Shock formation in a negative ion plasma

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An experimental investigation of the effect of negative ions on shock formation in a (collisional) Q machine plasma is described. Shock formation was observed only when the ratio of the negative ion to positive ion density, ϵ , exceeded about 0.9. © *1998 American Institute of Physics*. [S1070-664X(98)02108-9]

I. INTRODUCTION

The conditions under which large density pulses might develop into sharp fronts or "shocks" were investigated in a Q machine by Andersen *et al.*¹ Under normal operating conditions, with equal electron and ion temperatures, $T_e = T_i$, Landau damping prevented the formation of a shock, and only a "spreading" of the pulse was observed. However, when the ratio T_e/T_i was made as large as about 3 or 4, by cooling the ions through ion-neutral collisions, shock formation was observed. A subsequent study² of the effect of an increase of the T_e/T_i ratio on the propagation and damping of sinusoidal waves (as opposed to pulses) also indicated a decrease of the (Landau) damping of the waves, supporting the conclusions of the "pulse" experiments.

As shown theoretically by D'Angelo *et al.*,³ a reduction in the collisionless (Landau) damping of ion acoustic waves can also be realized by the introduction of negative ions into a plasma. In the presence of negative ions, the ion waves exhibit two modes of propagation: a "fast" mode and a "slow" mode. As the percentage of negative ions is increased, the phase velocity of the fast mode increases. As a consequence, the number of ions interacting with the wave decreases and thus the damping is reduced. Both the appearance of this fast ion acoustic mode and the reduction in damping with increasing negative ion concentration have been verified experimentally.^{4–6}

In the experiment reported here, we investigated the conditions under which a shock wave might form in a collisional negative ion plasma. The experimental setup and plasma conditions are very similar to those used in Ref. 1. We find that for sufficiently high negative ion concentrations, plasma density pulses do not spread out but tend to maintain their structure or even steepen. If the percentage concentration of negative ions is below about 90%, the pulses spread out and no tendency toward shock formation is observed. Experiments on ion acoustic shocks formed in a collisionless plasma with negative ions have also been performed,⁷ under conditions substantially different from those of the present experiment.

The theory of shock formation in a (collisional) fluid plasma has been discussed in Ref. 1 and by Montgomery.⁸ Briefly, one finds that the equations used to describe nonlin-

ear ion acoustic wave propagation parallel to the B field lines are identical to the Euler equations used to describe an ideal (neutral) fluid. One expects that, in the absence of a damping mechanism such as Landau damping, a large amplitude plasma pulse may steepen into a shock as in sound waves in an ordinary gas. In the present case the removal of Landau damping is brought about by the addition of negative ions in the plasma.

A description of the experimental setup and methods is given in Sec. II. Section III contains the presentation and discussion of the experimental results. A summary and some concluding comments are presented in Sec. IV.

II. EXPERIMENTAL SETUP AND METHODS

The experiments were performed in the Iowa IQ-2 double-ended Q machine which provides a cesium (Cs^{+}) plasma ~ 6 cm in diameter and ~ 160 cm in length confined radially by a magnetic field up 0.6 T. The plasma is formed in the usual manner by contact ionization of cesium atoms on a hot (\sim 2500 K) tantalum plate (HP) [Fig. 1(a)]. The plasma column is terminated at the opposite end from the generating plate by a second tantalum hot plate which can also be heated up to \sim 2500 K. As in typical Q machines,⁹ the electron and ion temperatures were $T_e \approx T_i \approx 0.2$ eV. The plasma density *n* was measured from the ion saturation current I_{is} of a Langmuir probe using the relation ${}^{9}I_{is} = (nev_i/4)A_p$, where $v_i = (kT_i/m_i)^{1/2}$ is the ion thermal velocity and \dot{A}_p is the probe collecting area. For the experiments reported here the plasma density was in the range $1 \times 10^{11} - 4 \times 10^{11}$ cm⁻³. At these densities the mean free path for ion-ion collisions is ~ 1 cm.

Negative ion plasmas^{10,11} were produced by leaking into the vacuum vessel (base pressures $\sim 10^{-6}$ Torr) SF₆ gas in variable amounts up to partial pressures $\sim 2 \times 10^{-5}$ Torr. At each SF₆ partial pressure the ratio of the negative to positive ion density;

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

was determined from measurements of the reduction in the negative saturation current to a Langmuir probe (4 mm diameter Ta disk) that occurs as electrons become attached to the (relatively immobile) SF₆ molecules. Details of the measurement of ϵ have been described previously.^{6,12} ϵ increases monotonically with increasing SF₆ pressure, reaching values

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FIG. 1. (a) Schematic of the experimental arrangement; HP=hot plate, G=grid, LP=Langmuir probe. (b) A schematic of the density distribution along the axis when the grid is "closed."

of $\epsilon \approx 0.95$ for a relatively low SF₆ pressure $\sim 10^{-5}$ Torr, where collisions between the positive ions and SF₆ molecules are unimportant.

