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Typical frequency of the macroparticle oscillation in quasi- 2D dusty systems and estimation of some dusty plasma parameters

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Introduction

The dusty plasma represents a good experimental model for studying strongly coupled systems (liquid or solid). Laboratory dusty plasma is an ionized gas containing small grains of solid matter (dust) that becomes electrically charged. Most investigations of dusty plasma use the Yukawa (screened Coulomb) potential of interaction $U = (eZ_p)^2 \exp(-r/\lambda)/r$, where e is the electron charge, eZ_p – the charge of one grain. The properties of such systems with a strong coupling are of interest for the different fields of science [1,2].

Two dimensionless parameters responsible for the mass transfer and phase state in two dimensional (2d-) dissipative systems were found [3-5] for $\kappa = l_p/\lambda < 6$, where $l_p = n^{-1/3}$ is the mean interparticle distance, and n is the particles' concentration. These parameters are: the "screened" coupling parameter $\Gamma^* = 1.5\,(Z_p e)^2\,(1+\kappa+\kappa^2/2)\,\exp(-\kappa)/T_p l_p$, and the scaling factor $\xi = \nu_{fr}^{-1}\, eZ_p\,[2\,(1+\kappa+\kappa^2/2)\,\exp(-\kappa)/(\pi m_p l_p^3)]^{1/2}$, associated with the characteristic frequency ω_{fr} of the particle friction; here T_p is the temperature of particles with the mass m_p.

In earlier works [6] the experimental and numerical analysis of mass transfer processes at the small observation time was performed. In diffusion measurements the ratio of mean square displacement $\langle x^2\rangle$ to the observation time (mass-transfer evolution function $D(t) = \langle x^2\rangle/(2t)$) was calculated. For interacting particles at the small observation times this $D(t)$- function reaches its maximum and then it tends to the constant value that is the diffusion coefficient. Numerical simulations have shown that the behavior of $D(t)$- function in the liquid dust systems for the time less than some critical value is similar to the $D(t)$- function for particles in solid. This function may be obtained from the motion equation for one-dimensional harmonic oscillator with some characteristic frequency ω_c:

$$\frac{d^2 x_j^2}{dt^2} = -\nu_{fr}\frac{dx_j^2}{dt} - 2\omega_c^2 x_j^2 + 2\left(\frac{dx_j}{dt}\right)^2. \qquad (1)$$

In the case of 2d- hexagonal crystal, the characteristic frequency ω_c is determined from $\omega_c^2 = \omega_h^2 \approx 6(1-\pi^{-2})\,(eZ_p)^2\exp(-\kappa)(1+\kappa+\kappa^2/2)/(\,l_p^3\, m_p\, \pi)$. The obtained results are in an agreement with the numerical simulations of 2d-systems (see Fig. 1) as well as with the results of measurements of $D(t)$- function in dust mono- layer formed in RF- discharge plasma [6].

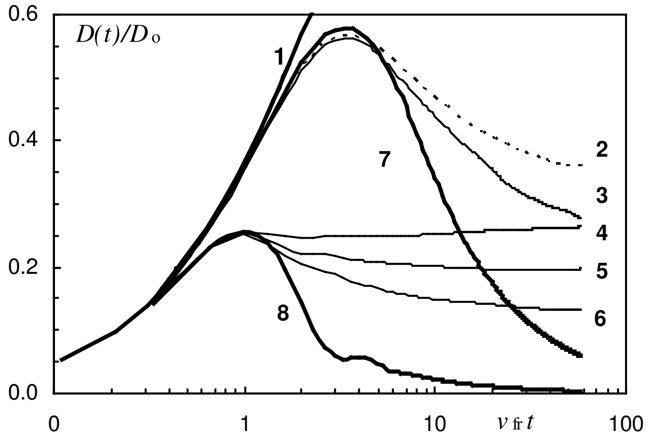
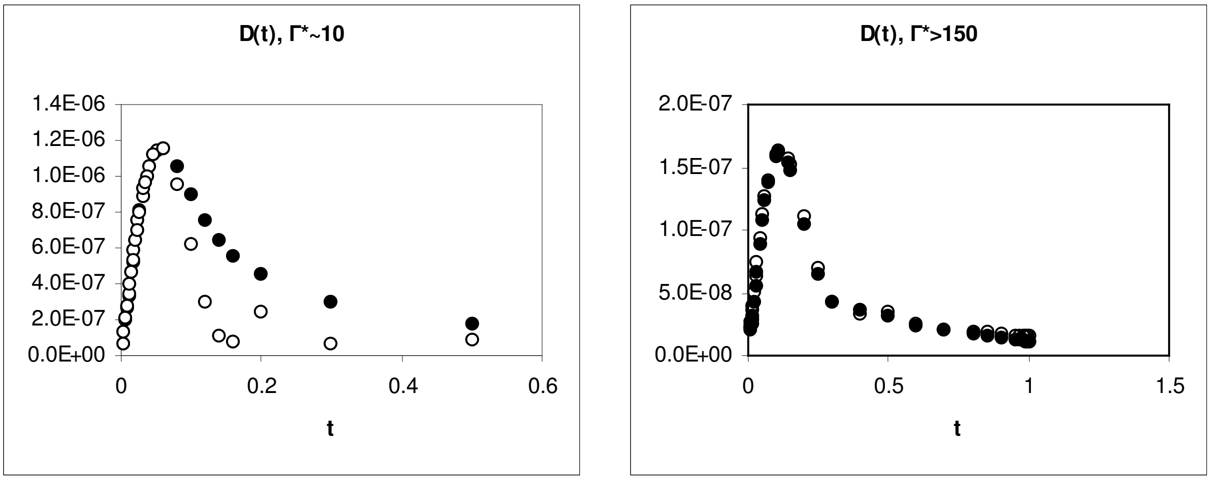


