J. Plasma Physics (1997), *vol.* 58, *part* 4, *pp.* 623–631. Printed in the United Kingdom
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Propagation of a large-amplitude rarefactive ion acoustic pulse

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(Received 15 May 1996 and in revised form 22 August 1996)

In an experiment carried out in a linear, unmagnetized plasma, evolution and propagation of nonlinear, rarefactive ion–acoustic pulses have been investigated. The nonlinear rarefactive pulse is observed to undergo fissioning as it propagates. Measurements of the ion velocity distribution function within the pulse indicate strong modifications of the distribution functions at velocities in the neighbourhood of the ion acoustic speed. Wave–particle interaction is thus shown to play an important role in the observed behaviour. Large-amplitude rarefactive pulses, while showing multiple fissioning, also exhibit a large-amplitude, low-frequency ($\approx$ 30 kHz) oscillatory tail, downstream of the main pulse. The oscillatory tail is unlike the expected Airy function that normally accompanies a weakly nonlinear rarefactive pulse. The observations suggest the existence of ion-hole-like structures on the downstream side. The mechanism of the excitation seems to be through modification of the ion phase space due to trapping of ions in the negative potential well of the rarefactive pulse.

1. Introduction

Weakly nonlinear ion acoustic waves are described by the KdV equation. The KdV equation admits soliton-type of solutions. Because of their interesting characteristics, these solitons have been studied experimentally by several authors (see Ikezi *et al.* 1975; Lonngren *et al.* 1982, and references therein). The experimental results on ion acoustic solitons and the related theory have been reviewed by Ikezi (1978), Tran (1979), Nakamura (1979) and Lonngren (1983). A compressive perturbation is known to evolve into a soliton owing to the balance between the nonlinear steepening and dispersion effects. However, in a purely two-component plasma, rarefactive pulses do not evolve into solitons. The KdV equation predicts, however, that an initial depletion in density will evolve into a wave train. This analytical deduction has been confirmed by the numerical and experimental results of Okutsu and Nakamura (1979). In an experiment by Saxena *et al.* (1981), a rarefactive pulse of large (10%) amplitude evolved into the predicted wave train, but the leading rarefactive pulse was observed to fission as it propagated away from the launcher; this behaviour could not be explained on the basis of the KdV equation. In order to understand the propagation characteristics of highly nonlinear rarefactive ion acoustic waves, it seems important to invoke wave–particle interaction, since

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https://doi.org/10.1017/S0022377897005965 Published online by Cambridge University Press

particle trapping by the fields plays a very significant role in the propagation of such perturbations.

Numerical as well as theoretical investigations of two-stream instabilities (Roberts and Berk 1967; Kako *et al.* 1971) predicted that these instabilities evolve into a train of vortex–like structures in the electron phase space. Experiments in a highly magnetized system by Saeki *et al.* (1970) confirmed these predictions. The electron phase-space vortices appear as stable BGK equilibria (Bernstein *et al.* 1957). It has been suggested by Dupree (1982) that these could play an important role in the description of strong Langmuir turbulence. In all these theoretical investigations, the ions were treated as an immobile charge-neutralizing background. The development of corresponding configurations in the ion phase space were studied numerically by Sakanaka (1972). A numerical integration of the ion Vlasov equation was carried out assuming the electrons to be Boltzmann-distributed, as exemplified by the ion two-stream region behind electrostatic ion shocks. A unified theoretical treatment of both ion and electron phase-space vortices was presented by Bujarbarua and Schamel (1981). Pécseli *et al.* (1984) have reported the first experimental observation of a stable phase-space vortex in the ion two-stream region behind electrostatic ion acoustic shocks. These observations have been supported by numerical simulations based on the stationary solution of the ion Vlasov equation using a water-bag distribution model (Sato and Okuda 1980; Pécseli *et al.* 1984). The observation of an ion hole was also reported by Tsikis *et al.* (1985) in a double-plasma machine.

