

Manipulation of Dusty Plasma Properties via Driving Voltage Waveform Tailoring in a Capacitive Radiofrequency Discharge

N. Kh. Bastykova, Z. Donkó, S. K. Kodanova, T. S. Ramazanov, and Zh. A. Moldabekov

Abstract—Dust particle layers are routinely established in radio-frequency plasmas, where their levitation height is defined by the balance of forces acting on the particles. Here, based on particle-in-cell simulations, we demonstrate the effect of excitation waveform on this levitation height, by using harmonic and alternating-phase waveforms that may as well include an additional dc component. We also demonstrate that the dust charge can be tuned by the properties of the excitation waveform and suggest that the dust component of the plasma can be heated through a variation of the excitation waveforms via a mechanism similar to second-order Fermi acceleration.

Index Terms—Dusty plasma, force balance, particle-in-cell (PIC) simulation.

I. INTRODUCTION

DUSTY plasmas have a number of unique features that have been attracting attention from different branches of physics [1]. The manipulation of individual dust particles and their ensembles is of great interest both for the theoretical understanding of the fundamental properties of strongly coupled systems and for applications. In recent years, a considerable progress has been made on the manipulation of dusty plasmas using lasers [1]–[3] and via modification of external electric and magnetic fields [4], [5].

Customized or tailored voltage waveforms [mainly composed of consecutive harmonics of a base radio frequency (RF) with given phase angles] have been found to influence the spatiotemporal dynamics of discharge plasmas without a dust component (ionization rate, mean electron energy, ion energy distribution functions, etc.) considerably [6]. Peculiarities of the plasma dynamics under specific excitation waveforms may as well affect the dust component of the plasma. Dusty plasmas are non-Hamiltonian systems [7], and fluctuations of the dust

charge can lead to heating of dust particles [8] in a process that is similar to the second-order Fermi acceleration. Usually, fluctuations of the dust charge are considered as a random process with a Gaussian distribution. Such a mechanism may explain a rather high kinetic temperature, up to several electronvolts, of the dust component in the complex plasmas formed in gas discharges [9]. For the case of astrophysical grains, this mechanism can strongly affect the rate of grain coagulation [8].

In this paper, we investigate via particle-based simulations the effect of the excitation waveform on the discharge characteristics and the levitation height of a dust layer that is assumed to consist of monodisperse grains. We also demonstrate that the driving voltage waveform influences the dust charging environment, which provides a way of heating of the dust system via alternating the driving voltage waveforms.

In Section II, a description of the simulation method is outlined. The results are presented and discussed in Section III, while a short summary is given in Section IV.

II. SIMULATION METHOD

The discharge is described by particle-in-cell simulation incorporating Monte Carlo treatment of collision (PIC/MCC) processes [10]–[13]. The code considers one spatial dimension and traces about 2×10^5 superparticles, representing electrons and argon ions. We assume that the number density of the dust particles is low, and consequently, the presence of the dust has no influence on the discharge characteristics. This approach—although it is not completely self-consistent—avoids the problems that arise because of the extremely different timescales of the motion of electrons, ions, and the dust particles [14], [15]. For the interactions of charged particles with electrode surfaces, we consider secondary electron emission (with a yield of $\gamma = 0.15$) and the reflection of electrons (with a probability of $\eta = 0.5$).

The main aim of our simulations is to determine the following:

- 1) the spatiotemporal distributions of several discharge characteristics, like the ionization and excitation rates, electric field and potential, charged particle densities, and mean electron energy;
- 2) the different forces acting on the dust particles, the dust charge, and the equilibrium position, x_d , where the dust layer settles in the discharge.

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The spatiotemporal distributions are calculated in the simulation in a straightforward manner, by sampling and accumulating values of quantities at discrete values of position within the electrode gap and discrete values of time within the period of the (base) RF waveform.

