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Shock Formation by a Velocity-Modulated Ion-Beam Injection in a Magnetized Plasma with Negative Ions

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Abstract

Nonlinear evolutions of density pulses excited by a velocity-modulated ion beam injected into a plasma with negative ions are investigated. A ramp modulation of ion beam velocity gives rise to a density perturbation of the ion beam, which grows as a result of bunching, then a shock like structure is formed eventually. The front slope of the perturbation during the evolution is dependent on the density ratio ε of negative to positive ions. When ε is small, positive slope is steepening. On the other hand, when ε is large, it is observed that a density perturbation with negative slope is steepening.

Keywords:

velocity modulation, ion beam, shock formation, negative ion, SF_6^-

1. Introduction

The behaviors of modulated ion beam in plasmas are of current interest, particularly in connection with plasma instability and heating. Spatial evolution of density perturbations produced in an ion beam-plasma system is demonstrated by Sato *et al.*, using a double-ended Q machine plasma [1]. In case of sinusoidal modulation, initial growth and subsequent amplitude oscillation are observed and explained by the linear wave theory with fast and slow beam modes. Ramp modulations also give rise to an initial growth of the perturbations, which evolve into a single pulse propagating along the ion beam. However, the behaviors of the ion perturbations in case of large amplitude modulation have not been investigated together with the effect of negative ions.

Negative ion plasmas, which include negative ions in addition to electrons and positive ions [2], are of crucial importance in space plasmas, fusion-oriented plasmas, and material-processing plasmas which sometimes include dust particles charged up negatively. Most of the important effects of negative ions on plasma phenomena are ascribed to a reduction of the electron shielding. This effect was well demonstrated for propagating and damping of linear ion acoustic waves in a collisionless negative ion plasma with SF_6^- [3]. Nonlinear propagations of ion acoustic waves in negative ion plasmas were also investigated by Takeuchi *et al.* [4] in a single-ended Q machine plasma. The positive and negative density jumps have been evolved into compressive and rarefactive ion acoustic shocks, respectively, depending on the density ratio ε of negative to positive ions. The critical ratio ε_{cr} observed between positive and negative steepening is well explained on the basis of the KdV equation.

In this paper, we investigate the characteristics of nonlinear evolution of perturbations excited by a velocity-modulated ion-beam in a plasma with negative ions.

2. Experimental Apparatus

The experiment is carried out in a double-ended Q machine with a vacuum chamber of 20.8 cm in diameter

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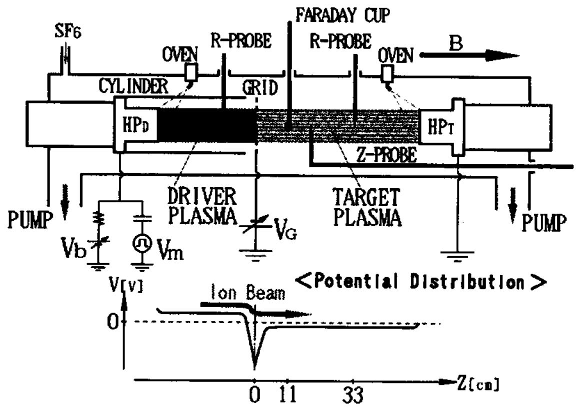

Fig. 1 Experimental apparatus.

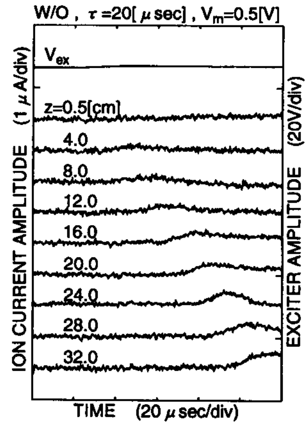

Fig. 2 Evolutions of perturbations when the beam energy is positively modulated in a plasma with no negative ions at V_m = 0.5 V.

