Characteristics of a dusty nonthermal plasma from a particle-in-cell Monte Carlo simulation

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Nonthermal dusty plasmas can be found in plasma-processing applications as well as in space phsyics. A model based on a particle-in-cell Monte Carlo simulation has been developed to study the physical properties of such plasmas and the plasma-dust particle interactions. Assuming a uniform dusty plasma with a given size and concentration of dust particles, the model provides self-consistently the average electric field necessary to sustain the plasma for a given current density flowing through it, the charge and floating potential of the dust particles, the potential distribution, and the velocity distribution functions of electrons and positive ions. The model has been applied to situations where the distance between dust particles is much smaller than the electron Debye length (particulates interact electrostatically with each other) as well as situations where the distance between dust particles is larger than the Debye length (particulates are isolated electrostatically from each other). Questions concerning the momentum and energy transfer from electrons and ions to dust particles are also discussed. Simple scaling laws are also derived and compared with the numerical results.

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I. INTRODUCTION

Low-pressure nonthermal plasmas such as those used in plasma etching or deposition can generate solid particles whose size ranges from molecular to hundreds of micrometers [1–7]. The formation of these particulates (or dust particles) is system dependent and is not well understood. They may be introduced in the discharge by plasma surface interaction [4,5] or created in the volume by polymerization of the gas or its dissociation products [6,7]. The presence of dust particles in the plasma is a serious problem in etching and deposition applications because of the contamination of the substrates being processed. On the other hand, the ability of these plasmas to generate nanoscale particulates could be attractive and find some applications in material science if the size and physical properties of these particulates can be controlled [8–10].

In this paper we shall concentrate on the problem of the electrical interaction between small particles and nonequilibrium plasmas, without considering the production mechanisms of these particles. Plasma-dust interaction in laboratory plasmas has been studied by Emeleus and Breslin [11] before it was an important issue for plasma processing and a good introduction to this problem is given in this reference.

Small particles in plasmas behave as microscopic problems. Like a floating probe, they acquire a negative charge due to the large mobility of electrons with respect to positive ions. Their charge and potential adjust in such a way that at steady state, the flux of electrons to the dust particle is exactly balanced by the ion flux. Other processes such as secondary emission from the dust due to ion bombardment, photoemission, and thermionic of field emission can also affect the charging of a small particle in a plasma. Plasma-dust particle interaction is therefore relevant to probe theory which has attracted a considerable attention in the past [12–15]. An important research effort has also been directed toward the understanding of the charging of spacecraft or of natural objects such as dust grains in space plasmas and a large part of the literature devoted to this subject [16–20] is also relevant to our problem.

However, in most of the studies cited above, the plasma is considered to be a source of charged particles, electrons, and ions, with given velocity distribution functions, and its properties are supposed to be unaffected by the presence of dust particles. Since each dust particle acts as an electron and ion sink, it is clear that a large concentration of dust particles will have some effects on the plasma properties (at least in laboratory plasmas) and on the plasma sustainment conditions.

It is the purpose of this paper to study in a self-consistent way the charging of the dust particles due to the plasma environment as well as the charge in the plasma properties due to their presence, in the context of laboratory plasmas. Large concentrations of dust particles are more likely to occur in radio-frequency plasmas. In these plasmas, negative ions or heavy negatively charged particles are confined by the oscillating sheaths (the mobility of these particles being much smaller than the electron mobility, they cannot reach the electrode during the anodic part of the cycle for that electrode [21,22]). Experimental measurements [1,23] in low-pressure parallel-plate rf discharges have shown that the dust particles tend to accumulate near the plasma-sheath boundary. This phenomenon has been attributed [24] to the positive ion drag force which pushes the dust particles toward the electrodes and which is balanced by the sheath electric force at the plasma-sheath boundary. However, in some conditions, large concentrations of particulates in the bulk plasma have also been observed, with a not-so-important accumulation near the sheaths [6]. It is this kind of situation which is studied in the present paper where for simplicity we consider a uniform dc plasma. The dust particle density and size are supposed to be given (with a monodisperse size distribution) as well as the nature and pressure of the gas. The conditions we have chosen are close (except for dc instead of rf excitation) to the experimental conditions of Boufendi *et al.* [25] where dust particles created in a silane-argon plasma are subsequently trapped in a pure argon plasma where the size and density of the dust particles can be kept constant for a long time. Comparisons between models using the results of the present paper and the experiments of Boufendi *et al.* [25] are described in a related paper [26]. The plasma we considered is a dc macroscopically uniform plasma similar to the positive column of a low-pressure glow discharge [11,27]. In such a plasma, the electric field adjusts so that creation (ionization) and loss (volume recombination, recombination on the walls, attachment, etc.) of charged particles are balanced. In our problem, the only creation and loss processes which are taken into account are direct electron impact ionization of the gas atoms and absorption on the dust particles, respectively.

Under these conditions, the questions we are addressing in this paper are the following: (1) What are the current-voltage characteristics of a dusty plasma, i.e., what is the change in the plasma impedance due to the presence of dust particles for size and density typical of processing plasma? Practically, the knowledge of the plasma impedance could be used to detect in a simple way the formation of dust particles in the plasma [28]. (2) How are the electron and ion transport properties (density, velocity distribution function) affected by the presence of dust particles? (3) When the concentration of particulates is such that the distance between them is less than the electron Debye length (i.e., several dust particles lie within a Debye sphere), the particulates can no longer be considered to be isolated and start to interact electrostatically with each other. How do the charge and floating potential of the particulates adjust under these conditions? (4) What are the forces acting on the dust particles due to momentum transfer from electrons and ions and what is the energy transfer from charged particles to dust particles? Some of these questions have been discussed by Mc Caughey and Kushner [29] on the basis of a numerical model. However, this model was not fully self-consistent and could not be applied to situations where the particulates interact electrostatically.

A self-consistent particle-in-cell Monte Carlo (PIC-MC) simulation of a dusty positive column plasma has been developed to address these questions. The conditions considered are similar to those of the experiments of Boufendi *et al.* [25] dusty 0.1-torr argon plasma with 10^8-cm^{-3} dust particle density and size in the hundreds of nanometers range. Results for larger size and lower densities will also be discussed.

We present in Sec. II a brief overview concerning the charging of small particles or probes in a nonthermal plasma. Section III contains a description of the particle-in-cell Monte Carlo simulation. Results are presented and discussed in Sec. IV. Some simple analytical scaling laws are derived in Sec. V and compared with the numerical results. The validity of the model and its possible extension to rf conditions are discussed in Sec. VI.

II. CHARGING OF DUST PARTICLES IN A NONTHERMAL PLASMA

A. Isolated particle

A dust particle immersed in a plasma acquires a negative charge and potential which adjust in such a way that the particulate current to the particulate is zero at steady state. An ion sheath forms around the particulates, its length being related to the electron and ion Debye lengths. For conditions where the electron and ion mean free paths between collisions with neutrals are much larger than the sheath length, the spatial variations of electron and ion number densities and potential are solutions of Vlasov and Poisson's equations, the boundary conditions being (1) the charged particle velocity distribution functions given (generally Maxwellian with temperature T_e and T_p for electrons and positive ions, respectively), with the plasma density being n_∞ far from the particulate, and (2) the total current to the particulate is set to zero.

Berstein and Rabinowitz [14] and Laframboise [15] have solved this problem in the context of probes, with different representations of the ion velocity distribution function. Very often in such problems, the electron density is supposed to obey a Boltzmann law [$n_e = n_\infty \exp(eV/kT_e)$, where V is the local potential, k the Boltzmann constant, and e the elementary charge] although more exact expressions accounting for electron absorption on the particulate or on the probe can be obtained analytically. Analytical expressions can also be derived for the ion density if one assumes, for example, that the ion energy distribution function is monoenergetic [14].

