Dust-void formation in a dc glow discharge

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Experimental investigations of dusty plasma parameters of a dc glow discharge were performed in a vertically oriented discharge tube. Under certain conditions, dust-free regions (voids) were formed in the center of the dust particle clouds that levitated in the strong electric field of a stratified positive column. A model for radial distribution of dusty plasma parameters of a dc glow discharge in inert gases was developed. The behavior of void formation was investigated for different discharge conditions (type of gas, discharge pressure, and discharge current) and dust particle parameters (particle radii and particle total number). It was shown that it is the ion drag force radial component that leads to the formation of voids. Both experimental and calculated results show that the higher the discharge current the wider dust-free region (void). The calculations also show that more pronounced voids are formed for dust particles with larger radii and under lower gas pressures.

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I. INTRODUCTION

Dusty, or complex, plasma is an ionized gas of electrons, ions, and micron-sized particles of condensed matter, which can be found in space, industrial devices, and technological applications (see Refs. [1–8]). In laboratory conditions, dusty plasma is usually studied in radio-frequency (rf) [9–15] and dc glow discharges [15–38], as well as in a combined rf+dc discharge mode [39–43]. In dc glow discharges, dusty plasma is investigated in both a stratified [16–19,24,30] and nonstratified (homogeneous along the discharge tube) positive column such as in “Plasmakristall-4” (PK-4) experiments [22,23,28,29,32,40,41].

PK-4 setup was developed for investigations of dusty plasma in earth (gravity) conditions [22,23,28,29] and in microgravity conditions in parabolic flights or aboard the International Space Station [32,39–41,44]. In gravity conditions, dusty plasma was observed as well-pronounced dust formations (clouds) in the electrode sheaths of rf discharges and in the striations of a dc glow discharge. In microgravity conditions, dust particles fill almost the whole volume of the rf discharge chamber, and in dc discharges dust particles are captured along the axis of the positive column in conditions without striations.

The formation of a great void in rf discharges in microgravity conditions is a well-known phenomenon [12–14,45]. Different theoretical models were developed to describe this phenomenon [12–14,45–62]. It was commonly accepted that the ion drag force is responsible for the void formation in the central part of rf discharges. The ion drag force is driven by an outflow of ions from an ionization source toward the surrounding dust cloud, which has a negative space charge [47].

There is some evidence that the dust-free regions can be observed in the nonstratified positive column of a dc discharge in microgravity conditions [38]. The observation of the dust-free regions in the cloud of dust particles in the center of a combined rf+dc discharge in gravity conditions was recently reported by Mitic [43]. However, the formation of dust-free voids in a pure dc discharge in striations in gravity conditions has not been observed and studied yet.

The aim of this paper is to investigate the possibility of the formation of dust-free voids in the clouds of dust particles in the positive column of a dc discharge. A previously developed model [62,63] for radial distributions of plasma parameters of a dc glow discharge was modified to take into account the ion drag force and is presented in Sec. III. The results of the numerical calculations are presented in Sec. IV. The discussion and conclusion are presented in Sec. V.

II. EXPERIMENTAL SETUP

The experiments were carried out in a dc glow discharge generated in a vertically oriented cylindrical glass tube with an inner diameter $D_{in} = 4.5$ cm and an inter electrode distance of 50 cm (see Fig. 1). The experimental setup was described elsewhere [15,26,27]. The discharge was generated in He at pressures $p = 0.2 – 0.4$ Torr and discharge currents $I_d = 1 – 15$ mA. Particles were stored in a container with a grid positioned above the anode. When the container was shaken the particles fell downwards through the grid. We used monodispersed melamine formaldehyde particles with a diameter $1 \mu m$ and a density of $1.51 \text{ g/cm}^3$ and polydisperse spherical particles of glass with a diameter approximately 3–5 $\mu m$.