Figure 1. The functions of $D(t)/D_o$ vs. $t\nu_{fr}$ for non-interacting particles (curve **1**), and for simulated 2-d systems with $\xi = 0.23$ and different Γ^*: **2** - 27; **3** - 56; and with $\xi = 0.93$ and different Γ^*: **4** - 12; **5** - 27; **6** – 56. The curves **6** and **7** are the approximations of presented simulations by Eq. (9) with $\omega_c = \omega_h$.

In this work, we estimate ω_c based on experimental data and the above-stated approach. Then, with the help of the obtained values of ω_c, we estimate the charge of grains and electron temperature in dusty plasma.

Determination of the typical frequency

The experiment was performed using a high-speed high-resolution video camera. The following parameters were varied during the experiment: the effective coupling parameter Γ^* (5-200), pressure of the buffer gas (P ~ 5-30 Pa), the concentration of grains (100-250 grains/cm^2). The radius of the grains was l_p = 6.37 mkm, density of the material – ρ = 1.5 g/cm^3, the buffer gas – argon.



a **b**

Figure 2. Evolution of the mass-transfer process: (a) Γ^*~ 40 (liquid-like dusty system), ω_c ~30 s^{-1}; (b) Γ^*>150 (dusty crystal) ω_c ~13 s^{-1}. ● stands for the experimental data, ○ – for the theoretical values, calculated from Eq.(2).

Figure 2 (a,b) shows the evolution of mass-transfer for theoretically and experimentally gained data, with Γ^*~ 40 (liquid-like dusty system) and Γ^* >150 (dusty crystal). Here we can clearly see that the solution obtained for Eq. (1) is valid for the liquids only on the small observation times, and in case of crystalline systems we can use this solution at all time scales. We can write the effective coupling parameter Γ* as [6] $\Gamma^* = 1.5\pi\ (\omega_c^2 l_p^2 m_p)/(6T_p[1-1/\pi^2])$. The value of Γ^* is traditionally restored from the pair correlation functions of macroparticles. But this method has essential disadvantages. First of all, during the process of filming of the grains some particles from the neighbouring layer can come to a focus of video camera. As a result, the obtained from a correlation function mean interparticle distance is undervalued, what influences the determination of Γ^*.

Estimation of the electron temperature and the charge of the grains

For the Coulomb screening potential, as was stated above, the characteristic frequency is $\omega_c^2 = \omega_h^2 \approx 6(1-\pi^{-2})\ (eZ_p)^2\exp(-\kappa)(1+\kappa+\kappa^2/2)/(\ l_p^3\ m_p\ \pi)$. Thus, assuming that the value of the screening length λ lies between ion and electron Debye radiuses ($\lambda_i \leq \lambda \leq \lambda_e$), we can easily determine the value of dust charge eZ_p from the measurements of ω_c.

We used the Orbit-Motion Limited (OML) approach to explore the charging of macroparticles. Two cases were considered: 1) the grains are charged with the thermal flows of ions and electrons; 2) the grains are charged with the directed ion flows and the thermal flows of electrons. The second situation takes place, for example, in the near-electrode area of RF-discharge, i.e. in the conditions of typical laboratory experiments.

With information on plasma concentration, we can write the value of λ and the dust charge eZ_p (from the measurements of ω_c) as function of T_e, assuming T_i ~0.03 eV. Then we can find the electron's temperature from a balance equation of ion and electron flows $I_i=I_e$ for both cases considered. The calculations were conducted for different values of the coupling parameter and ion/electron concentrations (~ 10^8-10^{10} cm^{-3}). The obtained results show that if λ is considered to be close to λ_i, the electron temperature must be above 100 eV; but the electron temperature in the near-electrode area of RF-discharge cannot exceed 4-7 eV. For the case of $\lambda \sim \lambda_e$ we can obtain T_e ~ 2-3 eV for both approaches for ion flow that are in good agreement with the experimental data on the electron temperature in RF-discharge [7].

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