Ion-acoustic waves in a plasma with negative ions

B. Song, N. D'Angelo, and R. L. Merlino
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242-1479

(Received 14 May 1990; accepted 8 October 1990)

Propagation and damping of ion-acoustic waves have been investigated in a Q-machine plasma consisting of K^+ positive ions, SF_6^- negative ions, and electrons. The phase velocity of the ion-acoustic "fast" mode increases with increasing ϵ, the concentration of negative ions. The wave damping decreases with increasing ϵ, and nearly disappears, for the highest wave frequencies investigated, when $\epsilon \gtrsim 0.9$. Both results are in agreement with predictions from Vlasov theory.

I. INTRODUCTION

Laboratory plasmas with appreciable fractions of negative ions have been available for a number of years. For instance, von Goeler *et al.*[1] directed a beam of CsCl onto the hot tungsten plate of a Q machine, thus forming a plasma consisting of Cs^+, Cl^-, and electrons. Wong *et al.*[2] introduced SF_6 gas into an argon discharge. Electron attachment to SF_6 molecules produced a plasma with SF_6^- negative ions. Sheehan and Rynn[3] conducted a very detailed investigation of negative-ion plasma sources, one of their methods consisting of the introduction of SF_6 gas into a standard Q-machine plasma. Since SF_6 has a large electron capture cross section for low-energy (~ 0.2 eV) electrons, this method is particularly effective in producing SF_6^- negative ions, even at partial pressures of the $SF_6 \lesssim 1 \times 10^{-5}$ Torr. We have employed this same method in the Iowa Q machine (IQ1), to produce an alkali plasma with an appreciable fraction of negative ions. A paper by Song *et al.*[4] provides a detailed description of the plasma source, as well as of the methods used to determine the negative-ion concentrations. Experimental studies of waves in negative-ion plasmas have been reported by Wong *et al.*[2] for ion-acoustic waves, and by Song *et al.*[4] for electrostatic ion-cyclotron (EIC) waves. Theoretical investigations were conducted by D'Angelo *et al.*,[5] D'Angelo,[6] and Galvez and Gary[7] for ion-acoustic waves, and by D'Angelo and Merlino[8] or EIC waves.

In the present paper we report on our experimental investigation of ion-acoustic waves in a Q-machine plasma, consisting of K^+ positive ions, SF_6^- negative ions, and electrons. The "fast" mode predicted in Ref. 5 was first observed by Wong *et al.*[2] in a discharge plasma. We thought it worthwhile to conduct our investigation in a different type of negative-ion plasma source, particularly in view of the fact that the very small damping rate predicted in Ref. 5 for the "fast" wave mode, at large negative-ion concentrations, was not borne out by the results of Wong *et al.*[2] [see their Fig. 4(b)]. Our present results confirm the observation by Wong *et al.*[2] and the prediction of Ref. 5 of a large increase of the "fast" mode phase velocity as the negative-ion concentration ϵ increases beyond ~ 0.7. In addition, they also demonstrate that, as predicted in Ref. 5, the "fast" mode has a negligible damping at large ϵ.

In Sec. II of the paper we present a description of the experimental methods and results and the comparison of the results with the theoretical predictions.[5] Section III contains the conclusions.

II. EXPERIMENTAL METHODS AND RESULTS

The experiments were performed in the Iowa single-ended Q machine (IQ1), described, e.g., in Ref. 4. A potassium plasma column ~ 1 m long and confined radially by a magnetic field of up to ~ 5 kG, is produced by surface ionization of potassium neutral atoms on a hot (~ 2300 K) tantalum plate. At the opposite end the plasma column is terminated by an electrically floating steel endplate. Typical plasma parameters are an electron density $n \approx 10^9$–10^{10} cm^{-3}, electron and ion temperatures $T_e \approx T_{K^+} \simeq 0.2$ eV, and a base pressure in the vacuum vessel of $\sim 1 \times 10^{-6}$ Torr. SF_6 gas in variable amounts can be introduced into the vessel by means of a leak valve, the SF_6 partial pressure generally being varied in the range 0–1×10^{-5} Torr. At each SF_6 pressure, the percentage concentration of negative ions,

$$\epsilon = n_{SF_6^-}/n_{K^+},$$

was determined by the same method used in Ref. 4 and, previously, by Wong *et al.*[2] As SF_6 gas is introduced into the device and more and more electrons attach to SF_6 molecules, the negative saturation current to a Langmuir probe, $I_{-,s}$, decreases, since the mobility of the negative ions is well below that of the electrons. It is easily seen that

$$\epsilon = 1 - I_{-,s}/I^0_{-,s},$$

where $I^0_{-,s}$ is the value of $I_{-,s}$ when the SF_6 pressure is zero.

