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LASER PLASMA

Electron Acceleration by Langmuir Waves Excited by a Laser Pulse in a Semi-Infinite Plasma

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Abstract—Results are presented from a theoretical investigation of the acceleration of test electrons by a Langmuir wave excited by a short laser pulse at half the electron plasma frequency. Such a pulse penetrates into the plasma over a distance equal to the skin depth and efficiently excites Langmuir waves in the resonant interaction at the second harmonic of the laser frequency. It is shown that the beam of electrons accelerated by these waves is modulated into a train of electron bunches, but because of the initial thermal spread of the accelerated electrons, the bunches widen and begin to overlap, with the result that, at large distances, the electron beam becomes unmodulated.

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1. INTRODUCTION

In recent years, much attention has been devoted to laser methods for charged particle acceleration in a dense plasma (the present status of this line of research is elucidated in [1–8] and in the literature cited therein). In a number of experiments [9, 10], it was observed that, in strong fields (on the order of 1 GV/cm) excited by a short laser pulse in an overdense plasma, the electrons were accelerated to relatively low energies (of about 100 MeV). Here, we attempt to explain why the lengths of the efficient electron acceleration, l_{acc}, are short under conditions such that the plasma is homogeneous on much longer spatial scales and the Langmuir wave that is efficiently excited by the laser pulse does not break. In this case, in accordance with the results of full numerical simulations (see [11]), conditions are satisfied for efficient wave excitation at the second harmonic of laser radiation at $a_0 \equiv eA_0/mc\omega \geq 1$ (where m and e are the mass and charge of an electron and A_0 and ω are the electric field amplitude and carrier frequency of the laser pulse). In [12], it was shown that, in a one-dimensional semi-infinite plasma, a short laser pulse excites a packet of Langmuir waves that propagates into the plasma at a speed close to the electron thermal velocity.

The present paper is devoted to investigating electron acceleration by a packet of Langmuir waves excited by a short laser pulse in a semi-infinite overdense plasma. We consider the acceleration of test electrons without allowance for their inverse effect on the laser pulse and wave packet, i.e., under the assumption that the field is prescribed. With this approach, we naturally obtain an upper estimate for the energy of the accelerated electrons. We study how the acceleration dynamics of the test electrons depends on their initial thermal spread, as well as on the shape of the laser pulse.

2. EXCITATION OF LANGMUIR WAVES BY A SHORT LASER PULSE IN A SEMI-INFINITE PLASMA

Let us consider a laser pulse that is incident normally from vacuum onto a semi-infinite homogeneous plasma with the electron temperature T_e. The carrier frequency ω of the pulse is assumed to be half the electron plasma frequency ω_p. Such a pulse penetrates into the plasma over a distance equal to the skin depth $\lambda = 2c/\sqrt{3}\omega_p$. In this case, because of plasma nonlinearity, a Langmuir wave propagating from the skin layer into the plasma is resonantly excited at the second harmonic of the laser field.

For a laser pulse with the intensity profile

$$F(\tau/\tau_L) = \begin{cases} \sin(\pi\tau/\tau_L), & 0 \leq \tau \leq \tau_L, \\ 0, \quad \tau \leq 0, & \tau \geq \tau_L, \end{cases} \tag{1}$$

the longitudinal electric field of the Langmuir wave propagating into the plasma is described by the following expressions [12]:

$$\psi(\tau, \varsigma) = -\frac{1}{2}\int_0^{\tau} d\tau_0 \int_{-\infty}^{\zeta} d\zeta_0 \theta(\tau_0 - |\zeta_0|) J_0(\sqrt{\tau_0^2 - \zeta_0^2})$$
$$\times \sin\left(\pi\frac{\tau - \tau_0}{\tau_L}\right)\cos(\tau - \tau_0) e^{-\alpha(\zeta - \zeta_0)} \quad (2')$$
$$+\frac{1}{2}\int_0^{\tau} d\tau_0 \int_{\zeta}^{\infty} d\zeta_0 \theta(\tau_0 - |\zeta_0|) J_0(\sqrt{\tau_0^2 - \zeta_0^2}) \sin\left(\pi\frac{\tau - \tau_0}{\tau_L}\right)$$
$$\times \cos(\tau - \tau_0) e^{-\alpha(\zeta_0 - \zeta)}$$

