Ion Acoustic Shocks Formed in a Collisionless Plasma with Negative Ions

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Ion acoustic shocks are formed in a plasma with negative ions, where $T_e \geq T_+ \gg T_-$ (T_e, T_+, T_-: temperatures of electrons, positive ions, and negative ions, respectively). Depending on the ratio ε of negative to positive density, a steepening of positive or negative density jumps is observed. For $\varepsilon < \varepsilon_c$ ($\approx$0.65, critical value), positive density jumps evolve into compressive shocks. For $\varepsilon > \varepsilon_c$, however, negative density jumps evolve into rarefactive shocks. The ratio ε_c observed is well explained on the basis of Korteweg–de Vries equation. [S0031-9007(97)04802-3]

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There often appear new plasma phenomena in negative ion plasmas which include negative ions in addition to electrons and positive ions [1,2]. They are of crucial importance to be investigated in space plasmas and material-processing plasmas, both of which contain various kinds of negative ions, including dust particles charged up negatively in some cases. In fusion-oriented plasmas, an effect of negative ions has to be clarified in conjunction with negative ion beams used for plasma heating.

Most of the important negative ion effects on plasma phenomena are ascribed to a reduction of the electron shielding. This effect was well demonstrated for propagation and damping of linear ion acoustic waves in a collisionless negative ion plasma with SF_6^-, which was produced in single-ended *Q*-machine plasmas [2,3]. As well known theoretically [4], the ion Landau damping is so strong for ion acoustic waves in such an isothermal plasma as a *Q*-machine plasma of $T_e \approx T_+$ (T_e, T_+: electron and ion temperatures, respectively) that there is a big ballistic contribution to the wave propagation. Even in the single-ended *Q*-machine plasma of $T_e \geq T_+$ with ion flow in Ref. [2], the ion Landau damping is strong for ion acoustic waves, although the ballistic effect can be neglected [5]. In the presence of negative ions, however, T_e is replaced by $T_e/(1 - \varepsilon)$, yielding an increase in the phase velocity and, thus, a decrease in the Landau damping of ion acoustic waves, where ε is a density ratio of negative to positive ions. This is equivalent to the increase in T_e/T_+, which was performed by an electron heating via the electron cyclotron resonance [6] or an ion cooling via elastic ion collisions with neutral particles introduced [7] for formation of ion acoustic shocks in single-ended *Q*-machine plasmas. Negative ions provide a new branch of ion acoustic waves [negative ion acoustic (NIA) mode] in addition to the ion acoustic mode [positive ion acoustic (PIA) mode] mentioned above [1,2]. The relations $\Delta n_+ \propto \Delta n_e$ ($\approx e\Delta\phi/T_e$) and $-\Delta n_- \propto \Delta n_e$ ($\approx e\Delta\phi/T_e$) are satisfied for the PIA and NIA, respectively, among the perturbations associated with the wave propagations, where Δn_+, Δn_-, and Δn_e are the density perturbations of positive ions, negative ions, and electrons, respectively, $\Delta\phi$ is the potential perturbation, and $\Delta n_+ \approx \Delta n_- + \Delta n_e \approx \Delta n$ (plasma density perturbation). When the positive ion mass is smaller (larger) than the negative ion mass, the phase velocity of the PIA is larger (smaller) than that of the NIA. Then, the PIA and NIA are called fast (slow) and slow (fast) modes, respectively.

Here, we are interested in nonlinear propagation of ion acoustic waves in collisionless negative ion plasmas. In general, on the basis of the Korteweg–de Vries (KdV) equation, rarefactive solitons are predicted to be formed in addition to compressive solitons in the presence of negative ions [8]. Experiments on the KdV rarefactive solitons were carried out in Ar discharge plasmas of $T_e \gg T_+$, T_- (negative ion temperature), which include negative ions F^-, although ε was not definitely measured [9]. In this case, the negative ion mass (mass number: 19) is smaller than the positive ion mass (mass number: 40) and the soliton formation is concerned with the NIA (fast mode). Therefore, the solitons observed are "compressive" in the sense that they are associated with the compression of the negative ion density, although this compression is accompanied by the depression of the electron density for the NIA.

