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The Kelvin–Helmholtz instability in a plasma with negatively charged dust

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The effect of negatively charged dust on the Kelvin–Helmholtz (parallel velocity shear) instability is investigated experimentally in a magnetized cesium plasma. The dust generally has a stabilizing effect on the instability, although, in some cases, the addition of negatively charged dust into the plasma results in a slight increase in the instability fluctuation amplitude. The results are in general agreement with theoretical predictions.
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I. INTRODUCTION

The Kelvin–Helmholtz (KH) parallel velocity shear instability (PVSI) is a fluid instability that may occur in a plasma which is flowing parallel to a magnetic field with a flow velocity that varies in a direction perpendicular to the magnetic field. This instability was first analyzed theoretically by D'Angelo[1] who showed that in a nonuniform plasma with equal electron and ion temperatures, instability will occur if the quantity which characterizes the shear, $\partial v_{0z}/\partial x > \sqrt{2}\lambda c_i$, where v_{0z} is the ion flow velocity along the magnetic field, x is a coordinate transverse to the magnetic field, λ is the inverse e-folding length of the density gradient, and c_i is the ion thermal speed. Thus, if $\partial v_{0z}/\partial x \approx \Delta v_{0z}/l$ and $l \approx 1/\lambda$, the instability will occur for Δv_{0z} on the order of the ion sound velocity. The essential features of the theory were confirmed experimentally by D'Angelo and von Goeler[2] who observed low-frequency (few kHz) electrostatic fluctuations in a thermally ionized cesium plasma (Q machine) when the relative drift between ions in adjacent layers was $\sim c_i$.

The instability was also studied both theoretically[3] and experimentally[4] in plasmas with negative ions. The negative ions were generally found to have a *destabilizing* effect on the instability, i.e., the mode was excited at lower values of the shear parameter $S \equiv (1/\omega_{c+})(\partial v_{0z}/\partial x)$, where ω_{c+} is the ion gyrofrequency, when the negative ions were present. However, it was also found that for a fixed negative ion concentration, increasing the ratio, m_-/m_+ of the mass of the negative ion relative to the positive ion, had a generally *stabilizing* effect (see Fig. 6 of Ref. 3).

The effect of extremely massive (effectively immobile) and negatively charged particles (dust grains) was investigated theoretically by D'Angelo and Song[5] using a fluid analysis. A summary of the results from this analysis will be presented in the following section. In this paper we present results of an experimental study of the effect of negatively charged dust on the KH (PVSI) instability. The experiment was performed in a double-ended Q machine, using an arrangement for producing sheared ion flow nearly identical to that used by D'Angelo and von Goeler[2] (the ''ring+disk'' experiment).

Experimental studies of the effect of negatively charged dust on ion acoustic and electrostatic ion cyclotron waves as well as observations of the very low-frequency dust acoustic wave are summarized in the review paper by Merlino *et al.*[6]

This paper is organized as follows: Section II contains a summary of the relevant theoretical results. Details of the experimental apparatus and methods are presented in Sec. III. The results are given in Sec. IV. Section V contains a discussion of the results and the conclusions.

II. THEORETICAL BACKGROUND

The analysis of the KH (PVSI) instability in a dusty plasma by D'Angelo and Song[5] follows closely the earlier work of D'Angelo[1] on the corresponding mode in a normal plasma without dust.

In a Cartesian frame of reference, the magnetic field, **B**, is in the positive z direction, and an ion density gradient exists in the x direction. The ion density distribution of the unperturbed state is of the type $n_{+0}(x) = \overline{n}_{+0} e^{-\lambda x}$, with $\overline{n}_{+0} = \text{const}$. The ions flow along **B** with a velocity that depends only on the x coordinate, the ion zero-order (unperturbed) velocity vector being given by $\mathbf{v}_{+0} = [0, v_{+0y}, v_{+0z}(x)]$, with $v_{+0y} = \text{const}$. The plasma electrons are assumed to be in Boltzmann equilibrium both in the zero-order and in the first-order (perturbed) state, while the dust grain, all of the same size, are so heavy that they do not participate in the plasma motion. Each grain charge is equal to $-eZ$. The quantity $\epsilon = n_{d0}/n_{+0}$ indicates the ratio between the dust density and the ion density in zero-order. Since charge neutrality is preserved, the product ϵZ indicates the fraction of the negative charge, in any volume, which resides on dust grains, $\epsilon Z = 0$ meaning that all of the negative charge is in the form of free electrons and $\epsilon Z = 1$ corresponding to the complete absence of free electrons.

