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Manipulation of the plasma-dust layer in high-frequency discharge with an additional alternative phase

N.Kh. Bastykova[1,*], S.K. Kodanova[1], T.S. Ramazanov[1], Z. Donko[2]

[1] Scientific-Research Institute of Experimental and theoretical physics, Al-Farabi Kazakh National University, Almaty, Kazakhstan

[2] Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary

∗ *E-mail:* bastykova_nuriya@physics.kz

In this work the properties of complex plasma and the manipulation of plasma-dust layer in high-frequency discharge with an additional alternative phase have been investigated. The computer simulation of the high-frequency capacitive discharge has been carried out under the influence of an additional alternative phase on the basis of the particle-in-cell and Monte Carlo (PIC / MCC) methods. The parameters describing the kinetic and transport properties (density and temperature of electrons, electron and ion heating rates) of complex plasma of high-frequency capacitive discharge have been obtained. The charging processes of dust particles, the forces acting on dust particles, as well as the equilibrium positions of the dust particles in the plasma have been studied. A method for manipulating particles of micro and nano sizes in a low-temperature complex plasma has been developed. The results have shown that the dust charge can be tuned by the properties of the excitation waveform and in connection with it we have suggested 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.

Keywords: Complex plasma, Radiofrequency discharge, Dust particles, Particle method in cells, Monte Carlo method.

Манипуляция плазменно-пылевого слоя в высокочастотном разряде с дополнительной альтернативной фазой

В данной работе были исследованы свойства комплексной плазмы и манипуляции плазменно-пылевым слоем в высокочастотном разряде с дополнительной альтернативной фазой. Компьютерное моделирование высокочастотного емкостного разряда осуществляется под воздействием дополнительной альтернативной фазы на основе методов «частицы в ячейке» и «Монте-Карло». Были получены параметры, описывающие кинетические и транспортные свойства (плотность и температура электронов, скорости нагрева электронов и ионов) комплексной плазмы высокочастотного емкостного разряда. Были изучены процессы заряда пылевых частиц, силы, действующие на пылевые частицы, а также равновесные положения пылевых частиц в плазме. Была разработана метод манипуляции частицами микро- и нано размеров в низкотемпературной комплексной плазме. Результаты показывают, что заряд пылевых частиц может быть настроен по свойствам формы возбуждения, и в связи с этим мы предполагаем, что пылевая составляющая плазмы может быть нагрета путем изменения форм возбуждения с помощью механизма, аналогичного ферми второго порядка ускорение.

Ключевые слова: Комплексная плазма, Высокочастотный разряд, Пылевые частицы, Метод частиц в ячейках, Метод Монте-Карло.

Қосымша балама фаза бойынша жоғары жиілікті разрядтағы тозаңды-плазмалы қабатты бақылау

Бұл мақалада кешенді плазманың қасиеттері мен тозаңды-плазмалы қабаттың жоғары жиілікті разрядтағы қосымша баламалы фазамен басқаруы зерттелді. Жоғары жиілікті сыйымдылықты разрядты қосымша балама фазаның әсерімен компьютерлік моделдеу «ұяшықтардағы бөлшектер» және «Монте-Карло» әдістері негізінде жүзеге асырылды. Жоғары жиілікті сыйымдылықты разрядтағы кешенді плазманың кинетикалық және транспорттық қасиеттерін (электрондық тығыздығы мен температурасы, электрон мен иондардың қызу жылдамдығы) сипаттайтын параметрлері алынды. Тозаңды бөлшектердің зарядталу процестері, оларға әсер ететін күштер, сондай-ақ плазмадағы тозаңды бөлшектердің тепе-теңдік орындары зерттелді. Төмен температуралы кешенді плазмадағы микро- және нано өлшемді бөлшектерді басқару әдісі алынды. Тозаңды бөлшектердің зарядын қозу пішінінің қасиеттері арқылы реттеуге болатынын нәтижелер көрсетті, осыған байланысты біз екінші ретті ферми үдетуі секілді қозу пішінін өзгерту механизмі арқылы плазмалық тозаңды компонентті қыздыруға болатыны туралы болжам жасалды.

