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Oblique interactions of dust density waves

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Abstract. Self-excited dust density waves (DDWs) are studied in a striped electrode device. In addition to the usual perpendicularly (with respect to the electrode) propagating DDWs, which have been frequently observed in dusty plasma experiments on the ground, a low-frequency oblique mode is also observed. This low-frequency oblique DDW has a frequency much lower than the dust plasma frequency and its spontaneous excitation is observed even with a very low dust density. It is found that the low-frequency oblique mode can exist either separately or together with the usual perpendicular mode. In the latter case, a new mode arises as a result of the interactions between the perpendicular and the oblique modes. The experiments show that these three modes satisfy the wave coupling conditions in both the frequencies and the wave-vectors.

Keywords: dust density wave, wave-interaction, wave-coupling, ion streaming instability
PACS: 52.27.Lw, 52.35.Fp, 52.35.Mw, 52.35.Qz

INTRODUCTION

Dust acoustic wave (DAW) is one of the low-frequency modes involving collective motions of massive charged dust particles in dusty plasmas [1]. DAWs have been studied extensively since early 1990s in both theory and experiment [2, 3, 4, 5, 6, 7, 8, 9]. Large amplitude DAW can be externally excited by modulating voltages on an electrode immersed in the plasma [5]. It can also happen spontaneously under certain experimental conditions, in particular, as a result of the ion-stream instability in the plasma sheath region [10, 11]. In the latter case, the wave is often referred to as a self-excited dust-density-wave (DDW).

Recently, self-excited DDWs have been observed under different experimental conditions [4, 5, 6, 7, 8, 9]. Most experiments showed that the self-excited DDWs propagate along the direction of the ion flow. However, in an experiment under micro-gravity conditions [11], DDW was observed to propagate obliquely to the ion-drift direction. A theoretical model of ion-stream instability was proposed to explain these observations and it showed a transition from wave propagations aligned with the ion flow at low speeds to propagations at an angle when the ion-drift velocity approaching the Bohm velocity [12]. Fortov *et al* pointed out that a finite electric field inside the dust cloud is necessary for the self-excitation of the DDWs, which is consistent with the experimental observations. In addition, it was found [13] that finite dust temperature is also important to interpret the dust density instability. A kinetic theory [14] indicated that it is essential to take into account the finite dust temperature in order to match the theoretical dispersion relations and the experiments. This kinetic theory also showed that, although the

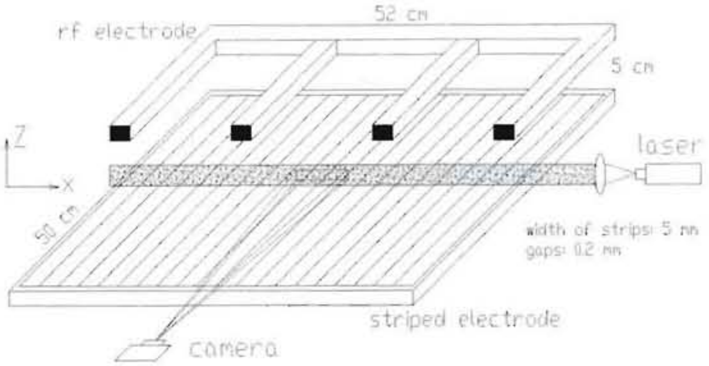

FIGURE 1. The sketch of the striped electrode device.

DAWs experience a strong Landau damping due to the fact that the dust-drift velocity is comparable with the phase velocity of the waves, positive growth rates are still possible in a wide range of conditions because of the strong ion flow. A stability boundary was recently proposed by Merlino [15] based on a one-dimensional fluid model of a current-driven dust acoustic instability. The model also identified the crucial roles of the zeroth-order electric field, which is related to the streaming ions, and the background neutral density, which is determined by the gas pressure, in the spontaneous excitation of DAWs.

We present here the observations of the self-excited DDWs in a recently built striped electrode device [16]. We first show a spontaneous excitation of an oblique mode, which propagates at an acute angle with respect to the ion flow direction. This oblique mode has a much lower frequency than the dust plasma frequency and it was spontaneously excited even with a low dust density. Next, with the increase of the dust density, the DDW mode along the ion flow direction was also self-excited (to be referred to as the perpendicular mode). In particular, by carefully adjusting the dust density, the coexistence of the low-frequency oblique mode and the perpendicular mode has been realized and coupling of different dust density modes is observed.

