A dusty plasma device for producing extended, steady state, magnetized, dusty plasma columns

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We describe a rotating-drum dust-dispersal device, which we have used, in conjunction with an existing Q machine, to produce extended, steady state, magnetized plasma columns. The dusty plasma device (DPD) is to be used for the investigation of waves in dusty plasmas and of other plasma/dust aspects. The device is capable of generating dusty plasmas in which as much as $\sim 90\%$ of the negative charge is attached to dust grains of 1–10 μm size.

I. INTRODUCTION

"Dusty plasmas" occur in several situations of astrophysical interest,[1] such as nebulas, planetary magnetospheres, and comet tails. A review of dusty plasmas in the solar system has been published by Goertz.[2] Phenomena related to the presence of electrically charged dust grains in the earth's summer mesopause have been discussed by Havnes *et al.*[3]

Dust particles as contamination particles in rf-produced plasmas have been investigated by Carlile *et al.*[4] and Bouchoule *et al.*[5] This type of work is somewhat along the lines of the so-called "colloidal plasma" research reviewed many years ago by Sodha and Guha.[6] A device for the dispersal of micron- and submicron-sized particles in a vacuum has been described by Sheehan *et al.*[7] and used by them in conjunction with the alkali plasma of a Q machine.[8,9] Several aspects of the physics and technology of dusty plasmas were addressed at the Fourth Workshop on Dusty Plasmas held at the University of Iowa, Iowa City, Iowa on September 11–13, 1990 (U. of Iowa Report, Goertz, ed., 1990).

In the present paper we describe a rotating-drum dust-dispersal device, which we have used in conjunction with an existing Q machine to produce an extended, steady state, magnetized, dusty plasma which may be suitable to the investigation of wave properties[10–12] and, possibly, of other plasma/dust aspects. Section II contains a description of the plasma device and of the rotating-drum, dust-dispersal setup, while Sec. III reports on the diagnostics of the dusty plasma. Section IV contains a discussion.

II. THE DUSTY PLASMA DEVICE

Our dusty plasma device (DPD) utilizes, as the basic plasma source, a Q machine[8,9] in which a potassium plasma column of ~ 4 cm diam and ~ 80 cm long is produced by surface ionization of potassium atoms from an atomic beam oven. The atoms are ionized on a tantalum surface which is heated by electron bombardment to a temperature of 2500 K. The surface is, thus, hot enough to emit large amounts of thermionic electrons which, together with the K^+ ions, form the basic constituents of the plasma. In the normal operation of a Q machine, the plasma density, n, is generally in the range $10^7 \leqslant n \leqslant 10^{11}$ cm^{-3}, with ion and electron temperatures $T_i \approx T_e \approx 0.2$ eV. The neutral gas pressure is, typically, in the low 10^{-6} Torr range, so that the mean-free-paths for ion–neutral or electron–neutral collisions are larger than the machine length. By contrast, at a plasma density $n \approx 10^{10}$ cm^{-3}, the mean-free-path for ion–ion collisions is ~ 10 cm.

The plasma column is surrounded, over a portion of its length, by a metallic cylinder ("drum") coaxial with the plasma (Fig. 1). On the inside, over a length of 30 cm, the cylinder has a number of rings, of 5 cm ID, and a thin cylindrical grid (mesh size 60 lines/in.), which together provide a number of "slots" into which dust is poured before the vacuum vessel of the Q device is pumped out [Figs. 2(a) and 2(b)]. The cylinder can be rotated around its own axis by an external motor, the rotation rate of the cylinder being variable continuously up to 180 rpm. As the drum rotates, dust is carried up above the plasma column and allowed to fall through it. A continuous dust recycling takes place, providing within the plasma column an amount of dust which depends, for a fixed initial loading of the "slots," on the rotation rate of the dust chamber. After the initial loading, several days of operation are possible before the dust chamber is reloaded.

An important feature of this dust chamber setup is that it provides a dusty plasma which, in addition to being steady state and magnetized, is also rather extended (linear dimensions of ~ 4 cm diam and ~ 30 cm length). In this last respect, our dusty plasma is different from that described by Sheehan *et al.*,[7] where dust is allowed to fall from a dust "shaker" over regions of only ~ 1 cm linear size.

Two types of dust have been used in our experiments: Al_2O_3 (nominal grain size 0.3 μm) and kaolin (hydrated aluminum silicate, $Al_2Si_2O_7nH_2O$). Electron microscope pictures of kaolin dust grains are shown in Figs. 3(a) and 3(b), while Fig. 4 presents a histogram of the size distribution of the kaolin grains. As can be seen, most grains have sizes smaller than ~ 20 μm, although larger grains are also present, a few with dimensions as large as ~ 100 μm.