Кілт сөздер: Кешенді плазма, Жоғарғы жиілікті разряд, Тозаңды бөлшек, Ұяшықтағы бөлшектер әдісі, Монте-Карло әдісі.

Introduction

Complex (dusty) plasma is actively studied all over the world, both for a fundamental understanding of the dynamics of strongly coupled open systems [1-4] and for practical purposes [5-7]. In the laboratory, dust plasma is investigated in various types of gas discharge [8]. At the present time, the development of new technologies based on combined discharges [9] begins, in connection with which, studies on the behavior of complex plasma in such systems become relevant. The most important applications include etching and precipitation in the crystal, in the production of individual microcircuits, solar cells and the creation of biocompatible surfaces. Also of great interest is plasma in a high-frequency (RF) discharge at atmospheric pressure for medical applications [10-12]. These applications are very demanding and require research of discharge characteristics to optimize the interaction of plasma with the surface. Control of the ionic properties of plasma is a key issue, since most processes are caused by ions. The need to different types of plasma sources and excitation schemes: a capacitive discharge operating at different frequencies, as well as hybrid (DC-RF and capacitive inductive) sources [13-14]. In addition to their interest in these areas, a discharge with high-frequency voltage exhibits a complex physics that attracts much attention. The kinetics and mode of heating of electrons are key properties of the HF discharge, since they are the basis for multiplication of charges in order to balance losses in a stable state. To date, the development of plasma diagnostics and modeling methods allows carrying out and investigating these discharges.

Manipulation of individual dust particles and their ensembles is of great interest, both for a theoretical understanding of the fundamental properties of strongly coupled systems and for practical applications. In recent years, considerable progress has been made in controlling dusty plasma by means of lasers [15-16] and by modifying external electric and magnetic fields [17].

In this paper, we present the results of computer simulation of complex plasma properties in a combined radio frequency capacitive discharge (RF) with an additional alternative phase.

Theoretical basis of particle in cell and Monte-Carlo methods

Particle in cell (PIC) is the most common simulation method for describing the kinetic and transport properties of complex plasmas. The method, which belongs to the particle-grid class, was introduced in the 1960s and developed significantly over the next decades [18-19]. The idea of using a computational grid avoids the need to take into account the pair interaction of all individual particles. Another approach is to use "superparticles", which are a large number of charged particles (electrons and ions). In [20], electromagnetic effects are described in the scheme of the particle in cells method, and then electrostatic effects are considered in this paper.

The Monte Carlo method (MCC) is usually used in the simulation of collisions at low pressure. The combination of particle in cells and Monte Carlo methods is called the PIC/MCC approach. The PIC/MCC simulation cycle consists of the following steps [21-22]:

(i) at each time step, the charge of the superparticles (which can be located anywhere within the discharge gap) is assigned to the grid cells;

(ii) Poisson's equation is solved on the grid: the potential distribution is calculated from the charge distribution taking into account the potentials (or currents) applied to the electrodes as boundary conditions;

(iii) the forces acting on the particles are obtained by interpolating the electric field (as a result of differentiating the potential) to the positions of the particles;

(iv) new positions and particle velocities are determined from the solution of the equation of motion;

(v) because of the finite volume of the plasma, the interactions of particles with surrounding surfaces (for example, reflections, absorption, secondary emission) are taken into account;

(vi) collisions of the traced charged particles with each other and with the atoms of the background gas are verified and performed. In the PIC / MCC simulation, elastic scattering, excitation and ionization processes for electrons are usually taken into account, and for cold-gas approximation, for electron-atom collisions. For ions, it is usually sufficient to take into account elastic collisions, with the exception of high voltages, where excitations and ionization can also occur during ion-atom collisions.

Following the recommendations of Phelps [23], the momentum transfer cross section of elastic collisions of ion on atom Q_m is divided into isotropic and backscattering $Q_m = 2Q_b + Q_i$. Recharging at collisions and backscattering cross sections were discussed in Ref. [24]. It can be noted that at high ion energies these cross sections are equal. A similar approach was developed in Ref. [25] regarding the anisotropic elastic scattering of electrons by heavy particles. Subsequently, they were used in studies of electron transport and ions [26].