When analytical expressions are used for electron and ion number densities, the problem reduces to an implicit Poisson equation (i.e., the space charge depends on the potential) which can be solved iteratively [14,15,30]. When the ion temperature in the plasma is large enough that ions are not deflected by the sheath potential, the ion density can be considered as a constant equal to n_∞ and Poisson's equation takes the well-known implicit form

$$\frac{d^2V}{dr^2} + \frac{2}{r}\frac{dV}{dr} = -\frac{e}{\epsilon_0} n_\infty [1 - \exp(eV/kT_e)] , \quad (1)$$

where r is the radial distance to the particulate.

If one can assume $|eV/kT_e| \ll 1$, the right-hand side of this equation can be linearized and one obtains the Debye-Hückel solution:

$$V(r) = V_D \frac{a}{r} \exp[-(r-a)/\lambda] , \quad (2)$$

where V_D is the floating potential of the particulate, a is its radius, and $\lambda = [(\epsilon_0 kT_e)/(n_\infty e^2)]^{1/2}$ is the electron Debye length. The assumption of a constant ion density is generally not a good approximation and a careful analysis of the ion trajectories in the sheath around the particulate leads to better (numerical) solutions of the potential distribution [14,15]. Parameters such as the ratio between the radius of the particulate and the electron Debye length play an important role in the calculation of the ion trajectories, the constants of motion being the ion energy and angular momentum. Depending on the values of these parameters, an ion can be either absorbed by the particulate (or probe), reflected, or trapped (collisions will actually prevent indefinite trapping) by the potential around the particulate [14,15]. Daugherty *et al.* [30] have shown recently that for conditions where the particulate radius is small with respect to the electron Debye length the Debye-Hückel potential formula (2) still gives a good representation of the potential distribution if the parameter λ is taken to be a "linearized Debye length" whose value is between the ion and electron Debye lengths but closer to the ion Debye length.

B. Large concentration of dust particles

When the concentration of particulates increases, the distance necessary for the electron-positive ion plasma to shield each particulate can become larger than the distance between them and the dust particles start to interact electrostatically. Under these conditions the plasma behaves as a three-component plasma (electrons, positive ions, and negatively charged dust particles).

The dust particles can therefore no longer be considered isolated when the average distance between them, d, is not large with respect to the electron Debye length λ. If N_D is the dust particle concentration, electrostatic influence between particulates will occur when $d = N_D^{-1/3} \sim$ or $< \lambda$. If the distribution of dust particles in the plasma can be considered to be uniform (cubic network), the condition of macroscopic neutrality of the plasma implies that on the average, the electron and ion space charge within a cube of dimension d around each particulate is exactly equal to the charge carried by the particulate. In such a situation, the actual (not Debye) shielding distance has to be less than about half the distance between particulates [17]. One of the consequences of the shielding of the particulate charge within one elementary cell of the network is that the average electron number density in the plasma can be much smaller than the average positive ion density if N_D is large enough (i.e., when $d < \lambda$) [17,19,20].

Whipple, Northrup, and Mendis [17] have developed a "spherical capacitor model" where elementary cells around the dust particles are supposed to be spherical instead of cubic, in order to make the problem tractable analytically. If b is the cell radius ($2b$ is of the order of the distance between particulates) and a the dust radius, and if n_e and n_p are the space-averaged electron and ion number densities, the charge Q_D on the dust particle must satisfy the equation

$$Q_D = -(n_p - n_e)(4/3\pi)(b^3 - a^3) . \qquad (3)$$

This relation ensures the charge neutrality of the cell and is equivalent to imposing a zero electric field at $r = b$ (Gauss's theorem).

Assuming that the electron and ion densities are related to the electrostatic potential by the Boltzmann factor, $n_e = C_e \exp(eV/kT_e)$ and $n_p = C_p \exp(-eV/kT_p)$, and linearizing these expressions, Whipple, Northrup, and Mendis obtain from Poisson's equation an analytical expression for the potential distribution. For large electron Debye length to particulate radius ratios (e.g., $\lambda/a > 20$ for $b/a = 50$) the potential distribution becomes independent of the Debye length and depends only on Q_D, a, and b. This distribution can be obtained very simply analytically by integrating Poisson's equation for constant n_e and n_p with a zero-field boundary condition at $r = b$ and $E(a) = Q_D / 4\pi\epsilon_0 a^2$.

The spherical capacitor model is a very simple and elegant way to account (only through boundary conditions) for electrostatic interactions between dust particulates in a plasma. The approach we have used to describe self-consistently (without assuming given shapes of electron and ion distribution functions) the plasma-dust particles interaction presents some similarity with the spherical capacitor model. The principles of this approach are described below.

III. PRINCIPLES OF THE PIC-MC MODEL OF A DUSTY PLASMA

A. Principles of the model

To study the plasma-dust particle interaction in a laboratory, positive column like plasma, we want to obtain the electron and ion velocity distribution functions (which can be very different from Maxwellian distributions), the charge of the dust particles, and the potential distribution. Assuming that the only mechanisms for creation and loss of charged particles are respectively direct electron impact ionization of the gas molecules and absorption on the particulate, the average plasma electric field has to adjust in order that the losses on the particulate and ionization be in balance.

In order to obtain a self-consistent solution of this problem, it is necessary to solve the electron and ion Boltzmann equations coupled with Poisson's equation. As in the spherical capacitor model of Whipple, Northrup, and Mendis [17], we assume that the dust particles and plasma form a periodic network. In these conditions, symmetry considerations enable us to solve the above equations only in one elementary cell of the network, using adequate boundary conditions. The shape of an elementary cell should be cubic for consistency with periodicity. In order to avoid the numerical complexity associated with a full three-dimensional (3D) geometry, we approximate the cell and dust particle geometries by cylinders whose radii are noted as b and a, respectively, and lengths $2b$ and $2a$. The axes of the cylinders are parallel to the direction of the average electric field (discharge axis) sustaining the plasma and to the total current density flowing through it. Assuming axial symmetry, the problem reduces to two dimensions in space.

In this geometry the problem is solved using a particle-in-cell [31,32] Monte Carlo simulation (2D cylindrical in space, 3D in velocity). Particle-in-cell Monte Carlo simulations have recently been used for the modeling of rf discharges (1D in space) and some examples of such simulations can be found in Refs. [33,34]. In particle-in-cell Monte Carlo simulations, the trajectories of a large number of electrons and ions under the effect of electrostatic forces and collisions with neutrals are followed in the phase space , the electric field being recalculated at each time step. In our model, the electric field is calculated by solving the 2D Poisson equation in an elementary cell at each time step. The charged particle trajectories between collisions are obtained by integrating the equations of motion in the known electric field. Collisions are treated with a classical Monte Carlo simulation [35] using a null collision technique. When an electron or ion trajectory intersects the dust particle surface, the charged particle is supposed to be absorbed and is removed from the simulation. Since only one elementary cell is considered, boundary conditions for the trajectories and electric field and potential on the cell surface are very important. The boundary conditions which have been used are described below.

B. Boundary conditions for the charged particle trajectories

When an electron or ion exits the cylindrical cell volume through one face, it is reinjected with the same velocity on the opposite face, its position on the face being uniformly distributed (and deduced from a random number generated by the computer). Note that this boundary condition does not imply periodicity for the charged particle densities. We found it necessary to redistribute the position reentry of the charged particle on one face when it exits the cylinder through the opposite face, in order to avoid correlations: A perfectly periodic distribution of dust particles would imply some preferential paths for electrons and ions (around the midplanes between dust particles) which are not "natural." Radially redistributing the positions of the charged particles on the faces of the cylinder avoids this effect. An electron or ion whose trajectory intersects the side of the cylinder delimiting the cell is supposed to be reflected by this surface.

