Residual dust charges in an afterglow plasma

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Abstract. An on-ground measurement of dust particle residual charges in the afterglow of a dusty plasma was performed in a rf discharge. An upward thermophoretic force was used to balance the gravitational force. It was found that positively-charged, negatively-charged and neutral dust particles coexisted for more than one minute after the discharge was switched off. The mean residual charge for 200 *nm* radius particles was measured. The dust particle mean charge is about $-5e$ at pressure of 1.2 *mbar* and about $-3e$ at pressure of 0.4 *mbar*.

Keywords: Discharging, dust, plasma, residual charges, afterglow
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INTRODUCTION

Dusty or complex plasmas are partially ionized gas composed of neutral species, ions, electrons and charged dust particles. In laboratory experiments, these particles can be either injected or grown directly in the plasma. Injected dust particles are usually micron-size particles. And with their small mass, they can be confined near the electrode where the electric force counterbalance with gravity. Microgravity condition is necessary to study dust clouds of micrometer size particles filling the whole plasma chamber [1]. In laboratory, dense clouds of submicron particles light enough to completely fill the gap between the electrodes can be obtained using reactive gases such as silane [2] or using a target sputtered with ions from plasma [3, 4, 5, 6]. Dust particle charge is a key parameter in complex plasma. It determines the interaction between a dust particle with electrons, ions, its neighboring dust particles, and electric field. The determination of the dust particle charge is so one of the basic problems in any complex plasma experiments. The knowledge of dust charge will allow us to understand the basic properties of dusty plasma, particle dynamics in dust clouds, and methods to manipulate the particles.
In this paper, we report the first on-ground experiment on the residual charges of dust particles after decay of a dusty plasma. The experiment was performed in the PKE-Nefedov reactor where the dust particles were physically grown in discharge chamber. It was found coexistence of positively and negatively charged dust as well as and non-charged dust for more than one minute after the discharge was switched off. The residual charges for 200 *nm* radius particles have been measured for two different pressures. It was revealed that dusts kept the residual charges only when the discharge was abruptly switched off. In the case when the discharge power is decreased slowly until the plasma disappeared, there was no residual charge on dust particles.

EXPERIMENTAL PROCEDURE AND RESULTS

The work presented here is performed in the PKE-Nefedov (Plasma Kristall Experiment) chamber designed for microgravity experiments [1]. It is a rf discharge operating in push-pull excitation mode. It consists of 4 *cm* diameter parallel electrodes separated by 3 cm. The injected power varies in the range $0-4$ *W*. Dust particles are grown in an argon plasma ($0.2-2$ *mbar*) from a sputtered polymer layer deposited on the electrodes and coming from previously injected dust particles (3.4 μm, melamine formaldehyde). A detailed description of this experiment and previous results are presented in Ref [1, 4, 3]. For the study concerning residual charges, the top electrode was cooled. An upward thermophoretic force was applied to dust particles in order to counterbalance gravity [7] when a plasma is off. In order to study particle charges, a sinusoidal voltage produced by a function generator with amplitude ± 30 *V* and frequency of 1 *Hz* was applied to the bottom electrode. Induced low frequency sinusoidal electric field $E(r,t)$ generated

dust oscillations if they kept a residual electric charge. A thin laser sheet perpendicular to the electrodes illuminates dust particles and the scattered light is recorded at 90° with standard charge coupled device (CCD) cameras with 25 images per second. Video signals were transferred to a computer via a frame-grabber card with 8 bit gray scale and 560×700 pixel resolution. In order to avoid edge effect, a field of view over $8.53 \times 5.50\ mm^2$ restrained to the center of the chamber is used for residual charge measurement. By superposition of video frames particles trajectories have been obtained. The coordinates of the particles were measured in each third frame. The amplitude of the oscillations was figured out from the measured particle positions. Absolute values for the oscillation amplitude were obtained by scaling the picture pixels to the known size of the field of view.
From the measurement of oscillation amplitude, the residual charge on a dust particle can be obtained. As the gravity is compensated by the thermophoretic force, the equation of motion for one dust particle, neglecting its interactions with other dust particles, can be reduced to:

