Simultaneous Excitation and Interaction of Nonlinear Ion-Acoustic and Beam-Mode Waves in an Ion-Beam–Plasma System

Tadao Honzawa
Department of Electronic Engineering, Utsunomiya University, Utsunomiya 321, Japan

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The simultaneous excitation of nonlinear ion-acoustic and slow beam-mode waves has been experimentally found to occur in an ion-beam–plasma system. Further, the collision between the two different nonlinear modes is observed to result in the formation of a new mode, probably corresponding to a nonlinear explosive mode theoretically predicted by Yajima, Kono, and Ueda.

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Since Sagdeev[1] presented a theory on the formation of ion-acoustic solitary waves in collisionless plasmas, many theoretical,[2] computational,[3] and experimental[4] works were reported on this nonlinear wave. Many other works on the nonlinear wave are cited in recent review papers.[5] On the other hand, it was theoretically shown by Ostrovskii, Petrukhina, and Fainshtein[6] that when a plasma included an ion beam, ion-acoustic solitary waves in such a plasma could be amplified by the beam. After this appeared, Okutsu *et al.*[7] studied experimentally the amplification of the solitary waves by a steady ion beam in a linearly unstable ion-beam–plasma system. Subsequently, Yajima, Kono, and Ueda[8] presented a theoretical and computational work on the formation and interaction of ion-acoustic and beam-mode solitons in a linearly stable or unstable ion-beam–plasma system, using fluid equations for hot electrons, cold ions, and cold beam ions, and neglecting all dissipative effects. In this Letter, I wish to report observations of the simultaneous formation and interaction of nonlinear ion-acoustic and slow beam-mode waves in an ion-beam–plasma system. I believe that this is the first experiment on the excitation and interaction of two different nonlinear modes in the beam-plasma system.

Experiments on the nonlinear waves in the beam-plasma system were performed by use of a double plasma (DP) device with multidipole magnets[9] at the Utsunomiya University. Details of the device are described elsewhere.[10] The device contained two independent plasmas separated by a negatively biased grid. There was an ion-rich sheath with width ~1 cm near the grid.[10] Plasma parameters were as follows: density $N_e \simeq (2\text{–}5)\times 10^8$ cm^{-3}, electron temperature $T_e \simeq 2\text{–}3$ eV, and electron-to-ion temperature ratio $T_e/T_i \simeq 20\text{–}30$. Argon gas was introduced into the device up to $P \lesssim 3\times 10^{-4}$ Torr. Mean free paths for ion-neutral collisions were much longer than wavelengths or soliton widths. Waves and ion flows were regarded to be almost one-dimensional because of the large diameter of the grid.

The wave excitation method used here was the same as the conventional one used for soliton excitation in the device.[4] Under optimum conditions for the soliton excitation, a flow of slow ions was observed to be continuously injected into the "target" plasma from the "driver" plasma, even if no pulse was applied.[10] Therefore, when a positive potential pulse was externally applied to the driver plasma, some of the slow ions could be accelerated and become "burst" (or pulsed beam) ions. As a result of this, the flowing ion density was observed to be depressed during the pulse duration at small x in the sheath,[10] where x is the distance from the grid.

At an early stage of the wave evolution, the locally developing two-stream instabilities,[11] caused by the interaction between the burst ions and the background plasma, were observed to grow very rapidly and to form large-amplitude ion-acoustic and slow beam-mode waves at the front but in different parts of the density-depressed region (see Fig. 1). Here, one can find that the ion-acoustic wave (mode A) is always formed at a position (the front edge of the density depression) forward of the birth place of the beam mode (mode S). Further, the maximum growth rates of the two modes are estimated to be as high as 2×10^6 sec^{-1} [see Fig. 2(a)]. In addition, though the large perturbations observed may be outside the scope of weak perturbation theory, one can tentatively show from the observed ion energy distributions, as demonstrated in Fig. 3, that in the linearly unstable region ($x < 1$ cm) the derivatives of the ion velocity distribution with respect to the ion velocity, $\partial f_i(v)/\partial v$, are positive near the wave velocities U_w, so that Landau growth[12] is possible. Furthermore, it is found from Fig. 2(a) that the amplitudes of both the nonlinear waves are saturat-

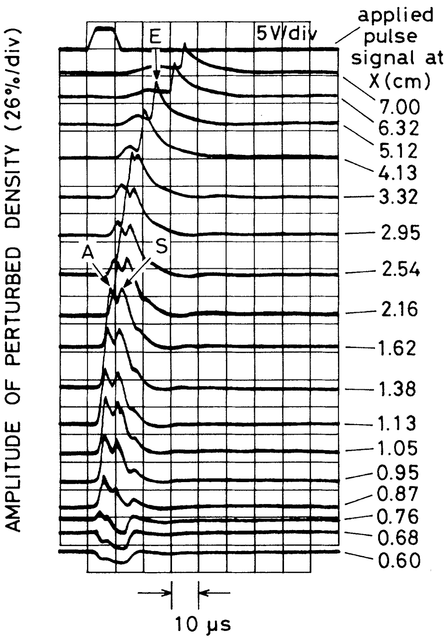

FIG. 1. Oscilloscope traces of the perturbed plasma density observed at various positions. Here, the applied pulse height V_{ex} is 4 V. *A*, ion-acoustic mode; *S*, slow beam mode; *E*, new mode.

ed at $x \sim 1$ cm and thereafter ($x > 1$ cm) slowly decrease, where $[\partial f_i(v)/\partial v]_{U_w} \lesssim 0$ can be confirmed from the corresponding ion energy distributions in Fig. 3. Consequently, assuming the usual perturbation theory to be available, one can conclude that the beam-plasma system is linearly stable at $x \gtrsim 1$ cm.