C. Boundary conditions for the electrostatic field and potential

As mentioned above, the symmetry of the system implies charge neutrality in each cell and therefore a zero electric field flux through the cell cylindrical surface (as in the spherical capacitor model of Whipple, Northrup, and Mendis [17]). Charge neutrality within the cell implies equality between the dust particle charge and the opposite of the electron and ion total charge within the cell. Knowledge of the electron and ion density in the cell at a given time therefore implies the charge on the dust particle. For symmetry reasons, the electric field perpendicular to the side of the cylinder must be zero. The electric field parallel to the discharge axis must be periodic. In our problem this axial field must have a nonzero average in order to sustain the plasma (i.e., to provide enough energy to the electrons to compensate by ionization the loss of charged particles on the dust). The average electric field which is necessary to sustain the plasma is related to the current density flowing through it. The boundary conditions for the electric field are thus the following.

Let x be the direction parallel to the cylinder axis (and average electric field) and $x=0$ and $x=b$ be the abscissa of the cylinder faces. The electric field perpendicular to the side surface of the cylinder is set to zero: $E_r(x,b)=0$ for $0<x<b$. The boundary condition for the electric field along x is periodicity: $E_x(b,r)=E_x(0,r)$ for $0<r<b$.

A convenient way to obtain the value of the average electric field for a particular value of the current density flowing through the plasma is to use a fictitious external circuit connected to the considered cell and consisting of a generator and a resistor whose voltage and resistance are given. Such a circuit has been included in the simulation. The conduction current density can be deduced at any time step of the simulation from the knowledge of the positions of the electrons and ions in phase space. The average voltage drop and average electric field across the cell can then be obtained from the external circuit. We therefore used the following boundary conditions for the potential: $V(b,r)=V(0,r)+V_C$, V_C being obtained from the circuit equation,

$$V_C=U-RsJ \ , \tag{4}$$

where J is the conduction current density (electron and ion), U is the generator voltage, R the resistance of the external circuit, and s the area of the face of the cylinder. At each time step, V_C is changed according to the new value of the current density. At steady state J and V_C must converge toward constant values. Another boundary condition is necessary for the potential and this corresponds to the reference potential. We take the reference potential on the dust particle (which is supposed to be conducting and therefore equipotential): $V_D=0$.

D. Evolution toward steady state

The simulation is started with an initial arbitrary phase-space distribution of electrons and ions. The initial charge on the dust particle is therefore also given (charge neutrality within the cell). The generator voltage and resistance of the external circuit are imposed. As the calculation goes on, the voltage across the cell varies and is given by the circuit equation (4). If the ionization rate is larger than the electron loss rate on the dust particle, the current density increases which leads to a decrease in the voltage across the cell, i.e., in the average electric field. After a number of time steps which is very dependent on the initial charged particle density distributions and on the generator voltage and external circuit resistance, the electron impact ionization rate, the electron loss rate on the dust particle, and the ion loss rate on the dust converge toward the same value. At this stage, the dust particle charge and floating potential, the voltage and current across the cell, and the charged particle distributions within the cell reach constant values.

Acceleration of convergence toward steady state has been achieved in some cases by integrating the ion Boltzmann equation (with the PIC-MC model) with larger time steps than those taken for the electrons. It has been checked that the results are independent of this acceleration process. More details concerning this method are given below (Sec. II E).

Since the numerical method is statistical, some fluctuations in quantities such as current density, voltage across the cell, and floating potential of the dust particle can occur. Convergence toward steady state can be made difficult by these fluctuations. In a statistical method, the fluctuations in the drift velocity are always larger than the fluctuations of the number density (because the drift velocity is the average of a quantity which can be positive or negative). The current density which is proportional to the drift velocity can therefore exhibit important fluctuations. These fluctuations introduce through the circuit equation (4) some fluctuations in the voltage across the cell and so on. In order to minimize this effect, the circuit equation (4) has been changed by replacing the current density J by the electron density averaged over the cell (R is no longer a resistor but is a given constant). This reduces considerably the fluctuations. Since the external circuit is used only to find the steady-state current voltage characteristics of the plasma, this "artifice" does not affect the results.

Note that in some of the results presented below (Sec. IV), the size of the cell is very small (large dust particle densities) and the real number of electrons or ions at a given time in each cell can be of the order of one or a few. This means that in such conditions there will be real fluctuations of the cell parameters such as charge of the dust particle or floating potential. In this paper we consider that we are averaging over a large number of real cells and we do not address the problem of fluctuations.

E. Charged particle weighting and other details of the PIC-MC simulation

In a particle-in-cell simulation [31–34] the number of particles, electrons, and ions used in the simulation is generally much smaller than the real number of particles in the plasma which is simulated so that each particle in the simulation represents a large number of real particles. This number defines the weight of the particle. Note that in some of the conditions considered in this paper the average number of real electrons or ions in a cell can be of the order or less than unity (see above). In such situations the weight of the charged particles can become less than 1 (i.e., there are more electrons in the cell in the simulation then in reality). Since we do not address here the problem of real fluctuations, this apparently awkward situation (particle weight less than 1) can be justified by considering that the simulation deals with one average cell.

Generally, in plasma simulations, the same weight is used for all charged particles, electrons, and ions. In our case, as mentioned above, the electron density might be much smaller than the ion density. In order to better control the statistics we choose to keep similar the number of simulated electrons and the number of simulated ions, and therefore to assign in some cases different weights to electrons and ions. One of the consequences of different weighting of electrons and ions is that when an ionization event occurs, the numbers of created electrons and ions are not the same (in the simulation). Practically, when an ionization occurs, one electron is created in the simulation and the number of new ions can be larger than 1, according to the ion to electron weight ratio (if this ratio is not an integer, a random number is used).

When acceleration of convergence is used (see above) the integration time step of ions can be much longer than that of electrons; when an ionization occurs, the number of ions created in the simulation must be therefore proportional to the time step ratio. The method of acceleration of convergence has been used and is seen to work well when the steady-state electron density is much smaller than the ion density (i.e., for electron Debye length much larger than the cell dimensions). When the electron and ion densities are close together the acceleration method can lead to instabilities, however.

Poisson's equation is solved with a standard overrelaxation technique, for a cylindrical geometry on a nonuniform grid, using the boundary conditions described above. The charged particles are weighted on the grid with a cloud in cell method [31]. Typical numbers of grid points used in the results presented below are of the order of 20 along the cell axis and 10 along the radius. Although the overrelaxation method is time consuming [fast Fourier transform (FFT) methods cannot be used because of the presence of the dust particle inside the cell] the variations of the electron and ion densities between two successive calls to the Poisson solver were small enough so that only a few iterations were necessary at each time step to obtain the potential distribution.

IV. RESULTS AND DISCUSSION

In all the results presented below, the buffer gas is argon at 0.1 torr (300 K). The plasma is supposed to be uniform and infinite, with a given uniform distribution of dust particles. Results are given for different size and density of the particulates. The problem is characterized by three important parameters which are dust particle radius a, cell particle diameter $2b$, and electron Debye length λ. The cell size is related to the dust particle density N_D by the relation $N_D \sim (2b)^{-1/3}$. Note that this relation is only approximate since, in order to make the problem 2D in space, the cells we consider are cylinders (volume $2\pi b^3$) and not cubes [volume $(2b)^3$].