$$m_d \ddot{z} = F_E(z,t) - F_{nd}(\dot{z}) \tag{1}$$

Taking $E(t) = E_0(z_{mean})\cos(\omega t)$ (the amplitude of the electric field E_0 is the one at the mean dust levitation height z_{mean}), the amplitude b of a dust particle oscillation can be obtained and thus the residual charge can be derived:

$$Q_{d_{res}} = m_d b(\omega, Z_d, E_0(z_{mean}))\omega\sqrt{\omega^2 + 4\gamma^2/m_d^2}/E_0(z_{mean}) \tag{2}$$

where $\gamma = (4/3)\sqrt{2\pi} r_d^2 m_n n_n v_{Tn}(1 + \alpha_{ac}(\pi/8))$ is the damping coefficient and $\omega = 2\pi f$ where f is the frequency imposed by the function generator. Oscillation amplitudes up to 1.1 *mm* have been measured (depending on the operating pressure) and charges from $-12e$ to $+2e$ for a pressure of 1.2 *mbar* and from $-6e$ to $+2e$ for a pressure of 0.4 *mbar* are deduced. It has been found that at high pressure dust particles keep a higher mean residual charge ($-5e$ compared to $-3e$) with error bars of $2e$ for each measurement.

DISCUSSION

The charging (discharging) process of dust particle in a plasma is governed by the contributions of all currents entering (or leaving) the dust surface, involving the plasma electron and ion currents, photoemission and thermionic emission current, etc.... In the most cases for discharge plasmas we can ignore the emission current and kinetics of the particle charge can be expressed as:

$$dQ_d/dt = J_i - J_e = -\pi e r_d^2 [n_e v_{T_e} e^{-\varphi} - n_i v_{T_i}(1 + \tilde{T}_e \varphi)] \tag{3}$$

where J_e and J_i ere the flux of electrons and ions onto the particle, $v_{T_{i(e)}} = \sqrt{8k_B T/\pi m_{i(e)}}$ the thermal velocity of ions (electrons), $\tilde{T}_e = T_e/T_i$, $n_i(e)$ is the density of ions (electrons) and $\varphi = e^2 Z_d/4\pi\varepsilon_0 k_B r_d T_e$ is the dimensionless surface potential of a dust particle. According to Eq.3, charge on dust particle depends on the electron-ion masses, temperatures and density ratios m_e/m_i, n_e/n_i, T_e/T_i. Thus to analyze the discharging of dust particle in afterglow plasma one need to consider the kinetic of plasma decay.
The plasma diffusion loss and electron temperature relaxation determine kinetics of the discharge plasma decay [8]. In presence of the dust particles plasma loss is due to diffusion onto the walls added by surface recombination on dust particles. Plasma density and electron temperature are exponentially decaying in the afterglow [8, 9]: with τ_L the time scale of the plasma loss, and τ_T is the time scale for electron temperature relaxation. The expressions for the time scales are given [10].
For the charging time scale less then plasma decay or temperature relaxation time scales the charge on dust particle is equilibrium, (ion and electron flux balance each other) $\varphi \simeq \varphi_{eq}$ and using Eq.3, φ_{eq} is given by:

$$(n_e/n_i)\sqrt{\tilde{T}_e} e^{-\varphi_{eq}} = \sqrt{(m_e/m_i)}(1 + \tilde{T}_e)\varphi_{eq} \tag{4}$$

In this case the expression for charge fluctuations and the charge fluctuation time scale are:

$$dQ_d/dt \simeq -(Q_d - Q_{deq})/\tau_Q \quad \text{with} \quad \tau_Q^{-1} \simeq v_{T_i} r_d/(4\lambda_{i0}^2)(1 + \varphi_{eq})\tilde{n} \equiv \tilde{n}/\tau_Q^0 \tag{5}$$

where τ_Q is the time scale for dust charge fluctuations and $\lambda_{i0} = \sqrt{k_B T/4\pi\varepsilon_0 n_0 e^2}$ is the initial ion Debye length.
The time scale for dust charge fluctuations strongly depends on plasma density and can vary from microsecond for

