INTERACTION OF DISPERSIVE ELECTROSTATIC PULSES WITH CHARGED PARTICLES

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Abstract

Interaction of charged particles with dispersive electrostatic pulses observed in Langmuir turbulence is numerically investigated. It is found that in spite of dispersion charged particles may be essentially trapped while penetrating through the pulses, and experience velocity variations expected for trapped particles. Transit-time acceleration/deceleration is also possible.

1. Introduction

This paper considers interaction of charged particles with dispersive electrostatic [es] wave packets. Although interaction of charged particles with sinusoidal waves has vigorously been studied in the past, that with wave packets has not been fully understood yet. In the latter transit-time interaction of electrons with unipolar, stationary, oscillating pulses of the form $E = E_o \exp[-(z/l)^2]\cos(\omega t)$ has been a main focus [1,2], where l determines the pulse size, and other notations are standard. Recently interaction of particles with *dispersionless*, travelling pulses of the form $E = E_o \exp[-(z - v_p t)^2 / l^2]\cos(kz - \omega t)$ was studied [3], where v_p is the phase velocity. In this case three types of interaction exist, i.e., transit-time acceleration, reflection in the wave frame and trapping, the last one occurring only for those particles that are initially located inside a pulse.

It was recently observed also that during low-density(<1%) electron beam-plasma instabilities unstable waves grow and saturate in the form of wave packets [3]. Afterward quasilinear-like processes follow, diffusing beam electrons to lower velocities. However, the diffusion is position-dependent, i.e., fast(slow) where the wave amplitude is large(small). Electron trapping causes wave modulation [3], the scale of which is given by $l \approx 2\pi v_b / \omega_t$, where v_b is the beam velocity, and ω_t is the bounce frequency averaged over the pulse. Such pulses tend to form irrespective of the initial beam temperature.

2. Dispersion effects

There are three types of dispersion effects, i.e., (1) spreading of pulse, (2) reduction of pulse velocity from v_p because $v_p > v_g$ mostly, where v_g is the group velocity, and (3) shift in the relative phase with respect to the envelope. Since the typical size of Langmuir pulses observed in simulations is 100-300λ_e, and particle velocity is 4-10v_e, typical interaction time is 10-

$100/\omega_e$, where λ_e, v_e, ω_e are the usual Debye length, the electron thermal velocity and the electron plasma frequency, respectively. It turns out that during the typical interaction time pulse shape remains almost constant. Furthermore in simulations we have $v_p \approx 6v_e$, while $v_g \approx 0.5v_e$, the effects (2) and (3) being important. Thus, we reach the pulse form $E = E_o \exp[-(z/l)^2]\cos(kz - \omega t)$, which resembles the one adopted to study pulse-particle interaction in beam-driven Langmuir turbulence [3].

3. Pulse-particle interaction

To analyze the motion of a charged particle interacting with an es pulse propagating along the z-axis, the equation of motion will be solved numerically

$$m\frac{d\mathbf{v}}{dt} = q\mathbf{E}\,, \tag{1}$$

where *m, q,* **v** are the mass, the charge, and the velocity of the particle, and ***E*** is the es field of the pulse, respectively. Let us consider the motion of a particle initially moving at velocity *V* along the z-axis through the pulse. Based on simulations [3] we assume that the es field of the pulse is of the following form

$$E = -\frac{d}{dz}\phi = \frac{d}{dz}\sum_{n=-7}^{7}\phi_o \exp[-n/\Delta n]^2 \cos(k_n z - \omega_n t),$$

where ϕ is the wave potential, Δn=2, k_{-7}=0.10, k_0=0.17 etc., and ω_n is the frequency corresponding to k_n. The normalized maximum field is $En = E/\sqrt{4\pi nkT_e}$ =0.48 and the half-width is $170\lambda_e$, where the notations are standard. Inside the half-width of this pulse there exist 4.5 wavelengths. For dispersionless pulses of the same form the final velocity of particle equals its initial velocity [4].

We first investigate the evolution of electron velocity as a function of *z*. Figure 1(a) depicts such plots for various initial velocities and phases. It is evident that far away from the