THE STRIPED ELECTRODE DEVICE

The striped electrode device is a cylindrical chamber with an inner diameter of 80 cm and a height of 40 cm. As sketched in figure 1, two square electrodes with dimensions around 52 cm × 50 cm are mounted horizontally inside the cylindrical chamber and the distance between the two electrodes is set to be around 5 cm. The upper electrode is capacitively coupled to an rf generator and the lower one is segmented into 100 stripes (Only 20 segmented stripes are shown in figure 1 and each stripe has a width of 5 mm and a length of around 49 cm in the horizontal plane.). Further details of the device were described elsewhere [16]. The dust particles are injected, by a dispenser mounted on the top cover plate of the cylindrical chamber, into the discharge area between the rf powered electrode and the striped electrode and are levitated above the striped electrode. The center of the

FIGURE 2. The snapshots of the dust cloud with horizontal (bottom panel) and vertical (top panel) density modulations.The lower bright edge at the bottom of each panel is from the reflection of the lower striped electrode.

dust cloud is illuminated vertically by a red laser with a central wavelength of 680 nm and the dust motion is captured by a charged coupled device (CCD) camera with a spatial resolution of 41 μm/pixel and a speed of 96 frames per second.A Nikon lens with a focal length of 85 mm is used and an interference filter with a bandwidth of 12 nm and a central wavelength of 680 nm is placed between the lens and the CCD in order to eliminate the scattering from the background plasma. The region of interest captured by the CCD camera is defined in the x-z plane with z being the vertical coordinate and x being the coordinate perpendicular to the stripes. In addition, we assume that all the parameters are constant along the longer side of the stripes, i. e., the y-direction. With the current optical arrangement, the camera with a pixel array of 2352×1726 can visualize about 9.4 cm along the horizontal (x-) direction and cover the full range in the vertical (z-) direction.

We present here two typical experimental observations with the same discharge conditions. Besides the above-mentioned parameters, the rf power is 100 Watt, the argon gas is used with a pressure of 8 Pa and a gas flow of 15 sccm, and the dust particles are with a mean diameter of 1 μm and a mass density around 4 $\mathrm{g/cm^3}$.

THE LOW-FREQUENCY OBLIQUE MODE

The self-excited DDWs are normally triggered by three methods. They are by decreasing the pressure of the neutral gas, by increasing the discharging power, and/or by injecting more dust particles. Many experiments showed that there exists a critical dust density for the spontaneous excitation of the DDWs, which is consistent with a recent theory [12]. However, except for one experiment under the micro-gravity conditions [11], all the previous experiments only observed the dust density modulation along the direction of the ion flow, and the DDWs propagate from the bulk plasma region to the deep sheath area adjacent to the electrode. In short, both the electric field and the ion flow align with the propagation direction of DDWs in previous studies.

In our experiments, different DDWs were observed. Before the dust density reached the critical density for the vertical oscillation, it was found that the dust density was modulated along the horizontal direction and a fine wave structure appeared with oblique wave fronts with respect to the lower electrode. The vertical oscillation of the dust particles grew quickly when the dust density reached a critical value and the dust density modulation in the horizontal direction was destroyed as a result. Two snapshots of the dust clouds were presented in figure 2 for two different density modulations. The bottom panel is for the case when the horizontal dust density modulation was observed and the top panel for the case when the dust density was modulated along the vertical direction. Below, these two modes are referred to as, respectively, the low-frequency oblique mode for the DDWs along the horizontal direction and the perpendicular mode for the DDWs along the vertical direction. By averaging the light intensities in the dust region for about 300 frames, it was shown that the dust density ratio between these two cases was about 1.6. During the transition from the low-frequency oblique mode to the perpendicular mode, we did not see a gradual change of the wave propagation direction. It was not likely that the DDWs were changing their propagation directions with the dust density. Spectral analysis showed that these two modes had quite different frequency components. The low-frequency oblique mode had a frequency around 5 Hz and the perpendicular mode had a frequency around 19 Hz. The frequency of the perpendicular mode is quite close to the dust plasma frequency, and can be regarded as an acoustic mode as reported in many publications. Both modes had a similar wavelength around 5 mm. However, the low-frequency oblique mode had quite complicated wave front structures. Two wave fronts were propagating at different angles with respect to the lower electrode and they merged in some regions. The relative amplitudes of the density perturbations for both modes were estimated, assuming that the dust density is proportional to the light intensity. We found that the relative amplitude of the perpendicular mode was around 0.35 and that of the horizontal oblique mode ~ 0.15.

Further experiments indicated that this low-frequency oblique mode existed even for a very low dust density and its amplitude could also be very high under certain conditions. Our experiments also showed a critical dust density for the spontaneous excitation of the perpendicular mode.

OBSERVATION OF THE WAVE COUPLING

As mentioned above, when the dust density is close to the critical density for the spontaneous excitation of the perpenicular mode, the perpendicular mode grows very rapidly and the low-frequency oblique mode is destroyed. However, if we increase the dust density with great caution, the coexistence of these two modes can be realized.

Figure 3 shows an image when the two modes coexisted. Besides the perpendicular mode and the low-frequency oblique mode mentioned already in the last section, a new mode was also observed. For a clearer demonstration, the different modes with different frequencies were decoupled by using the Fourier transform [12]. The spectral analysis of the light intensities showed that the frequencies of the low-frequency oblique mode, the perpendicular mode, and the new mode are respectively in the range of 4-6 Hz, 19-20 Hz, and 14-15 Hz. By averaging the image sequence of the dust cloud in terms

FIGURE 3. One snapshot of the dust cloud with horizontal and vertical modes spontaneously excited simultaneously and a new mode arising from the interaction between the horizontal oblique mode and the vertical mode is also indicated in the image.The lower bright edge at the bottom is from the reflection of the lower striped electrode.

