Dust particle trapping of ions in a dc glow discharge in neon

V V Shumova, D N Polyakov and L M Vasilyak
Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
E-mail: shumova@ihed.ras.ru

Abstract. The distributions of an average concentrations of ions in a positive column of glow discharge were simulated in pure neon and in plasma with micron size dust particles on the base of the drift-diffusion model. Simulations indicate that ion concentration within the dust structure may few times exceed that in a dust-free discharge. The discharge parameters were resulting analyzed in increase of ion concentration. The dust trap was demonstrated to require less energy input in a discharge than an increase of discharge current.

1. Introduction
The studies in the field of dusty plasma attract the current interest as an intensively developing branch of plasma physics [1, 2]. The interaction of plasma with dust particles is of interest due to wide field of actual and perspective applications of dusty plasmas in technology and in fundamental science. Dusty plasma is applied in surface treatment and modification, synthesis of nanoparticles, plasma coating [3, 4] and in medical applications [5]. The processes of plasma-particle interactions self-consistently determine the formation of dust structures in plasma, and the changes in plasma parameters induced by dust particles at various gas temperatures [6,7]. The correct simulation of ion concentration is important when describing plasma-chemical reactions of synthesis with their participation, or simulating processes of energy transfer in a plasma and calculating forces acting in plasmas, i.e ion drag force etc.

The problem of ion redistribution around a single dust particle was considered in detail in relation to a problem of dust particle charging. The plasma ions lose energy in collisions with atoms and may be trapped in finite orbits around a charged particle. The basic model is the orbit motion limited (OML) theory coming up to [8,9] that is known to be valid in collisionless plasma. The improved accuracy of particle charge gives the account of ion-atom collisions valid in the weakly collisional plasma, developed in [10–17]. These papers consider the number density distributions of ions around a negatively charged dust particle and demonstrate that the density of the trapped ions may be greater than the density of the free ions in the vicinity of a charged dust particle, that should be accounted in the screening of dust particle. All these studies consider the bulk plasma with a known ionization degree but do not regard the presence of neighboring dust particles. Another situation appears within a cloud of dust particles. In a plasma of dc discharge, the maintained dust cloud with rather high dust particle concentration, may change almost all measured discharge parameters: longitudinal and radial components of electric field, radial profiles of the average concentrations of plasma particles, the degree of
plasma ionization and excitation [18–23]. In [24] it was shown, that a dust structure maintained in a dc discharge may work as a plasma trap for ions where an ion concentration may exceed that in a free discharge. In present study, we analyze in more detail the possibility to create the excess of ion concentration in discharge with dust particles in dependence on the discharge parameters.

2. Model formulation

The simulations were based on the drift-diffusion model of the longitudinally uniform glow discharge positive column with dust particles developed in [20,21]. Neon plasma was considered to consist of ions, electrons, atoms and metastable atoms with the energy of 16.62 eV. Excitation and ionization was simulated with regard of stepwise and chemi-ionization as well as other principal collision processes in neon discharge at low pressures, all the details of which were represented in [22, 25]. The drift and diffusion of electrons, ions and metastable neon atoms were considered in the longitudinally uniform electric field with the longitudinal component $E_l$ and the self-consistent radial component $E_r$. The plasma losses appeared after diffusion of plasma particles towards the discharge boundary with radial coordinate $r = R$ or to the surface of dust particles. The electron-ion recombination in the bulk of the plasma was neglected.

The mean electron energy and transport coefficients were obtained using the SIGLO Database [26] and the electron Boltzmann equation solver BOLSIG+ [27]. The metastable atom mobility was extrapolated using data from [28].

The dust particle charge was calculated taking into account the ion-atom collisions in the approximation of collision enhanced collection (CEC) [15]. The flow of metastable atoms to the dust particle surface followed by quenching was simulated in gas-kinetic approximation. The distribution of dust particles inside the dust structure at $r \leq r_d$ was assumed as homogeneous: $n_d(r) = n_{d,0}$, where $n_{d,0}$ is a dust particle concentration on the discharge axis. In the tail of the dust particle distribution ($r > r_d$) the dust particle distribution was taken as exponentially blurred: $n_d(r) = n_{d,0} \exp[(r_d - r)/0.1R]$. The dust particle diameter was 2.55 µm, the radius of dust structure $r_d = R/2$. The concentration of dust particles in a dust structure was close to that observed in experiments in neon [24]. The first boundary condition was a vanishing concentration for all plasma species on the boundary of a discharge and the second followed from the symmetry on the discharge axis.

3. Results and discussion

In discharge without dust particles, the distribution of ions and electrons in the discharge cross section was close to theoretically predicted Bessel distribution. The influence of dust particles on distributions of plasma particles was controlled both by discharge parameters and the dust particle concentration and distribution. The plasma-chemical processes determining the ion and electron concentrations are the same, but the transformation of concentration profiles essentially differs for ions and electrons. In drift-diffusion assumption, $n_i(r)$ and $n_e(r)$ may be found from the solution of equations for their radial flow densities $J_i$ and $J_e$ given by equations:

\begin{align}
J_i(r) &= \mu_i n_i E_i(r) - D_i \frac{dn_i}{dr}, \\
J_e(r) &= -\mu_e n_e E_e(r) - D_e \frac{dn_e}{dr}.
\end{align}