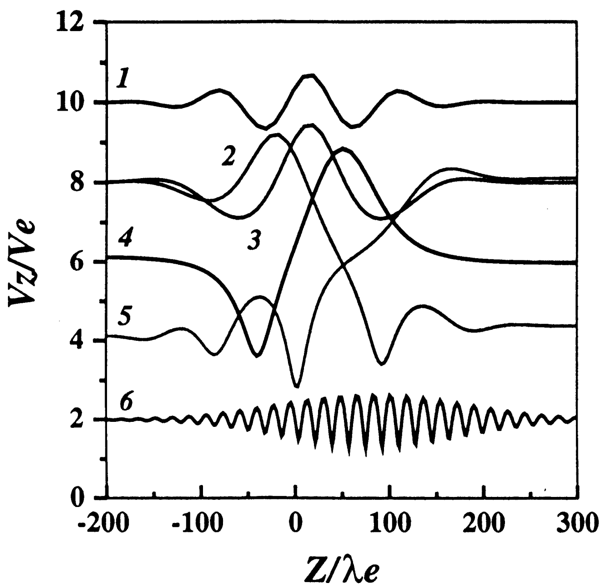

Fig. 1(a): v_z versus z_n

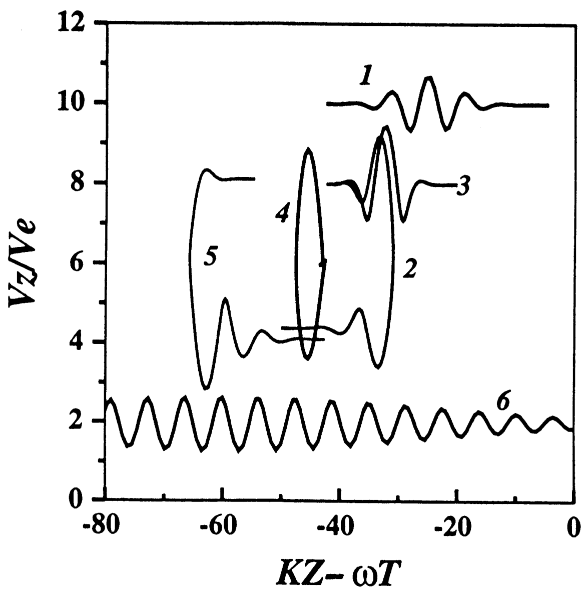

Fig.1(b): v_z versus. *phase*

phase velocity of the principal mode $v_p \approx 6.13 v_e$ there is no net gain nor loss of velocity as for dispersionless pulses. However, as the velocity approaches v_p from above (below) electrons start experiencing deceleration (acceleration). This is closely related to Landau damping. Evolution of the velocities here somewhat resembles that of particles interacting with dispersionless unipolar pulses [4]. At $V=v_p$ electron velocity oscillates once as if it travels through a bipolar pulse [4]. Figure 1(b) shows v_z plotted against the phase for the same electrons as those in Fig.1(a). It is observed that those electrons with relatively large velocity perturbations experience nearly one oscillation in the pulse as shown in [3]. The oscillation period is estimated as $l / v_p \approx 27/\omega_e$, while the bounce period for sinusoidal wave of the amplitude En =0.48 equals $22/\omega_e$. Considering the smaller effective amplitude of the pulse, the agreement is quite good. Moreover the maximum velocity variation of $\approx 6 v_e$ occurs for the electron denoted as "5"; it is comparable to $6.6 v_e$ expected for the sinusoidal wave above. Furthermore the center of the velocity variation is located at v_p, as expected for trapped particles. We can thus conclude that nearly resonant particles such as 2, 4 and 5 may be effectively "trapped" while passing through the pulse, while particles 1, 3 and 6 are not.