In low-temperature discharge plasma, dust particles usually acquire a large negative charge of $e_0 Z_d \sim 10^3 – 10^5 e_0$ (where $Z_d$ is the charge number of a particle). The axial electric field $E_z(z)$ ($z$ is the axial coordinate directed along the discharge tube axis) suspends a grain in the gravitational field in the striations of a glow discharge. The radial electric field $E_r(r)$ ($r$ is the radial coordinate) traps negatively charged dust particles in the central region of the discharge tube, preventing them from escaping to the wall. Thus, the charged dust particles form a “dust cloud” of about 3 cm in size within the striation region. In order to visualize dust particles in the discharge tube we illuminated the region where particles levitated with a diode laser beam (wavelength $\lambda = 532$ nm, power...
$P = 0–250 \text{ mW}$). The horizontal cross section of the discharge tube with dust particle cloud was visualized by a thin laser sheet created by means of a cylindrical telescope.

In Fig. 2 photos of a stratum glow with a cloud of dust particles are presented for different values of a gas discharge current $I_d$. The green light regions are produced by a laser-knife horizontal cross section, i.e., the scattered laser light on the discharge tube wall and the cloud of dust particles. The cross sections were obtained for the central part of the dust clouds. For low values of the discharge current ($I_d < 4 \text{ mA}$) the clouds of dust particles have the usual compact structures. In this case, there are no voids (dust-free regions) in the cloud, and the dust particle density distribution has a nonhomogeneous radial profile with a maximum in the center of the discharge tube. With an increase of the gas discharge current, the density of dust particles in the center of the cloud decreases. The cylindrical symmetry can be broken. For high-discharge currents ($I_d > 6 \text{ mA}$) the particles in the cloud are removed from the center of the discharge tube to its periphery. With a further increase of the discharge currents, the radius of the voids increases and the green glowing circle of dust particles becomes more pronounced.

In Fig. 3 the sketch of the vertical cross section of a dust particle cloud is presented. In the case of high-discharge currents ($I_d > 6 \text{ mA}$), the cloud of dust particles has a “cup”-like structure with no particles in the central and upper parts of the cloud. We can obtain different horizontal cross sections of the dust cloud starting from the bottom part of the cloud to the upper part of the cloud. The circle-like structure of the horizontal cross section of the dust cloud (with the voids) was received only for central and upper parts of the cloud. In Fig. 2 we present only horizontal cross sections for the central part of the dust cloud (corresponding to axis $r$ of Fig. 3).
III. MODEL

To describe the behavior of dust-free voids formation in the clouds of dust particles a one-dimensional self-consistent model for radial distributions of dusty plasma parameters was developed. We should note that the clouds of dust particles with voids in striations that we have observed in experiments are, in fact, three-dimensional objects. The axial inhomogeneity of the stratified discharge parameters plays a great role and should be taken into account. However, it is rather difficult to realize by means of a complete numerical modeling. In addition, the axial inhomogeneity in the central and upper parts of the clouds is several times lower than the radial one. The “cup”-like cloud is extended along the z axis as shown in Fig. 3. Thus, for the central part of the cloud we can consider only radial distributions of dusty plasma parameters and neglect axial inhomogeneity. The cloud of spherical dust particles with radii $r_0 \approx 2 \mu m$ was assumed to have some radial density distribution $N_d(r)$.

The Boltzmann equation for the electron energy distribution function (EEDF) was used in the conventional “two-term” approximation for isotropic $f_0$ and anisotropic (radial $f_r$ and axial $f_z$) components that are connected with the radial and axial components of the electric field, $E_r$ and $E_z(r)$ (for details, see Refs. [63,64]). The system of coupled equations for $f_0$, $f_r$, and $f_z$ can be obtained, which can be transformed to the second order differential equation for the isotropic part of EEDF, $f_0$:

$$
\frac{m_e}{2} \frac{d^2 f_0}{dt^2} = \frac{1}{r} \frac{\partial}{\partial r} \left[ \frac{r E_z f_0}{3H} \left( \frac{\partial f_0}{\partial \varepsilon} - e_0 E_z \frac{\partial f_0}{\partial \varepsilon} \right) \right] + \frac{\partial}{\partial \varepsilon} \left[ \left( C(\varepsilon)f_0 - G(\varepsilon)f_0 + S(f_0) \right) + S_{\text{ion}}(f_0) - S_d(f_0) \right],
$$

