

Nonlinear Evolution of a Wave Packet in Electron-Beam-Plasma

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The temporal evolution of a wave packet in electron-beam-plasma is observed experimentally. It is shown that the packet develops on electron time scales not into self-contraction but into asymmetrical widening. Particle trapping, indicated the distribution function of electron-beam, plays an important role in causing this phenomenon.

Keywords:

unstable electron-beam mode, temporal evolution of wave packet, k - ω spectrum, distribution function of electron-beam

When the waves in an electron-beam-plasma system are strong, nonlinear phenomena characteristically appear. In regard to this phenomena, it is important to discuss solitary waves or modulation instabilities [1]. A. Y. Wong *et al.* [2] showed experimentally a 3-D Langmuir-wave collapse of ion time scales driven by a pulsed electron-beam. T. Intrator *et al.* [3] reported the longitudinal self-contraction of modulationally unstable electron wave packets developing on electron time scales. We [4] showed that a wave packet can be stabilized by emitting a series of several burst waves. In order to investigate nonlinear phenomena at long distances, we introduce a new beam-plasma device, the length of which is 2 times longer than that of the previous one. In this paper, we report the nonlinear behavior of the electron time scales of the packet in plasma, induced by a low density electron-beam, and the distribution function of the electron-beam.

Plasma, confined by full-line cusps, is produced by DC-discharges between four heated filaments and the chamber wall in argon gas. Beam-electrons, which have initial energy $\phi_b = 50\text{eV}$, travel one-dimensionally into the plasma along an additional, axial magnetic field 0.01T. We confirm that the electron-beam near the injection point satisfies the cold-beam condition [5]. An energy analyzing probe is used to detect wave signals and to measure the distribution function of the electron-

beam. The probe consists of a discriminator grid and a collector shielded against electric fields, and is axially movable. The experiments are operated using pulsed electron-beams and test waves. Source signals of the test waves are generated by modulating carrier waves (90MHz) with solitary envelope waves (18MHz). Wave signals detected by the probe are divided into low and high frequency bands. Those signals are received in a 2-channel digitizing oscilloscope. We measure the wave signals at each z -position of 128 points. Typical parameters are $n_e \sim 1.5 \times 10^{14}\text{m}^{-3}$, $v_T \sim 3.1 \times 10^5\text{m/s}$, $n_b/n_e \sim 0.2\%$, $v_b/v_T \sim 14$, and $\Delta v/v_b \sim 0.03$, where n_e is the plasma-electron density, v_T is the plasma-electron thermal velocity, n_b is the beam-electron density, v_b is the beam-electron velocity, and Δv is the initial thermal spread of the beam-electrons.

Figure 1(a) shows the behavior of the packet at intervals of $\omega_{pe}t = 5.5$. Here, ω_{pe} is the electron-plasma frequency and k_0 is the wave number defined by ω_{pe}/v_b . As the packet propagates downstream, its shape evolves on electron time scales. The group velocity $0.45v_b$ is faster than v_T and is almost constant. After the packet with the initial growth rate $4 \times 10^{-2}\omega_{pe}$ (an open circle plotted in Fig. 1(c)) grows linearly, its amplitude becomes saturated. Figure 1(b) shows the $k - \omega$ spectrum evolution of the packet mapped with a level indicator at intervals of $\omega_{pe}t = 11$. Typical experimental

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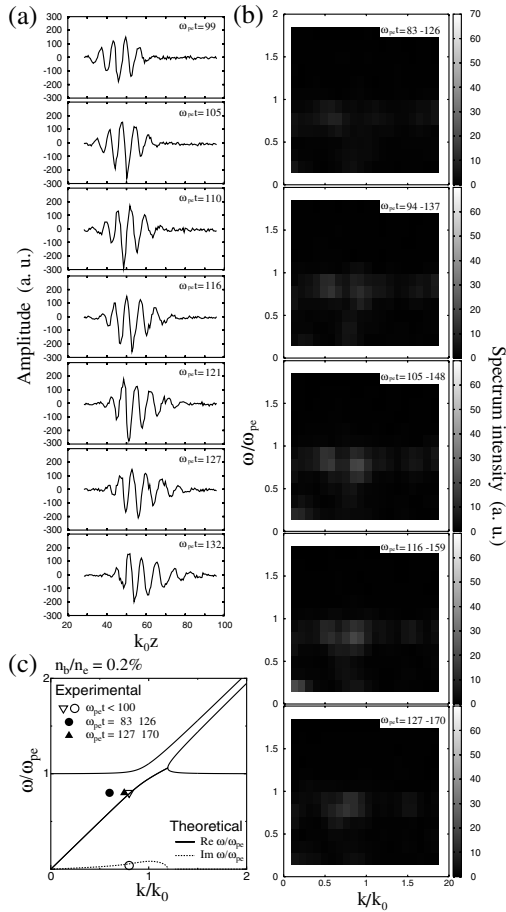