for $0 \le \tau \le \tau_L$ and

$$\psi = -\frac{1}{2}\int_{\tau - \tau_L}^{\tau} d\tau_0 \int_{-\infty}^{\zeta} d\zeta_0 \theta(\tau_0 - |\zeta_0|) J_0(\sqrt{\tau_0^2 - \zeta_0^2})$$
$$\times \sin\left(\pi\frac{\tau - \tau_0}{\tau_L}\right)\cos(\tau - \tau_0) e^{-\alpha(\zeta - \zeta_0)} \quad (2'')$$
$$+\frac{1}{2}\int_{\tau - \tau_L}^{\tau} d\tau_0 \int_{\zeta}^{\infty} d\zeta_0 \theta(\tau_0 - |\zeta_0|) J_0(\sqrt{\tau_0^2 - \zeta_0^2}) \sin\left(\pi\frac{\tau - \tau_0}{\tau_L}\right)$$
$$\times \cos(\tau - \tau_0) e^{-\alpha(\zeta_0 - \zeta)}$$

for $\tau \ge \tau_L$. Here, $\psi = E/E_*$ is the longitudinal electric field normalized to $E_* = \sqrt{3}E_m a_0^2/2$, $E_m = \frac{mc\omega_p}{e}$, $\tau = \omega_p t$ and $\zeta = z\omega_p/v_T$ are the dimensionless time and longitudinal coordinate; v_T is the electron thermal velocity; $\alpha = \sqrt{3}\, v_T/(2c)$, $\tau_L = \omega_p t_L$, with t_L being the laser pulse duration; $\theta(x)$ is the Heaviside step function; and $J_0(x)$ is the Bessel function.

The processes of the excitation and propagation of a Langmuir wave whose electric field in the plasma is described by relationships (2) were investigated numerically for the same values of the dimensionless parameters as in [12], namely, for $\tau_L = 12$, $\alpha_1 = 0.433$, and $\alpha_2 = 0.1083$, but for a different intensity profile of the laser pulse. For laser radiation with the wavelength $\lambda = 1.07$ μm, these values of the dimensionless parameters correspond to the plasma density $n_p = 4.5 \times 10^{21}$ cm^{-3} and the plasma frequency $\omega_p = 3.77 \times 10^{15}$ s^{-1}. We performed simulations for two values of the electron temperature: $T_{e1} = 32$ keV and $T_{e2} = 2$ keV. These temperature values do not affect the qualitative pattern of the electron acceleration and thus are not of fundamental importance for our analysis. They were chosen merely to reduce the computer time required to simulate the processes in question.

Figure 1 shows the spatiotemporal distribution of the longitudinal electric field of a Langmuir wave excited by a short laser pulse with intensity profile (1) for the dimensionless parameters $\tau_L = 12$ and $\alpha_1 =$ 0.433. In [12], a study was made of the propagation of a Langmuir wave excited in a plasma by a laser pulse with a sharp leading edge and with the intensity profile $F(\tau/\tau_L)$ of the form

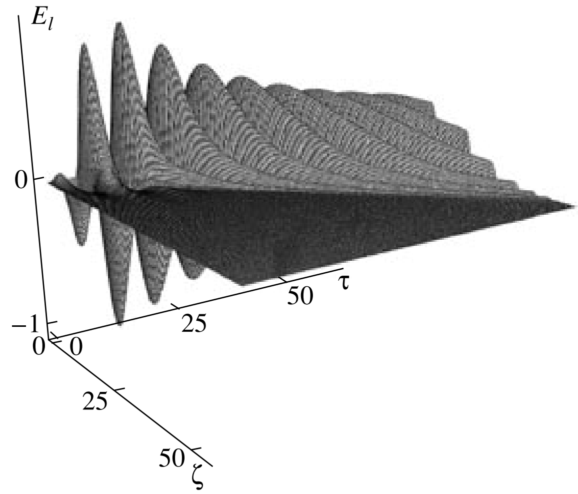

Fig. 1. Spatiotemporal distribution of the longitudinal electric field of a Langmuir wave excited by a short laser pulse for $\tau_L = 12$ and $\alpha_1 = 0.433$.

