33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.30I, P-4.042 (2006)

Residual electric charges on dust grains at plasma extinction

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Introduction

Complex (dusty) plasmas are partially ionized gases composed of neutral species, ions, electrons and charged dust particles. The experiment was performed in the PKE-Nefedov reactor [1, 2, 3] where dust particles were physically grown by sputtering in discharge chamber. It was found coexistence of positively and negatively charged dust particles as well as non-charged ones 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 residual charges only when the discharge was abruptly switched off. Indeed when the discharge power is decreased slowly until the plasma disappeared, there was no residual charge on dust particles.

Experimental procedure and results

For the study concerning residual charges, the top electrode was cooled down. An upward thermophoretic force was thus applied to dust particles to balance gravity [4] when the plasma is off. In order to study particle charges, a sinusoidal voltage produced by a function generator with amplitude $\pm 30\ V$ and frequency of $1\ Hz$ was applied to the bottom electrode. Induced 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° using standard CCD cameras with 25 frames per second. 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. By superimposition of video frames, particle trajectories have been obtained. Particle coordinates were measured in each third frame. The oscillation amplitude was figured out from the measured particle positions. Absolute values for the oscillation amplitude b were obtained by scaling the picture pixels to the known size of the field of view giving residual charge $Q_{d_{res}}$ on a dust particle:

$$Q_{d_{res}} = m_d b(\omega, Z_d, E_0(z_{mean}))\omega\sqrt{\omega^2 + 4\gamma^2/m_d^2}/E_0(z_{mean}) \qquad (1)$$

where $E_0(z_{mean})$ is the electric field at the dust particle mean height, γ 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 1.2 *mbar* and from $-6e$ to $+2e$ for 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 (decharging) process of dust particle in a plasma is governed by the contributions of all currents entering (or leaving) the dust surface. For discharge plasmas we can ignore the emission current and particle charge kinetics can be expressed as:

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

where $J_{e(i)}$ is electron (ion) fluxes onto the particle, $v_{T_{i(e)}} = \sqrt{8k_B T_{i(e)}/\pi m_{i(e)}}$ the thermal velocity of ions (electrons), $\tilde{T}_e = T_e/T_i$, $n_{i(e)}$ the density of ions (electrons), $\varphi = -eQ_d/4\pi\varepsilon_0 k_B r_d T_e$ the dust particle dimensionless surface potential. According to Eq.2, Q_d depends on m_e/m_i, n_e/n_i, T_e/T_i. To analyze the decharging of dust particle in afterglow plasma one needs to consider the kinetics of plasma decay determined by plasma diffusion loss and electron temperature relaxation [5]. In presence of dust particles, plasma loss is due to diffusion onto the walls and surface recombination on dust particles. Plasma density and electron temperature are exponentially decaying in the afterglow [5, 6] with τ_L the plasma loss time scale and τ_T the electron temperature relaxation time scale [7]. For charging time scale less than τ_L and τ_T the charge on dust particle is in equilibrium, $\varphi \simeq \varphi_{eq}$ and using Eq.2, φ_{eq} is given by:

$$(n_e/n_i)\sqrt{\tilde{T}_e} e^{-\varphi_{eq}} = \sqrt{(m_e/m_i)}(1+\tilde{T}_e)\varphi_{eq} \quad (3)$$

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

where τ_Q is the time scale for dust charge fluctuations and $\lambda_{i0} = \sqrt{k_B T \varepsilon_0/n_0 e^2}$ is the initial ion Debye length. τ_Q depends on plasma density and can vary from microsecond for initial stages of plasma decay up to seconds in case of almost extinct plasma. Taking into account Eq.4, the time dependence of τ_Q can be expressed [7]: $\tau_Q^{-1} = (\tau_Q^0)^{-1} exp(-t/\tau_L)$. The initial τ_Q is the shortest, τ_T is shorter than τ_L, and plasma losses mainly determined by diffusion. This means that dust particles did not affect plasma decay at initial stage. The first stage of the plasma decay ($t < \tau_T$) is characterized by T_e dropping down to the room temperature, while the plasma density