Large-amplitude rarefactive perturbations are associated with large negative potential structures, and hence the ions approaching this potential well will just slip into it. This may lead to trapping of ions in the potential well and modification in the well by dispersion and nonlinearity, leading to detrapping of the particles. Furthermore, under appropriate conditions, the trapping may lead to a depletion in ion density and a hole in ion phase space. Thus wave–particle interactions can be expected to play a crucial role in these perturbations.

This paper reports observations on launching and evolution of large-amplitude rarefactive ion acoustic waves in a linear unmagnetized plasma. Observations of the ion velocity distribution associated with these large-amplitude waves are also presented. Particle trapping and modification of the distribution function in the presence of a rarefactive pulse is observed. There are indications of phase-space vortex formation both in the main pulse and in the structures on the trailing edge of the wave.

2. Experimental set–up

The experiments were carried out in a linear, unmagnetized, uniform, plasma 50 cm in diameter and 120 cm long (Fig. 1). The chamber was pumped to a base pressure of 10^{-5} Torr and operated at neutral argon pressure of 10^{-4} Torr. The average plasma density obtained is $5\times10^{8}\,\mathrm{cm}^{-3}$, $T_e \approx 4.0\,\mathrm{eV}$, $T_i \approx 0.2\,\mathrm{eV}$ and $C_s \approx 3.0\times10^{5}\,\mathrm{cm\,s}^{-1}$. Waves were launched using a square pulse of rise time $\approx \omega_{pi}^{-1} \approx 1\,\mu\mathrm{s}$, applied to a circular grid of diameter 20.0 cm, with a repetition rate of 1 kHz. The rise time of the applied pulse was of the order of the inverse of the ion plasma frequency. The launcher pulse was superimposed on the floating potential of the launcher to ensure minimal plasma disturbance by the launcher between the pulses. The repetition rate

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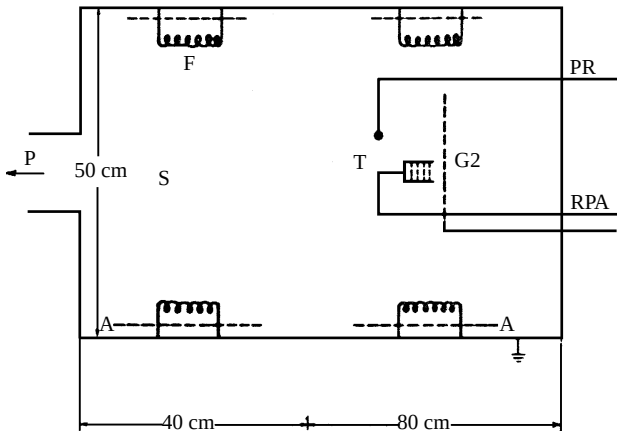


Figure 1. Schematic of the experimental device used.

of 1 kHz was chosen so that the effects of successive pulses do not interfere with each other.

The fluctuations in the electron saturation current to a circular disc-shaped cold Langmuir probe of diameter 1.0 cm were recorded to study the signal propagation in the plasma. The signals were averaged with a boxcar integrator to improve upon the signal-to-noise ratio. The ion distributions with and without the wave were measured using a three-grid retarding potential-energy analyser. The retarding potential analyser (RPA) used in this experiment was similar to one described by Ikezi and Taylor (1970). The first grid of the RPA, i.e. the entrance grid was left floating so that it reduced the flux of electrons in the interior of the RPA and simultaneously retained the Maxwellian nature of the ion distribution function inside (Emmert 1980). The spacing between the grids was kept within tens of Debye lengths.

The output of the RPA was also averaged using the boxcar integrator and digitized. The collector current $I(\phi)$ can be written as a function of the applied bias on the selector grid as

$$I(\phi) = \int_{\phi_1}^{\infty} Aevf(x, v, t)dv,$$

apart from a geometrical transparency factor. dI/dV would then be a measure of $f(x, v, t)$.