where $\varepsilon$ is the electron kinetic energy. Coefficients $C$, $G$, $S$ correspond to the collision terms and describe elastic and inelastic collisions. The value of the axial electric field $E_z$ is determined by the balance of electron and ion production in ionization $S_{\text{ion}}(f_0)$ and their losses on the walls of the discharge tube and on the surface of dust particles. Obviously, these processes are nonlocal. The recombination of ions and electrons with energies higher than the particle potential $e_0 \varphi_d = Z_d e^2 \varepsilon_0 / r_0$ on the dust particle surface is described by the last term, $S_{\text{ion}}(f_0) = N_d u_{\text{rec}}(\varepsilon) f_0(\varepsilon)$. The function $H(\varepsilon)$ describes the momentum losses in elastic and inelastic electron-atom collisions and momentum losses in electron-dust particle collisions. The isotropic part of EEDF determines the electron density:

$$
n_e = \int_0^\infty d \varepsilon \sqrt{\varepsilon} f_0(\varepsilon),
$$

the constant of ionization rate, and the constant of electron and ion absorption rate on the dust particle surface:

$$
k_{\text{ion}}^{(e)} n_e = \frac{2}{m_e} \int_0^\infty d \varepsilon \varepsilon Q_{\text{ion}}(\varepsilon) f_0(r,\varepsilon),
$$

$$
k_{\text{rec}}^{(e)} n_e = \pi r_0^2 \frac{2}{m_e} \int_0^\infty d \varepsilon (1 - |e_0 \varphi_d|/\varepsilon) f_0(r,\varepsilon).
$$

Here $Q_{\text{ion}}^{(e)}(\varepsilon)$ is the helium ionization cross section. The anisotropic distribution functions determine radial $j_{er}$ and axial $j_{ez}$ current densities of electrons.

For ion density radial distribution $n_i(r)$, a drift-diffusion equation with the terms of ions production in electron-atom collisions and their losses in absorption on the dust particle surface was used:

$$
\frac{\partial n_i}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} [r j_{ir}(r,t)] = k_{\text{ion}}^{(e)} n_i - k_{\text{rec}}^{(e)} N_d n_e,
$$

$$
j_{er}(r,t) = \mu_i n_i(r,t) E_z(r) - D_i \frac{\partial n_i}{\partial r},
$$

where $\mu_i$ is the ion mobility coefficient and $D_i$ is the ion diffusion coefficient. In pure noble gases without dust particles (i.e., outside the dust cloud), the coefficients of ion drift $\mu_i$ and diffusions $D_i$ are determined mainly by charge exchange collisions and are connected with each other by the Einstein relation ($\mu_i k_B T_i \sim D_i$). In a discharge with dust particles, the drift and diffusion coefficients depend on both gas density $N_g$ and dust particle density $N_d(r)$. It is obvious that the presence of the dust component leads to the decrease of ion mobility in the dust cloud. We take into account the dependence of these coefficients on dust particle parameters according to Refs. [63,65,66].

In previous works [62,63] devoted to the description of radial distributions of dusty plasma parameters of the positive column of a dc discharge, the radial distribution of dust particle density $N_d(r)$ was assumed to have an equilibrium Boltzmann distribution. Here, a drift-diffusion equation for negatively charged dust particles was used (as in Refs. [33–35,37,49–51,53,56,60,61,67]):

$$
\frac{\partial N_d}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} [r j_{dr}(r,t)] = 0,
$$

$$
j_{dr}(r,t) = \mu_d N_d(r,t) E_z(r) - D_d \frac{\partial N_d}{\partial r},
$$

where $\mu_d$ is the dust particle mobility coefficient, $D_d$ is the dust particle diffusion coefficient, and $F_z$ is the total force acting on dust particles. There are no source and no loss terms for dust particles in the right part of Eq. (7). At the left boundary, i.e., in the center of the cloud and in the center of the discharge tube, the spatial derivative of dust particle density $dN_d(r=0)/dr$ is equal to zero. At the right boundary of numerical region, the dust particle density was assumed to be equal to zero due to a very high value of electric potential at the discharge tube wall. The dust particles cannot overcome this potential and are confined in the center of the tube and form a dust cloud.

