Electron acceleration in an electron-beam-plasma

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Abstract: Narrow spreads have been observed next to electron holes in a strong electron-beam. There is the relationship between the position and the velocity on the spread tips, which indicates that the electron acceleration (or strong heating) occurs.

Key words: wave packet, electron hole, electron acceleration, electron two-stream instability

1. Introduction

Wave packets developing in an electron-beam-plasma system initially obey electron-beam mode properties described by a linear theory. Afterward, the packet amplitudes surely saturate because of nonlinear effects. Since modulational instability and electron-beam-trapping observed in laboratory plasmas can also be applied to space plasmas as nonlinear phenomena, it has still been important to investigate the system. According to computer simulations, it has been indicated that electron holes in phase-space determine potential structures in the earth's ionosphere and magnetosphere. However this has not been verified adequately in laboratory experiments.

In our previous works, electron-beam holes induced by self-trapping were experimentally observed in the case of a weak electron-beam as not leading strong turbulences. It was then clarified that there is the correlation between wave amplitudes and the holes. In this paper, we show electron acceleration in the case of a strong electron-beam.

2. Experiment

A cylinder chamber made of stainless steel, whose sizes are 0.26 m in diameter and 1.2 m in length, is filled with argon gas of low pressure 2.8×10^{-5} Torr, and a cold plasma is produced by DC-discharges between four heated filaments and the chamber wall. Then the plasma is confined by full-line cusps produced by twelve line-magnets mounted on the external surface. An electron-beam gun at $z=0$ is mounted on an end of the chamber, and emits a strong electron-beam with the diameter 50 mm, the duration time 3.5 (s, and the mean energy of $\phi_b = 50$ eV. The beam injected into the plasma behaves one-dimensionally along axial DC-magnetic field 0.01 T induced by six external coils. A wave packet excited in this experimental system is observed as potential perturbations by using a coaxial probe, whose tip is 0.3 mm in diameter and 2.0 mm in length. An energy analyzer, which has the aperture of diameter 5.5 mm, is adopted so as to observe a phase-space distribution of the beam. A collector in the analyzer, which is shielded against electric fields, can detect the beam currents discriminated by a biased grid.

These observations are synchronized with a test wave signal, which consists of carrier frequency 90 MHz and envelope width 50 ns (by the full width at half maximum, FWHM). The test wave signal is applied to a control grid of the gun at $t=0$ in order to excite a wave packet, and simultaneously triggers two digitizing oscilloscopes with 10^9 samples per second. The packet signal detected by the coaxial probe is amplified by a high frequency amplifier (0.1-1300 MHz). The beam current signal detected by the analyzer is divided into two, and they are in parallel amplified by a low frequency (LF) amplifier of DC-8 MHz band and a high frequency (HF) amplifier of 8-1300 MHz band. These amplified signals are individually received on two channels of the oscilloscopes with time-averaging, and those

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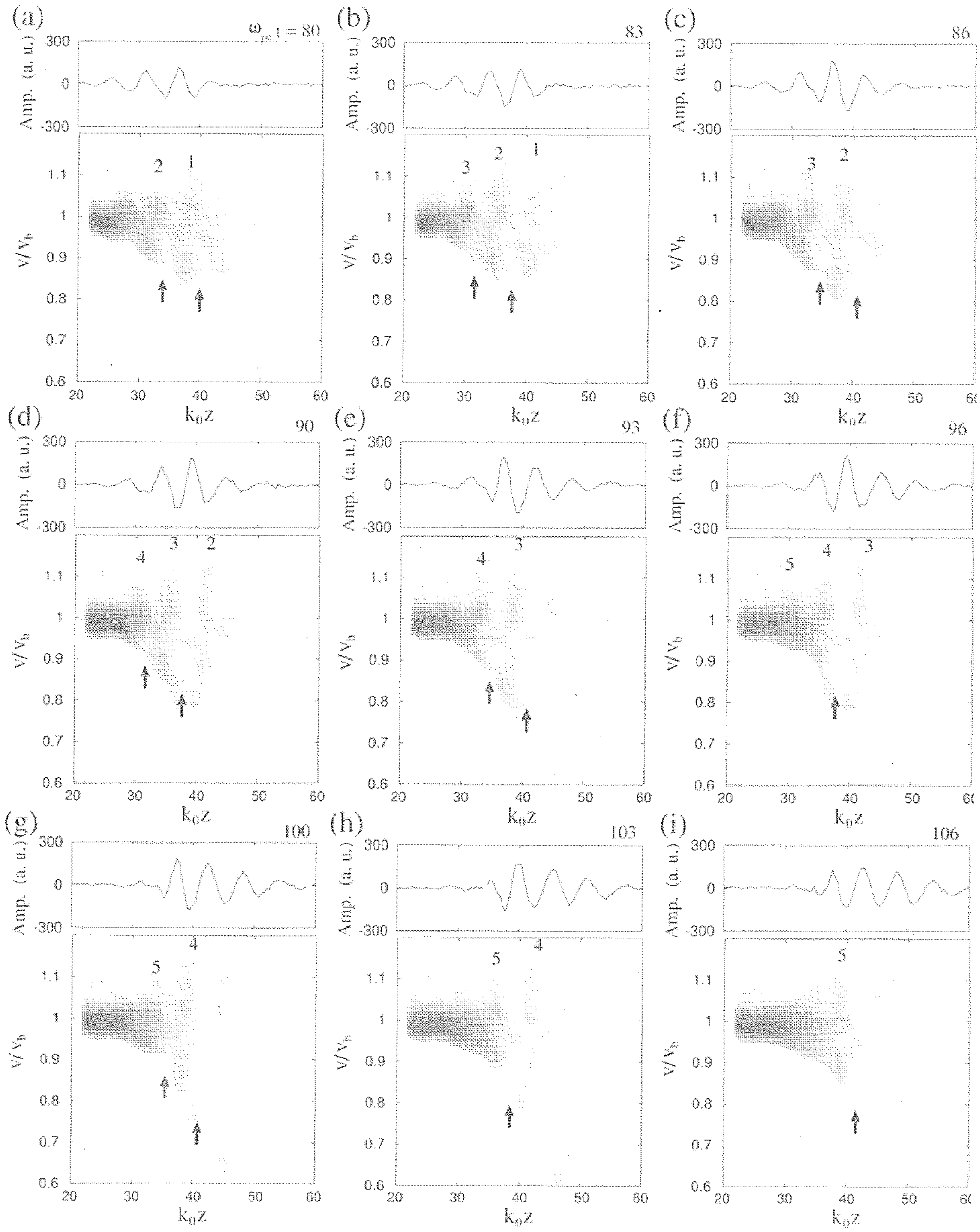