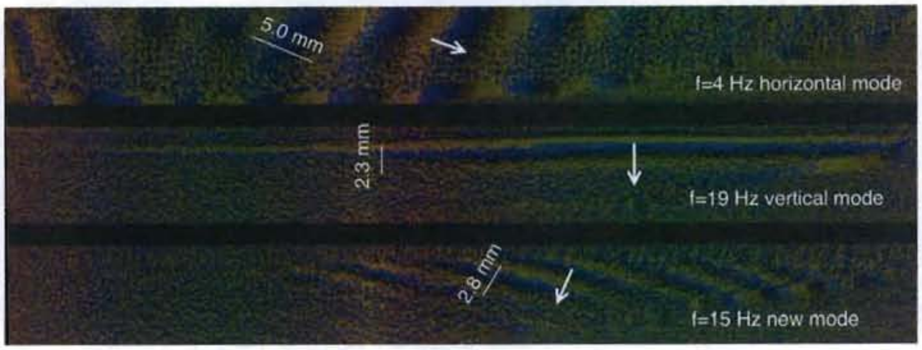

FIGURE 4. The averaged phase maps of different wave modes obtained by the Fourier transform.The length scale in each panel indicates the roughly estimated wave length for each wave structure.

of specified frequencies, the Fourier transform gives the averaged phase distribution of the signal with the frequencies in the full spatial region. In figure 4, the time-averaged phase distributions for three different frequencies, which corresponded to three wave modes, were mapped. It showed not only the coexistence of the low-frequency oblique mode and the perpendicular mode but also a new mode which was generated due to the interactions between these two modes. It was found that both the frequency and the wave vector summation conditions were satisfied within experimental errors.

SUMMARY

In conclusion, the spontaneous excitation of a low-frequency oblique mode was observed in a meter-size rf reactor. Compared with the normal self-excited DDWs shown in the previous experiments, this oblique mode has a frequency much lower than the dust plasma frequency and it can be self-excited even with a dust density below the normal critical density. Under certain conditions, the coexistence of this low-frequency oblique mode and the normal perpendicular DDW is possible. The interaction of the two waves produces a new mode whose frequency and wave-vector are determined by the three-wave coupling conditions.

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REFERENCES

1. N. N. Rao, P. K. Shukla, and M. Y. Yu, *Planet. Space Sci.* **38**, 543-546 (1990).
2. P. K. Shukla and M. M. Mamun, *Introduction to Dusty Plasma Physics*, Institute of Physics Publishing, Bristol and Philadelphia, 2002.
3. G. E. Morfill and A. V. Ivlev, *Rev. Mod. Phys.* **81**, 1353-1404 (2009).
4. J. H. Chu, J.-B. Du, and I. Lin, *J. Phys. D: Appl. Phys.* **27**, 296-300 (1994).
5. A. Barkan, R. L. Merlino, and N. D'Angelo, *Phys. Plasmas* **2**, 3563-3565 (1995).
6. C. Thompson, A. Barkan, N. D'Angelo, and R. L. Merlino, *Phys. Plasmas* **4**, 2331-2335 (1997).
7. V. E. Fortov, A. G. Khrapak, S. A. Khrapak, V. I. Molotkov, A. P. Nefedov, O. F. Petrov, and V. M. Torchinski, *Phys. Plasmas* **7**, 1374-1380 (2000).
8. V. E. Fortov, A. D. Usachev, A. V. Zobnin, V. I. Molotkov, and O. F. Petrov, *Phys. Plasmas* **10**, 1199-1208 (2003).
9. M. Schwabe, M. Rubin-Zuzic, S. Zhdanov, H. M. Thomas, and G. E. Morfill, Phys. Rev. Lett. **99**, 095002 (2007).
10. M. Rosenberg, *J. Vac. Sci. Technol.* **A 14**, 631-633 (1996).
11. A. Piel, M. Klindworth, and O. Arp, *Phys. Rev. Lett.* **97**, 205009 (2006); *ibid*, **99**, 209903(E) (2007).
12. A. Piel, O. Arp, M. Klindworth, and A. Melzer, *Phys. Rev. E* **77**, 026407 (2008).
13. E. Thomas, Jr., R. Fisher, and R. L. Merlino, *Phys. Plasmas* **14**, 123701 (2007).
14. M. Rosenberg, E. Thomas, Jr., and R. L. Merlino, *Phys. Plasmas* **15**, 073701 (2008).
15. R. L. Merlino, *Phys. Plasmas* **16**, 124501 (2009).
16. Y. F. Li, U. Konopka, K. Jiang, T. Shimizu, H. Höfner, H. M. Thomas, and G. E. Morfill, *Appl. Phys. Lett.* **94**, 081502 (2009).
17. I. Pilch, T. Reichstein, and A. Piel, *Phys. Plasmas* **16**, 123709 (2009).