The first order quantities are assumed to vary as $e^{i(K_y y + K_z z - \omega t)}$, with only a weak x dependence. Following standard procedure, the dispersion relation:

$$\zeta^2 - \beta\Lambda\zeta - \gamma(\gamma - \beta S) = 0, \tag{1}$$

is arrived at, where $\zeta = \Omega/\omega_{c+} = (\omega - K_y v_{+0y}$

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$-K_z v_{+0z})/\omega_{c+}$ is the Doppler shifted wave frequency in terms of the ion gyrofrequency, $\omega_{c+}=eB/m_+$. The following definitions apply:

$$A_+^2(\epsilon)=\frac{kT_+}{m_+}+\frac{kT_e}{m_+}\frac{1}{1-\epsilon Z},$$

$$\rho_+^2(\epsilon)=\frac{A_+^2(\epsilon)}{\omega_{c+}^2},$$

$$\beta(\epsilon)=K_y\rho_+(\epsilon),\qquad \gamma(\epsilon)=K_z\rho_+(\epsilon),\qquad \Lambda(\epsilon)=\lambda\rho_+(\epsilon),$$

$$S=\frac{1}{\omega_{c+}}\frac{\partial v_{+0z}}{\partial x},$$

and it is assumed that $\beta^2\ll 1$ and $\gamma^2\ll 1$. The instability condition is that ζ be complex. The critical shear parameter, minimized with respect to the K_z/K_y ratio, increases with increasing ϵZ, for negatively charged grains (see Fig. 1 of Ref. 5), indicating a generally stabilizing effect of the negative dust.

An alternative way of analyzing the instability is by obtaining, from Eq. (1), the instability growth rate as a function of ϵZ. For any fixed β, the growth rate Γ maximized with respect to the K_z/K_y ratio, is given by

$$\Gamma=[\tfrac{1}{4}\beta^2(S^2-\Lambda^2)]^{1/2}, \tag{2}$$

and for a plasma with equal ion and electron temperatures, $T_+=T_e=T$

$$\Gamma=\left\{\tfrac{1}{4}(K_y b)^2\frac{2-\epsilon Z}{1-\epsilon Z}\left[S^2-(\lambda b)^2\frac{2-\epsilon Z}{1-\epsilon Z}\right]\right\}^{1/2}, \tag{3}$$

where $b=1/\omega_{c+}(kT/m_+)^{1/2}$. For $A=(\lambda b)^2=0.116$, Fig. 1(a) shows the quantity $R=2\Gamma/K_y b$ as a function of ϵZ, for three different values of the shear parameter, S. An increase of ϵZ has generally a stabilizing effect, i.e., it produces a decrease of the growth rate, except for the largest shear and at low ϵZ, when a very mild increase of R with ϵZ is observed. Figure 1(b) shows R as a function of ϵZ, for a fixed value of the shear parameter $S=0.7$, and for three different values of the plasma uniformity parameter $A=(\lambda b)^2$. An increase of A reduces the growth rate, as expected from the stabilizing effect of the plasma density gradient.[1]

III. EXPERIMENTAL SETUP AND METHODS

The experiments were performed in the Iowa double-ended Q machine (IQ3), shown schematically in Fig. 2. The device produces a magnetized, fully ionized cesium plasma by surface ionization of cesium atoms from two atomic beam ovens on two, 6 cm diameter tantalum hot (~2000–2500 K) plates (HP) separated longitudinally by 1 m. The experiments were performed under the following conditions: Magnetic-field strength 0.3 T, plasma density in the range $5\times 10^9\ \mathrm{cm}^{-3}$–$10^{10}\ \mathrm{cm}^{-3}$, and electron and ion temperatures, $T_e\approx T_i\approx 0.2$ eV. The hot plates were operated under electron rich conditions with resulting Langmuir probe floating potentials on the order of -2 to -3 volts. Under these typical conditions the ions are accelerated away from each plate by a ~2 to 3 V sheath at the plate. For a Cs^+ ion, this results in an ion flow velocity along the magnetic field $v_i\sim 1-2\times 10^5$ cm/s. In a double-ended Q machine the plasma production from each plate can be balanced so as to produce a plasma with no net ion flow along the magnetic field, and hence no shear within the plasma column.