The calculation of the forces acting on the dust particles, the dust charge, and the levitation height proceeds in the following manner [16]. We expect this position to be in the vicinity of the electrode sheath/bulk plasma boundary above the lower electrode of the discharge, at a position defined by the balance of the vertical forces acting on the particles (we neglect the dust-dust interaction, due to the low dust density, so only vertical forces are important). We consider the three major forces: 1) gravity; 2) electrostatic; and 3) ion drag forces. The force due to gravity is given as

$$F_g = m_d g \quad (1)$$

where m_d is the mass of the dust particles. The electrostatic force is

$$F_{el} = \langle E(x) \rangle q_d \quad (2)$$

where $\langle E(x) \rangle$ is the time average of the electric field at position x (as obtained from the PIC/MCC simulation of the discharge without dust) and q_d is the dust charge. The calculation of this force needs the determination of the charge of the dust particles q_d . For that, the first step is to calculate the floating potential ϕ_d . For the determination of ϕ_d , we apply the method of [17], which is based on the interactions (collisions) between electrons and ions with the dust particles, described by cross sections that correspond to the orbital motion limited approximation. We assume that a dust particle is located at each computational grid point (x_k) in the simulation and carry out calculations for the floating potential at all grid points. This procedure is only needed to determine F_{el} , as a function of x , and finally, the real position of the dust layer is found by the balance of the three forces listed above. For the calculation of the floating potential ϕ_d , we run the PIC/MCC simulation for one RF cycle, and meanwhile calculate the electron and ion fluxes to dust particles (Γ_e and Γ_i), by summing for all electrons and ions, respectively

$$\Gamma_e(x_k) \propto \sum_p W_e v_p n_d(x) \sigma_{ed}[\varepsilon_p, \phi_d(x_k)] \quad (3)$$

$$\Gamma_i(x_k) \propto \sum_p W_i v_p n_d(x) \sigma_{id}[\varepsilon_p, \phi_d(x_k)] \quad (4)$$

where W denotes the superparticle weight, v_p is the velocity of the p th electron or ion, n_d is the dust density, and σ_{ed} and σ_{id} are the electron-dust and ion-dust collision (collection) cross sections [18], [19]. The floating potential of the dust particles is found iteratively, by the requirement that the fluxes, given by (3) and (4) become equal in the stationary state, at all positions. $\phi_d(x_k)$ is changed by ± 0.05 V after each RF simulation cycle at each grid point to reach the above-mentioned requirement. Having obtained $\phi_d(x_k)$, the equilibrium dust charge, assuming a radius r_d for the dust particles, is found adopting the simple capacitor model

$$q_d = 4\pi \varepsilon_0 r_d \phi_d(x_k). \quad (5)$$

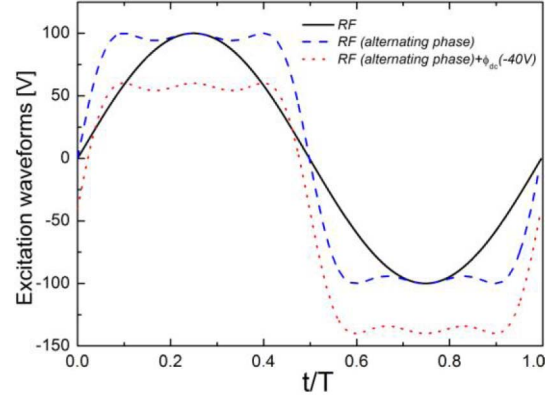


Fig. 1. Plasma excitation waveforms used in this paper.

From the value of the charge, we calculate via (2) the electrostatic force, with spatial dependence, $F_{el}(x)$.

The ion drag force results from the momentum transfer from the ions flowing to the dust particles [18], [19]. It consists of two parts: 1) ions absorbed by the dust particles and 2) ions deflected by the charge of the dust particles—these two force components are called the collection force and the orbit force

$$F_i(x) = F_{i, \text{coll}}(x) + F_{i, \text{orb}}(x). \quad (6)$$

The usual way to handle these processes is to adopt the binary collision approach. We proceed with the calculation based on the model of [19]. The required data (drift and mean velocities of the ions) are readily available from the PIC/MCC simulation.