and 167 cm long. Potassium ion plasmas produced by contact ionization at hot 52-mm-diam tungsten plates (HP) of 2300 K, placed at both ends of chamber under electron-rich condition, are confined by axial magnetic field of 2 kG, as shown schematically in Fig.1. The machine is operated as a double plasma (DP) device [5]. One of them, the "driver plasma", is surrounded by a small metal cylinder connected electrically to the hot plate HP_D. The other hot plate HP_T in the "target plasma" is grounded. Electrons of the two plasmas are separated from each other by a negatively biased grid of 100 mesh/inch. By applying positive bias V_b to HP_D, ions of the driver plasma flow into the target plasma as a beam. The ramp modulation bias V_m is –5 ~ 15 V and the rise time τ is 5 ~ 20 μsec. When $V_m > 0$, compressional pulses with positive density slope are exited. On the other hand, when $V_m < 0$, rerafactive pulses with negative density slope are generated. Plasma densities of the driver and target plasmas are $5 \times 10^8 \sim 1 \times 10^9$ cm^{-3} and the electron temperatures T_e are about 0.2 eV. The positive ion temperture is almost equal to T_e.

In order to produce a negative ion plasma, SF_6 gas is introduced into the Q machine. The SF_6 has a large electron attachment cross section at $T_e \leq 0.2$ eV to produce SF_6^- ions. The SF_6 gas pressure is varied in the range $0 \sim 1 \times 10^{-4}$ Torr, yielding $\varepsilon = 0 \sim 0.99$, density ratio of negative to positive ions. The negative ion temperature is estimated to be approximately 0.03 eV from SF_6 gas temperture. Under our condition, collision mean free paths of charged particles are longer than the plasma column length.

The evolutions of perturbations are measured by axially movable mesh probe (6-mm-diam, 200 mesh/inch) which is biased negatively to detect ion current. The current perturbations are detected through a resister to ground and the resulting voltage perturbations are displayed on a digital oscilloscope which is externally triggered by the signal generator.

3. Experimental Results and Discussions

Figure 2 shows the evolutions of ion density perturbations when the beam velocity is positively modulated by applying ramp voltage V_{ex} (= $V_b + V_m$) to the HP_D in case of no negative ions. Here, τ is 20 μsec, initial beam energy V_b is 4 V, and V_m is 0.5 V. Typical bunching position is defined by $l = v_1 v_2 \tau/(v_2 - v_1)$, where v_1 and v_2 are the velocities of ions before and after the modulation, respectively. When V_m = 0.5 V and V_b = 4 V, $l \simeq$ 23 cm, which is about the middle of the experimental region between the grid and HP_T. The perturbations excited grow gradually with propagating along the beam. Since the modulation amplitude of beam energy is small, the evolution of perturbation is interpreted by the linear wave theory as in Ref.[1]. On the other hand, when the modulation amplitude of beam energy is V_m = 5 V, a large amplitude density pulse is generated around a bunching position of $l \simeq$ 12 cm, accompanied by a steepening of the front slope as shown in Fig.3. Finally, a shock-like structure with positive density slope (positive shock) is formed and propagates with an almost constant velocity comparable to the average speed of ion beam, $v_0 = (v_1 + v_2)/2$.

Figure 4(a) shows the spatial evolutions of perturbation amplitude with modulation amplitude V_m as a parameter. The perturbation amplitude increases until a beam bunching position indicated by an arrow and

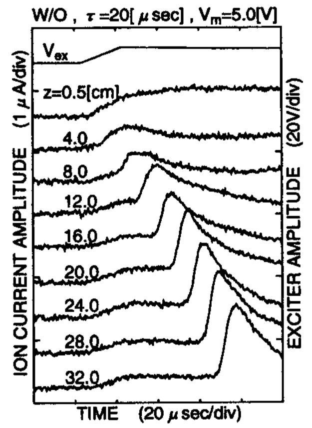

Fig. 3 Evolutions of perturbations when the beam energy is positively modulated in a plasma with no negative ions at V_m = 5.0 V.

