Negative ion-drag force in a plasma of gas discharge.

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Dusty (complex) plasma phenomena are recently widely studied in earth based laboratories and space experiments in a low temperature plasma. In experiments under microgravity conditions the charged dust particles are trapped with electrical potentials in the quasi-neutral part of the gas discharge, where the strength of the electrical field is small ($<1$V/cm). In order to study the dynamics of the dust particles a model for the dust particle-plasma interaction is needed. Here we present a model where in the ion flux and dust particle interaction we include the collisions of the ions with the gas atoms which will lead to qualitatively different results for the ion drag force. The latter is a key quantity in the understanding of the dynamics of complex plasma. Very interesting void (particle free area) formation phenomena were observed first in parabolic flight [1] and then in space experiments in high frequency discharge plasma. A number of recent theoretical works [2-6] were devoted to this problem. To calculate the ion drag force the OML model and its modifications were used in all those works. The latter model is only valid in the limit of low gas pressure, when the ion drift velocity by far exceeds the ion thermal velocity, and the ion motion can be considered as collisionless. In this work, we study the ion drag force acting on a single dust particle in the presence of an ion flux and a weak external electrical field. The collisions of the ions with the neutral atoms (i.e. resonance charge exchange collisions) are included in our approach. Applying the Monte-Carlo technique we solve the kinetic equations for the velocity distribution function of the ions. We assume that the positive ions and the negatively charged dust particle interact through a screened attractive potential $V(r) = (Z^2e/r)\exp(-r/\lambda_D)$ and $\lambda_D$ is the Debye screening length. The ion drag force (IDF) is the sum of two parts: a collision $F_i$ and a Coulomb $F_c$ force. The former is due to the ions colliding with the dust particles and the latter is associated with ion scattering due to the Coulomb interaction. In our calculations we follow the ion trajectories and determine the ion flux on the particle and the collision force acting on the dust particle as a result of the transfer of the ions momentum. The Coulomb force is
calculated by integrating the ion-dust particle Coulomb interaction along the ion trajectory and summing over all trajectories. We study the IDF for the experimental conditions of Ref. [7] for a radio frequency discharge operating in helium. The gas pressure varies within a range (37.5-150) Pa. The ion temperature $T_i = 0.026$ eV, and the external electrical field $E_0$ varies between 0.2V/cm and 10V/cm. In our calculations the screening length $\lambda_D$ varies from 20 m$\mu$m up to 100 m$\mu$m and the ion density $n_0$ from $10^8$ cm$^{-3}$ to 3.6times $10^9$ cm$^{-3}$. The dust particle radius is $R = 4.7$ m$\mu$m and charge $Z e = 3.6\times10^4 e$. In Fig.1 (a) the calculated ion drag force is shown for the different gas pressures and Debye screening lengths. For lower $P=75$ Pa and $\lambda_D = 20 m\mu$m side and collision part is positive whereas the Coulomb part is negative. Summarizing the result on the ion drag force we can say that in the collisionless case both Coulomb and collision part of the IDF are positive. Saying 'negative ion drag force' we mean the force acting in the direction against ion flux motion.

Fig. 1 The total ion drag force (a) and its components: collision and Coulomb part (b,c) as function of ion drift velocity in helium for particle of $R = 4.7 m\mu$m, $Z = 3.5\times10^4 e$ and $n_0 = 3.6\times10^9$ cm$^{-3}$, gas pressure $P=75$ Pa and $P=150$ Pa for $\lambda_D = 20 m\mu$m (circles) and 100 m$\mu$m (triangles).

For the considered cases of $P = 75$ Pa and $P=150$ Pa, the impact forces are positive and the Coulomb forces are negative in the limit of a small ion velocity. But for $P = 75$ Pa the absolute value of the collision force $|F_i|$ is larger that the Coulomb one $|F_c|$ and the total IDF is positive (see Fig.1(b)). In this case the IDF pushes the particle along the direction of the ion motion. The opposite situation is found for $P = 150$ Pa. The negative Coulomb force has a larger absolute value $|F_c|$ than the collision part $|F_i|$.
and the total IDF is negative \( F_c + F_i < 0 \) (see Fig.1(c)), and the IDF will be directed against the ion flow. Note that in the last case the collision part is negative, which implies that the ions bombard the particle surface mainly from the downstream side. In order to get an understanding of the nature of negative ion drag, we studied the ion density distribution around the particle at numerous gas pressures and Debye screening lengths. In the subthermal regime of ion motion the maximum of the ion density is situated in front of the dust particle and behind the particle we observe a reduction of the ion density. This is illustrated in Fig.2 where the ion density distribution, averaged laterally over an area with a small radius of 10 \( \mu \)m, is shown as function of z. With increasing ratio E/P the ion density in front of the particle first increases as well as absolute value of the negative IDF. With further increasing E/P the ion trajectory focus shifts to the area behind the dust particle and the ion drag force becomes positive. In Fig.2 the results are shown in the case that the IDF changes sign with increasing an electrical field. At E=0.25V/cm and E=0.65V/cm the IDF is negative and at E=10V/cm the IDF is positive. To understand better why the ion drag force could be negative let us consider the steady-state ion distribution around the dust particle. In subsonic ion velocity regime at higher gas pressure the ion density in front of dust particle is higher compared to undisturbed one and behind the particle the ion density is depleted. The Coulomb part of the IDF is negative in this case because the summation of Coulomb interaction between all ions and dust particle gives us the resulting force which directs against the ion flux. At the same time the collision part of the IDF is small due to often collisions of ions with neutral atoms. During resonance charge exchange scattering the fast ion gets the electron from neutral atom and new ion with subsonic energy starts to move in the external field. At high gas pressure the frequency of resonance exchange collision is high and the ions reach the dust particle surface with small drift velocity. In this case when the Coulomb part of IDF is

![Fig. 2 Ion density averaged in lateral direction plotted along the ion flux for \( \lambda_D = 100 \mu m \), P=150 Pa and electric field values 0.25, 0.65 and 10 V/cm.](image-url)
negative and the collision part is positive, but small, the total IDF is negative. As shown in our calculation at least an area equal to 5 Debye lengths should be included in order to obtain an accurate result for IDF. In Fig.3 we present a phase diagram which shows the regions of negative and positive IDF for different electrical fields and gas pressures. The transition from the negative to the positive values of the IDF happens at some critical electrical field which depends on P, Z and $\lambda_D$. In Fig.3 the curves refer to the critical points and separate the positive ion drag force location (above the curves) and the negative ion drag location (beneath the curves) for a typical particle charge of $3.5 \times 10^4 e$. Notice that the larger the Debye screening length, the larger the area of negative IDF. For the smallest $\lambda_D = 20 \mu m$ a negative ion drag force is found only for $P < 100$ Pa. In conclusion, this is the first detailed characterization of the forces acting on the dust particle in a weak electrical field and at higher gas pressure, which is essential in the study of dust particle transport in bulk plasma of rf discharge. In our study we concentrated on the subsonic and sonic ion motion regimes, and found the remarkable result that the ion drag force can be negative and thus acts on the negatively charged particle in the opposite direction to the ion flux. We wish to thank A. Melzer and A. Piel for fruitful discussion. This work was supported by the Flemish Science Foundation (FW0-Vl) and the NATO Science for Peace programme (974354).