Finally, the equilibrium position of the dust particles is derived from the force balance

$$F_{\text{tot}} = F_{el}(x_d) - F_g - F_i(x_d) = 0. \quad (7)$$

The calculations are carried out for an RF discharge with a plane-parallel electrode configuration, with an electrode separation of $L = 55$ mm. The bottom electrode (situated at $x = 0$) is powered, while the top electrode (at $x = L$) is grounded. The excitation frequency is $f_{\text{RF}} = 13.56$ MHz. The buffer gas is argon, at a pressure of $p = 1.8$ Pa, and the dust particles are assumed to have a radius of $r_d = 2.19$ μm . These conditions correspond to the experiments described in [16]. We consider the following types of driving voltage waveforms (see Fig. 1), with an amplitude of $\phi_0 = 100$ V:

- 1) harmonic RF voltage excitation: $\phi(t) = \phi_0 \sin[2\pi f_{\text{RF}} t]$;
- 2) excitation of the discharge with alternating phase of the driving voltage with an additional dc bias, $\phi(t) = \phi_0 \sin[2\pi f_{\text{RF}} t + \sin[2\pi(2 \times f_{\text{RF}})t]] + \phi_{\text{dc}}$, where the phase of the RF voltage alternates as $\sin[2\pi(2 \times f_{\text{RF}})t]$, and ϕ_{dc} is the additional dc voltage.

Combination of the two methods (the phase modulation and additional dc bias) gives more flexibility in realizing a control of the spatial profiles of electron (ion) density (temperature) and the forces exerted on dust particles. In addition, as it is shown below, there is the possibility to control interdust particle interaction keeping the vertical position of them nearly the same. Latest opens the way for investigation into the different kinds of nonlinear processes like phase transitions.

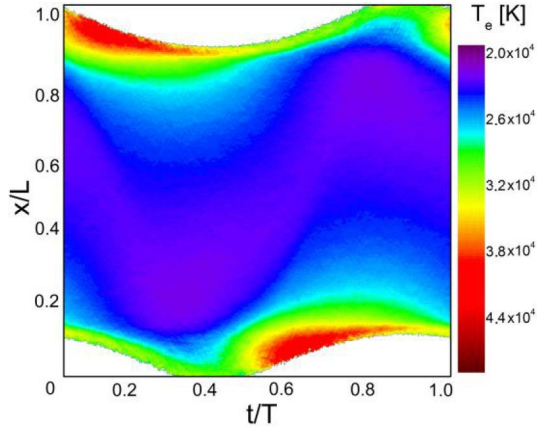


Fig. 2. Spatiotemporal profile of electron temperature for the case of harmonic RF excitation of the discharge. T is the period of the fundamental frequency (13.56 MHz). $p = 1.8$ Pa.

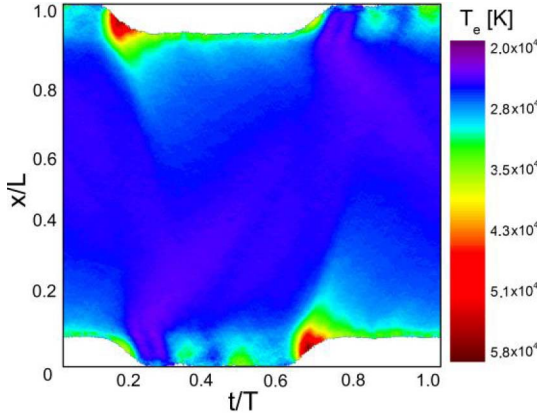


Fig. 3. Spatiotemporal profile of electron temperature for the RF discharge with alternating phase. T is the period of the fundamental frequency (13.56 MHz). $p = 1.8$ Pa.