$$F(\tau/\tau_L) = \begin{cases} \cos(\pi\tau/2\tau_L), & 0 \le \tau \le \tau_L \\ 0, \quad \tau \le 0, & \tau \ge \tau_L. \end{cases} \quad (3)$$

In both cases of laser pulses with a sharp and a smooth leading edge described by expressions (3) and (1), respectively, the excited Langmuir perturbation has an oscillatory spatial structure and its leading edge propagates at the electron thermal velocity. The maximum amplitude of the perturbation decreases because of the dispersive spreading. At each spatial point behind the leading edge of the propagating Langmuir perturbation, the electric field oscillates at the plasma frequency.

3. ELECTRON ACCELERATION BY A LANGMUIR PERTURBATION IN A PLASMA

The problem of the acceleration of electrons in a plasma by a propagating Langmuir perturbation whose longitudinal electric field is given by relationships (2) was solved in the following formulation. From 3000 to 8000 test particles were initially distributed uniformly within the plasma region $\zeta_p \ge \zeta \ge 0$, where ζ_p was chosen to be equal to 60. In the initial state, the particles were assumed either to be immobile or to obey a Maxwellian velocity distribution with a zero average velocity and a temperature equal to the plasma temperature, which was chosen to be $T_{e1} = 32$ keV or $T_{e2} = 2$ keV. In the initial plasma state, there were no Langmuir perturbations. As the excited Langmuir perturbation propa-

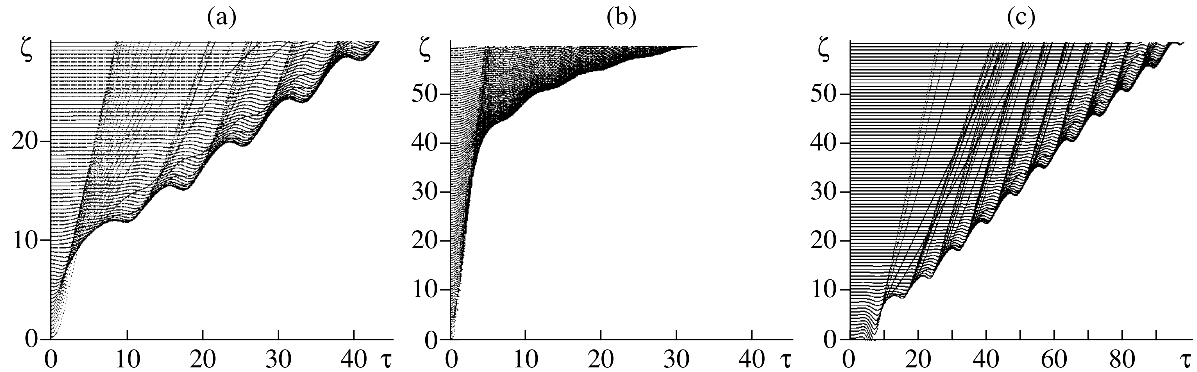

Fig. 2. Trajectories of test electrons accelerated by a Langmuir wave excited by a short laser pulse.

gated in the plasma, it entrained the test particles in an acceleration process.

The equations of motion of test particles in the electric field of Langmuir perturbation (2) have the form

$$\frac{d}{d\tau}\left(\gamma_i \frac{d\zeta_i}{d\tau}\right) = -\varepsilon\psi(\tau, \zeta_i), \qquad (4)$$

where $\gamma_i = [1 - \beta_T^2 (d\zeta_i/d\tau)^2]^{1/2}$ is the relativistic factor of the ith particle ($N \ge i \ge 1$, with N being the total number of test particles), $\beta_T = v_T/c$, and $\varepsilon = \sqrt{3}a_0^2/(2\beta_T)$.