In our work here, a negative ion plasma with SF_6^- is produced by introducing a small amount of SF_6 gas into a collisionless plasma with K^+ ions and electrons in a single-ended Q machine. Thus, $T_e/T_+ \gg 1$ is not satisfied and the negative ion mass (mass number: 146) is much larger than the positive ion mass (mass number: 39). In the presence of negative ions, depending on ε, compressive and rarefactive ion acoustic shocks are demonstrated to be formed. Here, the shocks are concerned with the PIA and thus "compressive" and "rarefactive" correspond to the compression and depression of the positive ion density, which are accompanied by the compression and depression of the electron density, respectively. The critical density ratio observed between compressive and rarefactive shock formations is reasonably explained by an analysis based on the KdV equation.

In our plasma, negative ions can be assumed to be immobile for the PIA because the negative ion mass is much larger than the positive ion mass. For simplicity, we also assume $T_+ \approx 0$ in spite of $T_e/T_+ \geq 1$ because T_e is replaced by $T_e/(1-\varepsilon)$ in the presence of negative ions. Then, we can derive the KdV equation given by

$$\frac{\partial n_{(1)}}{\partial \tau} + A n_{(1)} \frac{\partial n_{(1)}}{\partial \xi} + \frac{1}{2} \frac{\partial^3 n_{(1)}}{\partial \xi^3} = 0, \quad (1)$$

where $n_{(1)} = \Delta n_{(1)}/n_0$ is the first order normalized positive ion density perturbation, τ and ξ are the dimensionless time and distance, respectively, and $A = (2-3\varepsilon)/2(1-\varepsilon)$. With an increase in ε, a sign of A changes from positive to negative at $\varepsilon\ (=\varepsilon_c) = \frac{2}{3}$, yielding compressive solitons for $\varepsilon < \frac{2}{3}$ and rarefactive solitons for $\varepsilon > \frac{2}{3}$. These solitons are converted into compressive and rarefactive shocks, respectively, in the presence of various kinds of dissipations [10], such as the Landau damping, particle reflection and trapping, particle collisions, and high- and low-frequency fluctuations. They are small but cannot be completely neglected in our work. Thus, it is reasonable that we use Eq. (1) to find the critical density ratio ε_c between positive and negative steepenings, i.e., compressive and rarefactive shock formations.

The experiment is carried out in a single-ended Q machine with a vacuum chamber, 20.8 cm in diameter and 167 cm long, with pumping systems at both ends. A potassium plasma is produced by contact ionization at a hot 52-mm-diam tungsten plate (HP) of 2300 K under an electron-rich condition and is confined by an axial magnetic field of 2 kG, as shown schematically in Fig. 1. The plasma is terminated by the end plate at a distance of 110 cm from the HP, which is kept at a floating potential. A background gas pressure is 2.0×10^{-6} Torr. Under our condition, the plasma density $n_0 = (1 \sim 2) \times 10^9\ \mathrm{cm}^{-3}$, the electron temperature $T_e \approx 0.2$ eV $\geq T_+$ (ion temperature), and the plasma flow speed $\approx (5-10)T_e$. In order to produce a negative ion plasma, a 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 P_{SF_6} is varied in the range $0-1.0 \times 10^{-4}$ Torr, yielding $\varepsilon = 0-0.99$. The negative ion temperature is estimated to be approximately 0.05 eV. Under our condition, collision mean free paths of charged particles are longer than the plasma column length. More details of negative ion plasma production in a single-ended Q machine and related works are found in Ref. [2].

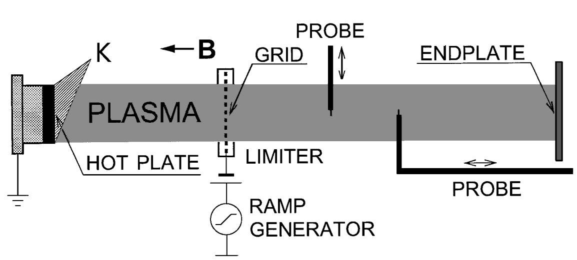

FIG. 1. Experimental setup.

In order to give a density perturbation to the plasma flow toward the end plate, a ramp voltage V_G is applied to a 60-mm-diam grid (0.02-mm-diam wire, 100 mesh/inch) at a distance of 33 cm from the HP, which is surrounded by a limiter with a hole of 50 mm in diameter. A small movable Langmuir is used to measure the plasma parameters and to detect propagating signals in the axial direction toward the end plate.