It should be noted that the kinetic properties of the particle in cell method negatively affect for the reading of collisions [27-28]. Nevertheless, PIC/MCC simulation provides a detailed analysis of the processes in plasma physics, providing spatiotemporal distributions of the quantities of greatest interest: particle distribution functions, ionization and excitation rate, electron heating rate, and fluxes and particle densities of various species.

The Monte Carlo method for describing the transport properties of electrons. There are two ways to describe the behaviour of charged particles in the presence of external forces: the observation of particle trajectories between collisions and the second is the processing of collisions of particles with a background gas.

The motion of particles between collisions is determined by the equation of motion:

$$m\ddot{\mathbf{r}} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}), \tag{1}$$

where q and m are the charge and mass of particle, respectively, $\mathbf{E}$ and $\mathbf{B}$ are electric and magnetic fields. In our case $\mathbf{B} = 0$. The particle trajectories are obtained by integrating the discredited formula (1) in time t. While the definition of the trajectory of particles between collisions is deterministic, the collisions are processed by a stochastic (probabilistic) method. And so this method was called "Monte Carlo". The approach relies on the generation of random numbers, which, however, have specific probability distributions based on physical principles. All events related to collisions should be described in the centre of mass system (CMS). Denoting through υ_1 and υ_2 both the velocities of the "incident" particle and the "target", respectively (in the laboratory (LAB) frame of reference m_1 and m_2 are their masses), the authors outlined the steps of the collision in simulation.

Check for a collision. The probability of a collision after a certain period of time Δt.

$$P(\Delta t) = 1 - \exp[-\mathrm{n}\,\overline{\sigma_T(\upsilon_r)\upsilon_r}\Delta t], \tag{2}$$

where σ_T is the total cross section, which includes the cross sections of all possible collision processes and $\upsilon_r = \upsilon_1 - \upsilon_2$ is the difference in the velocities of the collision participants. The average value $\overline{\sigma_T \upsilon_r}$ should be taken from the ensemble of atoms by the Maxwell distribution (temperature T_2) [29].

The approximation of cold gas is used in investigations, which assumes that the gas atoms are at rest (background); $\upsilon_2 = 0$. In this case υ_r becomes equal to the velocity of the electron υ_1. In connection with the large difference in the masses of the atoms and electrons, the collision in the laboratory system is the following approximation. The collision is calculated until the average electron energy is much higher than the thermal energy of the gas atoms. Or vice versa occurs only at very low values of the electric field strength.

In the cold-gas approximation ($\upsilon_2 = 0$ and thus $\upsilon_r = \upsilon_1$), the probability of collision during the time step Δt is determined by the following equation:

$$P(\Delta t) = 1 - \exp[-\mathrm{n}\,\sigma_T(\upsilon_1)\upsilon_1\Delta t]. \tag{3}$$

The simplest Monte Carlo simulation approach is based on (I) moving the particle in accordance with the equation of motion for time Δt (updating the position and velocity vectors) and

(II) verifying the occurrence of the collision using equation (3). In practice, it is necessary to choose Δt sufficiently small to realize the exact integration of the equation of motion and to withstand the probability of more than one collision, the motion of the particle will occur during a time step with a negligibly small value.

The results and discussions

The model is a one-dimensional (spatial) problem and considers 2 * 10^5 superparticles, which are electrons and argon ions. In this model, the interactions of charged particles with the surface of electrodes are taken into account in such processes as secondary electron emission and electron reflection from the surface.

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_{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.

We consider the following types of driving voltage waveforms (see Fig. 1), with an amplitude of ϕ_0 = 100 V:

1) harmonic RF voltage excitation: $\phi(t) = \phi_0 \sin[2\pi f_{RF}t]$;

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

In figure 2, 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.

Figures 3 (a) - 6 (a) show the spatiotemporal distributions of the characteristics of the plasma of a high-frequency discharge, where the distance between the electrodes (x / L) is shown vertically and the time step (t/T) along the horizontal line. Figures 3 (b) to 6 (b) show the spatiotemporal distributions of the characteristics of a high-frequency discharge plasma with an alternative phase, such as ionization and excitation rates, electric field and potential, charged particle density (electrons / ions), electron temperature, heating rates of charged particles (electrons / ions).