Figures 1 and 2(a) also indicate that, as time goes on, the beam-mode wave (mode *S*) overtakes the ion-acoustic one (mode *A*) and then the two waves coalesce into one pulse to form a new-mode wave (mode *E*). Neither the *A* nor *S* mode reappears after the collision. Here, one can recall that during an overtaking collision between two ion-acoustic solitons with comparable amplitudes they never coalesce into one pulse.[3,4] Furthermore, the new mode is different in nature from both the ion-acoustic and the slow beam-mode waves observed before the collision. For instance, the new-mode velocity was always observed to be slower than that of the ion-acoustic mode, as will be concretely shown below. Of course, it was much slower than the beam-mode velocity. This leads me to believe that the new mode corresponds to a nonlinear explosive mode, theoretically prdicted by Yajima, Kono, and Ueda.[8] However, the new-mode amplitude was observed not to grow explosively but to damp with increasing x under the present conditions [see Fig. 2(a)]. This is probably because there actually exist strong dissipative effects due to the finite ion temperature ($T_i \neq 0$), such as ion reflection from the wave front. It must be noted that the wave coalescence observed here does not come from these dissipative effects, because even in dissipative plasmas like the present one, two ion-acoustic solitons were observed never to coalesce into a third ion-acoustic soliton during the overtaking collisions.[4,5]

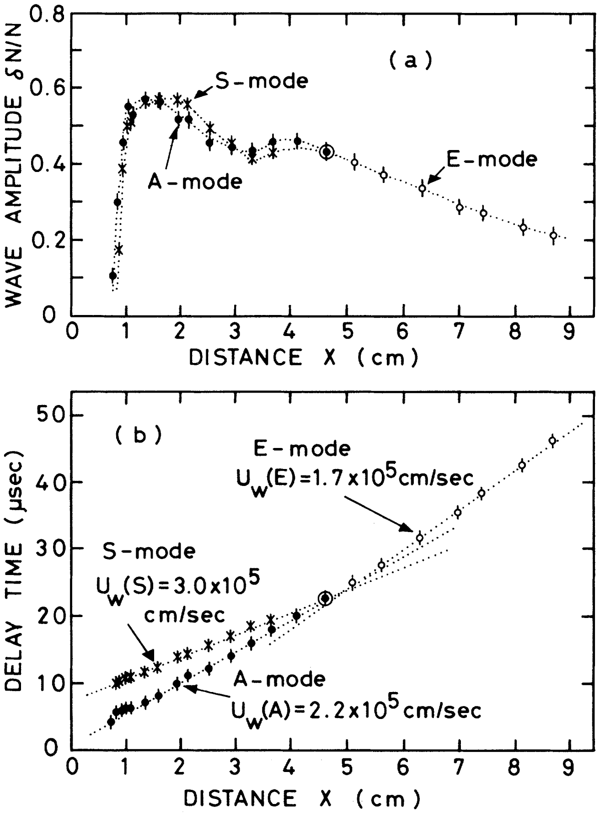

FIG. 2. (a) Wave amplitudes of the ion-acoustic mode (*A*), slow beam mode (*S*), and new mode (*E*) vs distance *x*. (b) Trajectories of the *A*, *S*, and *E* modes in the space-time plane.

Information on the wave velocities comes from the trajectories of the observed waves in the space-time plane, as shown in Fig. 2(b). This figure shows that the velocities of the ion-acoustic and slow beam-mode waves are $U_w(A) \simeq 2.2 \times 10^5$ cm/sec and $U_w(S) \simeq 3.0 \times 10^5$ cm/sec, respectively, and that the beam mode overtakes the ion-acoustic mode around $x \sim 5$ cm. Then, the new mode with velocity $U_w(E) \simeq 1.7 \times 10^5$ cm/sec is emitted at that position. Here, it is noticeable that for all the modes the wave velocities remain nearly constant despite the wave damping.[13] In addition, when the