It is assumed that the dust particle mobility and diffusion coefficients obey Einstein’s relation, $\mu_d k_B T_d \sim D_d$. It was shown that the temperature of dust particles in discharge plasmas is on the order of hundreds of kelvin (for moderate gas pressures) and can achieve very high values of 100 eV with the reduction of gas pressures $p \sim 0.1$ Torr [68,69]. In this paper, we use the intermediate value $T_d = 10$ eV because the choice of dust temperature was not very important for the obtained results. Calculations show that a decrease of dust temperature does not change the plasma parameters significantly.
Since there are no source and loss terms in the right part of Eq. (7), we do not need to take the actual values of mobility and diffusion coefficients only by taking into account the Einstein relation between them. They determine the time scale of dust particle motion and do not influence the final radial distribution of dust particles $N_d(r)$. In the paper the mobility coefficient of dust particles is 100 times smaller than the ion’s mobility coefficient. In the process of numerical calculation, the radial profile of dust particle density is evaluated and in the final state the radial flux of dust particles becomes equal to zero, $j_d(r) = 0$.

The total force, $F_{\text{tot}} = F_E + F_{id} + F_{dd}$, acting on a dust particle in the radial direction is the sum of electric force, $F_E = -eZ_d(r)E_z(r)$, ion drag force, $F_{id} = j_d(r)$, and particle repulsion force $F_{dd}$. The dust-dust interaction repulsive force $F_{dd}$ was calculated as in Refs. [53,63].

The ion drag force, $F_{id}(r)$, has the opposite direction compared to the electrostatic force $F_E$ and under certain conditions in the discharge tube can lead to the formation of a dust-free region in the central part of the discharge tube around its axis. Many papers are devoted to the evaluation of the ion drag force [13,23,70–74]. In this paper, the ion drag force $F_{id}$ was taken in the form [23,72]:

$$F_{id} = \frac{\sqrt{8\pi}}{3} n_i u_i v_{r} R_{C}^{2} m_i \left[ \Lambda + \sqrt{\frac{2}{\pi}} \kappa \left( \frac{\lambda_D}{l_i} \right) \right],$$

(9)

where $\Lambda(\beta_T)$ is the modified Coulomb logarithm [71]:

$$\Lambda(\beta_T) \approx 2 \int_{0}^{\infty} dx e^{-x} \ln \left( \frac{\beta_T + 2x}{\beta_T + 2x r_0/\lambda_D} \right),$$

(10)

and $\kappa(x)$ is a collisional function which takes into account the influence of ion-neutral collisions [23,72,74]:

$$\kappa(x) = x \arctan x + \left( \sqrt{\frac{\pi}{2}} - 1 \right) \frac{x^2}{1 + x^2} - \sqrt{\frac{\pi}{2}} \ln(1 + x^2).$$

(11)

Here the parameter of ion-particle coupling $\beta_T = e^2/|Z_d|/\lambda_D T_i$ is the ratio of the Debye length $R_{C} = e^2/|Z_d|/T_i$ to the plasma Debye length $\lambda_D = \sqrt{T_i/4\pi n_e e^2}$, $n_i u_i = j_d(r)$ is the radial component of ion flux, $v_{r_i} = (T_i/m_i)^{1/2}$ is the ion thermal velocity, $m_i$ is the mass of the ion, and $l_i$ is an ion mean three path.

The charge number of the dust particles $Z_d$ is found from the equality of electron and ion fluxes to the surface of the dust particles, $I_e + I_i = 0$ taking into account the electron and ion distribution functions (see for details Refs. [6,63,75,76]).