Numerical calculations were performed for $\varepsilon = 3.42$, which corresponds to $a_0 = 1$. Figures 2a and 2b show the trajectories of 300 test particles distributed uniformly at the initial instant over the interval $60 \ge \zeta_{i0} \ge 0$ (where ζ_{i0} are the initial coordinates of the particles) in the case of a laser pulse with a sharp leading edge for two values of the plasma temperature, $T_{e1} = 32$ keV and $T_{e2} = 2$ keV. Figure 2c shows the trajectories of 300 initially immobile test particles distributed uniformly over the same interval, $60 \ge \zeta_{i0} \ge 0$, in the case of a laser pulse with intensity profile (1) (i.e., with smooth leading and trailing edges) for the plasma temperature T_{e1} = 32 keV. In Fig. 2, we clearly see particle bunching and the onset and formation of a bunch of accelerated particles. A comparison between Figs. 2a and 2c shows that, for a laser pulse with a sharp leading edge, the first bunch of accelerated particles is much shorter. Comparing Figs. 2a and 2b, we see that, at a lower plasma temperature, a decrease in the propagation velocity of the Langmuir wave and the associated steep increase in its amplitude have a radical effect on the pattern of particle acceleration. The first bunch is formed by a relatively small group of particles located in the region $5.5 \ge \zeta_{i0} \ge$ 3.5. The particles that are at the back of this region catch up with those at its front to form a particle bunch, which then propagates at a constant speed. As the Langmuir perturbation propagates deeper into the plasma, it entrains newer and newer electrons in an acceleration process, so the number of bunches increases. We can see that, near the leading edge of the Langmuir wave packet, most of the electrons acquire energy much higher than the thermal energy, so they escape from the packet and stop interacting with it.

Figure 3 illustrates how the density modulation of the test particles depends on their thermal spread. Because of this spread, essentially no regular modulation in the particle density is observed. In Fig. 3, we show the time evolution of the number of the particles N (in arbitrary units) that cross the plane $\zeta = 60$. Let us now consider the effect of the energy spread of test particles on their acceleration by a Langmuir perturbation excited by a laser pulse in a plasma. Figure 3b displays the calculated trajectories of test particles having a temperature of 32 keV. The bunches of accelerated electrons are seen to be less pronounced than in the case of "cold" test particles (see Fig. 3a). A comparison between the time evolutions of the number of the particles that have crossed different planes ζ = const demonstrates that the modulation depth becomes considerably smaller because different bunches overlap (see Fig. 2). Bunches of charged particles are observed at relatively small distances ζ. Because of the thermal motion of the particles, the bunches widen substantially. At large distances ζ ($\zeta = 55$), the bunches overlap, so the beam of accelerated particles becomes unmodulated.

Figures 4–9 show the phase planes of test particles with a thermal spread corresponding to the plasma temperatures T_{e1} (Figs. 4, 5) and T_{e2} (Figs. 6, 7) and those without thermal spread at different times. Figures 8 and 9 were obtained for a laser pulse with a smooth intensity profile, in contrast to Figs. 4–7, which refer to a pulse with a sharp intensity profile. In all these figures, the dimensionless momenta $\beta_i\gamma_i$ (where $\beta_i = v_i/c$) and the spatial positions of the particles are plotted on the ordinate and the abscissa, respectively.

Figure 4 shows the phase planes of test electrons whose initial thermal spread corresponds to the plasma temperature T_e = 32 keV and that are accelerated by a Langmuir wave excited by a laser pulse with a sharp intensity profile. The phase planes were calculated for the times τ = (a) 2.7, (b) 13.5, and (c) 30.6.