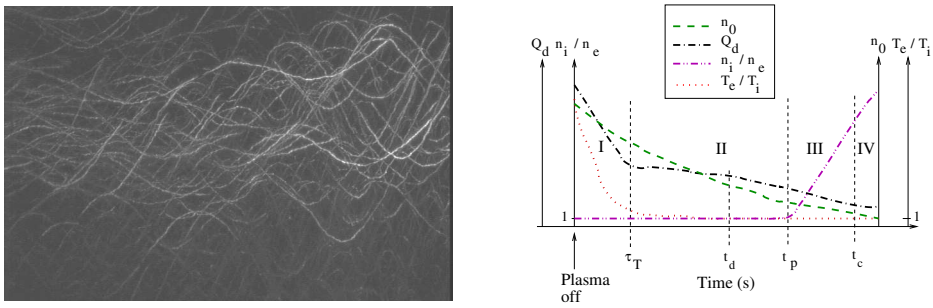

FIGURE 1. Right: Superimposition of video frames. Left: Qualitative time evolution of dust charge, plasma density and electron temperature at the afterglow Four stages of the dust plasma decay can be identified: I - temperature relaxation stage up to t_T II - plasma density decay stage up t_p, III- dust charge volume stage t_c, IV - frozen stage.

initial stages of plasma decay up to seconds in case of almost extinct plasma. Taking into account Eq.5, the time dependence of τ_Q can be expressed [10]

$$\tau_Q^{-1} = (\tau_Q^0)^{-1} exp(-t/\tau_L) \tag{6}$$

To understand the dusty plasma decharging dynamic we have to compare different time scales. It can be seen that the initial charge fluctuation time scale is the shortest, the temperature relaxation time scale is shorter or become shorter (for 0.4mbar) than the plasma decay time scale, and plasma losses mainly determined by the diffusion. The latest means that for condition given dust particle did not effect plasma decaying at initial stage.

The fig.1 presents the qualitative dependence of the main plasma and dust parameters in the afterglow. As we can see the fist stage of the plasma decay ($t < \tau_T$) is characterized by the electron temperature T_e drop down to the room temperature, while the plasma density (especially in case $\tau_T^0 < \tau_L^0$) is slightly decreased. As the charging time scale almost independent on $\tilde{T}_e$ (Eq.5), the charge is still determined by its equilibrium value (Eq.3). During the temperature relaxations stage the particle charge should decrease to the value:

$$Q_{rT} = (1/\tilde{T}_{e0})((\varphi_{eq}(1)/\varphi_{eq}(\tilde{T}_{e0})))Q_0 \simeq Q_0/62 \simeq -15e \tag{7}$$

where Q_0 is initial the dust charge in the plasma and Q_{rT} the value of dust residual charge at the end of first decay stage. The dust charge in the plasma Q_0 was estimated as $Q_0 = -950e$ solving numerically the equation 4, with given parameters $T_i = 300\ K$ and $T_e \simeq 3\ eV$, for the argon plasma with $n_i = n_e$. At the next stage of decay electron temperature is stabilized while the plasma density is still decreasing (see fig 1). So τ_Z continue increasing according to Eq.3 and Eq.5. When τ_Z becames comparable to τ_L, the particle charge can not be considered as equilibrium and to determined particle charge we should use the Eq.3. The time scale when the particle charge starts sufficiently deviated from the equilibrium can be estimated as

$$t_d \sim \tau_L^\infty \ln(((\lambda_{i0}/\Lambda)^2 \cdot (l_{in}/r_d)) \sim 6\tau_L^\infty \tag{8}$$

However as long as plasma is neutral ($n_e = n_i$) the charge on dust particle does not change. The plasma will keep quasineutrality until the decaying rates for the electrons and ions are same. It will be true in the case of ambipolar diffusion. When the nature of diffusion changed the electrons and ion start diffuse independently that will lead to changing n_e/n_i ratio and consequently the dust charge.