Equations for electrons, ions, and dust particles were complemented by the Poisson equation for a self-consistent electric field:

$$\frac{1}{r} \frac{\partial \left[ r E_z(r) \right]}{\partial r} = 4\pi e_0 [n_e(r) - n_i(r) - N_d(r)Z_d(r)].$$

(12)

Equations (1), (5), (7), and (12) form a complete system of equations for determining four unknown plasma parameters $n_e(r)$, $n_i(r)$, $N_d(r)$, and $E_z(r)$ in a self-consistent way. A time-dependent problem for electrons, ions, and dust particles based on the balance equations with the production and destruction terms obtained with the help of the Boltzmann equation for EEDF and the electric field obtained from the Poisson equation was solved. At each time step, the dust particle charge number was obtained and the axial electric field strength was recalculated with the help of the feedback between the discharge current $I_d$ and $E_z$. The procedure was repeated until a complete convergence of all plasma and dust particle parameters was achieved. It should be noted that we are not interested in time evolution of plasma parameters and consider only the final converged solution for the given gas discharge and dust particle parameters.

IV. RESULTS

The analysis of the papers devoted to investigations of void formation in a dusty plasma [12–14,45–62] shows that the void is formed in rf discharges when the ion drag force exceeds the electrostatic force (it is assumed that other forces, e.g., gravity and thermophoretic forces, are negligible). If the ion drift velocity $u_i = \mu_i E$ is proportional to the electric field strength $E$, the ratio of ion drag force $F_{id}$ and electric field force $F_E$ can be roughly presented in the form [12,59,62,71]

$$F_{id}/F_E \sim \mu_i n_i Z_d;$$

(13)

i.e., the ratio is proportional to ion mobility $\mu_i$, ion density $n_i$, and dust particle charge $Z_d$. The evaluation of this expression [62] showed that the condition $|F_{id}/F_E| \geq 1$ can be achieved more easily at low gas pressures ($\mu_i \sim 1/\rho n_e$), at high discharge currents ($n_i \sim I_d$), and for dust particles with larger radii ($Z_d \sim r_d$).

In our case, the voids are formed at the axis of the discharge tube. The radial component of the ion drag force $F_{id}(r)$ pushes dust particles out from the center of a dust cloud to the periphery in spite of the electrostatic force $F_E(r)$, which captures the particles at the axis of the discharge tube. The condition $|F_{id}(r)/F_E(r)| \geq 1$ is fulfilled in the region of the void. Thus, for the case of a dc discharge tube the condition for void formation can be roughly written as

$$|F_{id}(r)/F_E(r)| \sim n_i(r) Z_d(r)/p_{Ne}.$$  

(14)

First, to describe the obtained experimental results we calculate the radial dependencies of dusty plasma parameters for different discharge currents $I_d = 4 - 13.4 \text{ mA}$ at constant gas pressure $p = 0.38 \text{ Torr}$, and dust particle radius $r_d = 2 \mu\text{m}$. In Fig. 4(a) the radial distributions of dust particle densities $N_d(r)$ are presented for $I_d = 8, 10.4, 13.4 \text{ mA}$. At a low discharge current $I_d = 8 \text{ mA}$, the radial distribution of dust particle density $N_d(r)$ is a decaying function. The maximum density is at the axis of the discharge tube, $r = 0 \text{ cm}$. At a discharge current $I_d = 10.4 \text{ mA}$, the maximum in the radial distribution of dust particle density shifts some distance from the tube axis, $r \approx 1 \text{ cm}$. The local nonzero minimum is formed at the tube axis. It is the ion drag force radial component exceeding the electrostatic force that moves the particles from the center (see below). At discharge current $I_d = 13.4 \text{ mA}$, the maximum of dust particle density is at $r \approx 1.3 \text{ cm}$. Thus, the higher discharge current, the wider the void.

The calculations were also made for a smaller dust particle radius $r_d = 0.5 \mu\text{m}$ [see Fig. 4(b)]. It is seen that the maximums of dust particle density radial distributions shift
radius, the smaller the ion drag force. Thus, the formed voids are narrower. To describe the influence of gas pressure on the voids formation we have performed the calculation for lower gas pressure $p = 0.3$ Torr [see Fig. 4(c)]. It is seen that the lower the gas pressure, the higher the reduced mobility of ions and the wider voids are formed.