Sections IV A and IV B below correspond to situations where the relative values of these parameters are different. Section IV A presents some results corresponding to a distance between particulates $2b = 20$ μm (dust particle density of the order of 10^8 cm^{-3}) with radii ranging from $a = 100$ to 300 nm. These conditions are close to the experimental work of Boufendi *et al.* [25] where dust particles created in a silane-argon plasma are subsequently trapped in a pure argon rf plasma. For these values of the size and density of the particulates, we shall see that the electron Debye length is much larger than the distance between dust particles (even for large current densities flowing through the plasma) ($\lambda \gg 2b \gg a$). In Sec. IV B we present some results corresponding to situations where the electron Debye length is of the same order of magnitude as the cell size, but much larger than the dust particle radius ($2b=200$ and 1000 μm for $a=5$ and 50 μm, respectively) ($\lambda \sim 2b \gg a$). Potential distributions within the cell are discussed in Sec. IV C for conditions corresponding to the results described in Secs. IV A and IV B. Finally considerations concerning transfer of momentum and energy from the plasma to the dust particle are given in Sec. IV D.

A. Debye length much larger than dust radius and distance between particulates ($\lambda \gg 2b \gg a$)

In this section the dust particle density and radius are set to $N_D \sim 10^8$ cm^{-3} and $a=0.1-0.3$ μm. The distance $2b$ between dust particles is 20 μm. Figure 1 shows the average plasma electric field versus current density curve for three different values of the dust particle radius. It appears that the sustaining electric field is practically constant over a large range of current densities (from tens of μA/cm^2 to mA/cm^2). The small variations of the electric field with current density are due to statistical noise and do not indicate real trends. Note also that the results corresponding to values of the current density larger than a few mA/cm^2 are not realistic because second-kind processes (superelastic collisions, stepwise ionization) have not been taken into account. One can conclude from Fig. 1 that under the conditions of dust particle radius much smaller than distance between particulates and Debye length, the dusty plasma behaves electrically like a plasma controlled by ionization and attachment. In a plasma where the only creation and loss processes are direct electron impact ionization and attachment, the sustaining electric field is the field E_s for which ionization and attachment frequencies are equal: $\nu_i(E_s/p)=\nu_a(E_s/p)$ where p is the gas pressure. E_s depends only on the electron molecule cross sections and is independent of the current. The voltage versus current characteristic curve of such a plasma is therefore constant. As expected, the value of the sustaining electric field in the dusty plasma increases with dust particle radius. Note that the values of the reduced sustaining field E_s/p deduced from the simulation (Fig. 1) are large in these conditions of dust particle size and density: for $a=0.1$ μm, E_s/p is of the order of 100 V/cm torr, which is the same order of magnitude as the sustaining field in a strongly attaching gas such as SF_6.

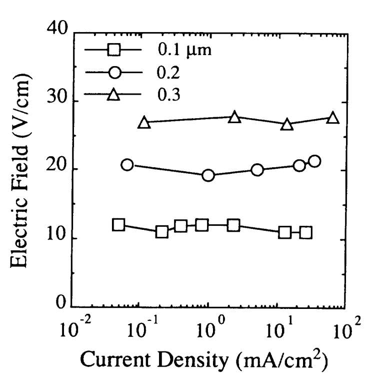

FIG. 1. Variations of the sustaining electric field with current density in a dusty argon plasma at 0.1 torr (300 K), distance between particulates 20 μm, and for three values of the dust particle radius.

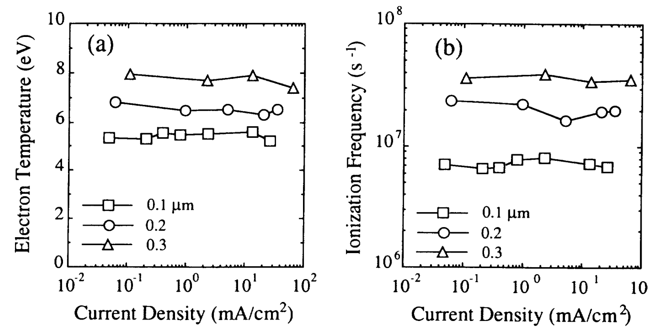

FIG. 2. Variations of (a) electron temperature and (b) electron impact ionization frequency with current density in a dusty argon plasma at 0.1 torr (300 K), distance between particulates 20 μm, and for three values of the dust particle radius (same conditions as in Fig. 1).

The electron temperature and ionization frequency averaged over one cell are plotted as a function of the current density in Fig. 2. As expected from Fig. 1, electron temperature and ionization frequency are constant (except for statistical noise) in this range of current densities. These values are very close to the electron temperature (defined as $\frac{2}{3}$ of the mean energy) and ionization coefficient which can be obtained in a pure argon plasma for the same value of the electric field. This means that under these conditions, the main effect of the presence of dust particles is to increase the electric field in the plasma. The electron-energy distribution function (EEDF) in the dusty plasma is very close to the EEDF in a pure ar-

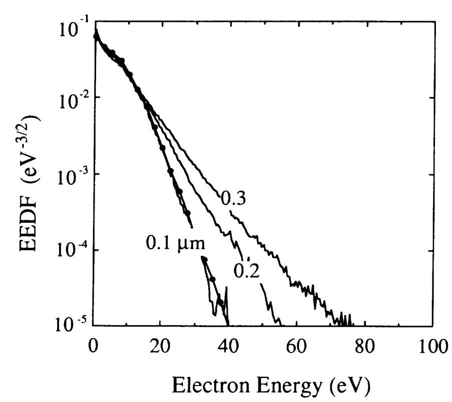

FIG. 3. Electron-energy distribution function (lines) in a dusty argon plasma at 0.1 torr (300 K), distance between particles 20 μm, and for three values of the dust particle radius (the corresponding reduced electric fields are 120, 200, and 280 V/cm torr, 300 K, for 0.1, 0.2 and 0.3 μm, respectively, see Fig. 1). The symbols correspond to the EEDF calculated in pure argon for the same reduced electric field (100 V/cm torr) as in the dusty plasma for a particulate radius of 0.1μm, (same conditions as in Fig. 1).

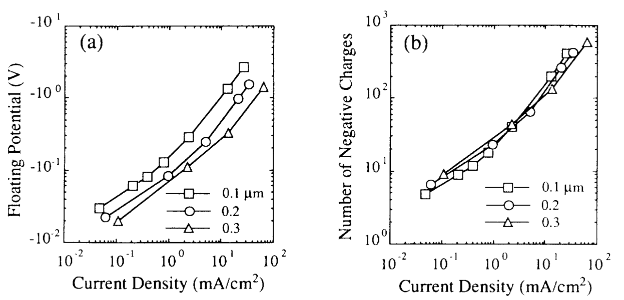

FIG. 4. Variations of (a) floating potential (the potential reference is the average plasma potential) and (b) number of negative charges with current density in a dusty argon plasma at 0.1 torr (300 K), distance between particulates 20 μm, and for three values of the dust particle radius (same conditions as in Fig. 1).

