Dependance of dust residual charge on plasma parameters

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Abstract

The dust residual charge distribution in the late afterglow of a dusty plasma has been measured for different operating pressures. It has been shown that the dust charge distribution can be approximated by gaussian function with mean value close to $-3e$, rms about $1e$ and a tail in the positive charge region. Numerical simulations of the evolution of the dust charge distribution showed that the shape of the charge distribution is very dependent on the transition from ambipolar to free diffusion during the plasma decay process.

Introduction

Dusty or complex plasmas are partially ionized gases 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. Dust particle charge is a key parameter in a complex plasma. It determines the interaction between a dust particle and electrons, ions, its neighboring dust particles, and electric field. The determination of the dust particle charge is one of the basic problems in any complex plasma experiment. Knowledge of the dust charge will allow us to understand the basic properties of dusty plasmas, particle dynamics in dust clouds, and methods of manipulating the particles.

In laboratory discharges, the charging of a dust particle is mainly due to the current of ions and electrons at the dust particle surface [1, 2]. It has been shown that the charge distribution is a gaussian and that the rms of stochastic charge fluctuation varies as $\sigma(Q_d) \simeq \delta\sqrt{Q_d}$, where δ is a parameter depending on plasma condition and close to 0.5 [3, 4, 5, 6, 7].

In decaying complex plasma, the dust particle mean charge as well as the charge distribution evolve with the other plasma parameters such as the plasma density and the electron temperature. It has been shown that in the late afterglow the dust particles do keep a residual charge of few electrons [8]. In [9], more detailed measurements were performed and the presence of positively charged dust particles has been evidenced. Comparison of these data with data from numerical simulations based on the OML equation for the dust particle (de)charging process shows that the transition from ambipolar to free diffusion plays a major role in the dust decharging process.

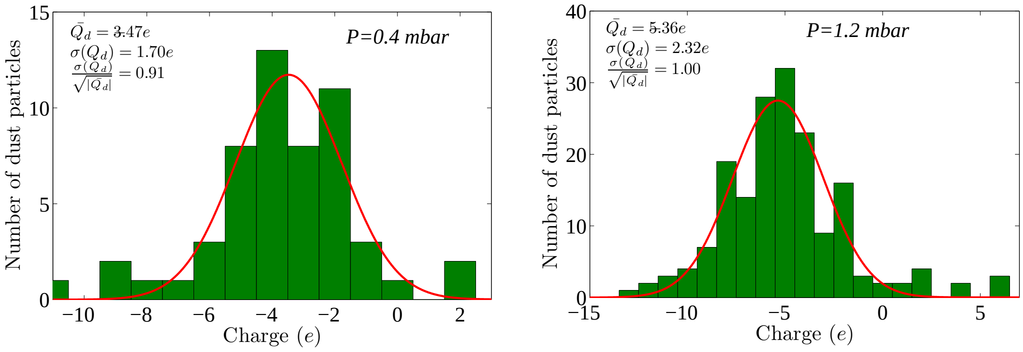

Figure 1: Experimental measurements of residual charges.

Experimental results

Dust particles were grown in an argon plasma ($0.2-2$ *mbar*) from a sputtered polymer layer deposited on the electrodes. The top electrode was cooled. An upward thermophoretic force was thus applied to dust particles in order to counterbalance gravity [10] when the plasma is off. A sinusoidal voltage produced by a function generator with amplitude $\pm 30\,V$ and frequency of $f = 1\,Hz$ was applied to the bottom electrode. The induced low frequency sinusoidal electric field $E(r,t)$ generated dust oscillations if they kept a residual electric charge. The residual charge of the dust particle $Q_{d_{res}}$ had been obtained from the oscillation amplitude b [9]:

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

where m_d is the mass of the dust particle, $E_0(z_{mean})$ is the amplitude of the electric field at the mean height of the dust particle, $\omega = 2\pi \cdot f$ the frequency of the sinusoidal electric field and γ the damping coefficient. The sign of the dust particle charge was deduced from the phase of the dust particle oscillation with respect to the excitation electric field. A more detailled description of this experiment can be found in Ref.[9].

The obtained dust particle charge distributions are presented in Fig.1 for two operating pressures. The mean residual charge is negative and its value is of few electrons for all cases. The rms of the charge distribution is of the same order of magnitude. The coefficient $\delta = \sigma(Q_d)/\sqrt{|Q_d|}$ is about the unity. This value is twice the value in a running discharge where it is close to 0.5 [3, 4, 5, 6, 7].