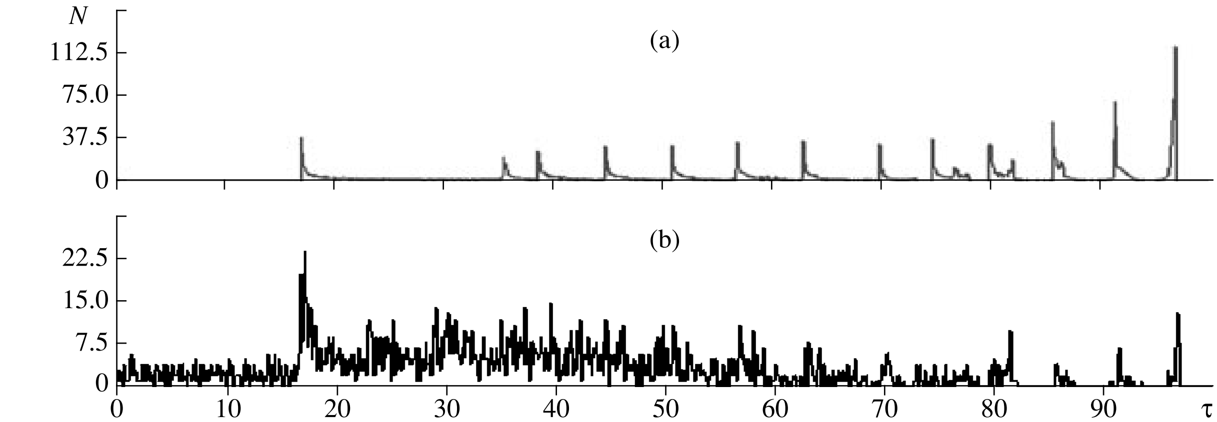

Fig. 3. Time evolution of the number of test electrons (a) without and (b) with an initial thermal spread that are accelerated by a Langmuir wave excited by a short laser pulse and cross the plane $\xi_p = 60$.

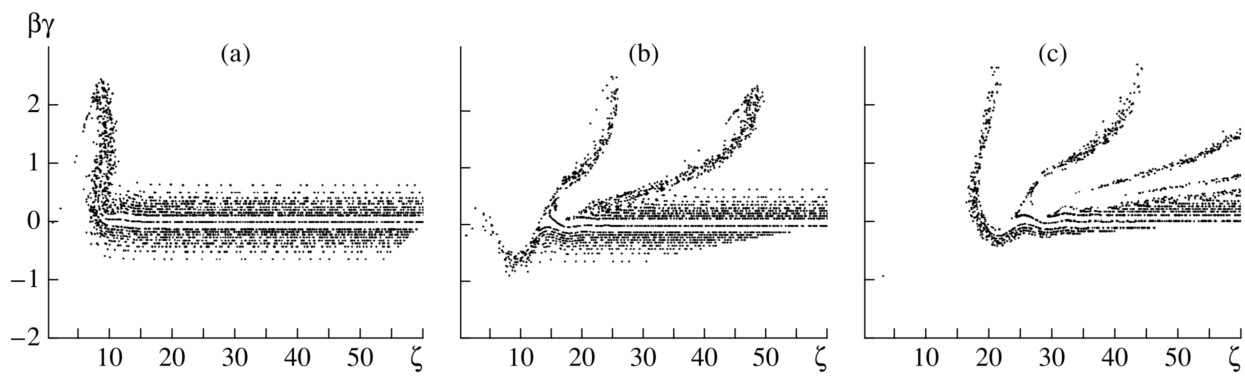

Fig. 4. Phase plane of test electrons whose initial thermal spread corresponds to the plasma temperature T_e = 32 keV and that are accelerated by a Langmuir wave excited by a laser pulse with a sharp intensity profile at the times τ = (a) 2.7, (b) 13.5, and (c) 30.6.

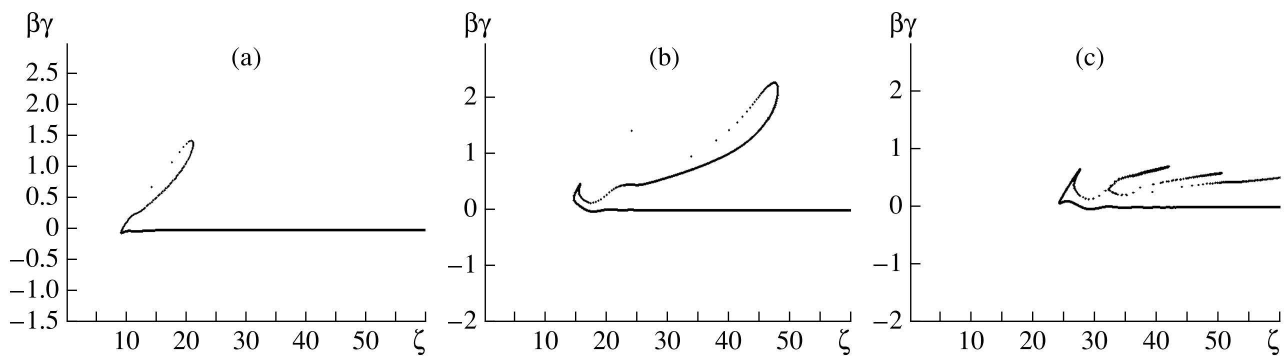

Fig. 5. Phase plane of test electrons that have no initial thermal spread and are accelerated by a Langmuir wave excited by a laser pulse with a sharp intensity profile for the plasma temperature T_e = 32 keV at the times τ = (a) 2.7, (b) 13.5, and (c) 30.6.

