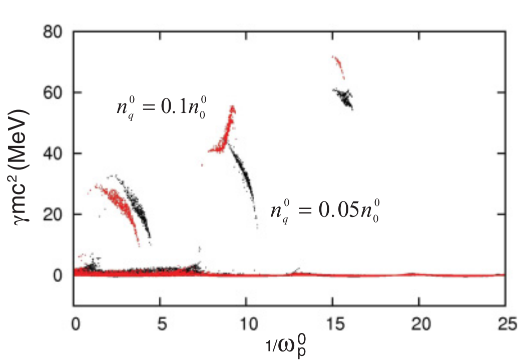

FIG. 4. (Color online) Electron energy γmc^2 (MeV) as a function of the propagation time $1/\omega_p^0$ with plasma density ripple for 10% density modulation [$n_q^0 = 0.1n_0^0$, gray (red) particles] and 5% density modulation ($n_q^0 = 0.05n_0^0$, black particles). Other simulation parameters are $a_{01} = a_{02} = 1$, $n_0^0 \approx 10^{19}$ cm^{-3}, $p_{z0} = 1.125mc$, and $q = 0.2k_p$,

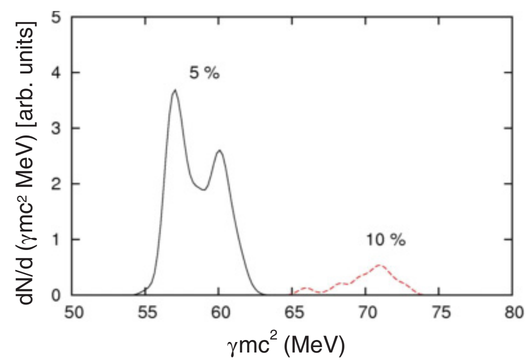

FIG. 5. (Color online) Energy spectra at the propagation time of $16/\omega_p^0$ with plasma density ripple for 10% density modulation [dashed (red) curve] and 5% density modulation [solid (black) curve]. Other simulation parameters are the same as those of Fig. 4.

density modulation are 10% ($n_q^0 = 0.1n_0^0$) and 5% density modulation ($n_q^0 = 0.05n_0^0$) of the uniform plasma density.

The results of the PIC simulations are shown in Fig. 4, which represents the energies of the macroparticles during acceleration in the presence of different ripple amplitudes [10%, gray (red) particles and 5%, black particles]. The electron energies are observed up to time of the order of $16/\omega_p^0$. The main purpose of this simulation is to analyze the effects of plasma density modulation on the electron energy gain by a plasma beat wave. To observe this, we consider two cases of different amplitudes of density modulations. The simulations based on the PIC code show the electron energy gain (in time of $16\omega_p^0$) to be almost the same as we observed from our analytical solutions for the same amplitude of the density ripple (10%). The simulation results also indicate that the small amplitude of the density modulation reduces the electron energy gain during acceleration. For stronger density modulation, the stronger sidebands can be excited. In this case, the strong trapping of the electrons in the coupling waves leads to electron energy enhancement. To confirm this, we show the energy spectra observed in simulations for the same parameters as those of Fig. 4. Figure 5 shows the corresponding energy spectra of electrons for different percentages of density modulations [10%, gray (red) curve and 5%, black curve] at the same time of $16/\omega_p^0$. The deviation (5%–10%) of the amplitude of the density modulation significantly reduces the number of accelerated particles but enhances the considerable electron energy gain during acceleration. The accelerated electrons from a rippled plasma have average energies of 72 MeV (for 10% amplitude of the ripple density) and 56 MeV (for 5% amplitude of the ripple density). However, the stronger plasma density modulation is reasonable for energetic electron beam generation (also predicted from analytical results). The smaller plasma density modulation is desirable for an adequate number of accelerated particles.

V. CONCLUSION

We studied the relativistic acceleration of electrons by the plasma beat wave in the presence of a periodic density modulation. The pump plasma beat wave excites two sideband plasma waves during the interaction with a density ripple existing in a plasma. These three plasma waves of different phase velocities can accelerate electrons to high energies in a stepwise way. Our study also shows that the electron can gain more energy by increasing the ripple spacing to speed up the wave. Furthermore, the electron energy gain is sensitive to the initial phase of the pump wave. The electron energy can also be maximized by optimizing the initial phase of the plasma beat wave due to the wave-particle phase matching. The initial electron energy plays an important role in gaining energy during acceleration. The higher initial electron energy increases the electron energy gain. If the electrons have considerable initial energies, the electrons' velocity can be comparable to the phase velocity of the plasma wave, resulting in a higher energy gain during acceleration. We also validate the theoretical treatment by the 2D PIC simulations. The simulation results revealed that a density ripple in a plasma leads to efficient acceleration of electrons by a plasma beat wave. The requisite amplitude modulation of plasma density enhances the electron energy gain during this mechanism. The simulation results are in good agreement with analytical results. The acceleration of the electrons by the plasma wave in the presence of a density ripple may be undesirable in laser-driven fusion, but it would be good for plasma accelerators.