In our experimental setup the dominant charging process of the dust grains is expected to be a collection of charged particles (K^+ ions and electrons) from the

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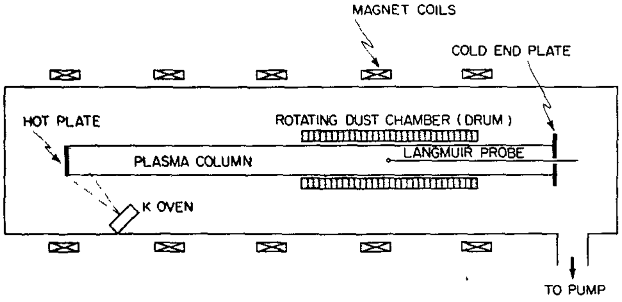

FIG. 1. Schematic diagram of the experimental setup, showing the *Q*-machine plasma column surrounded, over a portion of its length, by the rotating dust chamber ("drum").

plasma. Thus, the situation of a dust grain is similar to that of an electrically floating Langmuir probe, which charges up negatively to a potential $V\sim4(\kappa T_e/e)$ in a K^+ plasma. To estimate the charge state of a dust grain we may view the grain as a small sphere of radius a, although Fig. 3(b) provides clear evidence that a spherical shape is not the most common for kaolin dust. A sphere of radius a has a capacitance $C=4\pi\epsilon_0 a$. Then the charge on the grain, $Q=CV$, will be on the order of 5.5×10^3 elementary charge units for $a=10\ \mu\mathrm{m}$ and $\kappa T_e=0.2$ eV.

Another important quantity to consider is the time required for an uncharged dust grain to charge up to nearly equilibrium potential, $4\kappa T_e/e$. This time, τ, is on the order of Q/I, where I is the charging current which, initially, is $\sim 4\pi a^2 env_{e,\mathrm{th}}$, where $v_{e,\mathrm{th}}$ is the electron thermal speed, $\sim2\times10^7$ cm/s. If $n\approx10^5\ \mathrm{cm}^{-3}$ (see Sec. III), we find, for a grain with $a=10\ \mu\mathrm{m}$, that $I=4\times10^{-12}$ A. Thus, $\tau=Q/I=2\times10^{-4}$ s. Since the fall speed of a dust grain through the plasma is estimated to be ~1 m/s, it appears that at this plasma density, the grains attain their equilibrium charge while falling within a very thin layer at the top portion of the plasma column.

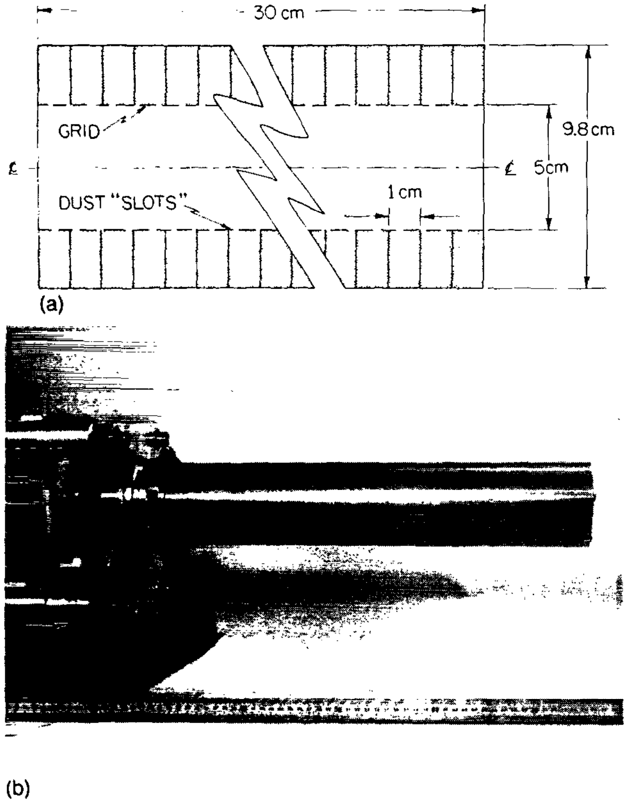

FIG. 2. (a) Schematic diagram of the rotating dust chamber (drum) and (b) photograph of the drum.