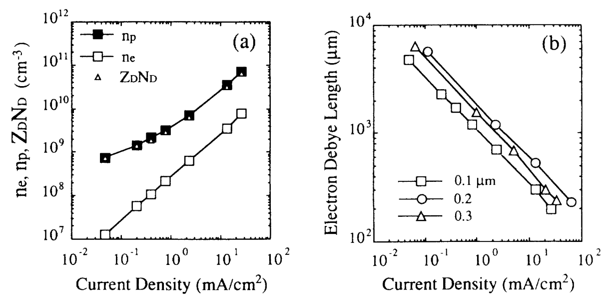

FIG. 5. Variations of electron number density *ne*, positive ion number density *np*, and charge number density $Z_D N_D$ of dust particles with current denstiy for 0.1 μm radius particulates; (b) electron Debye length vs current density for three values of the dust particle radius. Argon plasma at 0.1 torr (300 K), distance between particulates 20 μm (same conditions as in Fig. 1).

gon plasma for the same value of the reduced electric field, as shown in Fig. 3. This similarity can be understood if one looks at the variations of the dust particle charge and floating potential shown in Fig. 4(a) (the floating potential is defined here as the difference between the dust particle potential and the average potential in the cell, i.e., the average plasma potential). The floating potential is therefore much smaller than the electron temperature under these conditions and almost all the electrons, whatever their energy, can be absorbed by the dust particle. This explains why the presence of the dust particle does not induce a significant distortion of the EEDF with respect to an uncontaminated argon plasma for the same value of the reduced electric field.

The variations of the number of negative charges carried by the dust particle with current density are plotted in Fig. 4(b). This number is relatively low and of the order of a few tens of negative charges for current densities of one mA/cm^2. Since macroscopic neutrality must be satisfied within each cell, this implies that if Z_D is the number of negative charges on the dust particle and N_D their number density, the difference between ion and electron number densities in the plasma must be equal to $Z_D N_D$, i.e., a few 10^9 cm^{-3} if Z_D is a few tens and $N_D = 10^8$ cm^{-3}. It is therefore clear that under such conditions of large N_D, the electron number density has to be much smaller than the ion number density, as shown in Fig. 5(a) where the variations with current density of the electron and ion number densities averaged over one cell are shown. The dominant charged species in the plasma are therefore the positive ions and negatively charged dust particles. Figures 5(b) presents the variations of the electron Debye length with current density for different dust particle sizes and shows that the electron Debye length is always much larger than the distance between particulates under these conditions, even for large values of the current density.

B. Debye length of the same order of magnitude as the cell size and much larger than the dust particle radius ($\lambda \sim 2b \gg a$)

We present in this section some results corresponding to the following conditions: case (1), $N_D \sim 1.25 \times 10^5$ cm^{-3} (distance between dust particles: $2b = 200$ μm) and $a = 10$ μm; case (2), $N_D \sim 10^3$ cm^{-3} ($2b = 1000$ μm) and $a = 100$ μm.

Figure 6 shows the variations with current density of the average electric field, dust particle floating potential, electron temperature, and ionization frequency for case (1). Contrary to the previous cases described in Sec. IV A, the voltage current characteristic curve of the dusty plasma under these conditions is not constant but has a negative slope. The sustaining field decreases from 18 V/cm (180 V/cm torr) for current densities below 1 mA/cm^2 to less than 8 V/cm (80 V/cm torr) above 10 mA/cm^2. The floating potential increases from less than 1–10 V in the same current density range. The electron temperature and ionization frequency also decrease with increasing current density, the decrease in the ionization frequency being much more pronounced. Similar results have been obtained for case (2) and are presented in Fig. 7. These results can be understood as follows. For low values of the current density the floating potential is small and the situation is similar to that described in Sec. IV A, i.e., the sustaining electric field is almost independent of the current density. When the current density in-

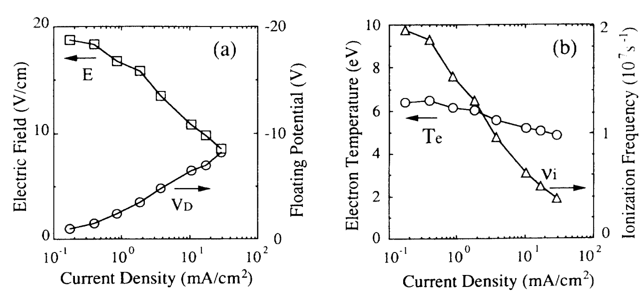

FIG. 6. Variations of (a) sustaining electric field and dust floating potential (the potential references is the average plasma potential) and (b) electron temperature and ionization frequency with current density in a dusty argon plasma at 0.1 torr (300 K), distance between particulates 200 μm, radius of particulates 5 μm.

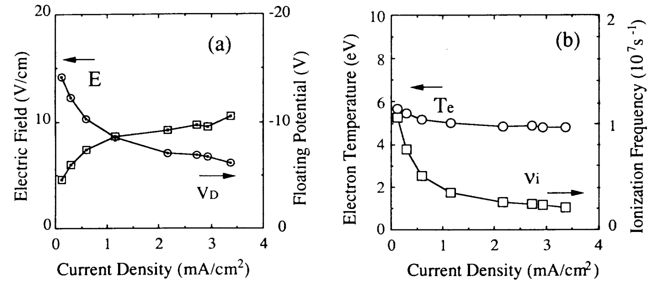

FIG. 7. Variations of (a) sustaining electric field and dust floating potential (the potential reference is the average plasma potential) and (b) electron temperature and ionization frequency with current density in a dusty argon plasma at 0.1 torr (300 K), distance between particulates 1000 μm, radius of particulates 50 μm.

creases, the electron and ion density and therefore the number of negative charges on the particulate increase. The floating potential therefore increases in magnitude with the current density. As the floating potential becomes closer to the mean electron energy, the electron loss frequency to the dust particle decreases since electrons are repelled by the negative potential of the dust particle and fewer and fewer electrons are able to overcome this potential barrier. Therefore the sustaining electric field decreases with increasing current density because the number of electrons able to reach the dust particle diminishes. If the current density increases further, one reaches a point where the electron Debye length becomes smaller than the distance between particulates. In that case plasma-dust particles interaction evolves toward a situation where the dust particles can be considered isolated and their electrical properties (number of negative charges, floating potential) should become independent of the current density or plasma density. This evolution toward isolated particles can be seen in Figs. 6 and 7. As the current increases above 1 mA/cm^2 in Fig. 7(a) the floating potential seems to evolve toward a constant value around 10 V (the electron temperature is about 5 eV in these conditions). Similarly, the sustaining electric field seems to converge toward a constant value around 6 V/cm (60 V/cm torr).

In summary, one can distinguish three regions in the voltage current characteristic curve of a dusty nonthermal plasma. For "low" current densities, the floating potential of the dust particle is small with respect to the electron temperature and the sustaining field is almost independent of the current density. For "intermediate" values of the current densities, the floating potential becomes sufficiently negative to repel most of the electrons and the sustaining electric field decreases with increasing current density. For "large" current densities, the dust particle becomes isolated and the floating potential and sustaining electric field become practically independent of current density. The meaning of "low," "intermediate," and "large" current densities in the above description is actually relative and depends on the cell size. For example, the cell volume is so small (10^{-8} cm^{-3}) in the conditions of Sec. IV A that, for electron and ion densities in the usual range for nonthermal plasmas, macroscopic neutrality implies very small values of the negative charge and therefore floating potential of the dust particle. Even for current densities up to tens of mA/cm^2 in this condition, we are in the "low" current density regime described above, i.e., the sustaining electric field stays constant. It would need current densities larger than hundreds of mA/cm^2 to obtain large enough floating potentials to induce a decrease in the sustaining electric field. For larger cell volume (8×10^{-6} cm^{-3}) such as case (1) of Sec. IV B, low current densities mean less than 0.1 mA/cm^2 (see Fig. 6). The limit between intermediate and large values of the current densities as described above correspond to a situation where the Debye length becomes smaller than the half distance b between particulates. This limit is above 20 mA/cm^2 for case (1) (see Fig. 6) and of the order of 2 mA/cm^2 for case (2) where the cell volume is much larger (10^{-3} cm^{-3}) (see Fig. 7).