ACKNOWLEDGMENTS

This research was financially supported by the Challenge Research Project of the National Research Foundation and the Asian Laser Center Project of Korea.

[1] C. Joshi, W. B. Mori, T. Karsouleas, J. M. Dawson, J. M. Kindel, and D. W. Forslund, Nature (London) **311**, 525 (1984).
[2] M. Colunga, J. F. Luciani, and P. Mora, Phys. Fluids **29**, 3407 (1986).
[3] P. Mora and F. Amiranoff, J. Appl. Phys. **66**, 3476 (1989).
[4] E. Esarey, P. Sprangle, J. Krall, and A. Ting, IEEE Trans. Plasma Sci. **24**, 252 (1996).
[5] W. B. Leemans, P. Volfbeyn, K. Z. Guo, S. Chattopadhyay, C. B. Schroeder, B. A. Shadwick, P. B. Lee, J. S. Wurtele, and E. Esarey, Phys. Plasmas **5**, 1615 (1998).
[6] N. Hafz, M. S. Hur, G. H. Kim, C. Kim, I. S. Ko, and H. Suk, Phys. Rev. E **73**, 016405 (2006).
[7] D. N. Gupta and H. Suk, J. Appl. Phys. **101**, 114908 (2007).
[8] D. Umstadter, J. Kim, E. Esarey, E. Dodd, and T. Neubert, Phys. Rev. E **51**, 3484 (1995).
[9] G. Bonnaud, D. Teychenne, and J. L. Bobin, Phys. Rev. E **50**, 36 (1994).
[10] S. Dalla and M. Lontano, Phys. Rev. E **49**, R1819 (1994).
[11] F. Amiranoff, D. Bernard, B. Cros, F. Jacquet, G. Matthieussent, P. Mine, P. Mora, J. Morillo, F. Moulin, A. E. Specka, and C. Stenz, Phys. Rev. Lett. **74**, 5220 (1995).
[12] L. Cicchitelli, H. Hora, and R. Postle, Phys. Rev. A **41**, 3727 (1990).
[13] Y. Kitagawa, T. Matsumoto, T. Minamihata, K. Sawai, K. Matsuo, K. Mima, K. Nishihara, H. Azechi, K. A. Tanaka, H. Takabe, and S Nakai, Phys. Rev. Lett. **68**, 48 (1992).
[14] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).
[15] E. Esarey, P. Sprangle, and J. Krall, Phys. Rev. E **52**, 5443 (1995).
[16] T. Katsouleas and R. Bingham, IEEE Trans. Plasma Sci. **24**, 249 (1996).
[17] J. P. Palastro, T. M. Antonsen, S. Morshed, A. G. York, and H. M. Milchberg, Phys. Rev. E **77**, 036405 (2008).
[18] C. M. Tang, P. Sprangle, and R. Sudan, Appl. Phys. Lett. **45**, 375 (1984).
[19] M. N. Rosenbluth and C. S. Liu, Phys. Rev. Lett. **29**, 701 (1972).
[20] K. Koyama, E. Miura, S. Kato, N. Saito, M. Adachi, A. Ogata, S. Masuda, and M. Tanimoto, in *Generation of Quasi-monoenergetic High-energy Electron Beam by Plasma Wave*, Advanced Accelerator Concepts: Eleventh Advanced Accelerator Concepts Workshop, edited by V. Yakimenko, AIP Conf. Proc. No. 737 (AIP, New York, 2004), p. 528 http://link.aip.org/link/?APCPCS/737/528/1.
[21] S. Fritzler, E. Lefebvre, V. Malka, F. Burgy, A. E. Dangor, K. Krushelnick, S. P. D. Mangles, Z. Najmudin, J. P. Rousseau, and B. Walton, Phys. Rev. Lett. **92**, 165006 (2004).
[22] H. Lin, Z. Xu, R. Li, and L. M. Chen, Phys. Plasmas **11**, 5167 (2004).
[23] P. K. Kaw, A. T. Lin, and J. M. Dawson, Phys. Fluids **16**, 1967 (1973).
[24] C. Darrow, W. B. Mori, T. Katsouleas, C. Joshi, D. Umstadter, and C. E. Clayton, IEEE Trans. Plasma Sci. **PS-15**, 107 (1987).
[25] C. Darrow, D. Umstadter, T. Katsouleas, W. B. Mori, C. E. Clayton, and C. Joshi, Phys. Rev. Lett. **56**, 2629 (1986).
[26] W. P. Leemans, C. Joshi, W. B. Mori, C. E. Clayton, and T. W. Johnston, Phys. Rev. A **46**, 5112 (1992).
[27] H. Suk, N. Barov, J. B. Rosenzweig, and E. Esarey, Phys. Rev. Lett. **86**, 1011 (2001).
[28] J. U. Kim, N. Hafz, and H. Suk, Phys. Rev. E **69**, 026409 (2004).