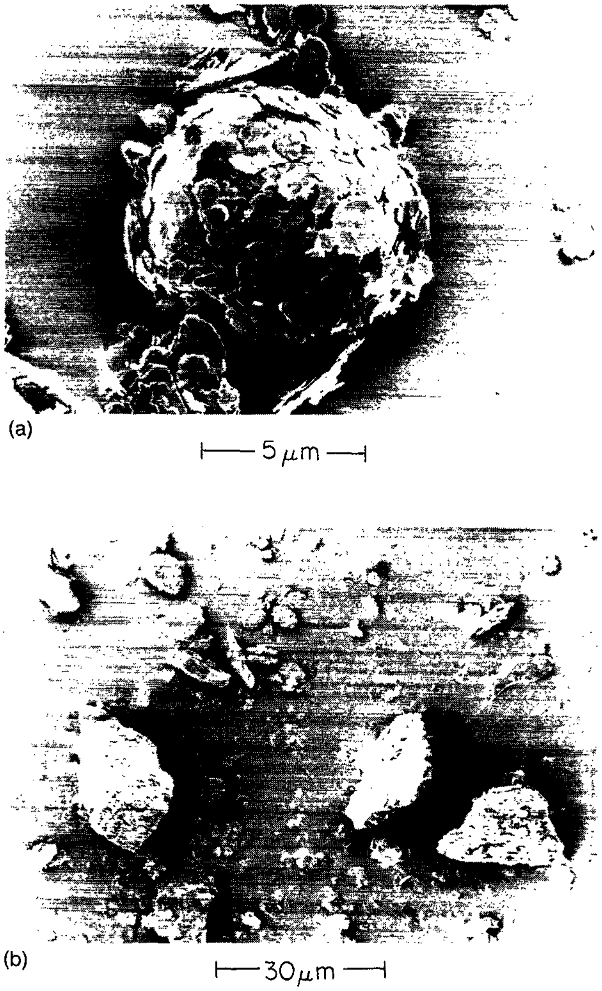

FIG. 3. (a) and (b) Electron microscope pictures of kaolin dust.

Finally, from a comparison of the various forces which may act on a typical kaolin dust grain in the plasma, we find that gravity is by far the most prominent. It is larger, by a few orders of magnitude, than electric and Lorentz

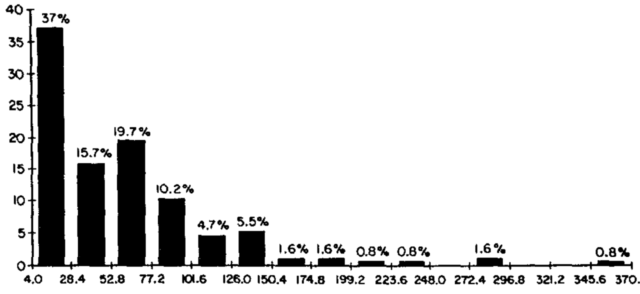

FIG. 4. The size distribution of the kaolin dust.

forces, the force from the radiation emitted by the tantalum hot plate of the Q device, and also the drag force exerted by the K^+ plasma flowing away from the hot plate.

This completes the description of the DPD. In the next section we describe the measurements we performed on the dusty plasma and the results we obtained.

III. DIAGNOSTICS OF THE DUSTY PLASMA

The main diagnostic tool of the dusty plasma consists of a Langmuir probe moveable along the axis of the plasma column (see Fig. 1) and made of a tantalum disk, 0.5 cm in diameter, oriented normally to the axis and the magnetic field. In the dusty plasma, the probe needs to be cleaned fairly often. An internal and retractable steel-wool brush was used to periodically clean the probe surface.

The way the probe is used to obtain information on the dusty plasma (in particular, on how the negative charge is divided between free electrons and negatively charged dust grains) is the same as used previously[13] in plasmas with appreciable fractions of negative ions. With dust present, the negative saturation current, J_- (dust), to a positively biased probe is smaller than the current measured with no dust, J_- (no dust). This reduction in the saturation current is due to the attachment of electrons on grains of extremely low mobility. The percentage of negative charge on free electrons in the dusty plasma $en_e/(en_e+QN)$, where N is the dust density and n_e the free electron density, is then given by $\eta=J_-(\text{dust})/J_-(\text{no dust})$, if the positive ion concentration is the same with and without dust. If the dust appreciably reduces also the positive saturation current, J_+, to the negatively biased probe, the parameter η which characterizes the charge state of the dusty plasma is

$$\eta=\frac{J_-(\text{dust})}{J_-(\text{no dust})}\,\frac{J_+(\text{no dust})}{J_+(\text{dust})}\,.$$

The dependence of the parameter η on variables such as plasma density, rotation rate of the dust chamber, and distance of the probe along the axis of the column, is described next.