Figure 8 shows the variations of the electron Debye length and number of negative charges on the dust particle as a function of current density. One can see by comparing Figs. 8 and 7 that the regime where the floating potential no longer increases with increasing current density corresponds to an electron Debye length becoming on the order of and smaller than the cell dimensions.

Finally, Fig. 9 shows electron distribution functions for two different values of the current density and sustaining field in the conditions of case (1). These distribution functions are compared with distribution functions obtained in a pure argon plasma, for the same value of the reduced electric field. It appears that in the low current case, the distribution functions with and without dust particles are very similar (for the same average electric field). This is again because for this relatively low value of the current density the floating potential of the dust particle is small and the electrons can be captured by the dust particle whatever their energy , i.e., each part of the distribution function is affected equally by the presence of dust particles (therefore the normalized distribution functions are the same). For higher values of the current density, the floating potential becomes larger (of the order of 8 eV) and only the electrons above 8 eV can be absorbed by the dust particle. This explains the difference in the

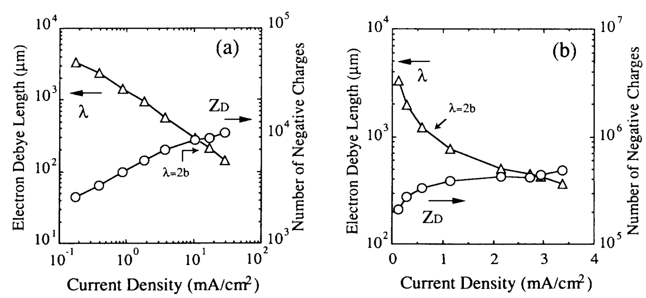

FIG. 8. Variations of electron Debye length λ and number of negative charges Z_D on the dust particles in a dusty argon plasma at 0.1 torr (300 K); (a) distance between particulates $2b=200$ μm, radius of particulates $a=5$ μm, (b) distance between particulates $2b=1000$ μm, radius of particulates $a=50$ μm.

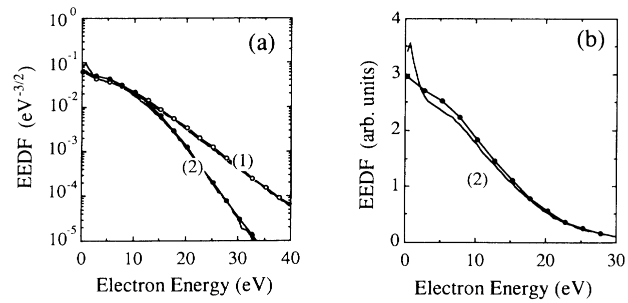

FIG. 9. (a) Electron-energy distribution function in a dusty argon plasma (straight lines) at 0.1 torr (300 K), distance between particulates 200 μm, radius 5 μm, for two values of the current density and electric field: (1) 0.86 mA/cm^2, 17 V/cm; (2) 29 mA/cm^2, 8.6 V/cm. The lines with symbols correspond to the EEDF calculated in pure argon for the same reduced electric fields as in the dusty plasma [(1) 170 V/cm torr, (2) 86 V/cm torr at 300 K]; (b) same as (a) with linear scale for the EEDF to enhance low-energy behavior and for the 29-mA/cm^2, 8.6-V/cm case only.

0–10-eV energy range [see Fig. 9(b)] between the distribution functions with and without dust particles for the same average electric field, in this case.

C. Distribution of potential and charged particle density around a dust particle

Figure 10 shows the calculated potential distribution in a cell for $2b = 200$ μm and $a = 5$ μm and for a current density of 0.86 mA/cm^2. The reference potential is taken on the dust particle (situated in the center of the cell). One can see on this figure that the floating potential in this case is around -2 V. The faces of the cylindric cell are equipotential, the potential difference between faces being of the order of 0.34 V. The average electric field is therefore (0.34 V on 200 μm) 17 V/cm (see Fig. 6). The spatial distribution of electrons and ions in the same case are plotted in Fig. 11. One can see the increase in the ion density in the vicinity of the dust particle. This feature is characteristic of a dust particle radius much smaller than the Debye length. The spatial distribution of the electron number density [Fig. 11(a)] does not exhibit strong gradient in this case. This is because the floating potential is relatively small, and less than the electron temperature (a density distribution following the Boltzmann law, i.e., proportional to $\exp[eV/(kT_e)]$ tends to a constant when kT_e is much larger than the floating potential). Note that the electron number density is much smaller than the ion number density in the whole volume of the cell. This means that we are in a situation where the electron Debye length [$=1.5$ mm, see Fig. 8(a)] is much larger than the distance between particulates, i.e., the electron space charge cannot neutralize the positive ion space charge within one cell. The plasma under these conditions is, as mentioned above, a positive-ion–negative-particulates plasma.

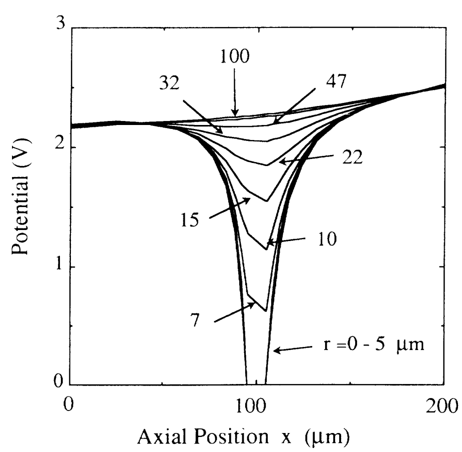

FIG. 10. Potential distribution in a cylindrical cell around a dust particle; dusty argon plasma at 0.1 torr (300 K), distance between particulates 200 μm, radius 5 μm, for a current density of 0.86 mA/cm^2 (average electric field 17 V/cm); r is the distance from the axis. The position of the dust particle center is $x = 100$ μm, $r = 0$ μm.

Figure 12 shows the electron and ion density distributions for a larger radius and a smaller density of dust par-

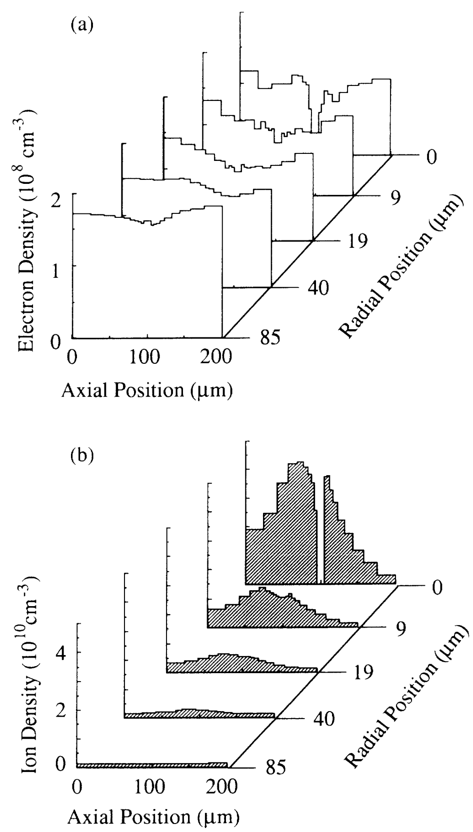

FIG. 11. (a) Spatial distribution of electron density (distance between particulates 200 μm, radius of particulates 5 μm) for a current density of 0.86 mA/cm^2, sustaining electric field 17/V/cm. (b) Spatial distribution of ion density (distance between particulates 200 μm, radius of particulates 5 μm) for a current density of 0.86 mA/cm^2, sustaining electric field 17 V/cm.

