Charging of dust grain and screening in a plasma at cryogenic gas temperatures

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1. Introduction

The problem Cryogenic dusty plasma is a gas discharge dusty system formed at very low (cryogenic) temperatures of gas. The experiments [1] conducted with liquid nitrogen and liquid helium cooled dc glow discharges showed that "cooling" of thermal motion of ions down to cryogenic temperatures leads to decreasing of ion Debye radius and formation of super dense dust structures where density of dust grains can be of the same order as plasma density and ion Debye radius can correspond to grain size. In this case, plasma dynamics and dust charging are sufficiently different from those at room gas temperature.

2. Distribution function of ions flux

The velocity distribution function of ions has not been considered although it is of paramount importance for the determination of characteristics of interaction between the ion flow and a charged dust particle. When determining the ion flow characteristics, one typically assumes that the mean kinetic energy of a directed ion motion is specified by the electrostatic potential. In this case, by analogy with the hydrodynamic motion we speak of an ion flow having the mean velocity u_0 and characterized by a shifted Maxwell function

$$f_0\left(v\right) = \left(\frac{m}{2\pi T_0}\right)^{3/2} \exp\left(-\frac{m(v-u_0)^2}{2mT_0}\right).$$

(1)

The velocity spread is determined by the ion temperature in the discharge, which is assumed to be equal to the atomic temperature $T_i = T_a = T_0$.

Let us suggest the following model to describe the distribution function of ions. Suppose the ions are uniformly accelerated and stop after each charge exchange. Then the kinetic Boltzmann equation for the spatially homogeneous case has the form [2, 3]

$$f(v) = c_1 \Theta(v) \exp\left(-\frac{mv^2}{2eE\lambda_{st}}\right), \qquad (2)$$

The distribution (2) is half the Maxwellian distribution with temperature $T = T_E \equiv eE\lambda_{st}$. But the difference of (2) from the shifted Maxwellian distribution (1) is essential.

The analysis of the effect of the distribution (2) on the characteristics of an ion flow around a dust particle is a separate problem [3], obviously to be solved in a numerical experiment only. From general considerations one can assume that the distribution function of ions in the form (2) is the most adequate in the construction of models for the description of experiments with a heightened gas pressure and with cryogenic temperatures [1]. Furthermore, the effect of ion collisions on their velocity distribution in the direction of the electric field is also important at subthermal flow velocities in a dc discharge [4].

Ion	He^+	He^+	He^+
T_a, K	293	77	4.2
$M = u_d / V_T$	1.80	3.99	18.5
$M_{eff} = u_d /(T_i / m)^{1/2}$	1.34	1.85	2.18
T_i, K	687	565	540
$T_{\parallel}$, K	1299	1313	1351
$T_{\perp}$, K	381	192	134
$T_{eff} = <\varepsilon> 2/3$, K	846	770	779

The results of Monte Carlo simulation helium ions flux in parent gas at different atom temperatures T_a are present in Table, u_d, V_T – ions drift and atom thermal velocities, $M = u_d / V_T$ - Mach number, $M_{eff} = u_d /(T_i / m)^{1/2}$ – effective Mach number, $T_{\parallel}$, $T_{\perp}$ - the temperatures to fit velocity distribution of ions in the direction along and orthogonal to the flow direction. Atom density is $n_a \approx 3.29 \times 10^{16}$ см$^{-3}$, electric field $E=20$ V/cm ($E / N = 61\, Td$).

In the dusty plasma the ion flow cannot be correctly determined if the ion resonant charge exchange is neglected. The velocity distribution of ions in the direction of the electric field is characterized by the half-Maxwellian distribution with the effective temperature which is equal to the energy gained by the ions during their free path. The velocity distribution of ions in the direction orthogonal to the flow is Maxwellian with the gas atom temperature. The results of Monte Carlo simulation helium ions flux in parent gas at different atom temperatures $T_a = 300, 4.2K$ are present in figures 1, 2.
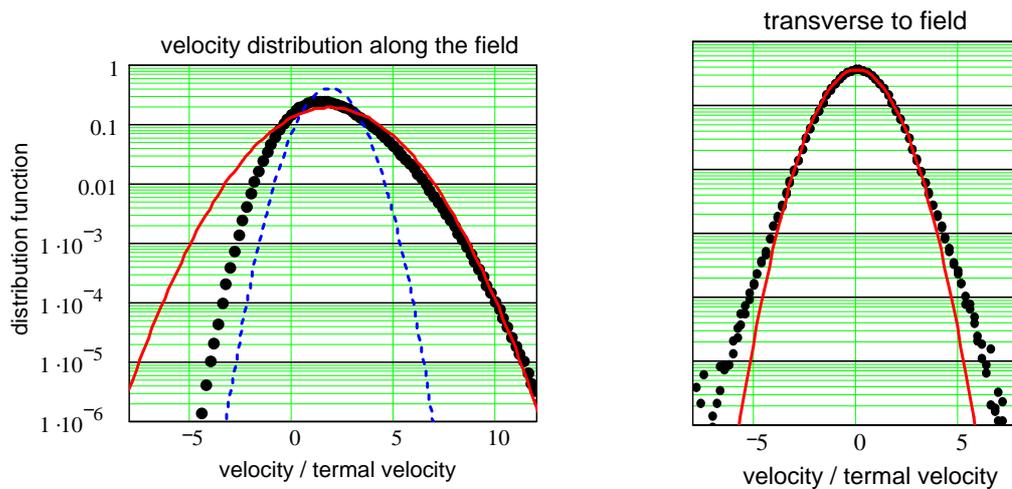
velocity distribution along the field