III. RESULTS AND DISCUSSION

In Figs. 2 and 3, the spatiotemporal profiles of the (effective) electron temperature, derived from the mean energy of electrons measured in the simulation, for the case of harmonic RF excitation (Fig. 2) and for the case of alternating phase excitation with no additional dc bias (Fig. 3) are shown, respectively. Comparing Figs. 2 and 3, one can see that the highest values of the effective electron temperature are found near the edges of the expanding sheaths. In the case of the (pure) harmonic excitation waveform, the highest values are in the order of ~ 4 eV, while in the plasma bulk we find ~ 2 eV. In the case of the alternating-phase excitation voltage, the electron dynamics changes considerably. The expansion of the sheaths becomes much faster, and consequently, the electron temperature rises to higher values compared with the case of the harmonic excitation. Here, T_e reaches values exceeding 5 eV, while in the bulk we observe similar values as in Fig. 2. Here, we do not discuss the impact of the additional dc bias on the spatiotemporal profiles of the electron temperature, as it was discussed in detail recently [20].

Due to large difference between masses of the electron, ion (atom) and dust particle as well as of their temperatures, these three subsystems have big difference in characteristic

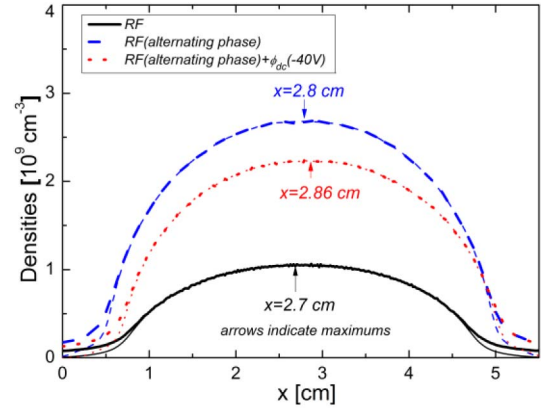


Fig. 4. Ion (thick lines) and electron (thin lines) density profiles for the different excitation waveforms considered.

time scales. This makes very difficult a self-consistent simulation of the evolution of the all subsystems simultaneously. Dust particles more inert in comparison with electrons. Thus, a dust particle's response lags behind of fast changes of the spatial profile of the electron density. However, evolution of the properties of the electrons affects ion density via the ionization rate of the atoms, and thus the mean value of the ion drag force acting on the dust grain.

In Fig. 4, the density profiles of the electrons and ions are shown for the three types of excitation waveform considered. The stronger electron heating following the fast sheath expansions in the case of the alternating-phase driving voltage leads to an increase by a factor of ~ 2.7 of the electron and ion densities in the plasma, compared with the harmonic RF excitation. The additional dc bias applied to the powered electrode (at $x = 0$) results in a decrease of the peak density and shifts the peak position of the density profiles toward the grounded electrode, as a consequence of the increasing length of the dc-biased sheath at the powered electrode. These changes in the discharge characteristics modify the levitation height of dust particle as well.

Fig. 5(a)–(c) shows the individual force components and the resulting total force acting on the dust particles, for the three different excitation waveforms. A general observation is that the spatial position of the dust levitation x_d is largely defined by the spatial dependence of the electrostatic and ion orbit forces. For the harmonic RF excitation, x_d is found to be 0.84 cm. Following the changes of the sheath length and ion fluxes under the excitation with phase-alteration, x_d decreases to 0.61 cm. The negative bias voltage, which leads to a longer powered sheath (see [16]), increases the position, to 0.81 cm, near to the original value found at the harmonic RF excitation waveform. We note that the collection force is not constant in time and we considered mean value of this force.