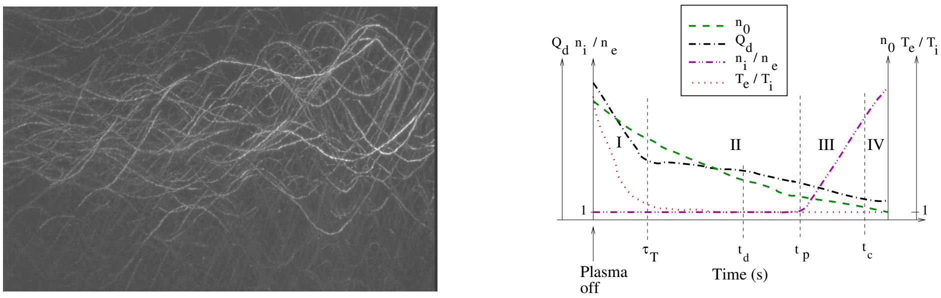

Figure 1: Left: Superimposition of video frames. Right: Qualitative time evolution of dust charge, plasma density and electron temperature during the afterglow Four stages of the dust plasma decay can be identified: I - temperature relaxation stage up to t_T II - plasma density decay stage up to t_p,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

is slightly decreased (fig.1). As τ_Q almost independent on $\tilde{T}_e$ (Eq.4), Q_d is still determined by its equilibrium value (Eq.2). During temperature relaxations stage, Q_d should decrease to:

$$Q_{rT} = (1/\tilde{T}_{e0})((\varphi_{eq}(1)/\varphi_{eq}(\tilde{T}_{e0})))Q_0 \simeq Q_0/62 \simeq -15e \qquad (5)$$

where Q_0 is the initial 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 $Q_0 = -950e$ with $T_i = 300\ K$ and $T_e \simeq 3\ eV$, for the argon plasma with $n_i \simeq n_e$. At the next stage of decay, T_e is stabilized while the plasma density is still decreasing (see fig 1). So τ_Q continue increasing according to Eq.2 and Eq.4. When τ_Q becomes comparable to τ_L, the particle charge cannot be considered as equilibrium and is determined by Eq.2. The time scale when Q_d starts to sufficiently deviate from the equilibrium can be estimated as $t_d \sim \tau_L^\infty \ln(((\lambda_{i0}/\Lambda)^2 \cdot (l_{in}/r_d)) \sim 6\tau_L^\infty$ (the ∞ exponant stands for very long time). However as long as $n_e \simeq n_i$, Q_d does not change. The plasma will keep quasineutrality until the decay rates for the electrons and ions are the same. It will be true in the case of ambipolar diffusion. When the nature of diffusion changed, electrons and ions start diffusing independently leading to n_e/n_i ratio and Q_d variations. It happens when the plasma screening length becomes comparable to the chamber size or when particle volume charge cannot be ignored. In the latest case the ion diffusion will be influenced by the negatively charged dust particles, while the electrons will be free to go. This influence is determined by the Havnes parameter $P_e = NZ_d/n_e$. 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 decay (temperature relaxation stage) P_e decreases due to dramatic decrease of Q_d while the plasma density did not change much. At τ_T, P_e reaches its minimum value. After this, P_e starts increasing. During this stage Q_d changes slowly while plasma number density decays fast (see Fig.1). P_e becomes ~ 1 at $t_p \sim \tau_L^\infty \ln(((T_{e0}/T_n))((n_0/(ZN_0))) \sim 8\tau_L^\infty$. 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 $t_c \sim \tau_L^\infty \ln \tilde{n}_c^{-1}$. At this time, the electrons start to run away faster than ions and the ratio n_i/n_e grows. The neutrality violation due to presence of dust particles happens before Debye length exceeds the chamber size ($t_p < t_c$). So the third stage of dusty plasma decay starts at t_p. Q_d is changed due to changing of n_e/n_i ratio. At this stage $t_d < t_p$, Eq.2 should be used for charge variation estimations. The upper limit of the charge change is between t_p and t_c ignoring J_e: $dQ_d/dt < J_i \Big|_{t_p}^{t_c} \simeq \pi e r_d^2 n_i(t_p) v_{T_i} (1 - (e/(4\pi\varepsilon_0 k_B r_d T_i))Q_d) \Big|_{t_p}^{t_c}$ which gives $Q_d = ((Q_{dT} - (1/\alpha))\exp(-K\alpha\Delta t) + (1/\alpha))$ 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 $-3e$. At the fourth stage of plasma decay, $t > t_c$, the plasma density decreased such that any further changes of Q_d become impossible. Thus the final residual charge for our conditions is expected to be about $Q_{d_{res}} \sim -3e$ which is well correlated with charges measured in the experiment.

Conclusion

Residual dust particle charges have been measured in late dusty afterglow plasma. Positive, negative and non-charged dust particles have been detected. Mean residual charge for 200 *nm* radius particles is about $-5e$ at 1.2 *mbar* and about $-3e$ at 0.4 *mbar*. A model for the dusty plasma decay was exploited to explain the experimental data. This model follows a four stage process: temperature relaxation stage, density decay stage, dust charge volume stage, and frozen stage. 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 ion density exceeds the electron density 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 particles show that a more detailed model has to be developed.

Acknowledgments

The PKE-Nefedov chamber has been made available by the Max-Planck-Institute for Extraterrestrial Physics, Germany, under the funding of DLR/BMBF under Grant No.50WM9852.

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