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Potential relaxation instability and ion acoustic waves in a single-ended Q-machine dusty plasma

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Abstract

The potential relaxation instability (PRI) is excited when the cold endplate of a single-ended Q-machine is biased positively. If a sufficient concentration of negatively charged dust is present, the PRI is eliminated and the current-driven ion acoustic (IA) instability is observed. As the concentration of the negatively charged dust is increased, the frequency of the IA waves also increases, in agreement with theoretical predictions.

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1. Introduction

When a sufficiently positive bias is applied to the cold endplate of a Q-machine, oscillations are excited at a frequency of 1–2 kHz. Time-resolved measurements of the plasma potential oscillations have shown that they are associated with a moving double layer. The instability is generally referred to as the potential relaxation instability (PRI) [1,2]. Song et al. [3] noted that if a sufficient concentration of negative ions (SF_6^-) is present, the PRI is eliminated and the current-driven ion acoustic (IA) instability is observed. As predicted from Vlasov theory calculations for a plasma containing negative ions [4], when the negative ion concentration is increased, the frequency of the IA waves increases and, as a consequence of a reduced ion Landau damping, the critical electron drift needed for their excitation decreases.

The close analogy of negative ion plasmas to plasmas containing appreciable amounts of negatively charged dust grains has been noted by Rao et al. [5] and D'Angelo [6], and several experiments [7–10] have confirmed it.

Here we report the result of an experiment very similar to that of Song et al. [3], except that instead of adding SF_6^- negative ions to the normal Q-machine plasma, negatively charged dust grains are introduced in the manner described by Xu et al. [11]. Section 2 of this paper describes our experimental setup and measurement techniques. The experimental results are presented and discussed in Section 3, while Section 4 contains a brief summary of our findings.

2. Experimental methods

The experiment utilizes as the plasma source a Q-machine [12] in which a fully ionized, magnetized ($B \lesssim 0.4$ T) potassium plasma column of ~ 4 cm diameter and ~ 80 cm long is produced by surface ionization of potassium atoms from an atomic beam

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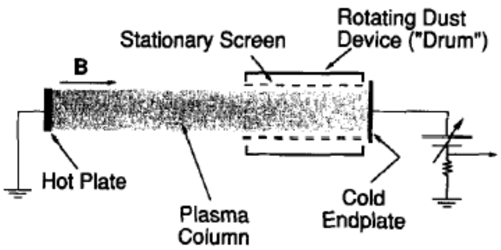

Fig. 1. Schematic diagram of the experimental setup.

oven on a hot (~ 2500 K) tantalum plate. The constituents of the plasma are K^+ ions and electrons with approximately equal temperatures $T_i \approx T_e \simeq 0.2$ eV, and densities in the range 10^5–10^{10} cm^{-3}. To dispense dust particles into the plasma, the plasma column is surrounded over the end portion of its length (~ 30 cm) by the device shown schematically in Fig. 1. This dust dispenser consists of a rotating metal cylinder ("drum") and a stationary screen. Dust particles, initially loaded into the bottom of the cylinder, are carried by the rotating cylinder up to the top and fall onto the screen. A series of stiff metal bristles attached to the inside of the cylinder scrapes across the outer surface of the screen as the cylinder is rotated. This continuous scraping vibrates the screen allowing the dust to fall evenly through the plasma column. The fallen dust which collects at the bottom of the cylinder is then recirculated.

The dust used is hydrated aluminum silicate (kaolin) of various sizes and shapes. The screen limits the dispensed grain sizes to < 100 μm. Approximately 90% of the grains have sizes in the 1–15 μm range, with an average grain size of ~ 5 μm.

The plasma diagnostics is performed by means of a Langmuir probe that also enables us to determine how the negative charge in the plasma is divided between free electrons and negatively charged dust grains. This is accomplished by measuring the decrease of the negative saturation current to the probe when the dust is turned on, relative to the case of otherwise identical conditions but without dust [8,10,11]. The quantity ϵZ (the percentage of negative charge per unit volume which resides on dust grains) is thus obtained, where $\epsilon = n_d/n_i$ is the ratio between dust and ion densities, and Z is the magnitude of the (average) negative grain charge in units of the elementary charge, e. Since the dust is distributed evenly within the cloud, the quantity ϵZ is also rather uniform, with the possible exception of the edges of the plasma column. At the end opposite the tantalum hot plate the plasma column is terminated on a stainless steel disk of 5 cm diameter, which is biased at a constant voltage of +20 V. A resistor of 250 Ω in series with the 20 V power supply allows a measurement of the current to the disk and of its fluctuations.

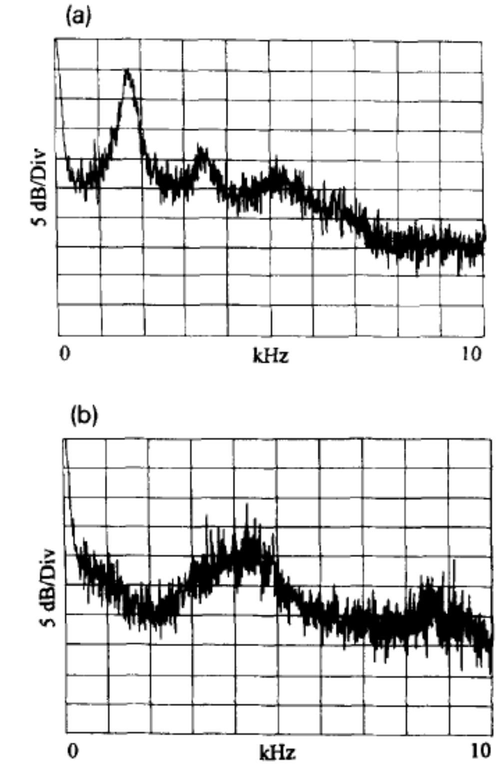

Fig. 2. Frequency spectra of plasma potential oscillations when the cold end disk is biased at +20 V. (a) Potential relaxation instability spectrum when no dust is present. (b) Ion acoustic wave spectrum with dust present ("drum" rotation rate 100% of full rate, $\epsilon Z \approx 0.8$). Frequency scale 0–10 kHz; vertical scale 5 dB/div.