The nature of the plasma diffusion changed when the plasma screening length becomes comparable to the chamber size or when the particle volume charge can not be ignored. In latest case the ion diffusion will be influenced by the negatively charged dust particle, while the electrons will free to go. The influence of the overall particle charge is determined by the value of Havnes parameter $P_e = NZ_d/n_e$. The initial value of P_e is small (~ 0.06 with $N = 2 \cdot 10^5 cm^{-3}$) and $n_{e0} = n_0 = 5 \cdot 10^9 cm^{-3}$) and there is no influence of dust. At the first stage of decaying (temperature relaxation stage) P_e decreases due to dramatic decreasing of dust charge while the plasma density did not change much. At τ_T, P_e reach it minimum value. After this P_e starts increasing. During this stage charge on dust changing slowly while plasma number density decays fast (see Fig.1). P_e becomes ~ 1 at

$$t_p \sim \tau_L^\infty \ln(((T_{e0}/T_n))((n_0/(ZN_0))) \sim 8\tau_L^\infty \tag{9}$$

The screening length becomes comparable to the chamber size, i.e. $\lambda_i(\tilde{n}_c) \sim \Lambda$ when the density drops down to $\tilde{n}_c = \lambda_{i0}^2/\Lambda^2$. This occurs at

$$t_c \sim \tau_L^\infty \ln \tilde{n}_c^{-1}. \tag{10}$$

At this time the electrons starts run away faster then ions and the ratio n_i/n_e grows. For our experimental condition $t_p < t_c$, thus the neutrality violation due to presence of dust particles happens before Debay length exceeds the chamber size. So the third stage of dusty plasma decay starts at t_p. During this stage the charge on dust particle is changed due to charging of n_e/n_i ratio. At this stage $t_d < t_p$, thus the kinetic Eq.3 should be used for estimations of the charge variation. The upper limit of the charge change can be estimate ignoring the electron current and considering the time interval between t_p and t_c,

$$dQ_d/dt < J_i \Big|_{t_p}^{t_c} \simeq \pi e r_d^2 n_i(t_p) v_{T_i} (1 - (e/(4\pi\varepsilon_0 k_B r_d T_i)) Q_d) \Big|_{t_p}^{t_c} \tag{11}$$

Solving Eq.11, the charge should evolve following:

$$Q_d = (Q_{dT} - (1/\alpha)) \exp(-K\alpha\Delta t) + (1/\alpha) \tag{12}$$

where $\alpha = e/4\pi\varepsilon_0 k_B r_d T_i \sim 0.28/e$, $K = \pi e r_d^2 n_i(t_p) v_{T_i} \sim 190e$, and thus $(K\alpha)^{-1} \sim 20\ ms \sim \Delta t = (t_c - t_p)$.
Therefore, the charge during the third stage decreases to $-4e$. At the forth stage of plasma decay, $t > t_c$, the plasma density decreased such that any further changes of dust became impossible and dust charge keep constant for a while. Thus the final residual charge for our condition is expected to be about $Q_{d_{res}} \sim -4e$ which is well correlated with the charges measured in the experiment.

CONCLUSION

Residual dust particle charges have been measured in the late afterglow of a dusty plasma. Positive, negative and non-charged dust particles have been detected. Mean residual charge for 200 *nm* radius particles was measured. The particle charge is about $5e$ at pressure of 1.2 *mbar* and about $3e$ at pressure of 0.4 *mbar*. A model for the dusty plasma decay was exploited to explain the experimental data. According this model the dust plasma decay occurring in four stages: temperature relaxation stage, density decay stage, dust charge volume stage, and frozen stage (ice age IV). The main decreasing of the dust charge happens during the first stage due to cooling of the electron gas. The final residual charge established during the third stage when the density of ions exceeds the density of electrons and the plasma density is still high enough to vary the charge. Measured values of the dust residual charges are in a good agreement with values predicted by the model. However the residual charge dependence on discharge condition and detection of positively charged particle show that more detailed model taking into account various phenomena (electron re-heating, electron release, afterglow chemistry) in decaying plasma have to be developed for better understanding of dust plasma afterglow.

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