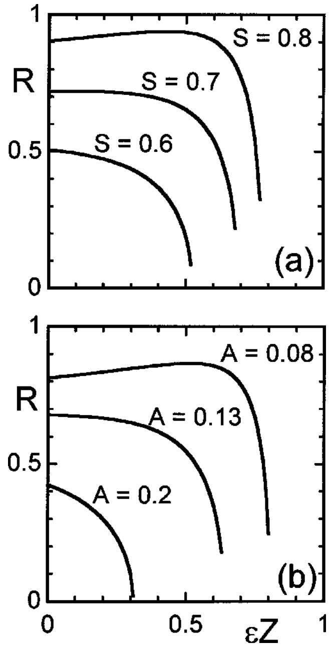

FIG. 1. Dependence of the theoretical normalized instability growth rate, R, on ϵZ. (a) R vs ϵZ for $A=0.116$, and three values of the shear parameter, S. (b) R vs ϵZ for $S=0.7$ and three values of the plasma density nonuniformity parameter, A.

To produce the shear in the ion flow the ''ring+disk'' setup[2] was used. A metal ring with an outside diameter somewhat larger than that of the plasma column and an inner diameter of 2 cm was located at one plasma cross section, and a metal disk of diameter 1.8 cm was located at another cross section, as shown also in Fig. 2. The ring and disk were centered on the plasma column and were separated by 50 cm. They were both oriented with their normal parallel to **B**. When the ring and disk are biased negatively (close to the floating potential), the ions are collected by the ring and disk, resulting in a counterstreaming flow between the inner core ions and ions in the outer annular layer. Shear in the parallel flow is then present in the annular region represented by the dashed lines in Fig. 2.

A measurement of the shear resulting from this configuration was made in a previous experiment[7] under very simi-

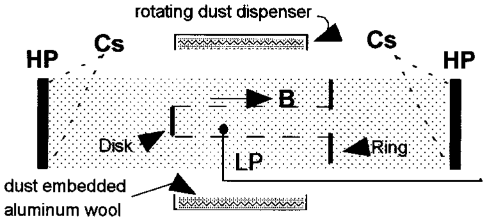

FIG. 2. Schematic diagram of the experimental setup used to produce a magnetized plasma with radial shear in the magnetic field aligned ion flow and the rotating drum used to disperse dust into the plasma.

lar conditions to those used in the present experiment. A Langmuir probe consisting of two electrically insulated disk collectors mounted back-to-back and biased at -5 V, was used to measure the radial distribution of the ion flux arriving at the probe from each hot plate. From these flux measurements, the radial profile of the ion flow velocity, $v_i(r)$, was obtained (see Fig. 4 of Ref. 7). The results clearly showed a roughly uniform flow speed in the outer annular plasma region and a uniform flow of comparable magnitude but opposite direction in the inner region. From this measurement, the radial derivative of the parallel ion flow, $\partial v_i(r)/\partial r$, was computed, which along with the ion gyrofrequency ω_{c+}, provided an estimate of the shear parameter $S=(1/\omega_{c+})(\partial v_i(r)/\partial r)\approx(2\times10^5\ \mathrm{s}^{-1})^{-1}[(1-4)10^5\ \mathrm{s}^{-1}]\approx0.5-2.0$.

Dust was introduced into the plasma using the rotating drum method.[8] The central 50 cm of the plasma column was surrounded by a metal cylinder which could be rotated about its longitudinal axis by a variable speed motor. The inside of the cylinder was covered by a coarse aluminum wool into which dust was embedded. When the cylinder was rotated a ''rain'' of dust grains would precipitate through the plasma column. The fallen particles would then be re-circulated through the plasma. Upon entering the plasma the dust grains would very quickly acquire a negative charge, thus reducing the free negative charge (electron) density in the plasma. The use of aluminum wool on the inside of the rotating cylinder is a slight modification of a previous design,[8] and results in the ability to operate at somewhat higher dust densities ($>10^5\ \mathrm{cm}^{-3}$). This was necessary, since the KH instability is present only at relatively high plasma densities, and thus higher dust densities are also necessary to produce observable effects on the instability.

The dust was kaolin (aluminum silicate) of nominal size 0.4 microns, but with a very broad size distribution ranging from hundreds of nanometers up to tens of microns.

