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Nonlinear Waves Observed in an Electron Beam-Plasma

KAWAKAMI Retsuo, MORI Ichiro and MORIMOTO Toshifumi[1]
The University of Tokushima, Minami-Josanjima, Tokushima 770-8506, Japan
[1]Takuma Radio Technical College, Kohda, Takuma, Kagawa 761-1192, Japan

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Abstract

Intense wave packets with hyperbolic secant forms and strongly modified wave packets with infirm amplitudes, which are excited by interaction of an electron beam with a plasma in a magnetic mirror field, are observed experimentally. It is found that the intense wave packet has the nature that an increase in its amplitude decreases its width. The nature is in agreement with that obtained by solving the nonlinear Schrödinger equation. It is also observed that density depletions appear at a certain gas pressure, where the intense wave packets are excited.

Keywords:

electron beam-plasma, magnetic mirror field, axial plasma density, density depletion, intense wave packet, sech form

1. Introduction

The beam-plasma interaction has been studied as a method of heating a plasma by many authors and interesting phenomena on waves have been found in experiments [1-4]. However, much still remains to be investigated because nonlinear wave phenomena occur actively when waves excited by the plasma instability grow.

In general, it is well known that in a beam-plasma system a plasma is formed as ionization of neutral gas by beam electrons and secondarily by plasma electrons in high-frequency fields and the secondary ionization produces an abrupt increase in plasma density. At gas pressures where plasma density increases abruptly in an electron beam-plasma under a magnetic mirror field, we have observed temporal evolutions of characteristic wave packets which correspond to nonlinear waves. In this paper our observation on the wave packets with interesting natures will be discussed.

2. Experiment

Our experiment is characterized as follows. An electron beam which has an energy of 2keV, a current of 20mA and a density of $1.1 \times 10^{14} m^{-3}$ is passed through a hole slit with a diameter of 8mm and injected continuously into a chamber, 0.4m in length and 0.16m in diameter, immersed in a magnetic mirror field with a mirror ratio of 1.4, the strength of which is 80 G at the center of the chamber. The beam, then, interacts with argon gas at 0.10 to 0.30mTorr in the chamber and produces a plasma, as shown in Fig. 1. The figure shows distributions of plasma density at 0.10 to 0.30mTorr as a function of axial distance from a beam injection entrance, for ion saturation current I_{is} varies in proportion to plasma density n if temperature for plasma electrons T_e is constant: $I_{is} \propto n\sqrt{T_e}$. Plasma density increases monotonously with increasing gas pressure at 0.10 to 0.21mTorr. We name the plasma state at such gas pressures the first stage of the beam-plasma discharge (BPD). The plasma density, however, increases abruptly at 0.22 to 0.30mTorr and the plasma state above 0.22mTorr is different from the first stage. It

Corresponding author's e-mail: retsuo@ee.tokushima-u.ac.jp

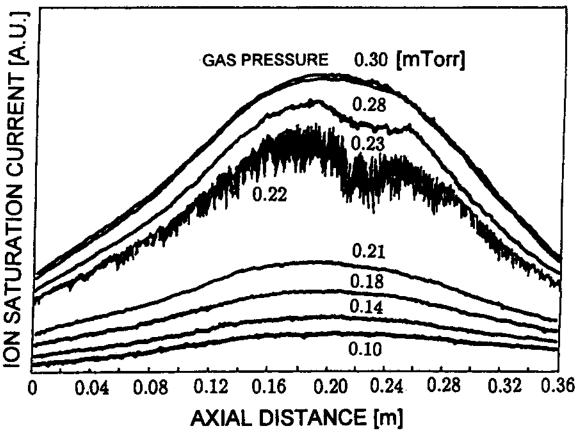

Fig. 1 Axial distributions of ion saturation current with gas pressures between 0.10 and 0.30mTorr.

should be noted in particular that density depletions appear at 0.22mTorr. We name such a plasma state the second stage of the BPD.