Fig. 1 A wave packet and a phase-space distribution f_b of a strong electron-beam from $\omega_{pe}t = 80$ (a) to $\omega_{pe}t = 106$ (i). Each upper shows the packet amplitude vs k_0z, and each lower f_b vs v/v_b and k_0z. Dark contrast corresponds to the beam density. The packet exhibits two processes of linear growth (exponential in $\omega_{pe}t \le 93$) and saturation (stable in $\omega_{pe}t \ge 93$). Narrow spreads of the beam are numbered at the tips.

data are stored in PC. Ends of coaxial cables are all connected to matching resistances 50Ω. These detections are carried out at each of 128 axial positions from $k_0z = 22$ to 75 (k_0 defined below). The LF and HF signals of the beam current are synthesized on PC in each cell of the discrimination energy and the position. Eventually, the first derivatives of the synthesized beam current with respect to the discrimination energy at the positions give a phase-space distribution of the beam.

Typical experimental parameters are as follows: plasma-electron temperature is about 0.8 eV, plasma-electron density $n_e \approx 1.0\times10^{14}$ m^{-3}, the electron-plasma frequency $\alpha_{pe}/2\pi \approx 90$ MHz, beam-electron density $n_b/n_e \approx 1.2\%$, electron-beam velocity $v_b \approx 4.2\times10^6$ m/s, and initial electron-beam spread $0.05v_b$ (FWHM). Here $k_0 \equiv \alpha_{pe}/v_b$ ($\approx 43\pi$ m^{-1}) is defined for normalization.

3. Results and discussion

Figure 1 shows a wave packet (upper sides) and a phase-space distribution f_b of a strong electron-beam (bottom sides) at intervals of $3.4/\omega_{pe}$. Here v/v_b, k_0z, and $\omega_{pe}t$ are the velocity, the position, and the time, respectively. Dark contrast corresponds to the beam density.

The packet is propagated downward, and has two evolutional processes of linear growth (in $\omega_{pe}t \leq 93$) and saturation (in $\omega_{pe}t \geq 93$). Five electron-beam holes, pointed by arrows, emerge discretely, and are also propagated downward. Parts of the beam, numbered from the downstream side, spread to the higher velocity side discretely. The typical profile of the packet in the growth process is as follows: phase velocity $v_\phi \approx 0.90v_b$, wave number $k \approx 1.08k_0$, frequency $\omega_r \approx 0.97\omega_{pe}$. We confirm that the profile is in agreement with the beam mode.

Initially, the holes generated around $v = v_\phi$, such as the third hole born around $\omega_{pe}t = 83$, become having fine and large circle with the packet growth. The holes are mostly in phase with the wave crests on the position, and the radii seem to be correlated with the crest amplitudes. These prove that the holes are induced by self-trapping of the beam. The holes can be regarded theoretically as right-handed vortices, though their rotations are invisible.

The beam detrapping should also be regarded because the trapped beam partly takes away the wave energy. Five narrow spreads are generated next to the holes. It seems that the spread tips have the relationship between the velocity and the position. Especially in the saturation process, the holes shift slightly to the lower velocity side, and the packet shape is asymmetrically deformed. These indicate that the trapped electrons despoil the wave energy, and thus the electron acceleration (or strong heating) occurs. The holes may contribute to the acceleration.

4. Summary

We have investigated a phase-space distribution with a wave packet in the case of a strong electron-beam. The packet obeys the beam mode initially, and five electron holes are generated by the self-trapping. Five narrow spreads of the beam like bunching are observed next to the holes. The spread tips have the relationship between the velocities and the positions. The spread increasing seems to be correlated with the hole shift and the packet deformation. These indicate that the electron acceleration (or strong heating) occurs as a result of taking away the wave energy.

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