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# Particle-Trapping Effects in Electron-Beam-Plasma

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**Abstract**

Wave packets and velocity distribution functions of electron-beams in an electron-beam-plasma system are investigated to find out particle-trapping effects. The dependency between the packet amplitudes and the distribution spreads, and the value of the bounce frequency indicate that the potentials of the packets trap the beam-electrons. The trapping appears to induce the beam scattering and the deformation of the packets.

**Keywords:**

particle-trapping, electron-beam-plasma, wave packet, velocity distribution function of electron-beam, coaxial probe, energy analyzer

## 1. Introduction

In an electron-beam-plasma system, it is well known that wave packets developing as an initial growth process in electron time scales obey the beam-mode properties described by a linear equation [1]. But the packets can not continue to grow infinitely, and begin to shift to the processes of saturation and damping before long. Since the packet is easy to be accompanied with nonlinear phenomena [2,3], it is necessary to discuss modulational instability [4], particle-trapping [5], and so on. Yamagiwa *et al.* [6] observed that a wave packet evolves into a packet train as continuously emitting some wave packets in a weak electron-beam plasma, $n_b/n_e < 0.3$ % ($n_b$ and $n_e$ are the electron-beam and the plasma density, respectively), and discuss its phenomenon by a nonlinear theory of Yajima *et al.* [7]. But Akimoto *et al.* [5] showed by computer simulations that the trapping effects outstand in the nonlinear regime of this system. It has been interesting that velocity distribution functions of electron-beams are investigated experimentally. In this study, the authors investigate nonlinear phenomena in the case of strong beams, $n_b/n_e \geq 0.3$ %, and the relationships between the packets and the distribution functions so as to pick up the signs of beam-electron trapping.

## 2. Experimental procedure

Plasma is produced in a cylinder chamber, whose sizes are 0.26 m in diameter and 1.2 m in length, filled with argon gas by DC-discharges between four heated filaments and its wall. Then the plasma is confined in full-line cusps [9] produced by magnets. Electron-beams injected into the plasma are pulsed, and travel one-dimensionally along $z$-axis magnetic field induced by coils. Wave packets excited by the beams are observed by using a coaxial probe. An energy analyzer [8] is adopted so as to observe velocity distribution functions of the beams. Figure 1 illustrates the schematic of experimental apparatus. A synchronized system with a test wave signal is introduced in the above observation. The signal, which is a single amplitude modulation wave, consists of carrier frequency of 90 MHz and half-width time of 50 ns, and is given to a control grid of beam gun to excite an initial wave packet. The signal is also given as a trigger to digital oscilloscopes simultaneously. Signals detected by the analyzer and the coaxial probe are amplified by a low frequency amplifier (DC–8 MHz) and a high frequency amplifier (0.1–1300 MHz), respectively. These amplified signals are received on 2-channel of the oscilloscopes. The observations are carried out at each of the axial positions of 128 points. Typical experimental parameters are as follows: electron plasma temperature 0.76 eV, electron plasma density $n_e = 1 \times 10^{14}$ m$^{-3}$, electron-beam velocity $v_b = 4.2 \times 10^6$ m/s, and electron-beam density $n_b/n_e = 0.3, 0.6, 1.2$ %.

## 3. Results and discussions

Figure 2 shows that a wave packet in the case of $n_b/n_e$ = 1.2 % evolves temporally along the beam path. Here $k_0z$ and $\omega_{pe}t$ is respectively the axial space and the time. The characterization parameters of wave packets against $n_b/n_e$ are given in Table 1. Here $\omega_{pe}$ is the electron plasma frequency, $k$ the wave number, $\omega(= \omega_r + i\omega_i$, $\omega_r = \mathrm{Re}(\omega)$, $\omega_i = \mathrm{Im}(\omega))$ the frequency, $k_0(\equiv \omega_{pe}/v_b)$ the defined wave number, and $v_\phi(= \omega_r/k)$ the phase velocity. $\omega_r$ is almost constant due to being almost determined by the frequency of the test wave. $k$ increases and $v_\phi$ decreases with $n_b/n_e$. This result means that the packets obey the beam-modes because the dispersibility

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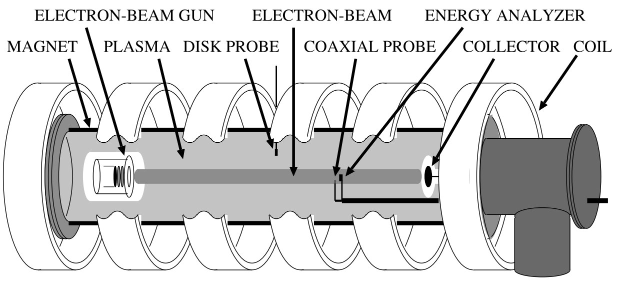


Fig. 1 Experimental apparatus.

depends on $n_b/n_e$. After the packet grows linearly in $\omega_{pe}t$ < 90, it shifts to saturation and damping process. Unfortunately, modulation instabilities or wave packet trains are not observed in the case of the above beams. Instead of those, the asymmetry deformation appears in the packet.