As shown in Ref. 4, an additional, more direct observation of the presence of negative ions is provided by the mass spectrometer described by Suszcynsky *et al.*[9]

Ion-acoustic waves are launched by the same grid method used, e.g., by Wong *et al.*[10] A grid consisting of wires 0.1 mm in diameter and 0.8 mm separation, is immersed in the plasma column ~ 40 cm from the tantalum hot plate and is oriented normal to the magnetic field. The grid is typically biased at -5 V, with a ~ 2 V peak-to-peak ac signal of variable frequency being superimposed on the dc bias. An ion-acoustic wave is thus launched, which can be detected downstream by a similar grid, biased at

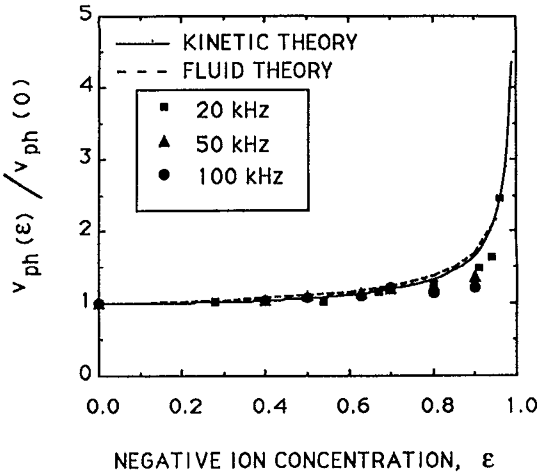

FIG. 1. The phase velocity of the ion-acoustic "fast" mode. The quantity $v_{ph}(\epsilon)/v_{ph}(0)$ vs ϵ, the concentration of negative ions, at three different frequencies. The solid line and the dotted line are predictions from kinetic theory and fluid theory, respectively.

-18 V, and movable along the axis of the column. Phase and amplitude measurements of the signal on the movable grid allow us to determine the phase velocity of the acoustic wave and its rate of spatial damping. The phase and amplitude data obtained by varying the distance, x, of the detector grid from the launcher grid are of the type reported many times in the past for this kind of measurement. Thus they need no detailed description here.

The experimental results on the phase velocity of the ion-acoustic "fast" mode[2,5] are summarized in Fig. 1. This figure shows the quantity $v_{ph}(\epsilon)/v_{ph}(0)$, namely the phase velocity at a concentration ϵ of negative ions normalized to the velocity at $\epsilon = 0$, as a function of ϵ. The experimental points were obtained at three different wave frequencies, $f = 20$, 50, and 100 kHz. The solid line is the phase velocity computed using the dispersion relation given in Ref. 5 from Vlasov's theory, for $T_e = T_{K^+}$, $T_{SF_6^-} = 0.2T_e$, and an assumed drift velocity of the plasma from the hot tantalum plate to the cold steel endplate of 1.2 $(2kT_{K^+}/m_{K^+})^{1/2}$. The dotted line, hardly distinguishable from the solid line, represents the predictions of fluid theory. The behavior of v_{ph} as a function of ϵ is evidently of the same type as reported by Wong *et al.*[2] from experiments in an argon discharge.

The results on wave damping are shown in Figs. 2(a)–2(c). The quantity $k_i u_{i,th}/\omega$ is shown as a function of ϵ, at wave frequencies $f = 20$, 50, and 100 kHz. Here k_i represents the imaginary part of the complex wave number $k = k_r + ik_i$, and is equal to $1/\delta$, δ being the damping length of the wave amplitude; $u_{i,th}$ is the thermal velocity of the K^+ ions and ω is the wave angular frequency. The solid lines are the predictions from Vlasov theory, for the same temperature and plasma drift conditions of Fig. 1. The experimental results of Fig. 2 show agreement with these calculations at the highest wave frequency (100 kHz). As the wave frequency decreases, and for negative-ion concentrations above ~0.5, the experimental data indicate a wave damping somewhat stronger than that expected from Vlasov theory. We suspect that this discrepancy is due to the presence of some collisional damping, which becomes increasingly important as the wave frequency is decreased. At a plasma density of $\sim 10^{10}$ cm^{-3}, the K^+–SF_6^- collision frequency is estimated to be on the order of 5×10^3–10^4 sec^{-1}, which is comparable to, although smaller than,