Let n be the plasma density inside the dust chamber (on axis), when the chamber is not rotated and, thus, the plasma has no dust. For a given dust loading of the slots and a given rotation rate of the drum (which, together, determine the concentration of the dust) Fig. 5 shows the variation of η with the plasma density, n. At high n the parameter η is nearly constant and close to unity, as the negative charge attached to the dust grains is only a very small fraction of the total negative charge in the plasma. As n is decreased, the negative charge on the grains remains nearly constant, since the concentration of the grains is unchanged and the charge on each grain is always on the order of $Q=4\pi\epsilon_0 a(4\kappa T_e/e)$, where a is some linear dimension of a typical grain (see, however, Sec. IV for further discussion). Therefore, at the lower n's, the parameter η must decrease.

For a fixed n, η varies with r, the rotation rate of the dust chamber (expressed as a fraction of the maximum rotation rate of 180 rpm), as shown in Fig. 6(a). Evidently, as r is increased from $r=0$ the amount of dust in the plasma must initially increase. However, an increase of r above ~ 0.7 appears to produce a decrease in the concentration of dust and, therefore, a return of η to near unity. This behavior of η at $r=0.7$, is presumably due to the fact that at this r the centrifugal force on the dust grains at the inner surface of the dust chamber effectively balances the

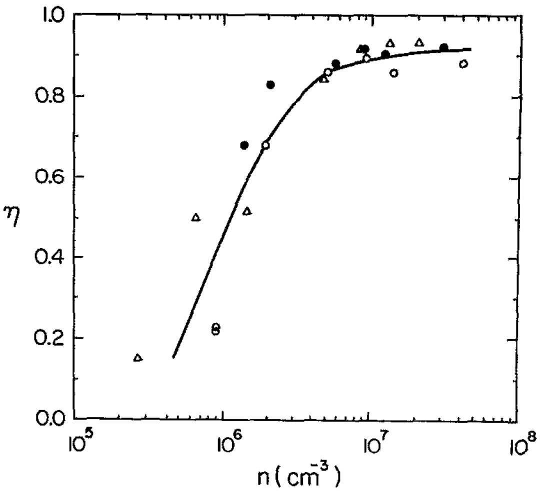

FIG. 5. The fraction of negative charge on free electrons, η, vs the plasma density, n, for a fixed dust density (kaolin dust).

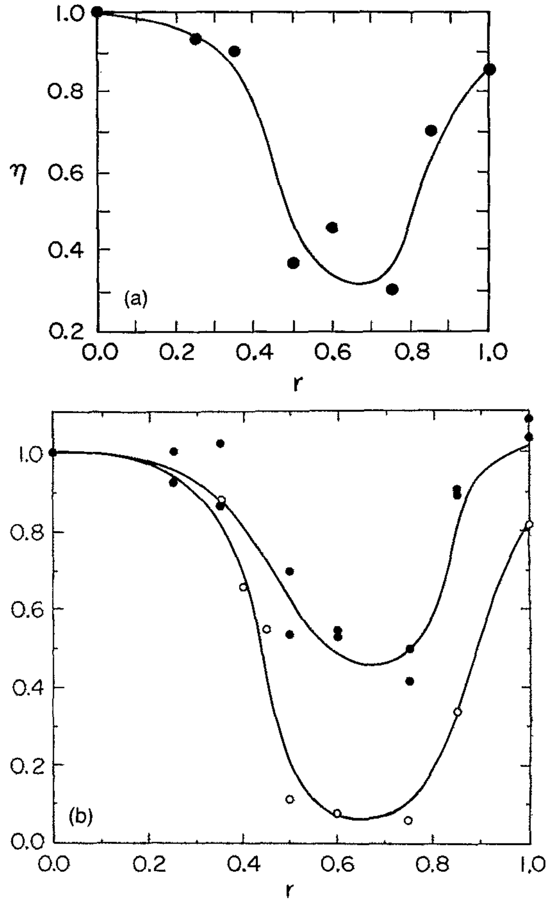

FIG. 6. (a) η vs r, the rotation rate of the drum, for $n=3.5\times10^5$ cm^{-3} (kaolin dust). (b) η vs r, for two different values of n. Dots, $n=7\times10^5$ cm^{-3}; circles, $n=2\times10^5$ cm^{-3} (kaolin dust).