Fig. 1 Temporal evolutions of wave packet; (a) amplitude vs $k_0 z$, (b) spectrum intensity vs k/k_0 and ω/ω_{pe} , and (c) linear dispersion relation and typical experimental data for $\omega_{pe} t < 170$.

data shown in Fig. 1(b) are compared in Fig. 1(c) with the linear dispersion relation for cold-beam-cold-plasma waves [5]. The spectrum of $\omega_{pe} t = 83 - 126$ indicates roughly the packet property for the saturation. A peak intensity at $k/k_0 \sim 0.6$ and $\omega/\omega_{pe} \sim 0.8$ is above the beam mode as shown in Fig. 1(c) and the phase velocity is faster than v_b . Nonlinear frequency shift [1] then seems to occur. After that, the packet begins cresting to pile up asymmetrically in the upstream side where the wave length is shorter than in the downstream side. This result differs entirely from self-contraction due to modulation instability [1]. The spectrum of $\omega_{pe} t = 105 - 148$ has two peaks split at $\omega/\omega_{pe} \sim 0.8$. Finally, the packet comes to widen with damping. The spectrum of $\omega_{pe} t = 127 - 170$ shows that the two peaks unite to one at $k/k_0 \sim 0.75$. As shown in Fig. 1(c), k of $\omega_{pe} t = 127 - 170$ is larger than that of $\omega_{pe} t = 83 - 126$, which implies that the

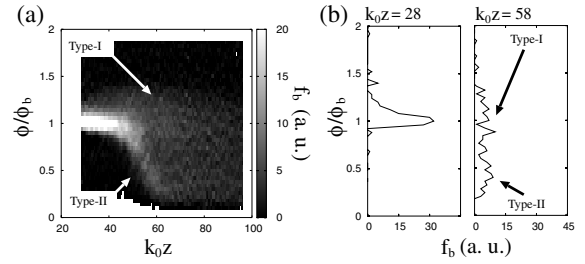


Fig. 2 Distribution function of electron-beam f_b of $\omega_{pe} t = 70 - 140$ vs $k_0 z$ and ϕ/ϕ_b ; (a) from a top view, and (b) from side views of $k_0 z = 28, 58$.

carrier wave of the packet is forced to decelerate.

Figure 2 shows the distribution function of the electron-beam f_b against distance $k_0 z$ and energy ϕ/ϕ_b at $\omega_{pe} t = 70 - 140$. The energy spread of $k_0 z \lesssim 45$ is narrow at $\phi/\phi_b = 1$. But there are two types for the spread at $k_0 z \gtrsim 45$. Type-I has a normal energy spread which becomes wide as k_z increases. Type-II has an abnormal energy spread extending to $\phi/\phi_b \sim 0.2$ at $k_0 z \sim 45 - 60$. The peak amplitude of the packet is almost always located within the special range of Type-II. Therefore, beam-electrons having high energy appear to construct Type-II.

Fast beam-electrons around the phase velocity are trapped by the carrier wave at the peak amplitude. The beam-electrons then lose their energy while bouncing repeatedly in the potential wells of the wave. We estimate that the energy loss of the electron-beam due to trapping is near 10%. The carrier wave deceleration indicated in Fig. 1 suggests that the beam-electrons trapped may have a slowing effect on the phase velocity at the peak amplitude. Thus, since the local value of k is large on the left and small on the right, the packet shape becomes deformed asymmetrically and the difference of the group velocities at those local positions enhances such deformation.

In summary, we observe experimentally the nonlinear evolution of the electron time scales of a wave packet in plasma, induced by a low density electron-beam. The packet widens asymmetrically after amplitude saturation, which differs entirely from self-contraction due to modulation instability. An abnormal energy spread of the electron-beam, Type-II, indicates that fast beam-electrons trapped by the carrier wave of the packet play an important role in the asymmetrical structure formation.

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