3. Results and discussion

In the experiment, application of negative pulses of different amplitudes to the grid, resulted in launching of waveforms of the type shown in Figs 2–4. The characteristic features of these waveforms were a large negative (rarefactive pulse) close to the launching grid followed by an oscillatory wave train at the trailing edge of the rarefactive pulse. We first discuss the features of the rarefactive pulse.

The rarefactive pulse of initial amplitude $\delta n/n \approx 6\%$ (Fig. 2) started out as a symmetric pulse of width $\approx 5.0\lambda_D$ close to the launcher. The pulse broadened owing to dispersion, and damped as it moved away from the launcher. The velocities of these pulses were found to be close to $2.94 \times 10^5\,\mathrm{cm\,s^{-1}}$. This is slightly smaller than the acoustic speed. The pulses with amplitude 6% also behaved in a similar

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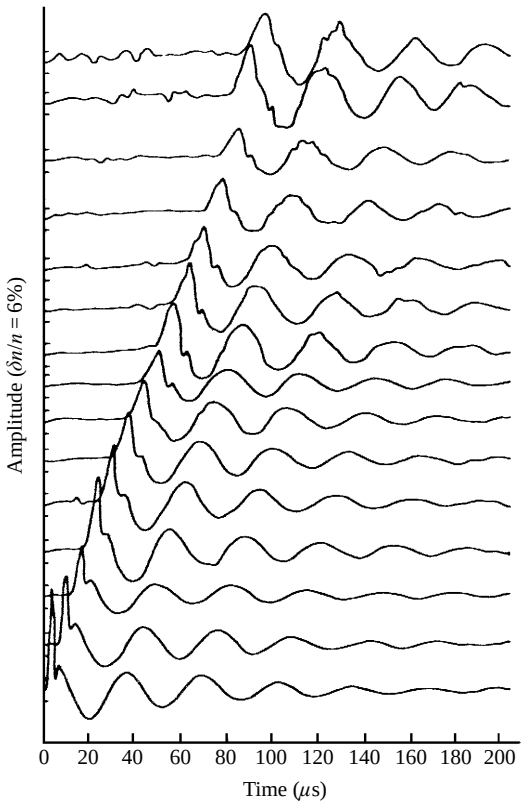


Figure 2. Examples of rarefactive-pulse propagation in a plasma for initial pertubations $\delta n/n \approx 6.0\%$. The successive traces are time records taken at different axial positions seperated by $14.0\lambda_D$. The quantity plotted in these figures is the electron saturation current, and the signal in this particular set is inverted. So a depletion in current in these curves is actually an increase in density. The vertical scale is 1.3%/div. for traces 1–3, 0.66%/div. for traces 4–8, 33%/div. for traces 9 and 10, 0.35%/div. for traces 11–13, and 0.18%/div. for traces 14 and 15.

fashion. But the pulses of $\delta n/n \approx 7.0\%$ (Fig. 3) showed some additional features. These pulses started out as symmetric pulses very close to the launcher, and were dispersed and damped as they moved away. The leading edge of the pulses became sharper than the trailing edges. The propagation of pulses of initial amplitude $\approx 9\%$ is shown in Fig. 4, where different traces give the time history at different distances from the grid. At a distance of about $(25\text{–}30)\lambda_D$, the pulses start to become asymmetric. Beyond this, each pulse splits into two pulses separated by a local maximum (trace 2 in Fig. 3). After splitting, the pulses moved at different speeds, one moving at a speed slightly lower than the acoustic speed. Further propagation beyond $(55\text{–}60)\lambda_D$ led to a further split into three pulses. Higher-initial-amplitude pulses split into even more pulses. Figure 5 shows the distance versus time of arrival of the main pulse and the pulses after splitting. For the pulse with initial $\delta n/n \approx 9.0\%$, one of the troughs was found to be moving with a speed $\approx 0.9C_s$ and the other at $\approx 1.2C_s$.