In the second stage a plasma has density $n \propto 10^{14} \sim 10^{15}\mathrm{m}^{-3}$ and temperature $T_e \approx 3\mathrm{eV}$; as a result, the plasma parameter $\Lambda_c = n\ \lambda_D{}^3$ becomes an order of $10^4 \sim 10^5 \gg 1$, where λ_D is the Debye length — In other words, collective-cooperative behavior becomes active in the second stage. Waves excited by interaction between the beam and the plasma are detected by a probe and observed directly by a digital oscilloscope.

3. Observation

Wave packets with intense amplitudes appear intermittently at 0.22mTorr in the second stage. A sample of wave packets observed at 0.245m from the beam injection entrance is shown in the top of Fig. 2. In the sample the two wave packets are identified by notations (A) and (B), respectively. The bottom two figures are redrawn views of the wave packets (A) and (B). For each wave packet, its envelope has a well-known shape of a hyperbolic secant, i.e., sech. A peak-to-peak value of the wave packet (A) is 2.6V and its full width at half maximum (FWHM) is 0.74μsec, and for the wave packet (B) the former is 4V and the latter is 0.53μsec. It is seen that amplitude of the wave packet increases with decreasing its FWHM. The relationship between the amplitude and the width is in agreement with a characteristic of solution $|S(x,\ t)|$, which satisfies the nonlinear Schrödinger (NLS) equation, expressed by

$$\left|S\ (x,\ t)\right| = A\ \mathrm{sech}\left[\sqrt{Q\ /\ P}\,Ax\right], \qquad (1)$$

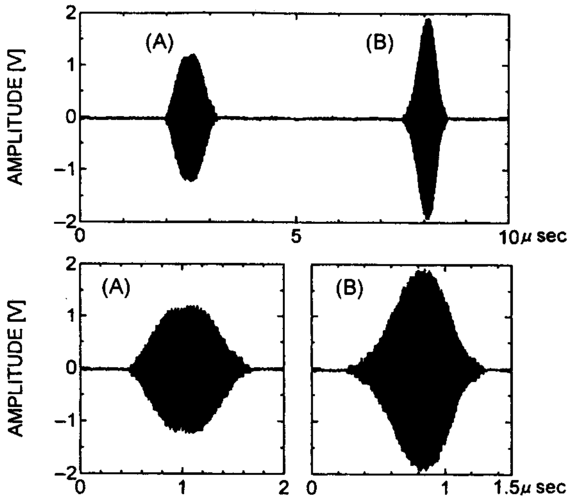

Fig. 2 A sample of wave packets, (A) and (B), observed at 0.245m under 0.22mTorr. The bottom two figures show redrawn views of the wave packets (A) and (B), respectively.

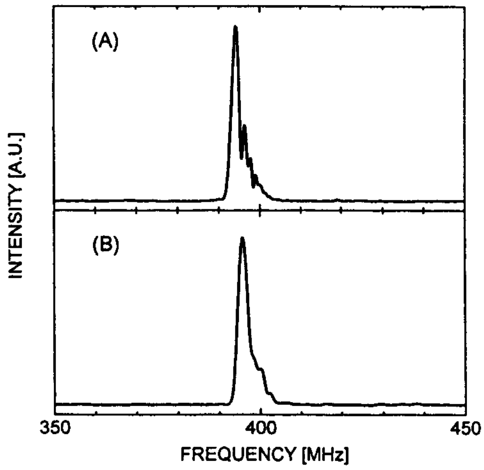

Fig. 3 Frequency spectrums corresponding to the wave packets (A) and (B) in Fig. 2.

where P and Q are parameters which stand for the strength of dispersion and nonlinearity in the NLS equation [5]. In eq. (1) an increase in A corresponding to the amplitude decreases FWHM of $|S(x,\ t)|$, for the FWHM is given by $2\ \mathrm{sech}^{-1}[1/2]/(\sqrt{Q/P}A)$.

Figure 3 shows frequency spectrums of these wave packets. The spectrums of (A) and (B) are almost the same and each of the spectrums has a localized structure with a FWHM of 3MHz around a carrier frequency of 396MHz.