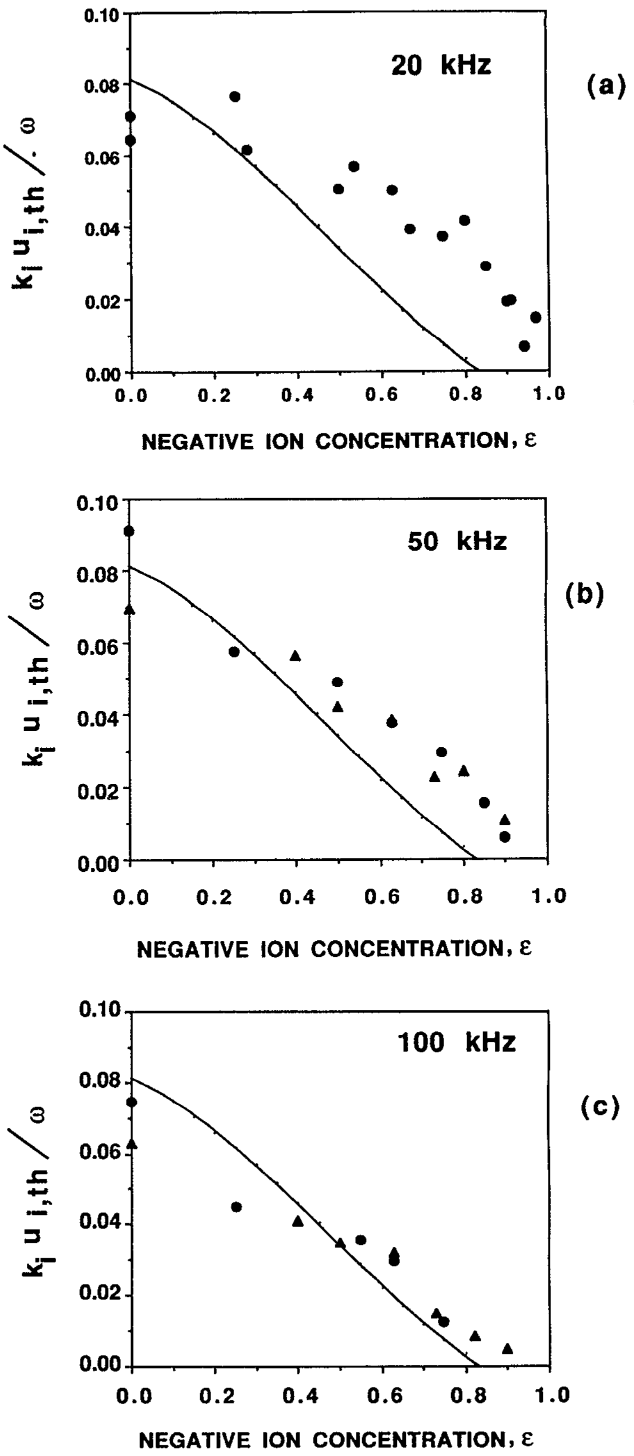

FIG. 2. The damping of the ion-acoustic "fast" mode. The quantity $k_i u_{i,th}/\omega$ vs ϵ, the concentration of negative ions. (a) $f = 20$ kHz, (b) $f = 50$ kHz, (c) $f = 100$ kHz. The solid lines are predictions from kinetic theory.

the wave frequency of 20 kHz. If we remember that the "fast" mode oscillations of the K^+ ions and of the SF_6^- ions occur out of phase,[2,5] it becomes clear that K^+/SF_6^- collisions might have a non-negligible effect on wave damping at the smallest frequencies and at $\epsilon \gtrsim 0.5$.

III. CONCLUSIONS

Ion-acoustic waves in a plasma with variable relative concentrations of negative ions have been investigated in a single-ended Q machine. The plasma consisted of K^+ positive ions, electrons, and SF_6^- negative ions formed by the attachment of electrons to SF_6 molecules.