In figures 3 and 4, the spatiotemporal profiles of the electron density and temperature, derived from the mean energy of electrons measured in the simulation, for the case of harmonic RF excitation and for the case of alternating phase excitation with no additional dc bias are shown, respectively. Comparing figures 4 (a) and 4 (b), 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 figure 4.

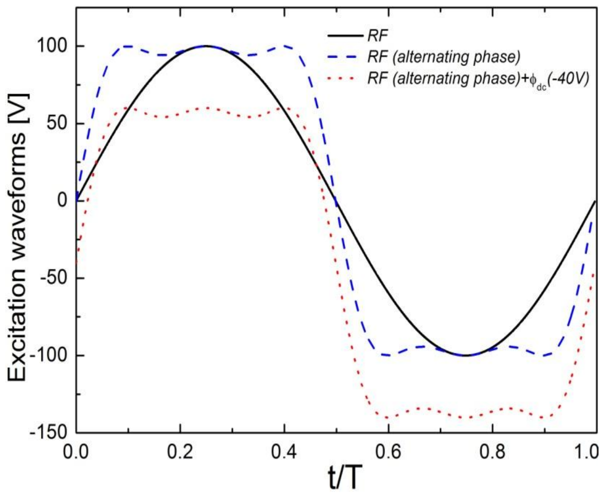


Figure 1 - Plasma excitation waveforms

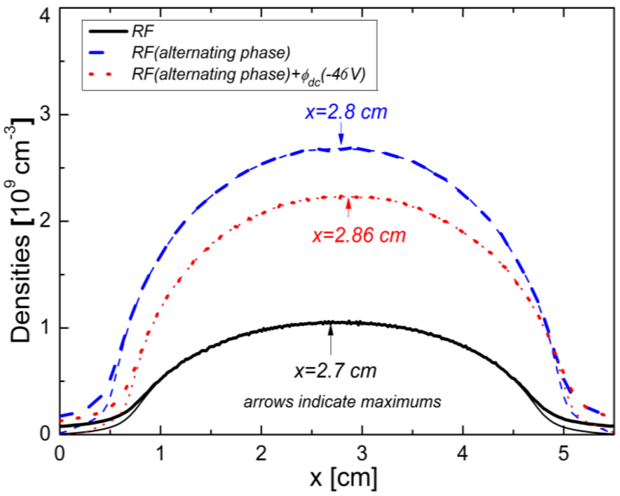
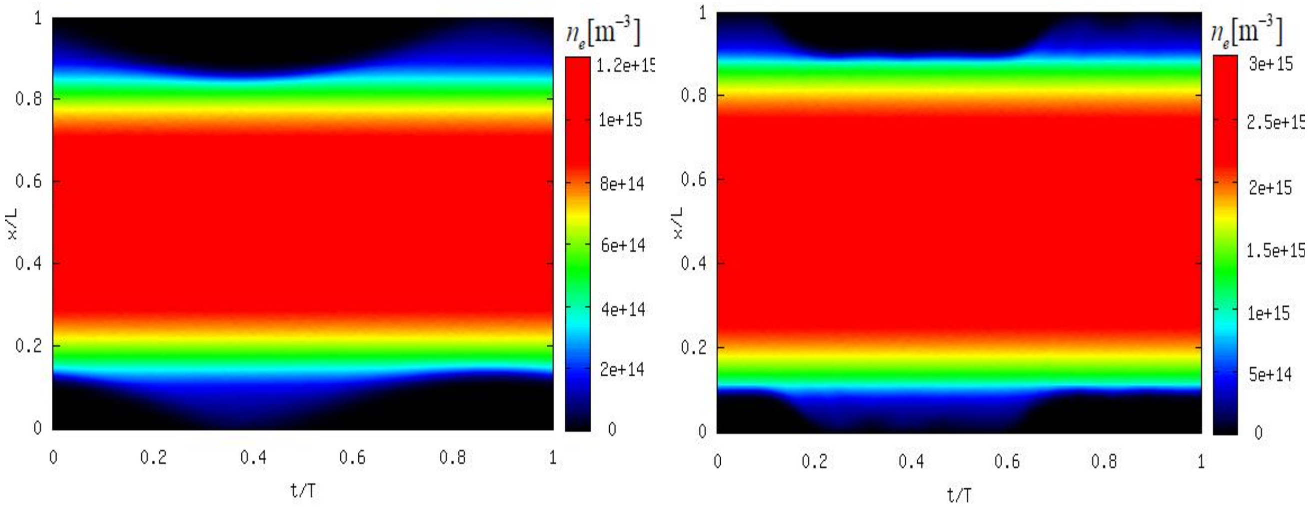
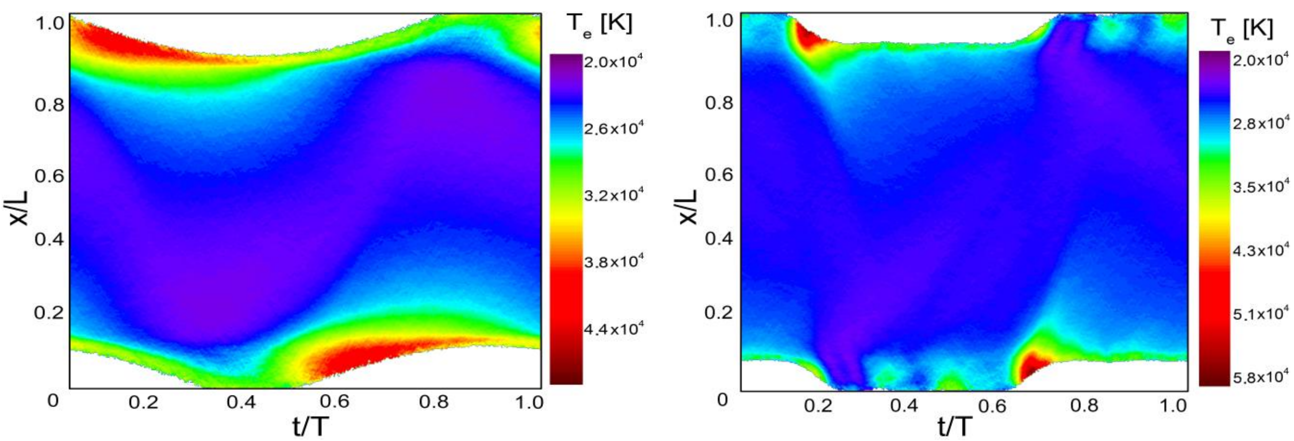


Figure 2 - Ion (thick lines) and electron (thin lines) density profiles for the different excitation waveforms



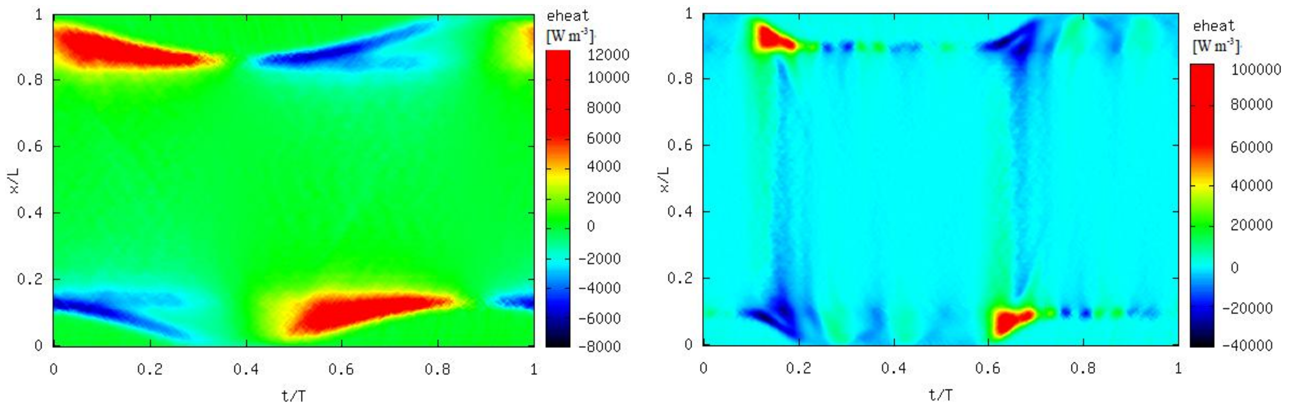
(a) (b)