One more parameter which influences the dusty plasma parameters is the total number of dust particles $N_{\text{tot}}$. It should be noted that this parameter is not easy to control in experiments. The number of dust particles and its radial profile are formed self-consistently. In calculations, we can set up different values of a total number of dust particles per unit length (per 1 cm) of the positive column, which is equal to the integral of particle density over the discharge tube cross section. In Ref. [63] we introduced the unit of this variable with the value $N_0 = 0.792 \times 10^5$ cm$^{-1}$. Figures 4(a)–4(c) illustrate $N_{\text{tot}} = 2N_0$. To reveal the influence of the total dust particle number, we also provide a calculation for the total dust particle number $N_{\text{tot}} = 0.5N_0$ [see Fig. 4(d)]. It is seen that the absolute values of dust particle densities are almost four times lower compared to $N_{\text{tot}} = 2N_0$ [Fig. 4(a)], and the maximums of distributions $N_{\text{f}}(r)$ stay almost in the same radial positions.

Figure 5 presents the radial distributions of charged particle densities for different discharge currents for conditions as in Fig. 4(a). In a discharge with dust particles, the ion density $n_i(r)$ increases and the electron density $n_e(r)$ decreases in the region of a dust cloud. It can be seen that the volume charge, $\Delta N(r) = n_i(r) - n_e(r) - N_d(r)Z_d(r)$, is almost equal to zero in the whole discharge cross section except the region near wall. Therefore, the condition of quasineutrality $n_i \approx n_e + N_dZ_d$ is fulfilled in the dust cloud, and, hence, the electron density is smaller than the ion density. Outside the cloud, the volume charge increases and is equal to the ion density at the tube wall. The electron density is almost equal to zero at the tube wall. The positive values of volume charge outside the dust cloud determine the radial distribution of the electric potential (according to the Poisson equation). It should be noted that the dotted lines in Fig. 5 denoted as $N_d(r)Z_d$ do not coincide with $N_d(r)$ in Fig. 4. The dust particle charge $Z_d(r)$ slightly increases (5%–10%) with the increase of the discharge current due to an increase of ion density.

Distributions of dust particle radial flux components $j_{dr}(r) = \mu_d F_d N_d - D_d \partial N_d / \partial r = 0$ [see Eq. (8)] are shown in Fig. 6. In a steady state, the total dust particle flux is equal to zero in the whole discharge cross section. The results show that in the present conditions the diffusion term of dust particle flux $D_d \partial N_d / \partial r = 0$ is negligible. The only valuable components of the flux are the components of the ion drag force $\mu_d F_d N_d$, the electrostatic force $\mu_d F_e N_d$, and the interparticle repulsive force $\mu_d F_{dd} N_d$. The interparticle repulsive force $\mu_d F_{dd} N_d$ is almost 10 times smaller than the other components. Thus, the radial distribution of dust particles is determined mainly by the ion drag force and by the electric force. At discharge current $I_d = 8$ mA the absolute values of all flux components are small. The ion drag force is almost equal to the electrostatic force except for the outer region of the dust cloud where the dust-dust repulsive force is presented and has a positive value. When the dust cloud is formed, i.e., there is a maximum in the radial distribution of dust particle density $N_d(r)$, the dust-dust repulsive force has negative values at the left side of
FIG. 5. (Color online) Radial distributions of charged particle densities: ions \( n_i(r) \) (solid line), electrons \( n_e(r) \) (dashed line), charge density of dust particles \( N_d(r)Z_d(r) \) (dotted line), bulk charge \( \Delta N(r) \) (dash-dotted line). (a) \( I_d = 8 \, \text{mA} \); (b) \( I_d = 10.4 \, \text{mA} \); (c) \( I_d = 13.4 \, \text{mA} \).

the maximum and the positive values at the right side of the maximum. At the highest discharge current \( I_d = 13.4 \, \text{mA} \) all the flux components as well as all the forces are equal to zero outside the dust cloud.

Figure 7 presents radial distributions of the radial component of the electric potential \( V_r(r) \) and the electric field \( E_r(r) \) for different discharge currents for conditions as in Fig. 4(a). It is seen that for a high discharge current \( I_d = 13.4 \, \text{mA} \), the radial electric field increases more rapidly at a small \( r \) and then has a local minimum in the position of dust particle density maximum. The electric potential radial distribution \( -V_r(r) \) increases monotonously with the distance from the center of the discharge tube. The higher the discharge current, the higher the slope, and the higher the wall potential.