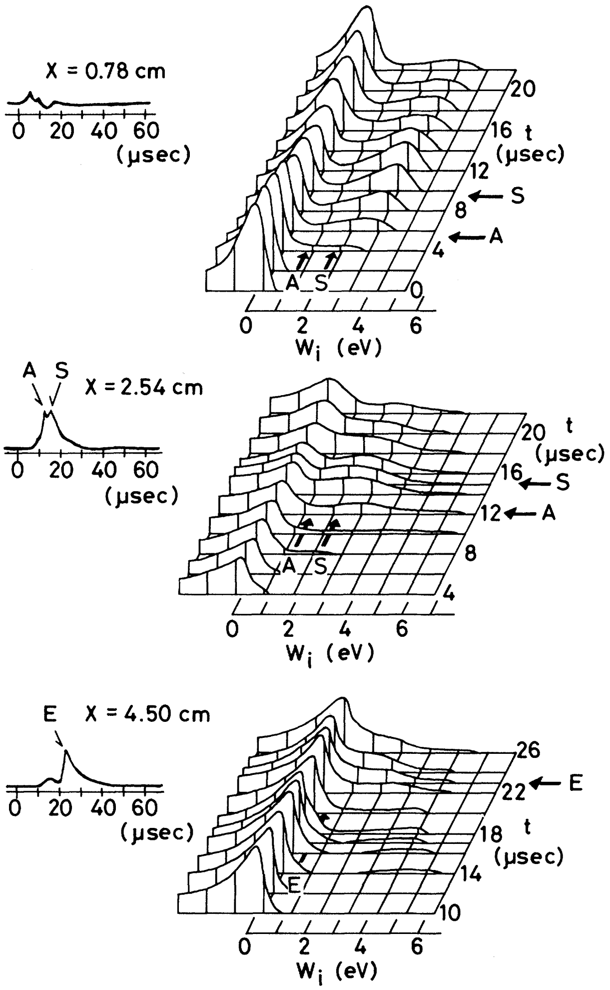

FIG. 3. Evolving ion energy distributions measured at various positions under the same conditions as for Figs. 1 and 2. Each mode exists around the crossing point of the two corresponding arrows in the energy-time plane. The waves are linearly unstable at $x < 1$ cm and stable at $x \gtrsim 1$ cm.

externally applied pulse height V_{ex} was changed, the wave velocity of each mode excited in the system was observed to change together with its maximum amplitude. For all the observed modes it was found that at V_{ex} from 2 to 6 V the relation between the maximum wave amplitude, $(\delta N)_{\max}/N$, and the velocity, U_w/C_s, could be expressed in a form such as

$$U_w/C_s \simeq 1 + \alpha(\delta N)_{\max}/N, \tag{1}$$

where the constant α has different values from 0.4 to 2 for the three modes and C_s, $(\delta N)_{\max}$, and N are the ion-acoustic velocity, the maximum perturbed plasma density, and the unperturbed plasma density, respectively. Although reliable relations between the maximum wave amplitude and pulse width could not be obtained, the relation (1) suggests that the nonlinear waves observed here behave as solitonlike waves with different velocities.

Next, we try to interpret the observed results with the help of the theory presented by Yajima, Kono, and Ueda.[8] According to their theory, there is a soliton dispersion relation in an ion-beam–plasma system as follows:

$$D(\Omega, K, a) = 0, \tag{2}$$

where Ω and K are the nonlinear frequency and nonlinear wave number of the solitons, respectively. With use of the quantities Ω and K, the soliton solution for the normalized density Φ can be expressed in the form

$$\Phi(\Omega, K) = 12K^2 \operatorname{sech}^2(Kx - \Omega t).$$

The relation (2) is characterized by a beam parameter such as $a = 2b^{1/3}/(1 - \mu^{-2} + b)$, where b is the average beam density divided by the average plasma density and μ is the beam velocity V_b normalized by C_s. From Eq. (2) it is derived that in the linearly unstable case ($a > \frac{2}{3}$) only the fast beam solitons (F solitons) are allowed. On the other hand, in the linearly stable case ($a < \frac{2}{3}$) three soliton modes are possible: the fast beam soliton (F soliton), the slow beam soliton (S soliton), and the ion-acoustic soliton (A soliton). In this case, the A and S solitons can exist stably at $K < K_c$ (critical wave number), which is determined by a. However, they cannot exist at $K > K_c$. This tells us that unlike-solitons with small amplitudes behave independently, even if they collide with each other. However, unlike-solitons with intermediate amplitudes can couple strongly with each other and form a nonlinear explosive mode, because the collision between them can make the combined wave amplitude large enough to satisfy the condition $K > K_c$.

Comparing the experiment with the theory, we find some differences between the experimental and theoretical conditions. The assumption of small beam density, $b \lesssim 0.01$, required for the linearly stable case in the theory seems not to be realistic for actual applications; b was estimated to be about 0.2 or larger in our linearly stable system. Further, the theory neglects all dissipative effects, which are always present in actual plasmas with finite ion temperature. Regardless of these differences, the theory[8] shows that the simultaneous excitation of the two different nonlinear modes and the same type collision between them, as observed in this experiment, possibly occurs in the linearly stable system, so long as the observed nonlinear waves can be regarded as solitons.

In conclusion, I have found experimentally that the simultaneous excitation of nonlinear ion-acoustic and slow beam-mode waves occurs in an ion-beam–plasma system, consisting of the burst ions and the background plasma. The collision of the two different nonlinear modes is observed to result in the formation of a new mode, probably corresponding to a nonlinear explosive mode theoretically predicted. The observed phenomenon is qualitatively interpreted by the theory.[8]

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