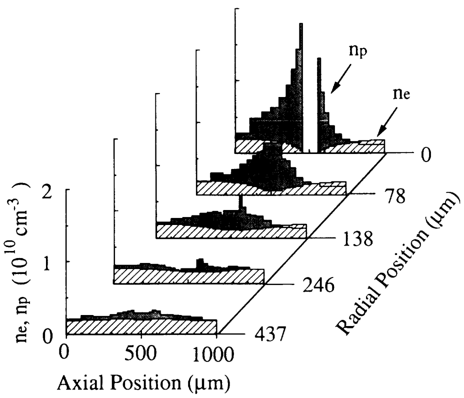

FIG. 12. Spatial distribution of electron and ion density (distance between particulates 1000 μm, radius of particulates 50 μm) for a current density of 3.5 mA/cm^2.

ticles (50 μm radius, distance between particulates 1000 μm). The current density (3.5 mA/cm^2) is such that the electron Debye length in this case is smaller than the cell dimension [0.36 mm, see Fig. 8(b)]. It appears clearly in Fig. 12 that the dust particle is shielded by the electron-ion plasma within the cell. In these conditions the dust particles can be considered to be isolated and do not interact electrostatically.

D. Momentum and energy transfer from electrons and ions to dust particles

The ion drag force on the particulate, due to momentum transfer from positive ions to the dust particles, has been deduced from the simulation and is represented in Fig. 13 for different dust particle size and density. For 0.1 μm radius and 10^8 cm^{-3} density of particulates, the ion drag force is of the order of 10^{-15} N for a current density of 1 mA/cm^2. It increases by 2 orders of magnitude when the current density increases from 0.1 to 10 mA/cm^2 (because of the increase in ion density). For 5 μm radius and 1.25×10^5 cm^{-5} dust particle density, the ion force is on the order of 10^{-12}–10^{-13} N (roughly proportional to the particulate radius). The ion drag force seems to reach a constant value when one approaches the

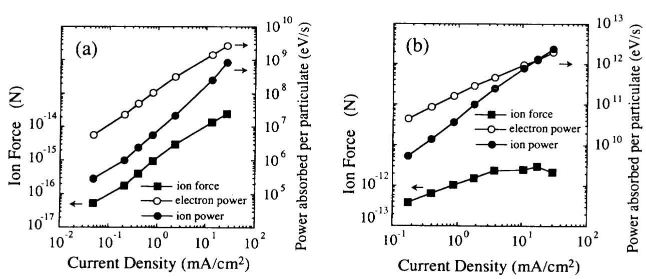

FIG. 13. Ion force on particulate and electron and ion power transferred per dust particle in a dusty argon plasma at 0.1 torr (300 K): (a) distance between particulates 20 μm, radius of particulates $a=0.1$ μm, (b) distance between particulates 200 μm, radius of particulates 5 μm.

conditions of isolated particulates (large current densities).

Figure 13 shows also that for low current densities the energy transferred by electrons to the dust particles is larger than the energy transferred by positive ions. This is because the floating potential is small in these conditions so that the average energy of electrons reaching the dust is much larger than the average energy of ions. When the current density increases (and thus the floating potential) the situation is reversed [see Fig. 13(b)] since electrons reaching the dust lose energy in the sheath while ions reaching the dust particle are accelerated. These results concerning the energy transfer from plasma particles to dust particles predicted by the model will be used in the future to determine the energy balance of the particulates and to estimate their temperature.

V. SCALING LAWS

In this section we present an analytical approach whose aim is more to derive some simple scaling laws than to obtain a rigorous or accurate analytical description of the plasma-dust particle interaction, to compare these scaling laws with results from the particle-in-cell Monte Carlo simulation.

We still consider that, due to periodicity and symmetry considerations, only one volume element around a dust particle need be studied. In order to solve the problem analytically, we must (1) write that the electron impact ionization rate is balanced by the electron loss rate on the dust particle, (2) equate the electron and ion currents to the dust particle, and (3) write Poisson's equation in the cell.

Let n_e and n_p be the average electron and ion number densities. The electron flux φ_e and electron current I_e to the dust particle can be approximated classically by

$$\varphi_e=\tfrac{1}{4}n_e v_e \exp[e\delta V/kT_e]\ ,\quad I_e=eA\varphi_e\ , \tag{5}$$

where v_e is electron thermal velocity, $\delta V=V_D-\langle V\rangle$, $\langle V\rangle$ is the average potential in the cell, and A is the total area of the dust particle ($6\pi a^2$ for a cylinder of radius a and length $2a$). The electron loss rate S_D to the dust particle is $S_D=\varphi_e A/W$, where W is the volume of the cell. For cylinders or spheres: $A/W=3a^2/b^3$ (a is the radius of the particulate, b the radius of the cell). The electron loss rate is therefore

$$S_D=\frac{3a^2}{b^3}n_e\frac{v_e}{4}\exp[e\delta V/kT_e]\ .$$

The ionization rate S_i can be defined by $S_i=n_e\nu_i$ where ν_i is the mean ionization frequency by electron impact. Equating S_D and S_i, we obtain

$$\nu_i=v_e\frac{3}{4}\frac{a^2}{b^3}\exp[e\delta V/kT_e]\ . \tag{6}$$

We have seen above (at least for low values of the floating potential) that the electron distribution function in the dusty plasma is very similar to the electron distribution function in pure argon for the same value of the average electric field. ν_i and T_e are therefore the same functions of E/p as in pure argon. Knowing the functions $\nu_i(E/p)$ and $T_e(E/p)$, Eq. (6) enables us to calculate the sustaining electric field for each value of the floating potential. Note that for conditions where the floating potential is much smaller than the electron temperature Eq. (6) reduces to

$$\nu_i \sim v_e \frac{3}{4}\frac{a^2}{b^3} .$$

One can check that this expression of the ionization frequency is in reasonable agreement with the numerical results of Fig. 2(a). For example, the numerical results give $\nu_i \sim 8\times10^6\ s^{-1}$ for $a=0.1\ \mu$m while the analytical expressions above gives $\nu_i \sim 10^7\ \mathrm{s}^{-1}$. However, the ionization frequency deduced from the numerical results increases with radius less rapidly than predicted by this analytical expression. This is probably because Eq. (5) neglects the possible effects of the directed electron velocity and tends to overestimate the electron current to the particulate when the radius of the particulate increases (which implies an increase in the plasma field and electron drift velocity). We have also checked that Eq. (6) predicts reasonably well the variations of ν_i with $[\delta V/kT_e]$ obtained with the numerical model (which can be deduced from Figs. 6 and 7).

It is also difficult to obtain an expression of the ion flux to the particulate because of the nonzero average plasma field superimposed on the field due to the ion sheath around the dust particulate. Assuming that the classical expression in the orbit motion limit of this flux [12,17,18] is still valid, we can write

$$\varphi_p = \tfrac{1}{4} n_p v_p [1 - e\delta V/kT_p] , \tag{7}$$

where v_p is the ion thermal velocity. Equating the electron and ion currents to the dust particle, we get

$$\frac{n_e}{n_p} = \left[\frac{T_p}{T_e}\frac{m_e}{m_p}\right]^{1/2} [1 - e\delta V/kT_p]\exp[-e\delta V/kT_e] . \tag{8}$$

This equation shows that the electron to ion number density ratio increases when the floating potential becomes more negative, i.e., when one goes from a situation where the particulates interact electrostatically to a situation where they can be considered to be isolated. For very low values of the floating potential, the electron number density can be much smaller than the ion density, the minimum value (for $\delta V=0$) of the ratio of electron to ion density being typically of the order of 10^{-2}–10^{-3}. This situation is not far from that of Fig. 5(a) and corresponds to large Debye lengths (and low current densities). Comparisons with the numerical results presented above show that Eq. (8) gives correct trends but is too small by about one order of magnitude. This is probably because Eq. (7) neglects the effect of the ion-directed velocity and underestimates the ion flux to the dust particle in our conditions. A better estimation of the ion flux could be obtained by replacing the thermal velocity and energy terms in Eq. (7) with the mean speed which accounts for the ion-directed velocity as suggested by Barnes *et al.* [36].