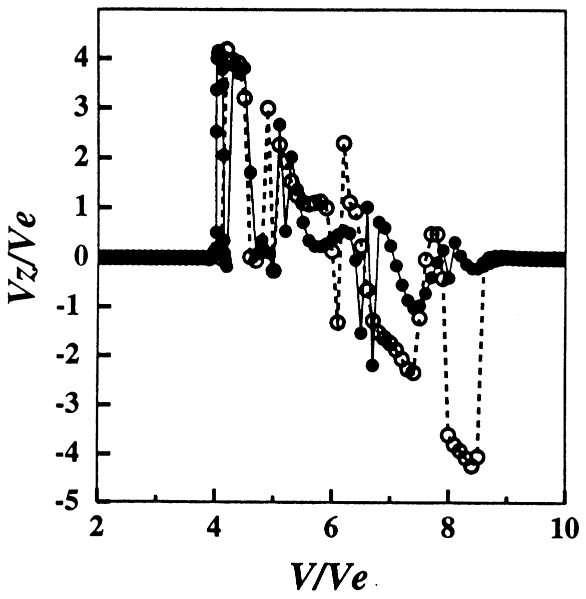

Fig. 2(a): final v_z versus V

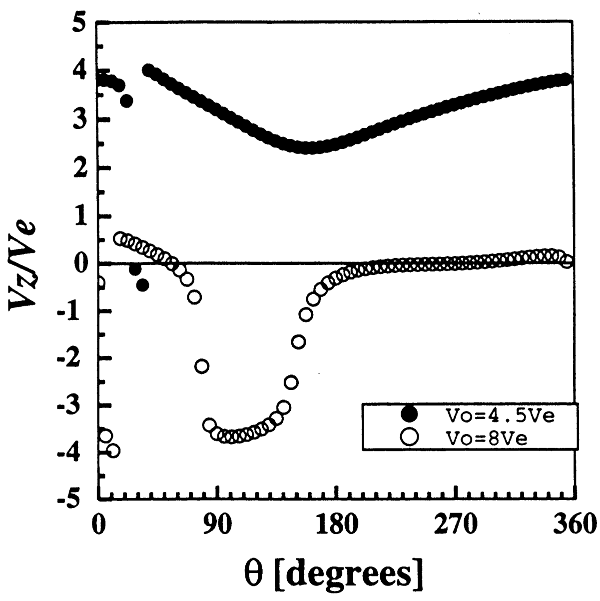

Fig. 2(b): final v_z versus θ_0

Figure 2(a) shows the dependence of final velocity variation v_z on initial velocity V. The velocities are normalized by v_e. The initial phases (θ_o) are either 0(filled circles) or 0.5π (circles). Only those electrons in narrow windows experience significant net velocity shift. As for dispersionless pulses [4] in general those electrons with $V>v_p$ are decelerated, while those with $V<v_p$ are accelerated. Maximum velocity perturbation is approximately equal to $\pm 4.2 v_e$. Figure 2(b) depicts dependence of final velocity perturbation v_z on θ_o for electrons with V=4.5v_e (filled circles) and 8.0v_e (circles). Slower electrons are accelerated with almost any θ_o, while faster ones with only $\theta_o \approx 10^\circ$ and $80^\circ < \theta_o < 160^\circ$ are accelerated. This is in part because the slower electrons are located well inside the window of V for acceleration as shown in Fig.1, while faster ones are near an edge of the window for deceleration. For example, electrons with V=8.2v_e, which is well inside the velocity window, are significantly decelerated with almost any θ_o. Nevertheless, the presence of fine structures in these figures are rather conspicuous.

Finally, Figure 3 shows the maximum velocity shifts averaged over θ_o at several V. The general trend of acceleration(deceleration) of particles propagating slower(faster) than v_p is observed. This trend of v_z being symmetric with respect to v_p was observed also for unipolar and bipolar impulses [4]. Figure 3 along with Fig. 2(a) demonstrates that in spite of the several cycles contained in the pulse and relative phase shift that occurs in the pulse the electrons that are resonant with the carrier wave can experience significant velocity shift, for they feel a relatively constant field while penetrating the pulse. The velocity range for this shift to occur is comparable to trapping width. Finally, the velocity shift is due to transit-time acceleration, which becomes increasingly important as the initial particle velocity is with of course some limits away from v_p.

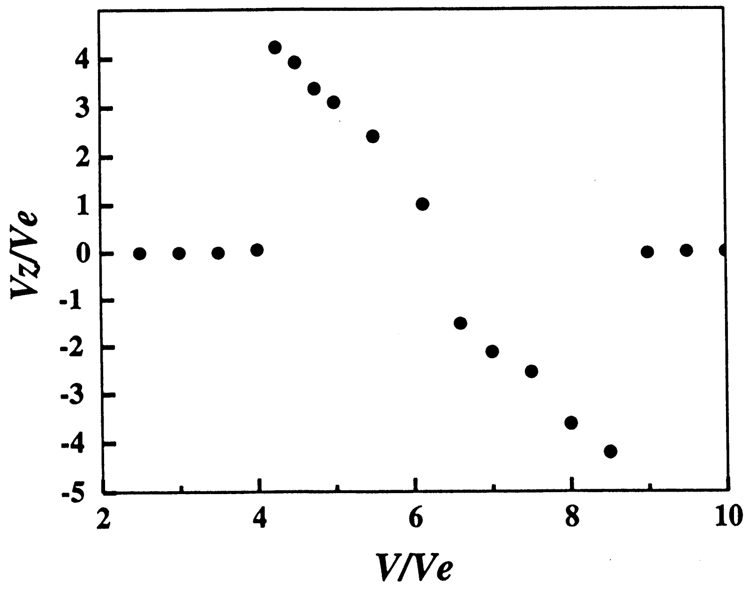

Fig. 3: maximum v_z versus V

4. Conclusions

In conclusion dispersive Langmuir pulses can essentially trap, and accelerate/decelerate electrons as other types of pulses and sinusoidal waves via transit-time acceleration / deceleration. This trapping can play a significant role in the evolution of Langmuir turbulence generated by relatively low-density electron beams of various temperatures.

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