In ambipolar plasma regime $J_e = J_i$. The radial flow densities $J_i$ and $J_e$ submit to the equations of continuity:

\begin{align}
\text{div } J_i &= q_i, \\
\text{div } J_e &= q_e,
\end{align}
Figure 1. Radial profiles of ions $n_i$ (red lines) and electrons $n_e$ (blue lines) at neon pressure 80 Pa for dust particle concentration $n_d = 5 \times 10^4 \text{ cm}^{-3}$ (lines 1, 4–6) and for discharge without dust (lines 2, 3, 7, 8) for two values of discharge current $I$, mA: 0.5 (lines 1–4) and 3 (lines 5–8).

where $n_i$, $n_e$, $\mu_i$, $\mu_e$, $D_i$ and $D_e$ are the ion and electron concentrations, mobilities and diffusion coefficients respectively, $q_i$ and $q_e$ are the corresponding source terms of species. Considering the principal collision processes in a plasma and plasma losses on dust particles, $q_i$ and $q_e$ are:

$$q_i = W_{ion} - n_d J_{d,i}, \quad (5)$$
$$q_e = W_{ion} - n_d J_{d,e}, \quad (6)$$

where $W_{ion}$ is the total rate of ionization through all possible mechanisms, that is equal for ions and electrons, and $J_{d,i}$ and $J_{d,e}$ are the flows of ions and electrons to the dust particle surface, that are different. This difference gives an effect of ion excess around the individual dust particle, and inside the dust cloud in average, in comparison with the surrounding plasma without dust particles. In figure 1 the deviations of radial ion and electron distributions in discharge with dust particle concentration $n_d = 5 \times 10^4 \text{ cm}^{-3}$ from Bessel’s are represented for two values of discharge current at neon pressure 80 Pa. For both values of discharge current, in the presence of dust particles, the electron profiles were depleted by dust particle absorption. The ion concentration profile was depleted also at high value of discharge current (3.0 mA), but at low current (0.5 mA) it increased. The diffusion coefficients of ions and electrons are quite different, that determines the different effects of dust particles on their distributions near the border of dust structure with the surrounding plasma. Due to ion trapping by dust particles, the ion profiles approximately reproduce the dust particle distributions.

With an increase in dust particle concentration, the depletion of electrons within the dust structure always increases. As far as we analyze the transformations of plasma particle concentration profiles under the maintaining the total value of discharge current, the depletion of free electrons should be compensated for with an increase of the electric field. In figure 2 are represented electron and ion profiles in discharge with increasing concentrations of dust particles. One can see the increasing depletion of electron concentration, accompanied with the increase in ion concentration with increase in dust particle concentration. To the right from the border of dust structure at higher $n_d$, one can see the sharp local maxima in the concentration.
Figure 2. Radial profiles of ion \(n_i\) (red lines) and electron \(n_e\) (blue lines) concentration at dust particle concentration \(10^{-5}n_d = 1\) (lines 3, 5), 2 (lines 2, 7) and 4 cm\(^{-3}\) (lines 1, 8) and for discharge without dust (lines 4, 6) for neon pressure 47 Pa and discharge current 3 mA.

profiles of both ions and electrons, that are formed as a result of joint action of processes of their production, drift, diffusion and losses. In the corresponding region of a discharge, there appear the flows of plasma particles directed to the axis of a discharge that is oppositely to the ambipolar diffusion flow. These are the flows that diminish the diffusion losses in a discharge with dust particles and enhance the energetic efficiency of ion trapping with dust particles.

Our numerical model permits to predict the discharge parameters resulting in the increase in the concentration of ions in a dusty plasma. In figure 3 is represented the relative ion concentration on the axis of a discharge \(\zeta = n_i^d(0)/n_i^0(0)\), where \(n_i^d(0)\) is the ion concentration in presence of dust structure with the given dust particle concentration, related to the value in discharge without dust particles \(n_i^0(0)\), in dependence upon dust particle concentration. With \(\zeta > 1\), we have a cumulation of ions in a dust trap.

One should note that due to the ion-trapping effect by dust particles, the cloud of dust particles may represent the more effective instrument for creation of a desired ion concentration in a desired part of discharge, than the discharge without dust particles with higher value of discharge current. In discharge without dust particles, the ion concentration is proportional to the discharge current (in the normal glow mode), while the energetic price paid for production of one ion is proportional to the electric power of a discharge. In discharge without dust particles the increase in ionization leads to proportional increase in losses through ambipolar diffusion to the boundary of a discharge. In a discharge with dust particles, the increase in ion concentration may be attained due to redistribution of ions from the periphery of a discharge towards it’s center, where the dust cloud was localized. In this case the ambipolar losses may be less. An additional advantage of ion trapping by dust cloud, is the flattening of ion profile within the dust structure, in comparison with Bessel profile in discharge without dust particles. This advantage may be a principal point in applications for plasma surface etching, deposition and coating. Especially should be mentioned the possibility to govern the localization of trapped ions in a discharge, using different contactless external means, such as operation of the spatial position and shape of dust structures using electron beam [29], or by applying an external thermal field [30–32].
Increasing the number of trapped ions can be achieved by increasing the concentration of dust particles, for example, by applying a magnetic field or by a cryogenic cooling of a discharge [33–35].

4. Conclusion

Dust particles absorb the plasma particles for their charging and give additional volume losses in a bulk of plasma that differ for ions and electrons. A dust structure maintained in a dc discharge may be considered as a plasma trap for ions with an ion concentration exceeding that in a free discharge. The possibility to create the excess of ion concentration in discharge with dust particles is shown to depend on the discharge parameters. The increase in ion concentration with increase in dust particle concentration is demonstrated. The effect of increase in the average ion concentration within the dust cloud is shown to be possible in a wide range of values of discharge current at a given neon pressure, but not with an arbitrary value of dust particle concentration.

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