At first, linear propagation and damping of ion acoustic waves are measured as a function of ε for small density perturbations generated by applying small-amplitude sinusoidal voltages to the grid. Two branches of propagations, i.e., the fast (PIA) and slow (NIA) modes are observed in the presence of negative ions. A drastic modification of the PIA is observed when ε approaches unity because T_e is replaced by $T_e/(1-\varepsilon)$ in this mode, i.e., the phase velocity increases and the damping rate decreases with an increase in ε. The results obtained are consistent with the observations in Refs. [2,3], being in good agreement with the theoretical prediction. Measurements below are performed on the PIA generated by density jumps Δn in the range of finite amplitude, where the wave propagation depends on Δn.

Typical propagations of $\Delta n > 0$ and $\Delta n < 0$ are demonstrated in Fig. 2, where initial density jumps $|\Delta n/n_0| \approx 0.12$ are generated by applying the ramp voltages $V_G = \pm 0.4$ V (uppermost traces) to the grid at $z = 0$ cm and the positive ion density ($\approx$plasma density) perturbations are measured in the z direction toward the end plate. At $\varepsilon = 0$ ($P_{SF_6} = 0$ Torr), we have a usual

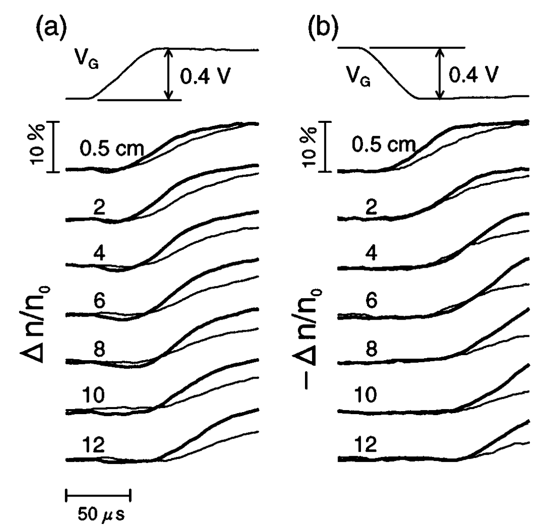

FIG. 2. Propagations of (a) positive density jumps at $\varepsilon = 0$ (thin lines) and 0.3 (thick lines) and (b) negative density jumps at $\varepsilon = 0$ (thin lines) and 0.9 (thick lines), generated by positive and negative ramp voltages (uppermost traces) applied to the grid, respectively.

single-ended Q-machine plasma in which the propagation fronts of both density jumps (thin lines) become broad gradually in the z direction. In the presence of negative ions, however, the front shapes (thick lines) depend on ε. For $\Delta n > 0$, there occurs a clear front steepening at $\varepsilon \approx 0.3$ ($P_{SF_6} \approx 2.3 \times 10^{-6}$ Torr), which is found in Fig. 2(a). On the other hand, for $\Delta n < 0$, there occurs a clear steepening at $\varepsilon \approx 0.9$ ($P_{SF_6} \approx 3.0 \times 10^{-5}$ Torr), as found in Fig. 2(b).

Spatial front variations are presented at $\varepsilon \approx 0.3$, 0.6, and 0.9 for $\Delta n > 0$ and $\Delta n < 0$ in Fig. 3. For $\Delta n > 0$, the steepening observed clearly at $\varepsilon \approx 0.3$ is found to disappear at $\varepsilon \approx 0.9$. On the other hand, for $\Delta n < 0$, the steepening is not recognized at $\varepsilon \approx 0.3$, while there appears the clear steepening at $\varepsilon \approx 0.9$. Either of the density jumps at $\varepsilon \approx 0.6$ has almost the same front shape, being accompanied by only a slight change of the slope, in the z direction.