Figure 3 - Spatiotemporal profile of electron density in RF discharge (a) and RF discharge with alternating phase (b) for L = 55 mm, V_{pp} = 100 V at pressure p = 1,8 Pa



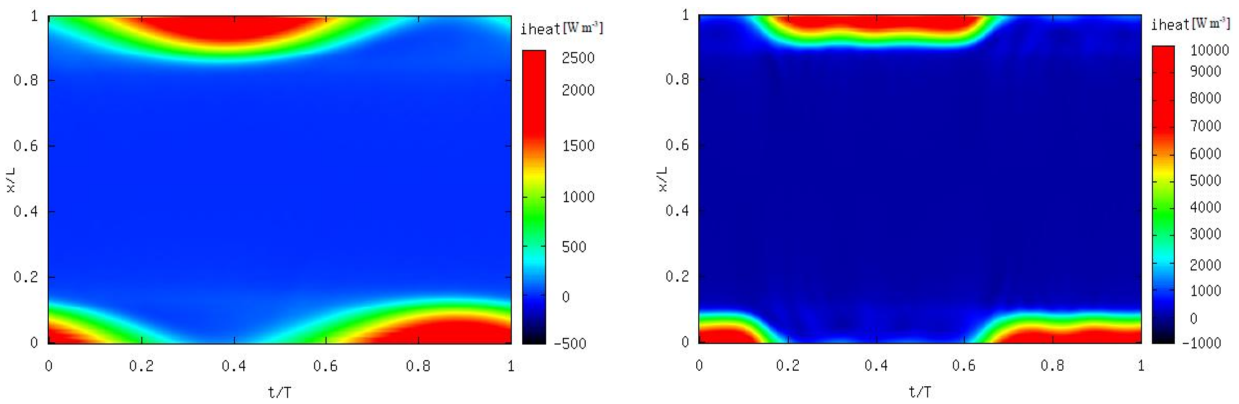
(a) (b)

Figure 4 - Spatiotemporal profile of electron temperature in RF discharge (a) and RF discharge with alternating phase (b) for L = 55 mm, V_{pp} = 100 V at pressure p = 1,8 Pa



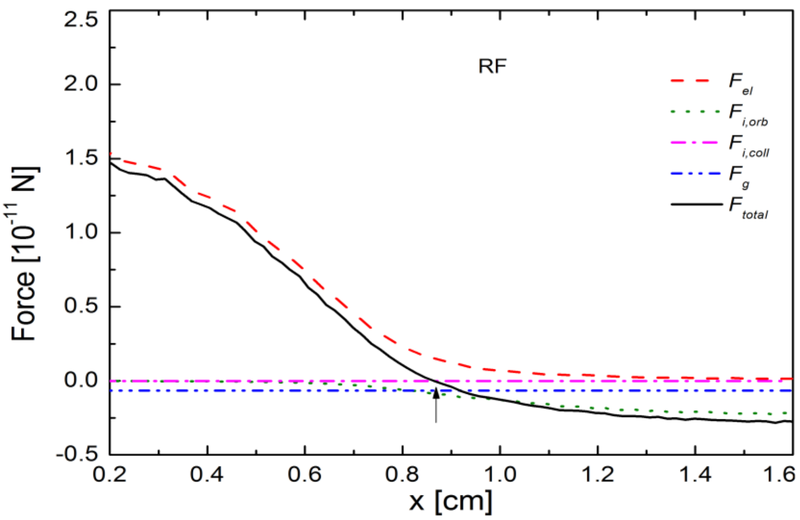
(a) (b)

Figure 5 - Spatiotemporal profile of electron heating rate in RF discharge (a) and RF discharge with alternating phase (b) for L = 55 mm, V_{pp} = 100 V at pressure p = 1,8 Pa



