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POLARIZABILITY OF DUST PARTICLE WITH TRAPPED IONS

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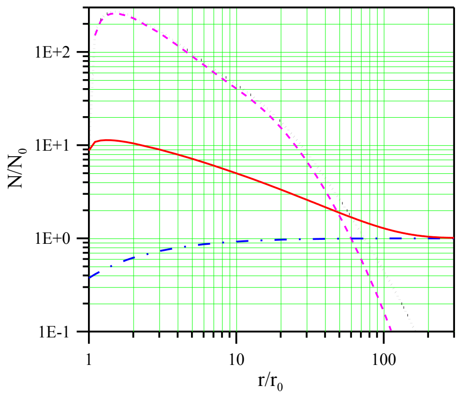
Dust particles in plasmas reveal an ability for self-organization and formation of chain and many-layer structures in RF and striated DC discharges due to the existence of an attractive force between the dust particles. Different mechanisms have been proposed for the dust particle attraction in complex plasma: attraction of dust particles in the wake potential, the shadowing force, and polarization of dust particles in an external electric field [1,2].

In this paper, we consider the polarization of the system of a negatively charged micron-sized particle with radius r_0 surrounded by a cloud of trapped ions in an external electric field in weakly collisional plasma when the ion Debye length λ_i is smaller than the mean free paths of ions and electrons. In this case, ions can lose energy in rare collisions with atoms and become trapped in finite orbits by the electric field of a charged particle [3,4,5]. In a steady state, the density of trapped ions, $N_{tr}(r)$, does not depend on gas pressure in the collisionless limit, $\nu \to 0$, and can be greater than the density of free (infinite) ions, $N_{if}(r)$, in the vicinity of a charged dust particle, and thus plays an important role in the screening of the particle.

To obtain $N_{tr}(r)$, we can use the balance equation for trapped ions formations and losses in rare charge exchange collisions of free and trapped ions with neutral atoms [5]:

$$N_{tr}(r)\,r^2 = \int_{r_0}^{R_{\max}} R^2 (N_{if}(R) + N_{tr}(R)) K(r,R)\,dR\,. \tag{1}$$

Kernel $K(r,R)$ takes into account averaging over the ions trajectories between turning points in the well of a self-consistent potential $\varphi(r)$ around a dust particle [5].



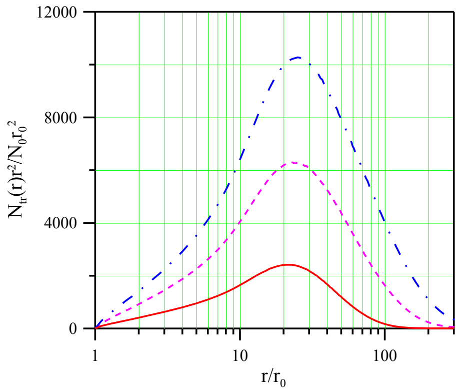


Fig. 1. Radial distributions of free ions $N_{if}(r)$ (solid line), trapped ions $N_{tr}(r)$ (dashed line), electrons $N_e(r)$ (dashed dotted line) and volume charge $\Delta N(r)$ (dotted line). $\lambda_i = 66\ r_0$.

Fig. 2. Radial distribution of the function $N_{tr}(r)\ r^2$ for different Debye lengths $\lambda_i = 33\ r_0$ (solid line), 66 r_0 (dashed line), and 99 r_0 (dashed dotted line).

In Fig.1, the solution for radial distributions $N_{tr}(r)$ of trapped ions is shown for a low-collisional limit. It can be seen that the radial density of trapped ions $N_{tr}(r)$ is a monotonously decreasing function of radius r. $N_{tr}(r)$ is larger than the density of free ions in the range from r_0 to $r \sim \lambda_i$. For $r \geq \lambda_i$, trapped ions density sharply decreases. However, trapped ions located near dust particle make relatively unsignificant contribution to the total amount of trapped ions. The function $4\pi\, r^2 N_{tr}(r)$ is presented in Fig.2. The majority of trapped ions are seen to concentrate in the spread layer or shell around $r_m \approx (0.25–0.5)\, \lambda_i$. It means that the "negatively charged dust particle and the positive shell of trapped ions" form a system that can be named a dusty "quasi-atom".