The main results of this experiment are

(a) As the negative-ion concentration becomes quite appreciable ($\epsilon > 0.5$), the phase velocity of the "fast" mode increases, as predicted by Vlasov theory calculations[5] and observed in argon plasmas with SF_6^- negative ions by Wong *et al.*[2]

(b) With increasing ϵ, the "fast" mode is seen to be less and less damped. At high wave frequencies ($f \approx 100$ kHz, the wave damping nearly disappears for $\epsilon \gtrsim 0.9$, while at smaller frequencies a residual damping still remains, most likely due to the effect of collisions between the K^+ and SF_6^- ions. The results on wave damping are well understood on the basis of Vlasov theory calculations. They differ somewhat, however, from the experimental results of Wong *et al.*[2] [see their Fig. 4(b)], who attributed their observation of a discrepancy with theory to a damping generated by turbulent wave fields.

We believe there are advantages in conducting experiments in plasmas with negative ions using a Q machine rather than a discharge plasma. In the first place the cross section for electron attachement to SF_6 molecules is much larger at the electron energy of $\sim$0.2 eV typical of Q-machine plasmas. This requires lower SF_6 partial pressures in order to attain appreciable negative-ion concentrations. In the second place, a Q-machine plasma is totally devoid of the energetic "primary" electrons which, although their number may be reduced to small values in suitably designed discharge devices,[2] are still an unavoidable constituent of plasma discharges. Finally, while in Q-machine plasmas the only type of positive ions present is provided by the alkali atoms ionized at the hot plate, in a discharge plasma it appears unavoidable that SF_6^+ positive ions are also produced, in addition to, e.g., Ar^+ ions. For these reasons, a Q-machine environment seems more likely to provide "cleaner" experimental conditions than other devices, thus facilitating the comparison of experimental results with theoretical predictions.

ACKNOWLEDGMENTS

We thank K. Nishikawa for providing computer software.

This work was supported by the Office of Naval Research and NASA.

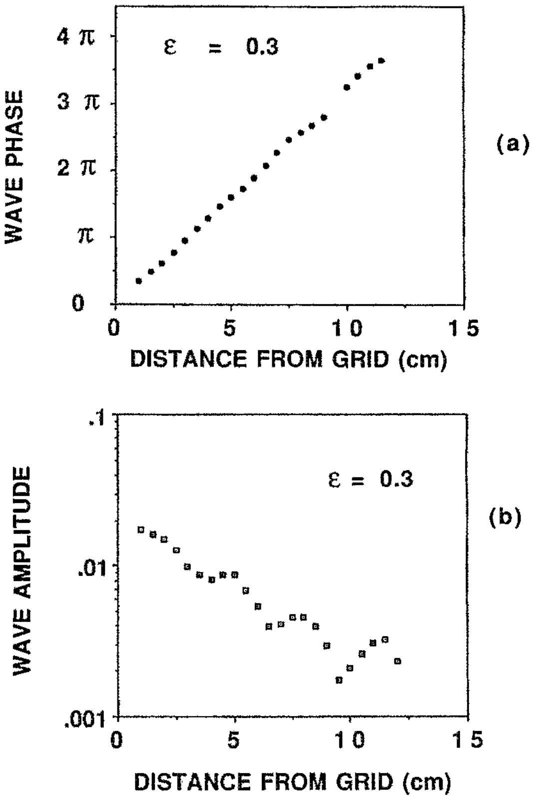

FIG. 3. The spatial beat of the fast mode and the "directly coupled signal" ($\epsilon = 0.3$, $f = 80$ kHz). (a) Wave phase versus distance from the launcher grid; (b) wave amplitude versus distance from the launcher grid.

APPENDIX: SPATIAL BEAT OF THE FAST MODE AND THE "DIRECTLY COUPLED SIGNAL"

At the higher frequencies used in the present study, we have sometimes observed an apparent spatial modulation in the wave phase and amplitude, as illustrated in Fig. 3. For a negative-ion concentration $\epsilon = 0.3$ and a wave frequency of 80 kHz, Fig. 3(a) shows the wave phase as a function of axial distance. It will be noticed that the experimental points, although providing a rather good measurement of the wave phase velocity, do not fall precisely on a straight line, but exhibit some small, spatially periodic deviation from a perfectly linear behavior. For the same conditions, Fig. 3(b) shows the behavior of the wave amplitude with axial distance. Again, superimposed on an average decay of the amplitude with axial distance, we observe a small spatially periodic modulation of the amplitude. A behavior of this type, in plasmas consisting only of positive ions and electrons, has been observed before by Sato *et al.*[11] and has been attributed by them to the effect of nonlinearities. In the experiments of Ref. 11 the wave amplitude was large, and nonlinear effects could conceivably have been responsible for the observed effect. In our experiments, on the other hand, the wave amplitude is generally small, $\sim 1\%$ or less, and thus a different explanation must be invoked. It appears to us that the features illustrated by Figs. 3(a) and 3(b) can be understood in terms of a spatial "beat" between two perturbations excited in phase at the launcher grid. Although of the same angular frequency, ω, they have different wave numbers and, thus, different phase velocity. If k_1 and k_2 are the wave numbers of the perturbations, δ_1, and δ_2 are the e-folding lengths for their amplitude decay away from the launcher grid, and P is the amplitude of wave #2 relative to wave #1 at the grid, it is easily shown that the overall wave amplitude is given by