To evaluate the steepening observed, we define a spatial slope $\Delta n/\Delta z$ for the density jump as illustrated in Fig. 4(a), i.e.,

$$\frac{\Delta n}{\Delta z} = \frac{\Delta n}{\Delta t} \times \frac{\Delta t}{\Delta z} = \frac{\Delta n}{\Delta t} \times \frac{1}{v_s}, \tag{2}$$

where Δt is a rise time of the density jump Δn, and v_s ($=\Delta z/\Delta t$) is a propagation speed of Δn. These definitions are useful for estimating spatial variations of normalized slopes $\alpha = (\Delta n/\Delta z)/(\Delta n/\Delta z)_{z=5\,\mathrm{mm}}$ of $\Delta n > 0$ and $\Delta n < 0$, which are shown at $\varepsilon = 0.3$, 0.6, and 0.9 in Figs. 4(b) and 4(c), respectively. The steepening can be found at $\varepsilon = 0.3$ and 0.6 for $\Delta n > 0$ and at $\varepsilon = 0.9$ for $\Delta n < 0$. In either case, we can observe this steepening in the spatial region up to a distance of 4–6 cm from the grid. For both $\Delta n > 0$ and $\Delta n < 0$, the steepening is found to be followed by a gradual decrease in the slope at $z \geq 4$–6 cm along the propagation. This is due to the ion Landau damping which becomes small with an increase in ε, but cannot be neglected in our experiment. The Landau damping is responsible for not only the formation but also the destruction of shock waves.

Dependences of the steepening on $|\Delta n/n_0|$ at $\varepsilon \approx 0.3$ and 0.9 for $\Delta n > 0$ and $\Delta n < 0$, respectively, show the

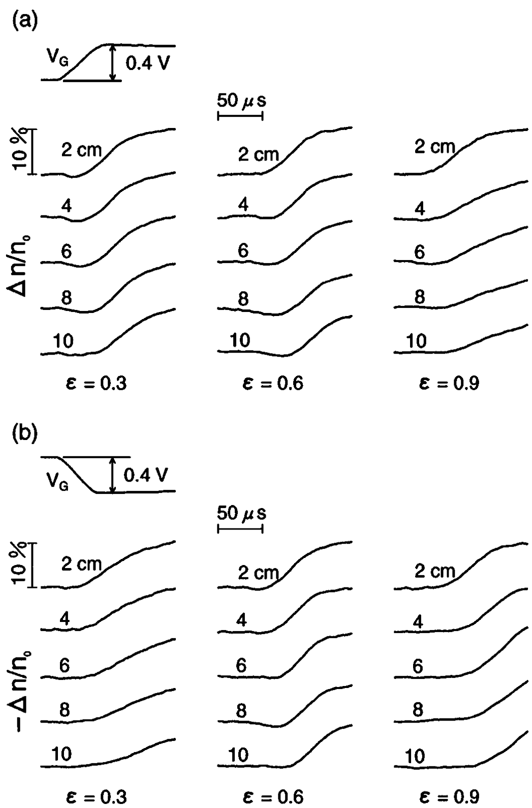

FIG. 3. Propagations of (a) positive and (b) negative density jumps generated by positive and negative ramp voltages (uppermost traces) applied to the grid, respectively, at $\varepsilon = 0.3$, 0.6, and 0.9.

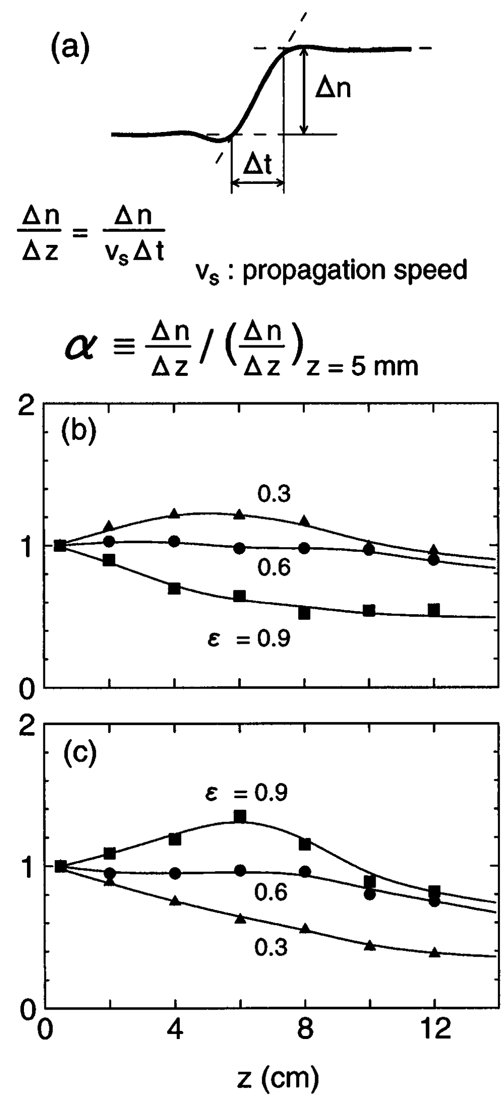

FIG. 4. Spatial variations of the normalized slopes α of (b) positive and (c) negative density jumps with ε as a parameter, which are defined as shown in (a), under the same conditions as in Figs. 2 and 3.