In an experiment by Saxena *et al.* (1981), a rarefactive pulse was found to fission into several pulses, which moved at different speeds. However, in this case, the

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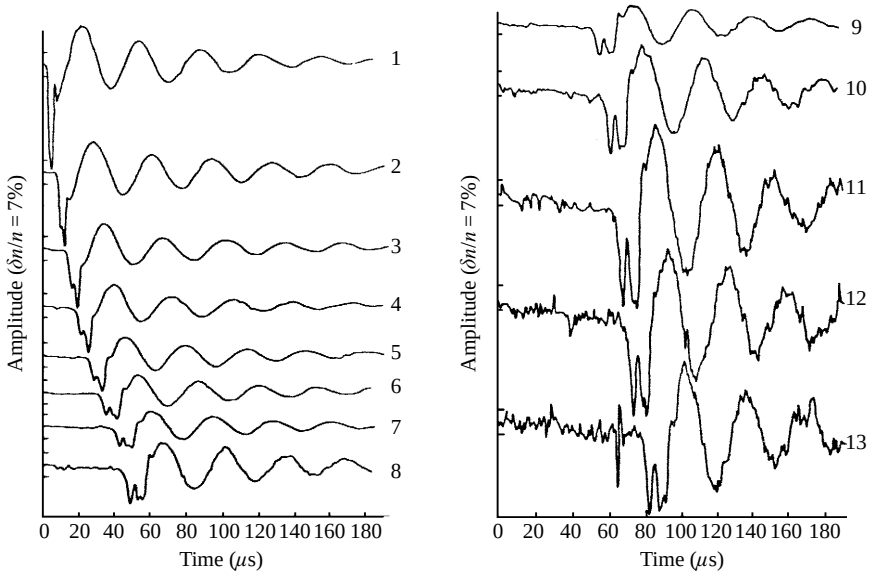


Figure 3. Example of rarefactive-pulse propagation in a plasma for initial pertubations $\delta n/n \approx 7.0\%$. The successive traces are again taken at different axial positions separated by $14\lambda_D$. The vertical scale is 1.5%/div. for traces 1 and 2, 1.62%/div. for traces 3 and 4, 1.7%/div. for traces 5–7, 0.84%/div. for traces 8 and 9, 0.34%/div. for trace 10, and 0.17%/div. for traces 11–13.

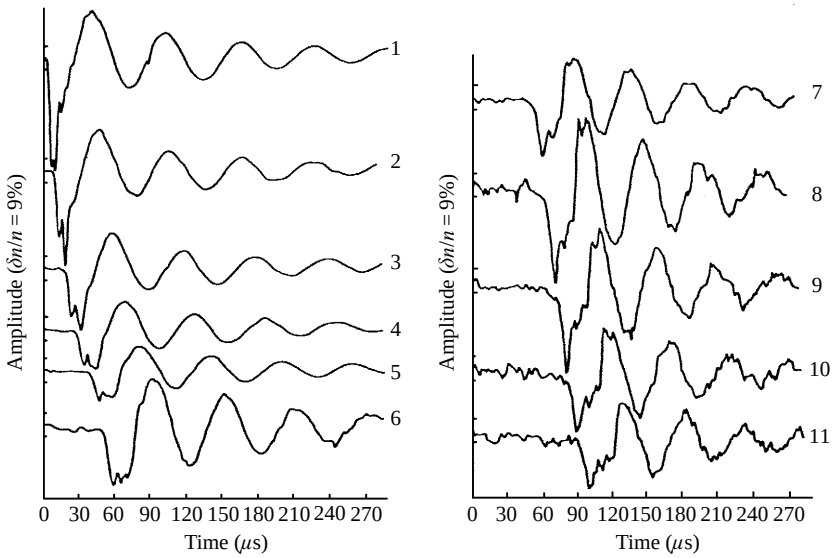


Figure 4. Example of rarefactive-pulse propagation in a plasma for initial pertubations $\delta n/n \approx 9.0\%$. The successive traces are again time records at different axial positions separated by $14\lambda_D$. The vertical scale is 1.5%/div. for traces 1–6, 0.64%/div. for traces 7 and 8, and 0.34%/div. for traces 9–11.