It is easy to show that for situations where the Debye length is larger than the cell size and if $b \gg a$, the floating potential can be estimated by $\delta V = Q_D/4\pi\epsilon_0 a$ for a spherical particulate, where Q_D is the charge of the dust particle. Because of charge neutrality within the cell volume, this equation can also be written as

$$\delta V = -\frac{e}{\epsilon_0}\frac{b^3}{3a}(n_p - n_e) . \tag{9}$$

This equation gives a reasonable estimate of the variations of the floating potential with electron and ion densities for large Debye lengths with respect to distance between particulates (low current regime) as can be checked in Figs. 5(a) and 4(a).

Equations (6), (8), and (9) together with the equation $J \sim e n_e \mu_e E$ for the total current density J (μ_e is the electron mobility in pure argon), with the knowledge of ν_i and T_e as a function of E/p, form a closed set of equations which can be used to obtain a rough estimation (and correct trends) of the parameters characterizing a dusty plasma for given dust particle size and density [Eq. (9) is valid only for Debye lengths larger than the distance between particulates].

VI. VALIDITY OF THE MODEL AND EXTENSION TO rf DISCHARGES

As mentioned above, the model described in this paper is based on the following assumptions: (1) The plasma is uniform (sheath effects are not included) and the dust particle concentration is uniform in the plasma, (2) the plasma is created by a dc discharge, and (3) electron impact ionization from the ground state is dominant.

We briefly discuss here the validity of these approximations and the possible extension of the model to rf discharges.

(1) The assumption of a uniform plasma is reasonable provided that the gap length or pressure is large enough so that the length of the plasma is longer than the distance necessary for energetic electrons coming from the sheath regions to reach an equilibrium with the plasma electric field. The dust particle concentration has also been supposed uniform in the plasma. Although it has been observed experimentally under some conditions that the dust particles tend to accumulate at the plasma sheath boundary, such accumulation has not been observed under the conditions of Sec. IV A [25,26]. Strong nonuniformity in the dust particle concentration is probably less likely to occur in situations where the distance between dust particles is much smaller than the electron Debye length because of the strong electrostatic interaction between dust particles in these conditions.

(2) The results presented above concerning a dc plasma could be extended to the positive column of a rf plasma if one can assume that the number of charges carried by the dust particles is not strongly modulated during a rf cycle. In that case, the results given by the dc model could be generalized to rf situations by replacing the calculated

dc sustaining field by an "effective field" related to the amplitude of the rf field. An accurate description of the rf regime is beyond the scope of this paper, but a very simple and rough approximation for frequencies in the 10-MHz range and for our pressure conditions, would be to consider that the rms plasma field in the rf regime is on the order of the sustaining field calculated in the dc case. On the other hand, it is easy to check that the charged particle loss rates calculated in this paper would lead to a small modulation of the number of charges carried by the dust particles, for frequencies in the 10-MHz range.

(3) Only electron impact ionization from the ground state of argon has been taken into account in the results presented above. Ionization from metastable levels can become important in a positive column plasma, depending on parameters such as the charged particle loss rate and the current density. Ferreira, Loureiro, and Ricard [37] developed a self-consistent model of a low-pressure argon positive column including stepwise ionization from metastable levels. In this model, the plasma electric field is obtained by equating the total ionization rate to the loss rate of charged particles to the discharge walls. The results of Ferreira, Loureiro, and Ricard can be used to estimate the importance of stepwise ionization in our calculations (charged particle losses to the wall are replaced, in our case, with electron and ion losses to the dust particles). In the results presented above, the dust particle concentration and size were such that the calculated ionization and electron loss frequencies were on the order of $10^7\ \mathrm{s}^{-1}$, corresponding to a rate on the order of $3\times10^{-9}\ \mathrm{cm}^{-3}\,\mathrm{s}^{-1}$. This large loss rate led, in our calculations, to values of the reduced plasma electric field on the order of 100 V/cm torr (i.e., $E/N \sim 3\times10^{-15}\ \mathrm{V\,cm}^2$). The model of Ref. [37] shows that, for such high values of the electric field, the contribution of stepwise ionization to the total ionization rate should be negligible in our conditions for current densities up to a few $\mathrm{mA/cm}^2$. We therefore expect the results presented above to be realistic in the in the range 0–10 $\mathrm{mA/cm}^2$.

VII. CONCLUSION

A 2D particle-in-cell Monte Carlo model has been developed to study the plasma–dust-particle interaction in a nonthermal plasma. This model provides, for a given density and size of particulates and assuming a macroscopically uniform positive column like dc plasma, the current-voltage characteristics curves of the plasmas, the charge and floating potential of the dust particles as well as the space distribution of potential and electron and ion density and distribution functions. Only the average behavior of the plasma–dust-particle system has been studied and the question of fluctuations has not been addressed. The model has been applied to a 0.1-torr argon plasma for conditions where the dust particles interact electrostatically (Debye length larger than the distance between particulates) as well as for conditions where the dust particles are isolated from each other by the electron–positive-ion plasma. No systematic study of the effect of gas pressure on the results has been done.

The model has shown the following.

(1) For large concentration of dust particles (i.e., for distance between particulates smaller than the electron Debye length), the floating potential and charge of the dust particle can be much smaller than in the isolated particle case. As long as the floating potential is small with respect to the electron temperature, the electric field which is needed to sustain the plasma stays constant and independent on the current density flowing through the plasma. In this situation the electron density is much smaller than the positive ion density and the plasma is dominated by positive ions and negatively charged dust particles.

(2) When the current density and therefore the electron density are large enough so that the distance between particulates is no longer negligible with respect to the electron Debye length, the floating potential and negative charge of the dust particle increase. The increase in the floating potential leads to a decrease of the electron loss frequency on the dust particles. The sustaining electric field therefore decreases with increasing current density.

(3) When the electron Debye length becomes small with respect to the distance between particulates, the floating potential and number of negative charges on the dust particle reach constant values corresponding to the case of isolated particles. In this limit, the sustaining electric field becomes independent of the current density.

This model could also be used to generalize the classical collisionless results of probe theory to situations where the sheaths are collisional and the distribution function are not Maxwellian.

The results presented in this paper can be used to predict the changes in the plasma impedance due to the presence of particulates in a radio-frequency discharge. These predictions and some comparisons with experiments are presented in a related paper [26].

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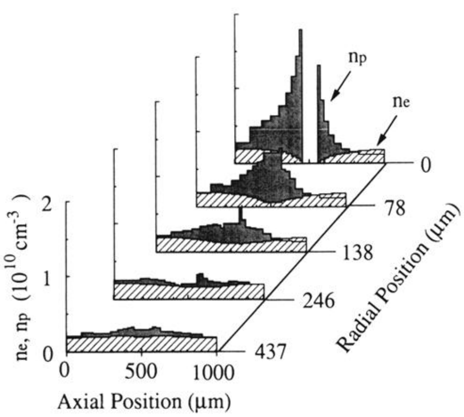

FIG. 12. Spatial distribution of electron and ion density (distance between particulates 1000 μm, radius of particulates 50 μm) for a current density of 3.5 mA/cm^2.