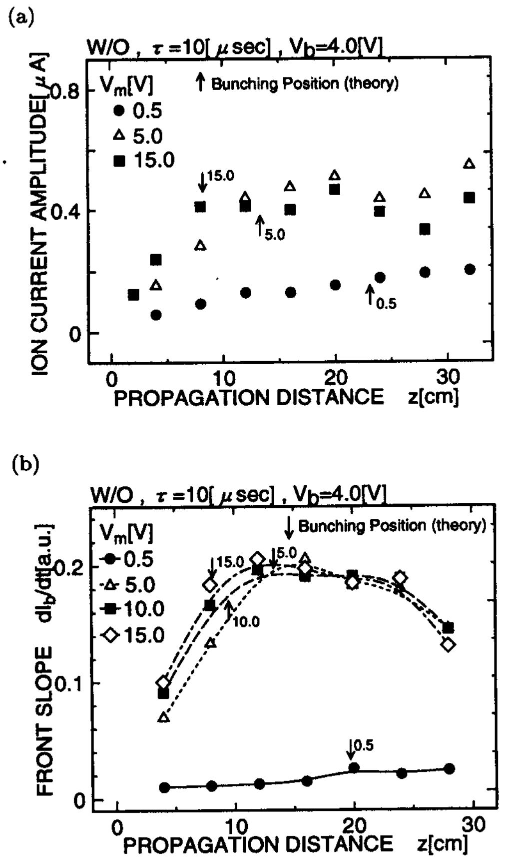

Fig. 4 Spatial variations of (a) saturation amplitude and (b) front slope with V_m as a parameter.

then the growth is saturated subsequently. It is found that the slope of the wave front also increases and is saturated around the bunching position as shown in

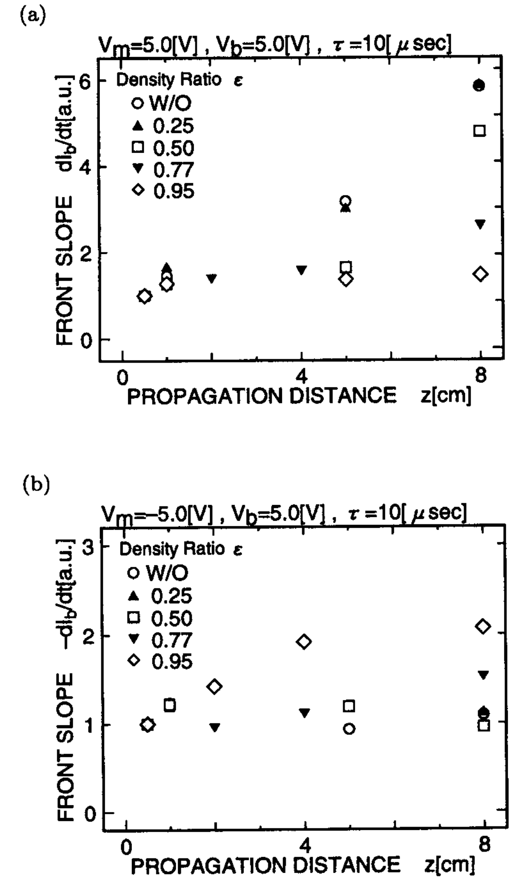

Fig. 5 Spatial variations of the front slope of the perturbations at (a) V_m = 5.0 V and (b) V_m = –5.0 V with ε as a parameter.

Fig.4(b). The saturation amplitude of the perturbations increases with V_m, but is not simply proportional to V_m.

The spatial evolutions of the slope of perturbations in the presence of negative ions are shown in Figs.5(a) and (b), where the beam velocity is positively and negatively modulated, respectively, with density ratio of negative to positive ions $\varepsilon \equiv n_-/n_+$ as a parameter. As ε increases, both saturation amplitudes for positive and negative modulations are decreased. But, in case of positive modulation, it is found that the front slopes for $\varepsilon = 0$ increase with the propagation. On the other hand, when $\varepsilon = 0.95$, the slope does not increase markedly. On the contrary, in case of negative modulation, the front slope steepens during the propagation when $\varepsilon = 0.95$, but no remerkable steepening is observed when $\varepsilon = 0$.

In our experiment the motion of negative ions SF_6^- is negligible because of the large mass compared with positive ions K^+. Therefore, negative ion density is almost undisturbed along the beam. Under this condition, the following model is presumed. When $V_m > 0$, compressive part with lower ε slows down in accordance with $C_s^* \simeq C_s/\sqrt{1-\varepsilon}$, then front slope decays. Reversely, when $V_m < 0$, rarefactive part with higher ε propagates faster, then front slope steepens. This effect is dominant when ε approaches 1.

4. Conclusions

Evolutions of perturbation excited by large amplitude velocity-modulation have been investigated in a negative ion plasma and shock-like structures are formed in a saturation state. The structure of the shocks depends on the density ratio ε of negative to positive ions. When ε is small, positive slope is steepening. On the other hand, when ε is large, negative slope is steepening. The method of velocity modulation is quite effective for generating positive and negative density perturbations in negative ion plasmas.

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