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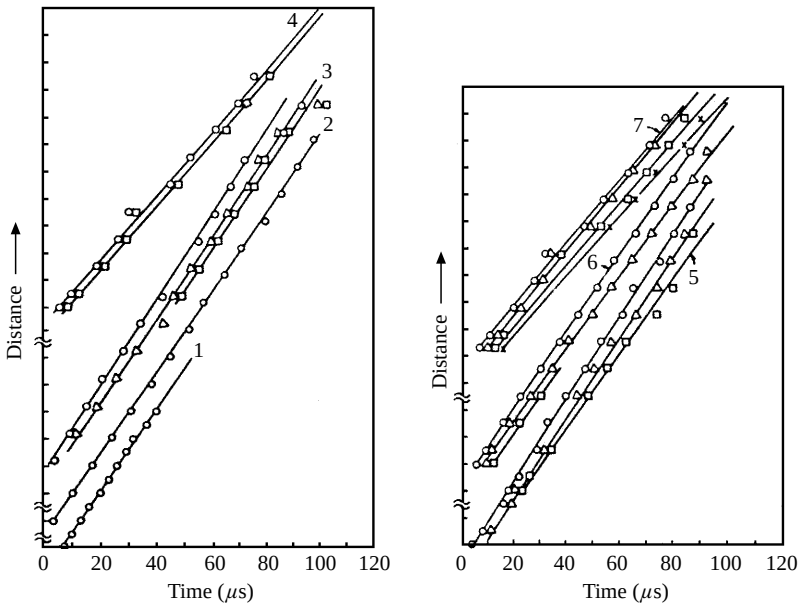


Figure 5. Time-of-flight measurements for different peaks in the main pulse: (1) initial $\delta n/n \approx 1.3\%$; (2) 6%; (3) 7%; (4) 9% (5) 10.5%. The launcher grid is at the origin. Fissioning was observed for amplitudes 7.0% and higher. Different curves in each set correspond to the different peaks after fissioning, moving at different speeds.

launcher pulse was a sine wave with time period longer than the ion plasma time period. The observations are also very different. In that case, as the pulse moved away from the grid the trailing edge of the pulse became steeper than the leading edge, whereas in our case it is the leading edge that is steeper. Also, in the experiment by Saxena *et al.*, the fissioning occurred at a distance of about (65–70)λ_D, whereas in the present experiment it occurred very close to the launcher, $\approx 25\lambda_D$. The important difference in the two experiments is the rise time of the pulse launched. In the case of Saxena *et al.*, the pulse was a slow pulse, $< \omega_{pi}^{-1}$, whereas our pulse has a rise time $\approx \omega_{pi}^{-1}$ as mentioned earlier. Therefore there is a possibility of a resonance phenomenon with ions.

The splitting of the initial pulses into more than one pulse cannot be understood on the basis of fluid theory. These are phenomena occurring at large amplitude of refractive pulses, having a negative potential structure, giving rise to the possibility of trapping of ions moving with speeds closer to C_s. In the actual experiment this interaction is possible, since the measurements show ion energies of 0.8 eV or so. This would lead to wave–particle interaction, modifying the particle distribution function, and the splitting could be a result of trapping and detrapping of the ions as the pulse propagates. These effects could lead to strong modifications of the ion velocity distribution functions for ions associated with the rarefactive pulse. In order to investigate this, the ion energy distribution was measured at a fixed location and various times of incidence of the rarefactive pulse with different amplitudes, marked in Fig. 6(*a*).