steepening at $|\Delta n/n_0| \geq 0.03$, which is remarkable at $|\Delta n/n_0| \geq 0.1$ for both jumps. The steepening is found to be stronger for $\Delta n < 0$ than for $\Delta n > 0$. Since the negative density jump steepens at larger values of ε, $T_e/(1 - \varepsilon)$ is larger in the case of the negative steepening than in the case of the positive steepening. This might be the reason for the stronger steepening of $\Delta n < 0$. With an increase in $|\Delta n/n_0|$, the propagation speeds increase while the jump widths decrease for both density jumps, as in the case of ordinary shock waves.

In order to find a critical value of ε for the steepening of $\Delta n > 0$ and $\Delta n < 0$, $d\alpha/dz$ is plotted as a function of ε for $\Delta n > 0$ and $\Delta n < 0$ in Fig. 5. Here, $d\alpha/dz$ is measured around $z = 2$ cm, where a clear steepening is observed. For $\Delta n > 0$, $d\alpha/dz$ decreases monotonously with an increase in ε (≥ 0.3). For $\Delta n < 0$, however, this value increases monotonously with an increase in ε. Both curves cross the abscissa at $\varepsilon \approx 0.65$, yielding a criteria ε_c for the steepening of $\Delta n > 0$ and $\Delta n < 0$. Around ε_c, we find almost the same front shapes of both density jumps in the z direction, as mentioned before, which are expected for shocks evolved from the modified KdV solitons [11,12].

Under our assumptions, Eq. (1) includes no effect of the Landau damping, yielding the steepening of $\Delta n > 0$ even for $\varepsilon = 0$. In the experiment, however, the Landau damping is not negligible especially for $\varepsilon \approx 0$ and the steepening of $\Delta n > 0$ is observed for $0.3 \leq \varepsilon$ (<0.65). The critical value $\varepsilon_c \approx 0.65$ observed for the steepening of $\Delta n > 0$ and $\Delta n < 0$ is in a reasonable agreement with the value $\varepsilon_c \approx \frac{2}{3}$ estimated from an analysis based on the KdV equation.

In conclusion, the positive and negative density jumps have been demonstrated to evolve into compressive and rarefactive ion acoustic shocks, respectively, depending on the density ratio of negative to positive ions, in a collisionless negative ion plasma of $T_e \geq T_+ \gg T_-$. In this work, the negative ion mass is much larger than the positive ion mass and the shock formation is concerned with the positive ion acoustic mode. There is the critical density ratio for the steepening of the positive and negative density jumps, which is well explained by the analysis based on the KdV equation. Our experiment has verified that compressive and rarefactive ion acoustic shocks are formed in a collisionless plasma, even when $T_e/T_+ \gg 1$ is not satisfied, in the presence of negative ions. The results can be applied to the formation of ion acoustic shocks in so-called "dusty plasmas" including large dust particles charged up negatively.

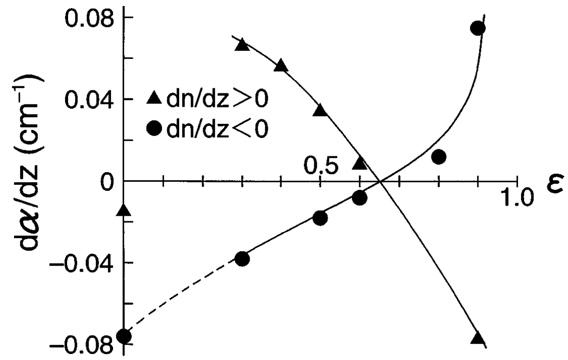

FIG. 5. Dependences of $d\alpha/dz$ of (▲) positive and (●) negative density jumps on ε around $z = 2$ cm under the same conditions as in Figs. 2–4.

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