We can estimate mean axial electric field strength \( E_z \) from experimental data with the help of the measured distances \( L_{st} \) between the neighbor strata. It is known that the axial electric potential drop \( U_{st} \) on the length of one stratum \( L_{st} \) is a constant value for the given type of gas [77–79]. It is often assumed that the potential drop \( U_{st} \) between strata is connected with the energy threshold of inert gas atom excitation. In the paper, the axial electric field strength was estimated as the ratio of helium lower energy excitation level \( U_{He} \sim 19.8 \, \text{eV} \) to striatum length \( L_{st} \) measured experimentally, \( E_z = U_{He}/L_{st} \). The calculated and experimentally estimated values of the axial electric field

FIG. 6. (Color online) Radial distributions of the product of dust particle density and the forces acting on dust particles: solid line for the ion drag force \( F_{id}N_d \), dashed line for the electrostatic force \( F_{EN_d} \), dashed dotted line for the interparticle repulsive force \( F_{dd}N_d \). (a) \( I_d = 8 \, \text{mA} \), (b) \( I_d = 10.4 \, \text{mA} \), (c) \( I_d = 13.4 \, \text{mA} \).
strength $E_z$ depending on gas discharge current are presented in Fig. 8. The strata length $L_{st}$ increases with the increase of the discharge current; i.e., the mean electric field strength $E_z$ decreases. It is also seen that the values of the electric field in the regimes with big dust particles $a = 2 \mu$m and a large total number $N_{tot} = 2N_0$ systematically have higher values than for regimes with small dust particles $r_d = 0.5 \mu$m and small total number $N_{tot} = 0.5N_0$. This fact is explained in terms of the ionization balance [33,76,80]; i.e., electron and ion losses on dust particles should be compensated in ionizing collisions, and an averaged electric field in a discharge should increase in the presence of dust particles.

It should be noted that the obtained conditions of the void formation [Eqs. (13) and (14)] are not trivial. We cannot simply increase the discharge current (or increase the particle radii or reduce the gas pressure) by a factor of two and receive a twofold more pronounced void. These parameters strongly depend on each other self-consistently. If we increase the discharge current, then the electric field axial and radial strengths, the charge of particles and other parameters will change adjusting to each other. This is what occurs in the experiments, and it is taken into account in our model.

V. CONCLUSION

The experimental investigations of the dusty plasma parameters of a dc glow discharge were performed in laboratory conditions. In the strong electric field of a stratified positive column in a vertically oriented discharge tube the clouds of dust particles levitated. Under certain conditions, dust-free regions (voids) were formed in the center of dust particle clouds (i.e., at the axis of the discharge tube). The behavior of voids formation was investigated for different discharge conditions (type of gas, discharge pressure and discharge current) and dust particle parameters (radius and total number).

A model for the positive column of a dc glow discharge in inert gases with dust particles was developed. The model is based on the solution of a nonlocal Boltzmann equation for the electron energy distribution function, drift-diffusion equations for ions and dust particles, and the Poisson equation for a self-consistent electric field. The electrostatic force confining the dust clouds at the axis of the discharge tube, the ion drag force acting on dust particles towards the discharge tube wall, and the interparticle repulsive force were taken into account. The radial distributions of the dusty plasma parameters in a dust cloud were calculated for different experimental conditions.

It is shown that it is the ion drag force radial component that leads to the formation of the voids. Both experimental and calculated results show that the higher the discharge current, the wider the dust-free region (void) formed. The calculations also show that more pronounced voids are formed for dust particles with larger radii and under lower gas pressures.

The obtained experimental and theoretical results can be treated as a “prediction” of the possibility of the void formation in Plasmakristall-4 experiments in a dc discharge mode, which are scheduled for the upcoming years on board the International Space Station [44]. Though the conditions of the void formation in Plasmakristall-4 setup in microgravity can slightly differ from our experiments due to the absence of axial inhomogeneity, the main conclusions of the work should be applicable.

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