In order to do this, the boxcar integrator was used in a fixed-delay mode; this means that the boxcar gets a trigger pulse each time after a preset delay with respect to the pulse applied on the launcher. Since the experiment is repetitive,

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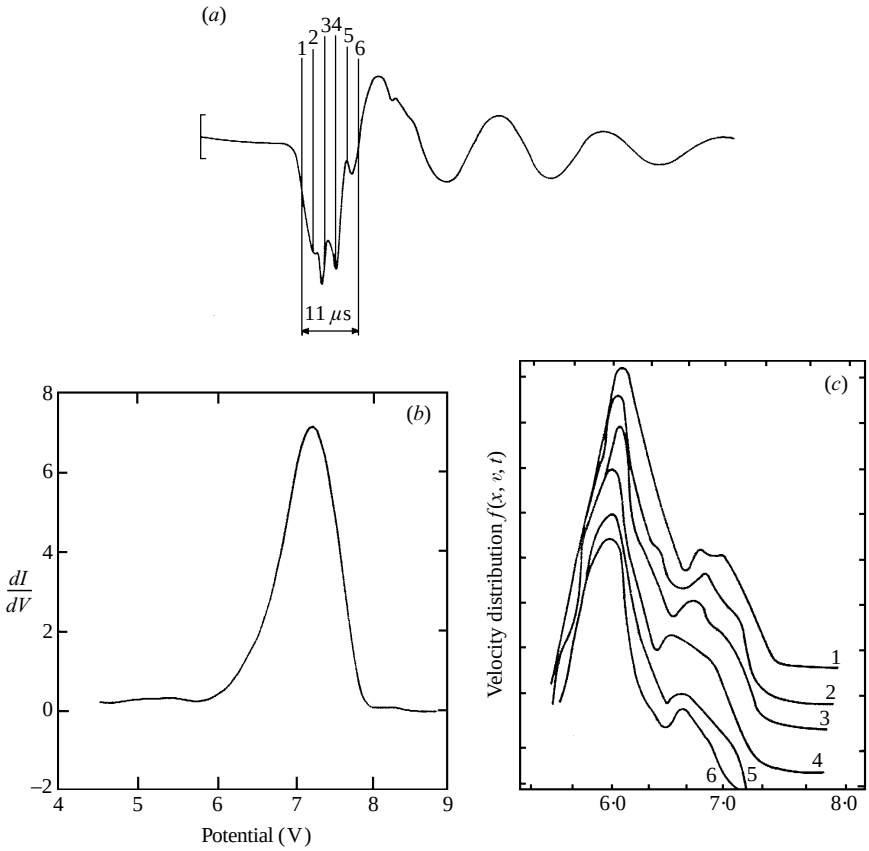


Figure 6. The RPA characteristic curves taken at positions marked at 1,2,3, . . . in the curve in (*a*), with respect to the applied bias on the selector grid. (*b*) Unperturbed distribution function in the absence of the wave. The full width at half-maximum is taken as the ion temperature in the plasma. The curve is smoothed using a 10-point moving average, and hence is slightly wider than the actual temperature, seen on a semi-log plot. (*c*) The figure clearly shows modification of the ion distribution function by the wave.

each trigger pulse triggers the boxcar at the preset delay to collect points on the signal coming from the collector of the RPA. Thus the boxcar output is a time average of the collector output. The ion energy selector grid was swept at a very slow rate of about 1 s, so that the boxcar output corresponded to the full I–V curve of the RPA at a fixed delay in the presence of the wave. By changing this delay, a few measurements were obtained, corresponding to different times of the wave being present at the location. The derivative of the collector current of the RPA was digitized and stored on a computer, and is shown in Fig. 6(*a*). In Fig. 6(*b*) we have shown a typical unperturbed ion distribution function at an instant earlier than the arrival of the pulse. Within the resolution of the RPA, one observes a very strong modification of the velocity distribution functions within the rarefactive pulse (Fig. 6*c*), in contrast with a smooth distribution function in the unperturbed region (Fig. 6*b*).