The correlations between wave packets and velocity distributions $f_b$ for $n_b/n_e$ = 0.3, 0.6, 1.2 % are respectively shown in Fig. 3(a), 3(b) and 3(c). These figures show the packets

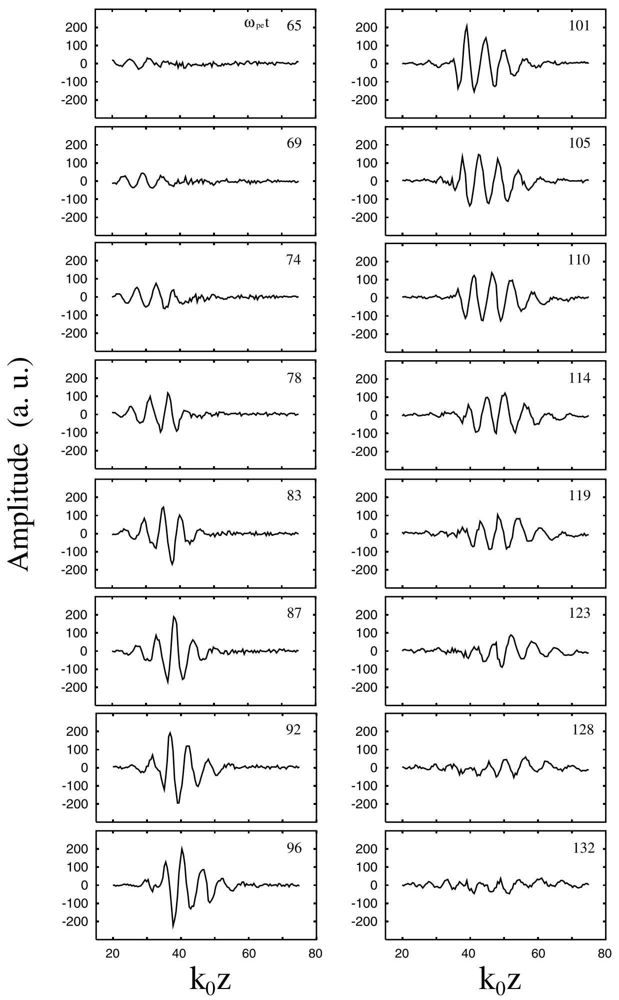


Fig. 2 The temporal evolution of the packet at time interval of $\omega_{pe}t$ = 4.5 in the case of $n_b/n_e$ = 1.2 %.

Table 1 The characterization parameters of the packets against the beam density $n_b/n_e$.

| $n_b/n_e$ (%) | $k/k_0$ | $\omega_r/\omega_{pe}$ | $\omega_i/\omega_{pe}$ | $v_\phi/v_b$ |
|---|---|---|---|---|
| 0.3 | 1.01 | 0.9 | 0.066 | 0.89 |
| 0.6 | 1.07 | 0.9 | 0.10 | 0.84 |
| 1.2 | 1.10 | 0.9 | 0.12 | 0.82 |

with the maximum amplitudes at each upper side, the distributions mapped on $v - z$ plane at each left side, and the distributions in several positions $k_0z$ at each right side. With increasing $n_b/n_e$, the spread of these distributions becomes larger towards the low side of the velocity space. In the case of $n_b/n_e$ = 1.2 %, the spread becomes unusual in $k_0z$ = 30 – 40 as two peaks arising. Those spreads exist around the peak positions of the packets, which seem to be involved by the packet amplitudes.

When a wave potential traps beam-electrons, the dependency between the potential $\phi$ and the trapping radius $\Delta v_t$ is described by $\Delta v_t^2 = 4e\phi/m$ [2,5], where $e/m$ is the specific charge of electron. Figure 4 plots on double logarithmic chart the packet amplitude against the velocity width $\Delta v$ between the phase velocity and the lower edge of the spread. The liner line fitted by $(\Delta v/v_b)^2$ implies that such plotting is consistent with the dependency. The upper horizon of this figure is the magnitude of the potential into which the trapping radius is converted, which gives $\phi$ = 0.56 V in $n_b/n_e$ 1.2 %. Then the bounce frequency $\omega_t$ (= $\sqrt{ek^2\phi/m}$) is 0.083 $\omega_{pe}$. Since $\omega_t$ is near $\omega_i$, the trapping effects can not be neglected. These above results indicate that the packet potentials trap the beam electrons. The distribution spreads seem to be constructed by the beam scattering due to trapping and detrapping. The local difference of the beam density generates that of $\omega_i$ and $v_\phi$, which may induce the deformation of the packet.

## 4. Conclusions

The authors investigate wave packets and velocity distribution functions of electron-beams to find out particle-trapping effects in an electron-beam-plasma system. The deformation of the packets and the distribution spreads of the beams are observed by using a coaxial probe and an energy analyzer, respectively. From the dependency between the packet amplitudes and the distribution spreads, and the bounce frequency estimated, it is concluded that the potentials of the packets trap the beam-electrons. The authors guess that the beam scattering due to trapping and detrapping induces the distribution spreads and the deformation of the packets.