Figure 5 shows the phase planes of test electrons that have no initial thermal spread and are accelerated by a Langmuir wave excited by a laser pulse with a sharp intensity profile at the plasma temperature T_e = 32 keV. The phase planes were calculated for the times τ = (a) 2.7, (b) 13.5, and (c) 30.6.

Figure 6 shows the phase planes of test electrons whose initial thermal spread corresponds to the plasma

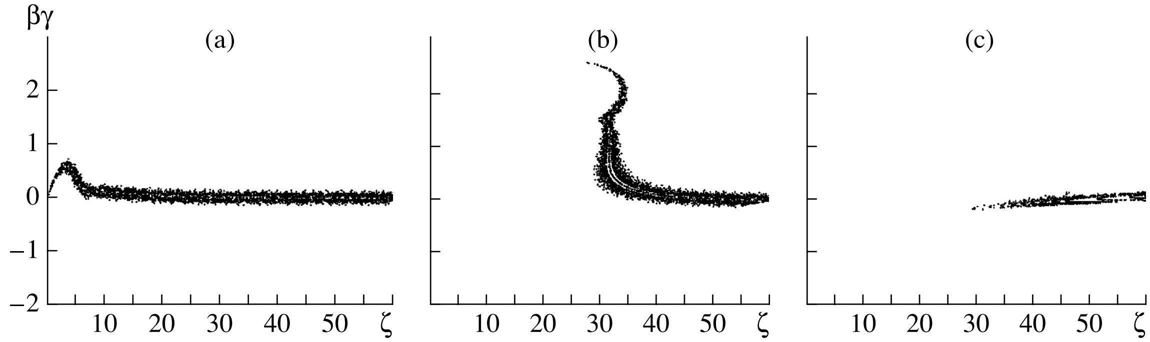

Fig. 6. Phase plane of test electrons whose initial thermal spread corresponds to the plasma temperature T_e = 2 keV and that are accelerated by a Langmuir wave excited by a laser pulse with a sharp intensity profile at the times τ = (a) 0.4, (b) 2.7, and (c) 13.5.

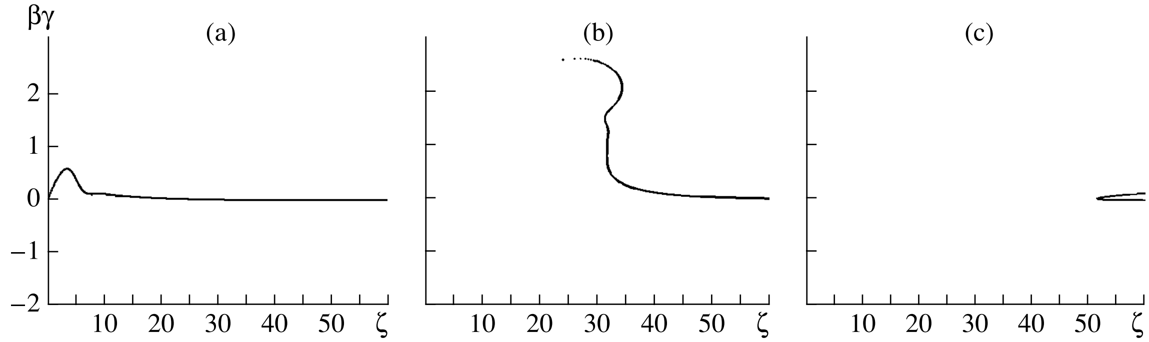

Fig. 7. Phase plane of test electrons that have no initial thermal spread and are accelerated by a Langmuir wave excited by a laser pulse with a sharp intensity profile for the plasma temperature T_e = 2 keV at the times τ = (a) 0.4, (b) 2.7, and (c) 13.5.