(a) (b)

Figure 6 - Spatiotemporal profile of ion heating rate in RF discharge (a) and RF discharge with alternating phase (b) for L = 55 mm, V_{pp} = 100 V at pressure p = 1,8 Pa



(a)

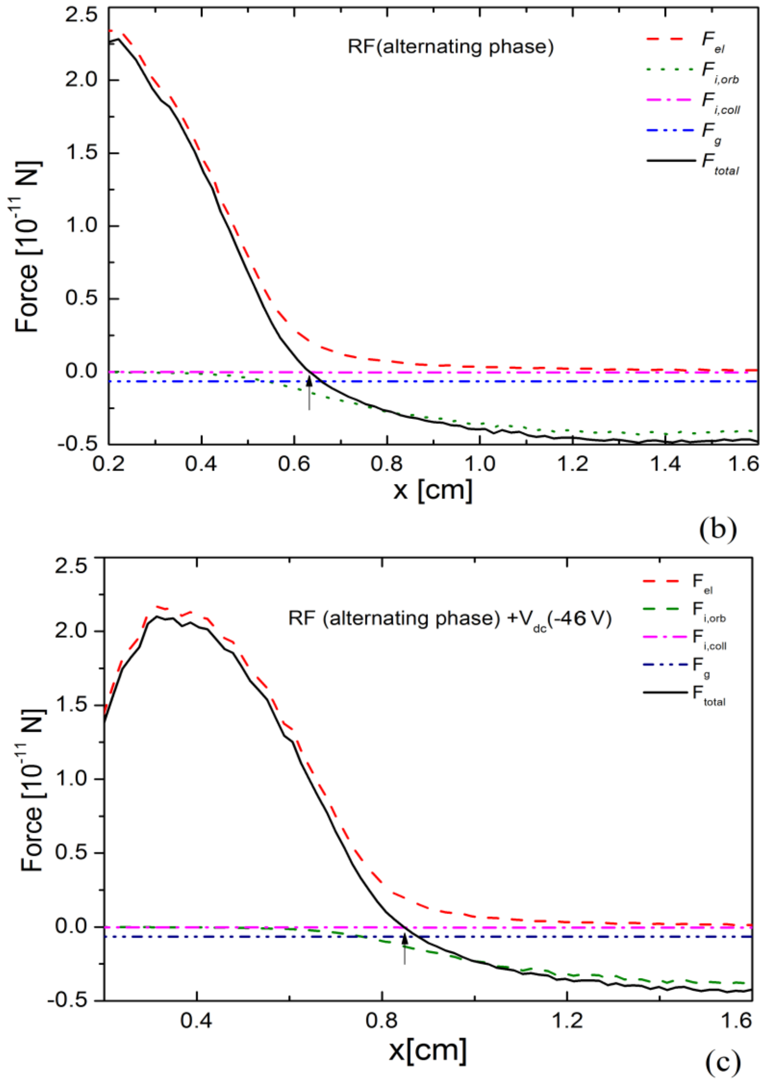


Figure 7 - Spatial dependence of the different force components in RF discharge (a) and RF discharge with alternating phase (b) and direct current (c), for conditions L = 55 mm, V_{pp} = 100 V at p = 1.8 Pa. The arrows indicate the equilibrium position of the dust particles for the corresponding conditions

Figures 7 (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, increases the position, to 0.81 cm, near to the original value found at the harmonic RF excitation waveform. 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 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.

Conclusions

In this work the properties of complex plasma and the manipulation of plasma-dust layer in high-frequency discharge with an additional alternative phase are investigated. The computer simulation of the high-frequency capacitive discharge is carried out under the influence of an additional alternative phase on the basis of the particle-in-cell and Monte Carlo (PIC / MCC) methods. The charging processes of dust particles, the forces acting on dust particles, as well as the equilibrium positions of the dust particles in the plasma are studied. A method for manipulating particles of micro and nano sizes in a low-temperature complex plasma has been developed. This method of manipulation of dust particles was tested at various plasma parameters (pressure, interelectrode distance, form of RF signal) of high-frequency discharge. 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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