About 30 cm from one of the hot plates a grid was inserted into the plasma column with its plane perpendicular to the magnetic field [Fig. 1(a)]. The grid is a tungsten mesh formed from 0.025 mm wires spaced 0.3 mm apart. It is normally biased at ~ -6 V with respect to the grounded hot plate and absorbs most of the ions from the hot plate, resulting in a plasma density distribution of the type shown in Fig. 1(b). By suddenly changing the grid bias to ~ -2 V, the grid "opens up," launching a plasma density pulse toward the other hot plate. In practice, this was accomplished by applying to the grid a train of square wave pulses with a rise time of $\sim 0.1 \ \mu s$, a pulse width of 10 ms, and pulse separation of 30 ms. Thus the grid remains in the "closed" configuration $(\sim -6 \text{ V})$ for 20 ms and is then rapidly switched to the "open" configuration (~ -2 V) for 10 ms. The duration of the "open" phase is chosen to allow sufficient time for the pulse to propagate to the other plate before the grid is closed. The time between pulses is chosen to allow the plasma to relax back to a steady state before the next pulse is launched.

III. RESULTS AND DISCUSSION

The experiments were performed in the following manner. A plasma with a specified negative ion concentration was produced and a train of square wave pulses applied to the grid. At several locations along the axis, the plasma density n was recorded as a function of time from the "opening" of the grid.

Figure 2(a) shows *n* vs *t* curves at various distances downstream from the grid, in the absence of negative ions, $\epsilon = 0$. Under these conditions we always observed a "spreading out" of the pulse with no indication of "steepening," as observed in the earlier experiments.¹ When SF₆ gas was leaked into the system to produce negative ion plasmas, no tendency toward steepening was observed for values of ϵ up to about $\epsilon \sim 0.9$. However, when ϵ was increased to about 0.95 [Fig. 2(b)], the pulses no longer spread out but maintained their shape or even steepened somewhat. This "steepening" is illustrated in Fig. 2 by comparing the sets of dashed lines in (a) and (b) which mark the advancement of the leading and trailing edges of the moving fronts. In Fig.



FIG. 2. (a) *n* vs *t* (from digital oscilloscope traces) at various axial locations in cm from the grid for $\epsilon = 0$ (no negative ions present). (b) *n* vs *t*, as in (a), but in the presence of a substantial ($\epsilon = 0.95$) negative ion concentration. In both (a) and (b) the horizontal dotted lines are the baselines for the uppermost traces; for clarity all other traces are displaced downward by equal amounts. The dashed lines mark the locations of the leading and trailing edges of the moving fronts in both cases. Convergence of these dashed lines in case (b) indicates steepening of the fronts, whereas the divergence of the dashed lines in (a) indicates spreading of the fronts.

2(a) the dashed lines diverge due to the front spreading out, while in Fig. 2(b) the dashed lines converge indicating a steepening. This type of behavior was repeatedly observed only at the highest values of ϵ .

The connection between the lack of spreading or steepening of the density pulses and the diminished effect of Landau damping is provided by measurements of the pulse speed, v_p , as a function of ϵ , shown in Fig. 3. For $\epsilon < 0.9$ the pulse speed remains relatively constant with increasing ϵ . A sharp increase in pulse speed only occurs for $\epsilon > 0.9$. This result is very similar to the one observed for sinusoidal "fast" ion acoustic waves launched into a negative ion plasma.⁶ In that case the increased phase velocity of the fast



FIG. 3. Measured density pulse propagation velocities v_p versus relative negative ion concentration ϵ . These data were obtained from the type of measurements shown in Fig. 2, of *n* vs *t* at various axial locations from the grid performed at several values of ϵ .

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mode at high ϵ 's was accompanied by a substantial reduction in wave damping. The reduction in damping was wellunderstood on the basis of Vlasov calculations which predicted the strong decrease in Landau damping at high values of the negative ion concentration. It seems reasonable that the lack of spreading of the pulses seen at high ϵ 's in the present experiment, might also be attributable to a decrease in Landau damping, if one imagines the "pulse" to be composed of many Fourier components.

IV. SUMMARY

The present and previous work relevant to shock formation in negative ion plasmas can be summarized briefly as follows:

(1) It was established in previous experiments¹ that a wave-particle interaction mechanism (Landau damping) prevented the formation of a shock wave in a plasma with $T_e = T_i$. By increasing the T_e/T_i ratio, by cooling the ions, the Landau damping was reduced and the formation of a shock structure was observed.

(2) More recent work on plasmas with negative ions⁴⁻⁶ further showed that the increase in wave phase velocity that results due to the presence of negative ions can be sufficient to eliminate the wave-particle resonance even when $T_e = T_i$.

(3) Finally, the present experiment has extended and fortified the conclusions of (1) and (2) by demonstrating that the elimination of a strong wave-particle interaction can lead to shock formation in a negative ion plasma.

We conclude by pointing out that a result similar to the one reported here in a negative ion plasma may also be expected in a plasma containing a sufficiently large percentage of negatively charged dust grains.

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