Such wave packets, however, do not appear with

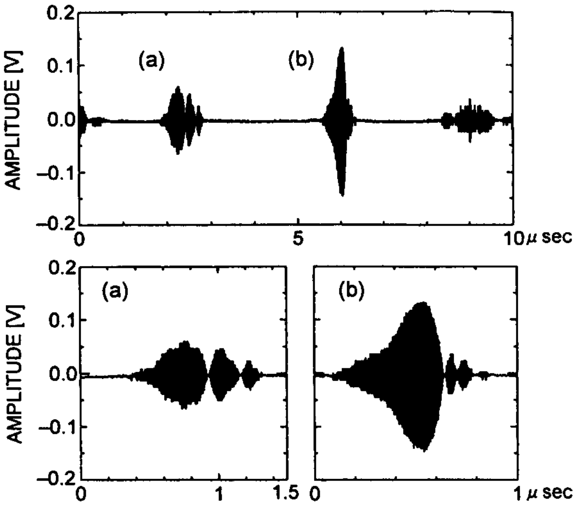

Fig. 4 A sample of wave packets, (a) and (b), observed at 0.245m under 0.30mTorr. The bottom two figures show redrawn views of the wave packets (a) and (b), respectively.

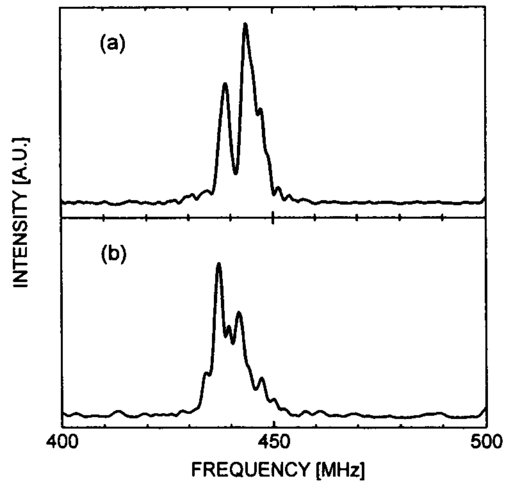

Fig. 5 Frequency spectrums corresponding to the wave packets (a) and (b) in Fig. 4.

the further increase of gas pressure. A sample of wave packets, (a) and (b), observed at the same position under 0.30mTorr is shown in Fig. 4. Likewise, in the sample the two wave packets are labeled (a) and (b) respectively and the bottom two figures show redrawings of the wave packets (a) and (b). There is no appearance of density depletions at this gas pressure. Amplitudes of the wave packets are infirm compared with those at 0.22mTorr, or the amplitudes become about one tenth as much as those at 0.22mTorr. Each envelope of the wave packets no longer follows a sech form and is strongly modified at a rapidly decreasing part. Frequency spectrums of the wave packets (a) and (b) broaden in comparison with those of (A) and (B), as shown in Fig. 5, and have peak values of intensity at about 438 and 442MHz. Here, a collision effect is not taken into account for the reason that an increase in plasma density between 0.22 and 0.30mTorr is slight. It is seen from these figures that the wave packets (a) and (b) are affected by some nonlinear interaction effect, such as the nonlinear Landau damping.

These results lead to the thing that the density depletions appear with the intense wave packets at 0.22mTorr. It is likely that pressures of the intense wave packets cause the density depletions through the ponderomotive force as a nonlinear effect.

4. Conclusion

We have observed characteristic wave packets experimentally, which are excited by interaction of an electron beam with a plasma column in a magnetic mirror field, at the second stage of the BPD where an abrupt increase in plasma density occurs. It turns out that the wave packets vary sensitively with gas pressure: wave packets at 0.22mTorr have intense sech forms and frequency spectrums, 3MHz in FWHM, localized around a carrier frequency of 396MHz, whereas wave packets at 0.30mTorr have infirm amplitudes, which are strongly modified at rapidly decreasing parts, and frequency spectrums with two peak values of intensity. In addition, it is observed that density depletions appear at the gas pressure where the intense wave packets are excited.

It also turns out that the intense wave packet with the sech form has the nature that its amplitude increases with decreasing its FWHM; the relationship between the amplitude and the width is in agreement with that obtained by solving the NLS equation.

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