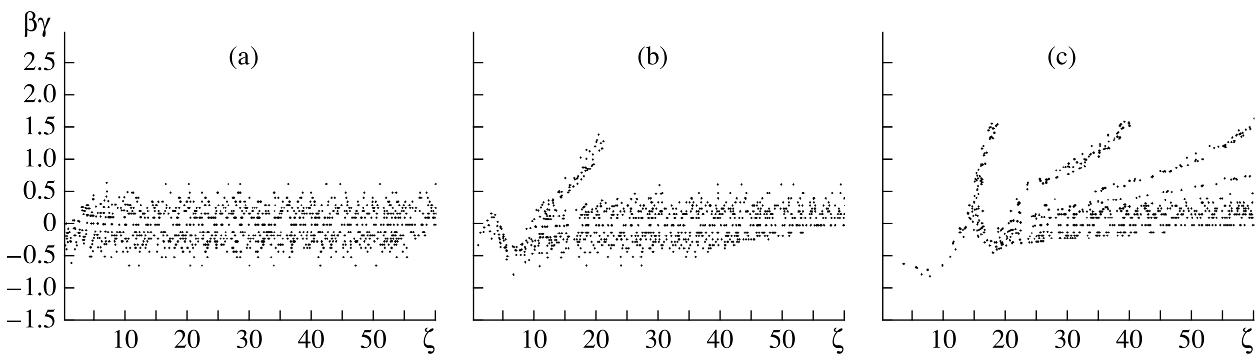

Fig. 8. Phase plane of test electrons whose initial thermal spread corresponds to the plasma temperature T_e = 32 keV and that are accelerated by a Langmuir wave excited by a laser pulse with a smooth intensity profile at the times τ = (a) 2.7, (b) 13.5, and (c) 30.6.

temperature T_e = 2 keV and that are accelerated by a Langmuir wave excited by a laser pulse with a sharp intensity profile. The phase planes were calculated for the times τ = (a) 0.4, (b) 2.7, and (c) 13.5.

Figure 7 shows the phase planes of test electrons that have no initial thermal spread and are accelerated by a Langmuir wave excited by a laser pulse with a sharp intensity profile at the plasma temperature T_e = 2 keV. The phase planes were calculated for the times τ = (a) 0.4, (b) 2.7, and (c) 13.5.

Figure 8 shows the phase planes of test electrons whose initial thermal spread corresponds to the plasma temperature T_e = 32 keV and that are accelerated by a Langmuir wave excited by a laser pulse with a smooth intensity profile. The phase planes were calculated for the times τ = (a) 2.7, (b) 13.5, and (c) 30.6.

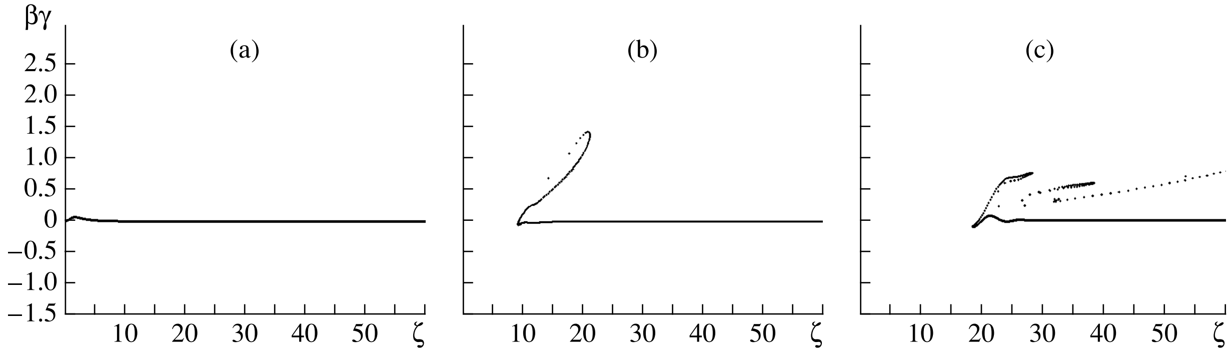

Fig. 9. Phase plane of test electrons that have no initial thermal spread and are accelerated by a Langmuir wave excited by a laser pulse with a smooth intensity profile for the plasma temperature T_e = 32 keV at the times τ = (a) 2.7, (b) 13.5, and (c) 30.6.