For the experiments described here the charged dust particles merely provided a negative charge background and did not participate in the dynamics of the wave motion. The presence of dust was determined by observations of the reduction in the electron saturation current to a positively biased Langmuir probe due to the collection of electrons by the dust grains. This method, which has been discussed previously,[9] also provided a measurement of the quantity, ϵZ, the fraction of negative charge per unit volume residing on dust grains in the plasma. ϵZ could be varied by changing the rotation rate of the cylinder. A linear relation between ϵZ and the rotation rate was found with ϵZ varying from about 0.2 to about 0.7 for rotation rates between 20% and 40% of the maximum rate.

IV. EXPERIMENTAL RESULTS

When the ring and disk are both biased a few volts negative to collect essentially the full ion saturation current, a counter-streaming exists between the inner core and outside cylindrical shell. Under these conditions we observed the excitation of low frequency oscillations, with frequencies mostly in the 1–4 kHz range. These oscillations were observed by monitoring the fluctuations of the floating potential of a Langmuir probe which had a spatial resolution of 2 mm. This is illustrated in Fig. 3(a), which shows traces of both the direct current (dc) (top) and alternating current (ac) (fluctuating component) probe floating potential, recorded as the probe was moved radially across the plasma column at an axial location corresponding to the midpoint between the two hot plates. The dc floating potential is typical of a Q machine plasma under the electron rich condition, the floating potential being approximately constant at about -3 volts in the plasma column. The ac potential, recorded on a 20 times more sensitive voltage scale compared to the dc case, shows fluctuations with a peak amplitude corresponding to the radial locations of the edge of the disk, i.e., in the region where the shear is expected to attain its maximum value. The oscillations disappear if the bias on the ring and disk is >-3 V, i.e., if the counter-streaming of the ions is essentially eliminated. The data of Fig. 3(a) refer to the situation in which no dust was present.

The effect of the dust on the KH mode is illustrated by the traces shown in Figs. 3(b), 3(d), taken under increasing values of the drum rotation rate. Evidently, the effect of the dust, in this case, is to produce a decrease in the KH mode amplitude. At a rotation rate of 35% [Fig. 3(d)], the mode is effectively eliminated, and the fluctuation level returns to the background level. We point out also that the traces of the dc potential are practically unchanged by the presence of the dust. Except at the very edges of the plasma column the dc floating potential traces are also relatively flat, indicating the lack of any radial electric fields in the body of the plasma, and in particular, in the shear layer.

The type of measurement shown in Fig. 3 were performed at several values of the drum rotation rate. From these measurements a plot of the KH wave amplitude ($e\Delta V/kT_e$, where ΔV is one-half the peak-to-peak fluctuation level) vs the corresponding ϵZ value (from the Langmuir probe measurements discussed in Sec. III) was made and is shown in Fig. 4 (solid dots). For these conditions the dust has a damping effect on the mode. For comparison, the solid curve in Fig. 4 shows a plot of the normalized linear growth rate [the imaginary part of ζ, from Eq. (1)] corresponding to the approximate experimental conditions: $b\approx0.2$ cm, $K_y\approx1\ \mathrm{cm}^{-1}$ ($m=1$ mode), $K_z/K_y\approx0.2$, and $\lambda\approx2\ \mathrm{cm}^{-1}$.

Finally, we note that in some cases in which the conditions were such as to produce a particularly strong shear, the mode amplitude was first observed to increase slightly with increasing ϵZ, up to a point before decreasing, similar to the behavior of the growth rate for high S values seen in Fig. 1.

V. DISCUSSION AND CONCLUSIONS

In general agreement with the theoretical results of Sec. II, we have observed that negatively charged dust tends to stabilize the KH instability. This conclusion is based on a comparison of the measured KH wave amplitude and theoretical linear growth rates. Although the wave amplitude is only a reflection of the nonlinear growth rate of the instabil-