3. Experimental results and discussion

The experiments described in this paper were performed at a plasma density generally in the range 10^6–10^7 cm^{-3}. When a positive bias of ~ 20 V was applied to the end disk, the potential relaxation insta-

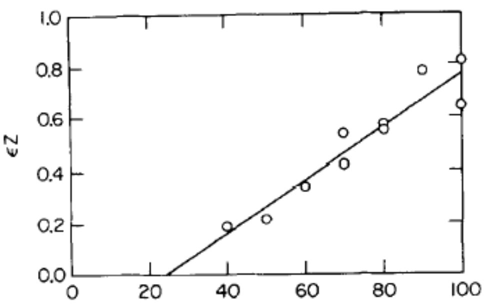

Fig. 3. The quantity ϵZ versus the "drum" rotation rate (in percent of full rate of 180 rpm).

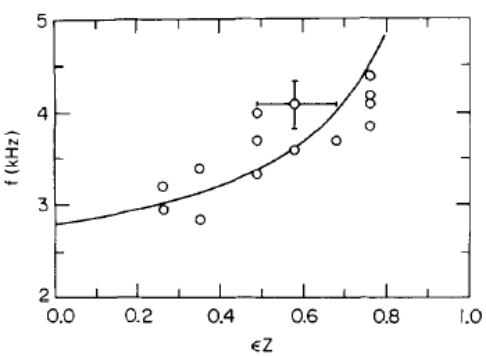

Fig. 4. IA wave frequency versus ϵZ. The circles represent experimental results; the full line is calculated from the dispersion relation in Ref. [6] (Eq. (8)).

bility was excited, with a frequency $f \simeq 1.5$ kHz. Fig. 2a shows a PRI spectrum, taken at a magnetic field of 0.4 T and with no dust in the plasma.

As the dust dispenser is turned on and a sufficient amount of dust is introduced into the plasma, the PRI instability is quenched, while somewhat higher frequency oscillations (Fig. 2b) are generated which, in analogy to the observations of Song et al. [3] in negative ion plasmas, are identified as ion-acoustic (IA) waves. The identification is confirmed by the following results on the variation of the wave frequency with the parameter ϵZ.

At a fixed plasma density, ϵZ could be varied by varying the rotation rate of the dust dispenser ("drum"), larger rotation rates providing a larger dust density. Fig. 3 shows the measured ϵZ versus the "drum" rotation rate (expressed in percent of the maximum rotation rate of 180 rpm). The quantity ϵZ was in each case determined by using a Langmuir probe and the method indicated in Section 2 and more fully discussed in Refs. [8,10,11]. The next step consisted in measuring the IA wave frequency as a function of the "drum" rotation rate. Then, utilizing the straight line in Fig. 3 for ϵZ versus rotation rate, we could express the wave frequency as a function of ϵZ. The experimental points obtained by this method are shown in Fig. 4 by circles. There is a clear increase of the wave frequency from $\lesssim 3$ kHz to ~ 4.5 kHz, as ϵZ increases from ~ 0.25 to ~ 0.8. The full line in Fig. 4 is calculated by using the dispersion relation

$$\frac{\omega}{k} = \left(\frac{\kappa T_\mathrm{i}}{m_\mathrm{i}} + \frac{\kappa T_\mathrm{e}}{m_\mathrm{i}}\frac{1}{1-\epsilon Z}\right)^{1/2},$$

where κ is Boltzmann's constant. It is obtained from Eq. (8) of Ref. [6]. The normalization is used $f = f_0 \simeq 2.8$ kHz for $\epsilon Z = 0$. Typical error bars are shown in Fig. 4, both for ϵZ and for the wave frequency. For ϵZ, the error may be estimated from the scatter of the points in Fig. 3 around the straight line, while the error on the frequency is obtained from IA wave spectra such as that in Fig. 2b. It appears that there is reasonably good agreement in Fig. 4 between calculations and experimental results.

In this experiment we did not attempt to determine, as a function of the ϵZ parameter, the critical electron drift velocity along $\boldsymbol{B}$ required for the IA instability. We nevertheless established that the addition of a substantial amount of negatively charged dust was sufficient, under our experimental conditions, for generating growing ion-acoustic waves. With no dust, these waves would not have been present.

4. Summary and conclusions

We have investigated the effect of negatively charged dust on the potential relaxation instability and the excitation of ion-acoustic waves in a single-ended Q-machine with a positively biased cold endplate.

The main results of our experiments are:

(1) The presence in the plasma of negatively charged dust may entirely eliminate the potential relaxation instability.

(2) Negatively charged dust favors the growth of current-driven ion-acoustic waves. As predicted by

both fluid and Vlasov theory, the wave phase velocity increases monotonically with increasing ϵZ, the percentage of the total negative charge per unit volume which resides on dust grains.

Acknowledgement

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