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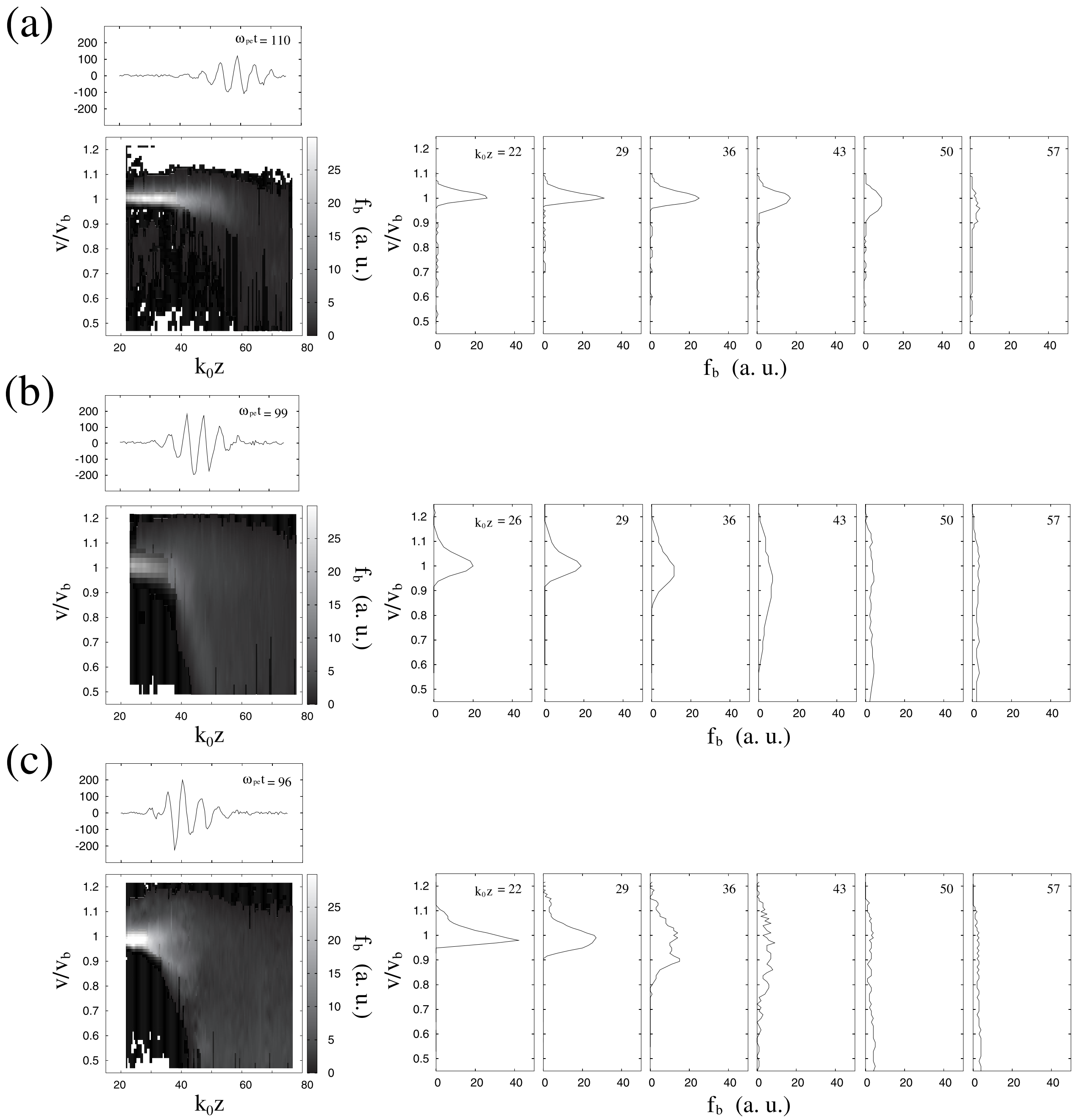


Fig. 3 The correlations between the packets and the distributions $f_b$ for $n_b/n_e$ = 0.3 (a), 0.6 (b), and 1.2 % (c). The packets with the maximum amplitudes are displayed at each upper side, the distribution mappings for $v - z$ plane at each left side,and the distributions of several positions at each right side.

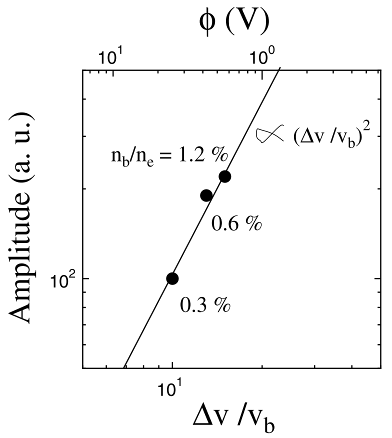


Fig. 4 The dependency between the packet amplitudes and the distribution spreads $\Delta v$. The upper horizon is the potential $\phi$. The fitting line is proportional to $(\Delta v/v_b)^2$.

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