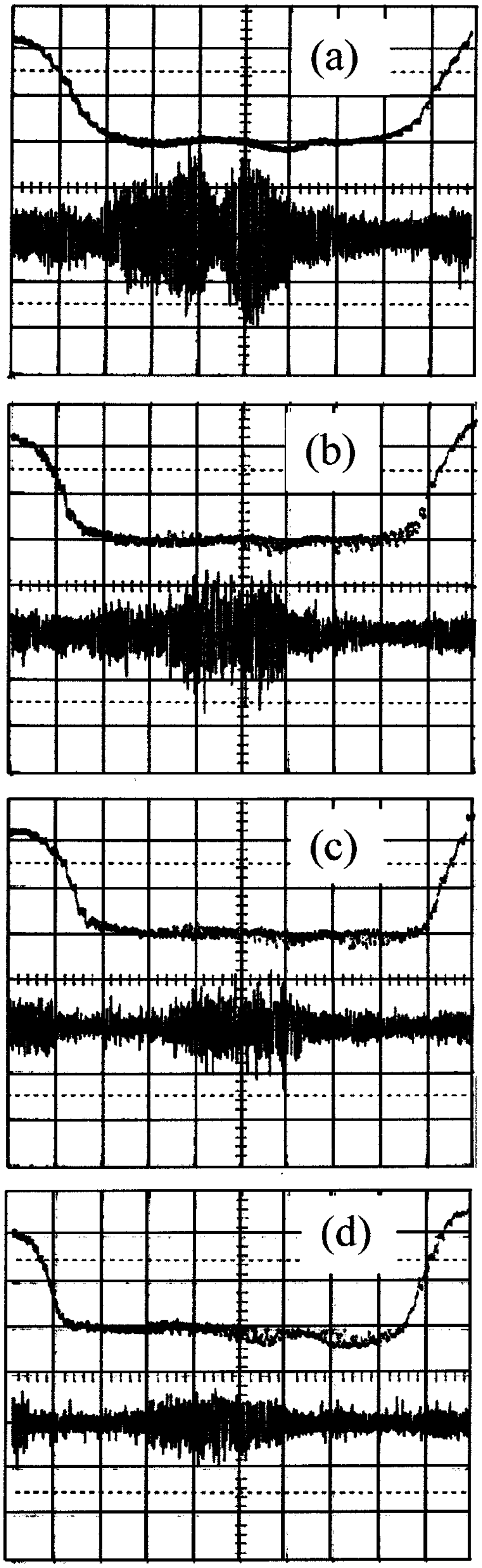

FIG. 3. Radial profiles of the floating potential of a Langmuir probe for various values of the rotation rate of the dust dispenser. For each case both the dc potential and ac component (fluctuations) of the potential are shown. The dc profiles are shown on a 1 V/div scale with 0 V at the top, and the ac potentials are on a 0.05 V/div scale. The radial scale corresponds to ~0.8 cm per horizontal division. Rotation rates shown are (a) 0% [no dust], (b) 22%, (c) 28%, and (d) 35%.

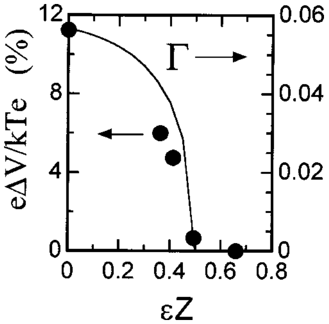

FIG. 4. Measured KH instability wave amplitude ($e\Delta V/kT_e$) vs ϵZ (solid dots). The solid line is the normalized theoretical growth rate, Γ for $S = 0.8$, $b = 0.2$ cm, $K_y = 1$ cm^{-1}, $K_z/K_y = 0.2$, and $\lambda = 2$ cm^{-1}.

ity, it is expected that the reduction in the linear growth rates with increasing ϵZ would also give rise to a decrease in wave amplitude.

One issue that needs to be considered is the possible reduction in the shear due to the interaction between the ions and the dust grains. We believe that the dust does not produce a large reduction in the shear for the following reasons. In the interaction of an ion with a dust particle the ion may be totally absorbed by the dust or it may be scattered. For relatively large dust grains the collection of ions by the dust is the dominant effect. In this case there is an attenuation of the ion flow but with no reduction in the shear. For smaller grains, ion collection is also important but Coulomb scattering process is equally likely. In our previous study of the effect of neutral collisions on the parallel velocity shear instability[7] we found experimentally that even at the highest values of the neutral collision frequency used there was no drastic reduction in the shear. For the present experiment we estimate that the corresponding ion–dust collision frequency is even smaller than the largest ion-neutral collision frequency used in the previous investigation. Thus, it seems reasonable to conclude that collisions between the ions and dust grains do not reduce the shear and hence that the observed decrease in wave amplitude is consistent with the theoretical predictions.

In closing we mention that non-linear aspects (vortex formation) of this ion velocity gradient instability in a dusty plasma have been considered by Bharuthram and Shukla,[10] who also discussed the relevance of this instability to astrophysical and space plasmas.

ACKNOWLEDGMENTS

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