These results demonstrate that the electron dynamics and the position of the dust particles can be controlled in nearly independent ways, by the change of the driving voltage waveform (including phase-modulation and using an additional dc bias). As the dust charging currents obviously change with the plasma density, which is in turn set by the waveform shape, different charging scenarios can be established at otherwise (nearly) the same levitation heights. The degrees of freedom

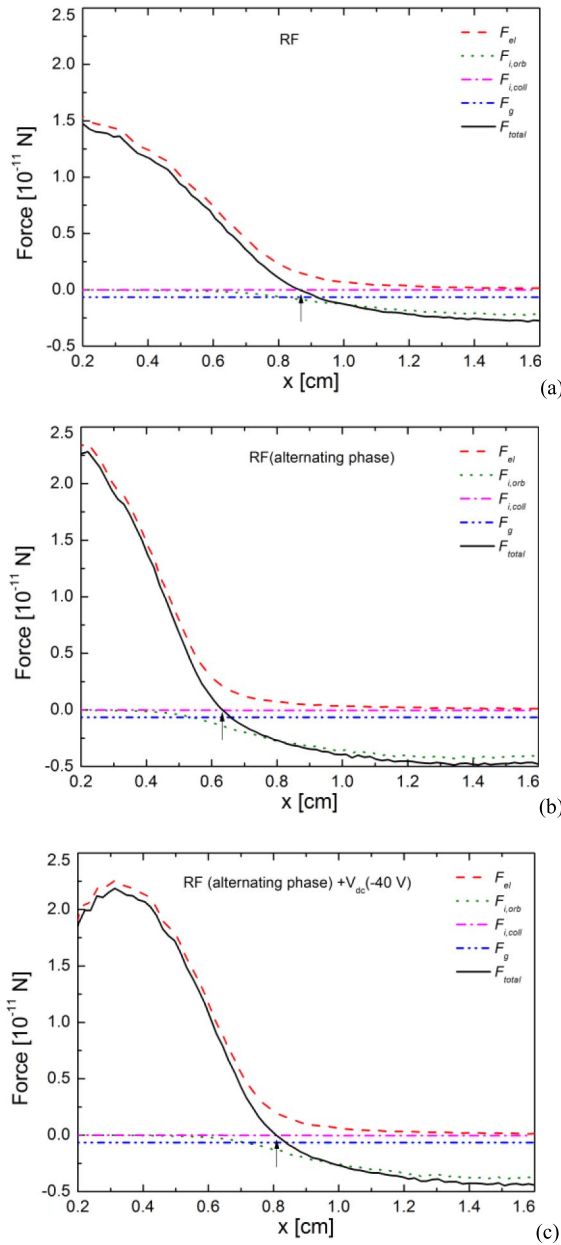


Fig. 5. Individual force components and the total force acting on the dust particles for the different excitation waveforms considered. (a) Harmonic RF excitation. (b) Alternating-phase excitation. (c) Alternating-phase excitation with -40 V dc bias. Arrows indicate the equilibrium dust levitation position as defined by $F_{tot} = 0$.

provided by waveform tailoring and switching between different waveforms open a way to heat the dust particle suspension in a way similar to the second-order Fermi acceleration, which may induce a transition between the liquid and solid phases.

Here, only mean value of the dust charge is considered, since under given parameters of the gas discharge plasma the dust charge fluctuations do not have considerable impact on the dust particle's levitation height.

IV. CONCLUSION

In this paper, we have demonstrated the effect of different driving voltage waveforms on the dynamics of capacitive RF plasmas and on the levitation height of dust particles

between the electrodes. The application of the RF excitation waveform with alternating phase was found to result in an increased electron temperature and plasma density and was revealed to have an effect of decreasing the dust levitation height. The additional dc bias, on the other hand, resulted in an increase of the levitation height and a moderate decrease of the plasma density. These two competing effects allow one to influence the dust charging mechanisms and screening length, while maintaining the levitation height, through which the energy balance of the dust system (similarly to Fermi acceleration) can be changed leading eventually to a phase transition.

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