Simulation

In order to simulate the afterglow of a dusty plasma, the following algorithm is used: plasma losses due to diffusion onto the wall of the reactor are simulate using a 0D fluid model in the

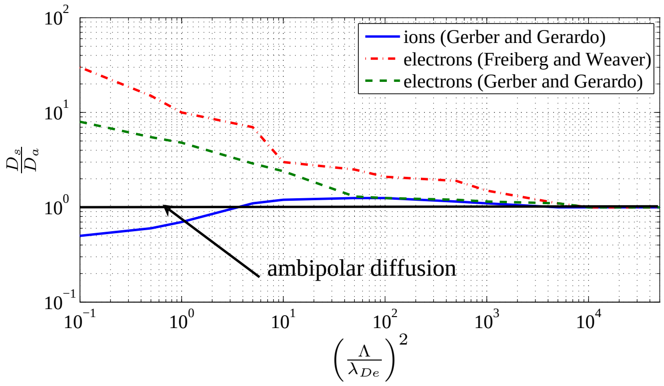

Figure 2: Evolution of the ratio D_s/D_a ($s = i,e$) as a function of $(\Lambda/\lambda_{De})^2$. These data are extracted from Refs.[11] and [12].

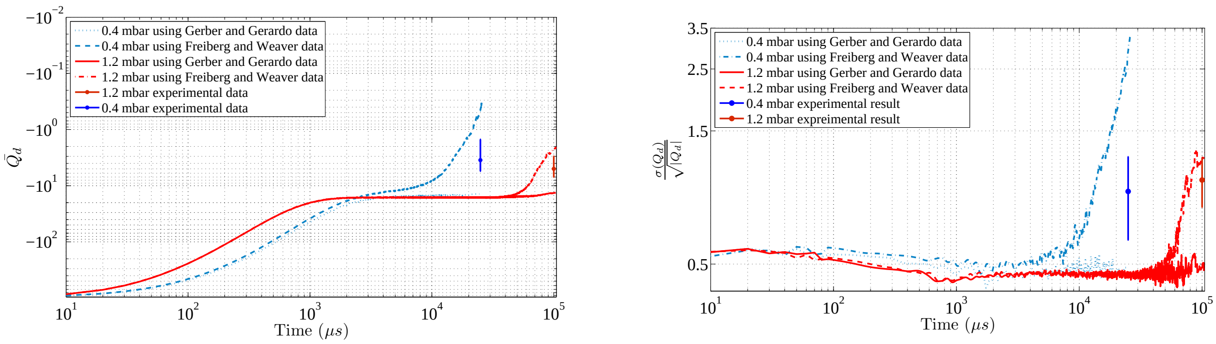

Figure 3: Left: Evolution of the mean charge. Right: Evolution of the ratio $\delta = \sigma(Q_d)/\sqrt{Q_d}$

same way as in a dust free plasma. The transition from ambipolar to free diffusion is taken into account by treating ions and electrons separately and using experimental data from Freiberg and Weaver [12] or Gerber and Gerardo [11] which give the ratio of ion diffusion coefficient D_i and electron diffusion coefficient D_e to the ambipolar diffusion coefficient D_a as a function of the ratio $(\Lambda/\lambda_{De})^2$ where Λ is the diffusion length and λ_{De} is the electron Debye length (Fig.2). The dust particle charge as well as the plasma losses due to recombination onto the surface of dust particles are computed trough a modified Cui and Goree alogorithm [7].

The initial ion density is $n_{i0} = 5 \cdot 10^9 cm^{-3}$ and the initial dust particle charge distribution is computed using a Cui-Goree algorithm [7] and the quasi-neutrality condition: $Z_d n_d + n_e = n_i$ where $Z_d = |Q_d/e|$. The initial temperatures are $T_e = 3\ eV$ and $T_i = 0.03\ eV$. The initial electron density n_{e0} is deduced from this calculation. The obtained mean charge is $\overline{Q_d} = -952e$ and the variance $\sigma(Q_d) = -17e$ leading to $\delta = \sigma(Q_d)/\sqrt{|Q_d|} = 0.55$. These values are typical for laboratory dusty discharges.

As it can be seen in Fig.3, the ambipolar-to-free diffusion speed hardly influences the evolution of the dust particle charges. Slow transition [11] leeds to a high residual charge (in absolute value) with a rms close to 0.5 which is far from experimental data which are closer to residual charge distribution simulated in a fast ambipolar-to-free diffusion case [12].

Conclusion

It has been shown that the dust residual charge distribution is very dependent on the transition from ambipolar to free diffusion. The mean value of the residual charge as well as the width of the distribution are very sensitive to the process. This give us the opportunity to use dust residual charge and dust charge distribution as a diagnostics for afterglow plasma. In particular residual charge measurement can be very useful for experimental study of the transition from ambipolar to free diffusion.

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