In the external electric field ***E***, the positive ion shell will shift against the negative core; thus a dust "quasi-atom" will acquire a dipole moment. The exact theory of the polarization of dusty "quasi-atom" is extremely difficult: external electric field breaks the spherical symmetry; weakly bound ions can be transferred to infinite orbits ("ionization" by the electric field), and so on. Here, we consider a simplified model based on the results of the radial distribution of trapped ions obtained above. We consider the group of trapped ions, which move in the well of effective potential $e\varphi_{eff}(r) = e\varphi(r) + J^2/2Mr^2$ with minimum at r_m ($\varphi'_{eff}(r_m) = 0$) between turning points r_1 and r_2 (J is the angular momentum of ion). It can be shown that ions can be trapped only for $J^2 < J^2_{Max}$, and the potential well can be formed only in the range $r_0 \leq r_m \leq R_{max}$ ($R_{max} = \lambda_i \cdot (1+\sqrt{5})/2 \approx 1.618\lambda_i$ for Debye-like potential). We assume that all trapped ions belonging to the group with r_m have a circular orbit with radius r_m. The effective potential in the vicinity of $r \approx r_m$ has a quadratic form

$$\varphi_{eff}(r) = \varphi_{eff}(r_m) + \varphi''_{eff}(r_m)(r - r_m)^2/2\,, \tag{2}$$

where $\varphi''_{eff}(r_m) = Z_d e\beta / r_m^3,\ \beta \sim 1$. The elastic restoring force acting on a trapped ion in this potential is equal to the external electric field ***E***: $F_r = -e\varphi''_{eff}(r - r_m) = -eE$, and trapped ion will acquire the dipole momentum $\vec{p}_d(r_m) = e(\vec{r} - \vec{r}_m) = e\vec{E}/\varphi''_{eff}(r_m)$. Assuming that in the layer dr_m around a dust particle there are $4\pi\, r_m^2 N_{tr}(r_m) dr_m$ ions, we can receive the estimation for the total dipole momentum of "quasi atom" with Z_{tr} ions:

$$\vec{P}_{d,tr} = 4\pi e\vec{E} \int_{r_0}^{R_{\max}} dr_m r_m^2 \frac{N_{tr}(r_m)}{\varphi''_{eff}(r_m)} \approx e\vec{E} Z_{tr} \int_{r_0}^{R_{\max}} dr_m r_m^2 \frac{N_{tr}(r_m)}{\varphi''_{eff}(r_m)} \Big/ \int_{r_0}^{R_{\max}} dr_m r_m^2 N_{tr}(r_m)\,, \tag{3}$$

where $Z_{tr} \approx (0.4\text{-}0.6)\cdot Z_d$ is the total number of trapped ions for $\nu \to 0$ [3,5].

Thus, we can estimate the value of polarizability coefficient of the "quasi atom":

$$\alpha_d = \beta^{-1}(Z_{tr}/Z_d) R_{\max}^3 \sim 4.24 (Z_{tr}/Z_d) \lambda_i^3 >> r_0^3\,. \tag{4}$$

In dusty plasma, the induced dipole potential of dusty "quasi atoms" can lead to an alignment of particles, formation of chain and multi-layer structures, and coagulation of dust grains.

The estimation is valid for fields $E < eZ_d/(R_{max})^2 \sim 25$ V/cm (for r_0=1μm, $\lambda_i = 33\, r_0$) when the displacement of ion cloud is smaller than the "radius" of an ionic shell, R_{max}. It should be stressed that with the increase of collisional frequency ν, the cloud of trapped ions gradually disappears and the coefficient of polarizability decreases.

Reference

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