transverse to field

Fig. 1. $T_a = 300\,K$, solid and broken curves - Maxwellian distribution, points - the result of Monte Carlo simulation of velocity distribution along and transverse to electric field.
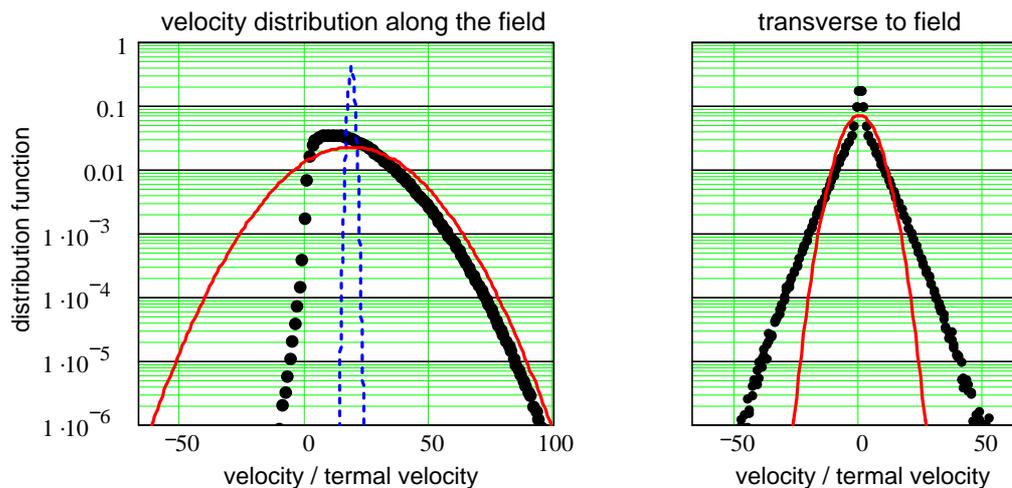
velocity distribution along the field

transverse to field

Fig. 2. $T_a = 4.2\,K$, solid and broken curves – Maxwellian, points - Monte Carlo.

3. PIC simulation results

Complete problem of plasma dynamics around a macroscopic body in the presence of plasma flows is highly nonlinear and therefore its numerical analysis is of major importance. Direct integration of the equations of motions of plasma particles represents a numerical experiment whose significance approaches experiments in the laboratory.

The problem was studied by using the PIC and molecular dynamics simulation method. The dynamics of plasma electrons and ions as well as the charging process of the

dust grain are simulated self-consistently. Grain charge, fluctuation, distributions of electron and ion number densities, and the electrostatic plasma potential are obtained for various pressures and temperatures of gas [2 - 4]. The results of PIC simulation of charge grain fluctuation at different atom temperatures T_a are presented on the fig. 3: red - $T_a = 4.2K$, green - $T_a = 77K$, black - $T_a = 4.2K$.
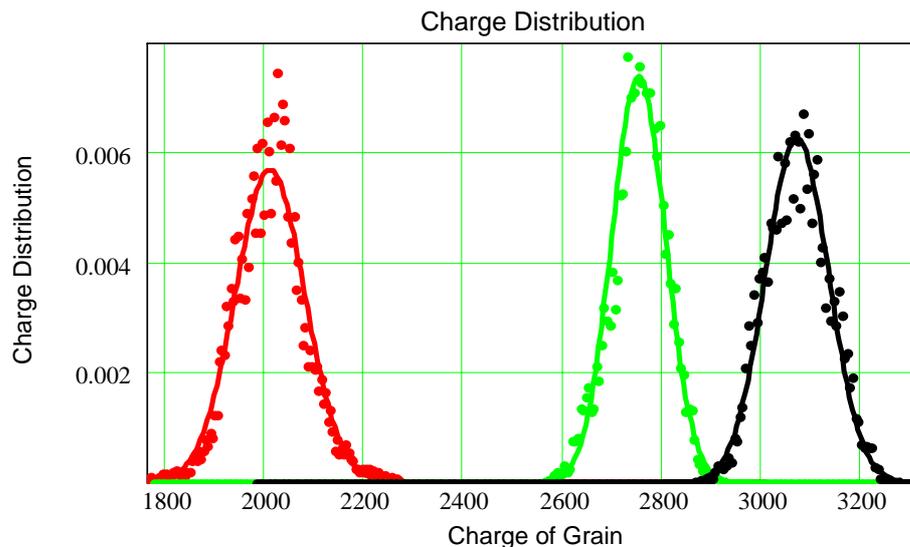
4. Conclusions

To conclude, we investigated characteristics of ion flux in dc glow discharges cooled by liquid nitrogen and liquid helium. In the dusty plasma the grain charge fluctuation, charging of grain at decreasing of gas temperature was investigated. The results of numerical simulation made it possible to analyze the kinetic processes leading to dust particle screening in a gas-discharge plasma and to verify the existing theoretical models and understood experimental results.

References

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