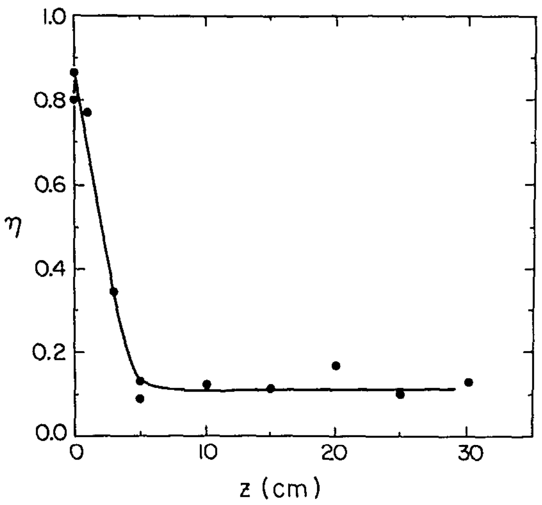

FIG. 7. η vs z, the axial distance of the Langmuir probe from one end of the dust chamber (kaolin dust).

force of gravity on the grains, i.e., $m_d\omega^2 R = m_d g$, where m_d is the mass of a dust grain, ω the angular speed of the dust chamber, R its inner radius, and g the acceleration of gravity. Figure 6(b) shows two curves of η vs r obtained at two different plasma densities. At the lower n, η drops to values less than ~ 0.1, whereas at the higher n, the minimum η is ~ 0.5. This behavior is in agreement with the results shown in Fig. 5.

A third interesting type of result is the variation of η with the axial distance of the Langmuir probe, z, along the dust chamber, $z=0$ corresponding to the chamber end closer to the tantalum plate. In the example of Fig. 7, η decreases from unity to ~ 0.1, over a distance of ~ 5 cm and then stays approximately constant over a distance of ~ 25 cm.

The results on diagnostics of a dusty plasma shown in Figs. 5 through 7 were obtained by using kaolin as the dust. As an example of results obtained with a different dust type (Al_2O_3, of nominal dust size of 0.3 μm), Fig. 8 shows the variation of η with the dust chamber rotation rate, r. Figure 8 may be compared with Fig. 6, obtained with kaolin dust.

IV. DISCUSSION

A rotating-drum dust-dispersal device, used in conjunction with an existing Q machine, has been described as a means of producing a dusty plasma of large enough dimensions that a variety of plasma experiments may be conducted.

Data such as those in Figs. 5 and 6 indicate that dusty plasmas can be produced in which the fraction of negative charge on free electrons can be made as small as $\sim 10\%$.

In discussing the data in Fig. 5, it was assumed (Sec. III) that, as the plasma density n is varied, the charge on each dust grain remains the same. This is only approximately true, however. When the distance, d, from a grain to its nearest neighbor is smaller than the Debye length, λ_D, the charge on each grain is not as large as in the case in which $d \gg \lambda_D$.

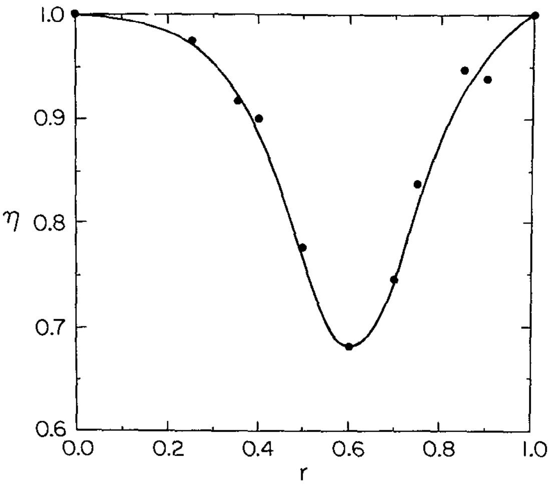

FIG. 8. η vs r, for aluminum oxide (Al_2O_3) dust, of nominal size 0.3 μm.

From the data in Fig. 5 the concentration, N, of dust grains provided by the rotating drum can be estimated, if the average size of the dust grains (and, thus, their negative charge) is known. For kaolin dust, typically, $N = 1\text{–}5 \times 10^2$ cm^{-3}, which translates into an average distance of a dust grain from its nearest neighbor of $d \sim 1/N^{1/3} \sim 0.1$ cm.

At a plasma density $n = 10^7$ cm^{-3}, the Debye length in a Q-machine plasma is $\lambda_D = 0.1$ cm. Therefore, for $n < 10^7$ cm^{-3} and with the above dust density, the situation is similar to that depicted in Fig. 4 of Goertz,[2] which illustrates the effects of placing the grains close to each other. The parameter P discussed by Goertz[2] has values $> 10^{-10}$ which, according to Goertz, implies important dust-plasma collective effects (see his Fig. 5 and associated discussion).

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