In a numerical study of a one–dimensional collisionless ion acoustic shock generated by injection of a plasma beam, Sakanaka (1972) reported the formation of

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a shock and phase-space vortices, for certain values of beam velocities. He argued that the initial discontinuity in the density gives rise to a peaked positive electric field. This field accelerates ions locally, resulting in an accumulation of ion density in front of the electric field and a depletion at the back of it. This depletion creates a negative electric field, which decelerates the ions. Phase-space vortices were observed as depletions in the ion density. These vortices were found to be moving with almost constant speed. The ion velocity distribution functions were seen to be modified as a result of vortex formation. The modifications seen in the numerical calculation by Sakanaka (1972) are very similar to the modifications of the distribution functions observed in our experiment. The measurement of the ion distribution energy showed strong modification near the phase velocity of the waves. This implies the formation of phase-space holes due to trapping of ions in the potential of the wave. These measurements are also similar to results of Pécseli *et al.* (1984) in a double-plasma device obtained for a shock wave formed by two-beam interaction.

In Figs 3 and 4 the first pulse is the main pulse of the rarefactive wave. This pulse is a negative potential structure, and its trailing edge resembles a shock-like structure. It was found that, along with this symmetric pulse, low-frequency oscillations ($\approx 30\,\mathrm{kHz} \ll f_{pi}$) appear on the trailing edge. Once formed, these oscillatory structures on the trailing edge travel in the system to the end of the device, without any appreciable change in the width. These oscillations damp as they move away from the launcher, the damping being similar to that for the main pulse.

The characteristics of these oscillations do not agree with the usual Airy-function type of response as reported by Ikezi *et al.* (1973). The Airy-function response seen by Ikezi *et al.* (1973) was observed at a frequency closer to the ion plasma frequency, which is 300 kHz for the parameters of the present experiment. In that experiment it was demonstrated that the period of the Airy type of oscillations increases with propagation distance as $x^{1/3}$. However, in our experiments the frequency of oscillations is much smaller than the ion plasma frequency and the periodicity does not change with the distance. The absence of an Airy-function response is also in close agreement with the numerical calculation of Sakanaka (1972). In his case also, Airy-function type oscillations were not observed.

The oscillations in the trailing edge and its propagation also indicate the formation of trapped particles in the phase space. The launched perturbation is at the time scale $\approx \omega_{pi}^{-1}$. The initial discontinuity in the density during the impulse leads to the formation of a sharply peaked electric field. The electric field would accelerate ions from this region and create a local depletion of ions. This situation is similar to that in numerical calculation by Sakanaka (1972) for two-beam instability. In his case the electric field generated by the initial discontinuity in density evolved into a shock followed by a hole in the ion phase space. These holes appeared as regions of density depletions in front of the shock very similar to the oscillations in the trailing edge in our case. In the above-mentioned numerical calculation, stable holes with width $\approx 100\lambda_D$ were observed. Widths observed in present experiments are $\approx 200\lambda_D$.

Hasegawa and Sato (1982) showed that a negative potential structure in the presence of a current in the plasma grows and evolves into a double layer. The formation of a double layer is facilitated by reflection of electrons from the wave potential. This impedes the current and leaves behind an ion-rich region. In the absence of this current the region remains depleted of ions, and a hole is formed

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in the phase space. The measurement of $f(v)$ in the main pulse in our experiment shows a modification of the ion distribution and strongly suggests the formation of a hole in the ion phase space. This hole is asymmetric, with shoulders of unequal amplitude. Stable holes with width $\approx 200\lambda_D$ are also observed at the trailing edges of the pertubations. The behaviour of these holes is similar to that predicted by calculations of Sakanaka (1972).

4. Conclusions

The propagation characteristics of rarefactive ion acoustic waves have been investigated in a linear unmagnetized plasma. The smaller-amplitude pulses behave in accordance with the predictions of the KdV equation. The waves with amplitude $\approx 1.2\%$ and more show several new features. The ion energy distribution is strongly modified in the presence of these pulses, and hence suggests the presence of strong wave-particle effects. These pulses were found to be moving with speed slightly smaller than the ion acoustic speed, and also the measurement of the ion energy distribution shows the presence of ions with higher energies $\approx 0.4\,\text{eV}$. The possibility of such an interaction exists.

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