Figure 9 shows the phase planes of test electrons that have no initial thermal spread and are accelerated by a Langmuir wave excited by a laser pulse with a smooth intensity profile at the plasma temperature T_e = 32 keV. The diagrams were calculated for the times τ = (a) 2.7, (b) 13.5, and (c) 30.6.

Each test particle is acted upon by a longitudinal electric field oscillating at the plasma frequency. The particle is entrained in the acceleration process when the electric field of the propagating intense Langmuir pulse has negative polarity at its position. The beam of accelerated electrons is a train of short bunches, whose intensity decreases from the head of the beam to its tail. The maximum energy of the first bunch, which is the longest one and in which the particle flux intensity is lowest, is approximately equal to 1.38 MeV. The subsequent bunches have energies from 88 to 200 keV.

Bulanov et al. [1] carried out analytical investigations and particle-in-cell simulations of the interaction between an obliquely incident, relativistically strong, ultrashort laser pulse with a highly inhomogeneous overdense plasma. They captured the phenomenon of "electron vacuum heating" in a highly inhomogeneous plasma, i.e., the formation of a cloud of fast electrons that have energies on the order of the oscillatory energy and expand into a vacuum. We think that the electron acceleration captured numerically in [1] for a particular case of a sharply bounded plasma with a density four times the critical one can more naturally be attributed to the mechanism considered in the present study—specifically, the acceleration by a resonantly excited (since the laser frequency ω is half the electron plasma frequency ω_p) Langmuir wave propagating in a plasma—rather than to the vacuum heating mechanism, because, according to Figs. 2 and 3 from [1], the electrons are mainly accelerated into the plasma at large distances from its boundary ($80c/\omega_p$) on time scales ($120\omega^{-1}$) appreciably longer than the laser pulse duration ($50\omega^{-1}$). We again emphasize that, in the acceleration mechanism considered above, the electrons are accelerated not only near the plasma boundary but also deep in the plasma, as the Langmuir wave propagates into it. Although, in [1], no quantitative information was given on the spatiotemporal structure of the electromagnetic field deep in the plasma (this information is required to compare the two acceleration mechanisms in question) and the initial plasma temperature was chosen to be zero (unlike in our study), Figs. 2 and 3 from [1] show that, throughout the laser pulse, the electron temperature increases substantially and becomes markedly higher than the temperature value chosen for one of the cases under analysis here, T_e = 2 keV. These figures also show that the electrons are accelerated not only in the boundary layer (see [1], Fig. 3a) but also deep in the plasma, at distances from the boundary that are as large as $(70–80)c/\omega_p$.

As for the possible Langmuir wave breaking, note that, according to the results of our earlier simulations [11, 12], a Langmuir wave excited by a laser pulse with $a_0 \approx 1$ (as in the case under analysis here) does not break. This can also be readily seen from a comparison of the length of the excited Langmuir wave with the amplitude of electron oscillations.

4. CONCLUSIONS

In the present paper, we have studied the acceleration of electrons by a Langmuir wave perturbation excited by a laser pulse in a plasma. We have found that, near the leading edge of the Langmuir wave packet, most of the electrons acquire energy much higher than the thermal energy, so they escape from the packet and stop interacting with it.

The results of our investigations show that, even when the electric field of the excited Langmuir wave packet is strong (on the order of several hundred MV/cm), the energy of the accelerated electrons is at most 1 MeV.

That the electron energies obtained in our numerical simulations differ from the energies reported in the cited experimental papers stems primarily from the fact that we considered laser pulses with $a_0 \approx 1$, which are far less intense than those used in experiments (a_0 = 3–5).

We have shown that the beam of initially cold, accelerated test electrons is a train of short bunches, whose maximum intensity decreases from the head of the beam to its tail. In a beam of accelerated test electrons with an initial thermal spread corresponding to the plasma temperature, the bunches widen and begin to overlap, with the result that, at large distances, the electron beam becomes unmodulated.

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