$$A(x)=\left[\exp\left(-\frac{2x}{\delta_1}\right)+P^2\exp\left(-\frac{2x}{\delta_2}\right)+2P\exp\left(-\frac{x}{\delta_1}\right)\exp\left(\frac{-x}{\delta_2}\right)\cos[(k_1-k_2)x]\right]^{1/2}, \quad \text{(A1)}$$

where we have assumed that wave #1 is represented by $A_1(x,t) = e^{-x/\delta_1}\cos(k_1x - \omega t)$ and wave #2 by $A_2(x,t) = Pe^{-x/\delta_2}\cos(k_2x - \omega t)$. In addition, the time of arrival of the wave at any axial position, x, is given by

$$\omega t=\tan^{-1}[g(x)/f(x)], \quad \text{(A2)}$$

where

$$f(x)=e^{-x/\delta_1}\cos(k_1x)+Pe^{-x/\delta_2}\cos(k_2x)$$

and

$$g(x)=e^{-x/\delta_1}\sin(k_1x)+Pe^{-x/\delta_2}\sin(k_2x).$$

We can apply these considerations to the results of our experiments [see Figs. 3(a) and 3(b)] by identifying wave #1 with the "fast" ion-acoustic mode and wave #2 with, e.g., the so-called "directly coupled signal," with $k_2 \ll k_1$ and $\delta_2 \gg \delta_1$, often observed in single-ended Q-machine experiments in which waves are launched by a grid, and presumably associated with the oscillation in potential of that portion of the column that is between the launcher grid and the cold endplate. The small spatial oscillation of $A(x)$ [Fig. 3(b)] would then be associated with the third term on the right-hand side of Eq. (A1), while the average amplitude decay, with damping distance δ_1, would be given by the first term. A detailed examination of Eq. (A2) shows that, as in Fig. 3(a), the phase will also exhibit a small spatial oscillation. It should be noted that in experiments in double-ended Q machines in which the endplate is hot and emits copious amounts of electrons, the potential oscillation on the launcher grid should cause only much smaller potential oscillations in the downstream side of the column and, therefore, the effect described here should be much less significant. However, in either case this effect, which seems to be reasonably explained by the straightforward mechanism described in this appendix, should not appreciably affect the measurements of the wave phase velocity and damping distance.

[1] S. von Goeler, T. Ohe, and N. D'Angelo, J. Appl. Phys. **37**, 2519 (1966).

[2] A. Y. Wong, D. L. Mamas, and D. Arnush, Phys. Fluids **18**, 1489 (1975).

[3] D. P. Sheehan and N. Rynn, Rev. Sci. Instrum. **59**, 1369 (1988).

[4] B. Song, D. Suszcynsky, N. D'Angelo, and R. L. Merlino, Phys. Fluids B **1**, 2316 (1989).

[5] N. D'Angelo, S. von Goeler, and T. Ohe, Phys. Fluids **3**, 1605 (1966).

[6] N. D'Angelo, J. Geophys. Res. **72**, 1541 (1967).

[7] M. Galvez and S. P. Gary, Phys. Fluids **29**, 4085 (1986).

[8] N. D'Angelo and R. L. Merlino, IEEE Trans. Plasma Sci. **PS-14**, 285 (1986).

[9] D. M. Suszcynsky, N. D'Angelo, and R. L. Merlino, Rev. Sci. Instrum. **59**, 1376 (1988).

[10] A. Y. Wong, R. W. Motley, and N. D'Angelo, Phys. Rev. **133**, A436 (1964).

[11] N. Sato, H. Ikezi, N. Takahashi, and Y. Yamashita, Phys. Rev. **183**, 278 (1969).