DUST GRAINS CHARGING OF LOW TEMPERATURE DUSTY PLASMAS UNDER ION ACOUSTIC PARAMETRIC INSTABILITY ONSET

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The process of dust grains charging in low temperature dusty plasmas of low pressure is considered under parametric ion acoustic instability development. The secondary electron emission from the dust grain surface and a dust grain polarization under the action of the self-consistent electric field are taken in account. The results of the numerical 2D3V simulation of dusty plasmas charging in RF discharge are presented in cylindrical geometry. For self-consistent simulation of dust grain charging process we use the numerical model that comprises three models: «Particle-in-Cell» (PIC), «Monte Carlo Collisions» (MCC) and «Particle-Particle Particle-Mesh» (P3M) models.

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INTRODUCTION

The presence of dusty grains considerably affects collective processes in plasma. They can change both the oscillation spectra and the plasma instabilities that exist in plasma without a dust and originate new oscillation branches and new specific instabilities.

The process of a dust grain charging in the low temperature plasma of low pressure is considered in this paper under the ion acoustic parametric instability onset. The results of 2D3V simulation of the dust grains charging in the RF discharge plasma are presented. Particle-Particle Particle-Mesh (P3M) model is used for the self-consistent simulation of the dust grains charging [1, 2]. The model choice is related to that, although the method particle-in-cell (PIC) proves its effectiveness for plasma simulation, it has an essential drawback for investigation of the dusty plasma. A space resolution in the PIC scheme is limited by the space grid step size which is, as a rule, of the order of the Debye radius. For low temperature plasma the Debye radius size is the order of tenth or hundredth part of centimeter. But the dust grain size belongs to micrometer range, so it is considerably less than the space grid step size. In PIC-model the particles are described as the charged clouds with a size of a space grid cell. This leads to the non-accurate representation of the particles interaction, when the distance between them becomes less than the spatial grid step size. Therefore, the interaction force in the PIC-model strongly differs from the Coulomb interaction on a small distance. To overcome this problem the P3M-model is used. This model is a combination of the PIC-model and the molecular dynamics (MD) technique. The long-range dust grains interaction with the charged plasma particles is described in correspondence to the PIC formalism. For the plasma particles that are located at the distance lesser than the Debye radius from the dust grain the interaction force is calculated by the direct particle-particle scheme using the exact Coulomb potential. At the same time the interaction force between the particles of the plasma itself are calculated by the PIC-scheme at the same region. To decrease the computer computation time for the direct particle-particle interaction the so-called "chain grid" is introduced additionally [1]. On the scales of the order of the dust grain size the motion of the plasma particles is calculated with a time step lesser than it is in the regions located far from the dust grains the typical time step in the PIC scheme is the order of 10^{-11} seconds. At the same time near the dust grains the typical time step is about 10^{-13} seconds. Plasma particles, which cross a surface of the dust grain, are considered as a source of the secondary electron emission.

1. DISPERSION EQUATION

If the relative motion of electrons and ions is caused by the action of a pumping field with the frequency of the order of the lower hybrid one, the excitation of ion acoustic parametric instability of the kinetic kind becomes possible [3]. This instability is excited by the electrons that move along the magnetic field with the velocity $v_{\|}$ which equals to the phase velocity of the beats between the pumping field and unstable oscillations. The frequency of the beats is equal to $\omega_s - p\omega_0$, and the longitudinal wave number is equal to $k_{\|} - pk_{\|0}$, where ω_0 and $k_{\|0}$ is the frequency and longitudinal wave number of the pumping wave. The velocity of the resonant electrons is equal to $v_{\|} = (\omega_s - p\omega_0)/(k_{\|} - pk_{\|0})$. The dispersion equation which determines the frequency of the ion sound and electron contribution into the growth rate has the view

$$D = \det \left\| a_{mn} \right\|_{m,n=-\infty}^{\infty} = 0\,, \tag{1}$$

where

$$a_{mn} = \delta_{mn} + \frac{\exp\left[-i(n-m)(\delta+\pi)\right]}{1+\delta\varepsilon_i(\omega - m\omega_o, \mathbf{k})} \times \sum_{p=-\infty}^{\infty} J_{p+m}(a_e) J_{p+n}(a_E)\, \delta\varepsilon_e\left(\omega + p\omega_o, \mathbf{k} + p\mathbf{k}_{\|0}\right). \tag{2}$$

The dispersion equation (1) with the elements (2) is written in the reference frame of ions which move under the action of external pumping field. The partial electron contribution $\delta\varepsilon_e$ into the dielectric permeability takes into account the collisions of electrons with neutrals and ions. The frequency of the collisions of electrons with ions is determined by the expression

$$\nu_{ei} = 0.75\sqrt{2\pi/m_e}\, e^4 nL \big/ T_e^{3/2}\,, \tag{3}$$

where L is the Coulomb logarithm, e is the elementary charge, n is the plasma density number, and T_e is the electrons temperature.

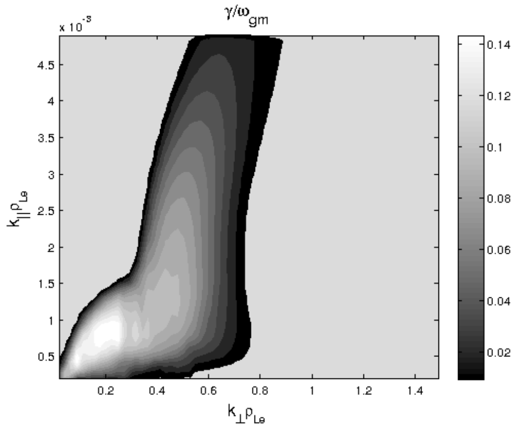

Fig. 1. Growth rate of the unstable oscillations, $q = 1030$

Consider the ion acoustic parametric instability development for the typical parameters of the RF discharge: the plasma number density, $n = 10^{12}$, the external magnetic field, $B_0 = 100$ G. The ion acoustic parametric instability arises under the velocity value of the electron oscillations $u_e = 5V_s$ and the frequency of the pumping field $\omega_0/\omega_{gm} = \omega_0/\omega_{LH} = 1.2$, where V_s is the ion sound velocity, $\omega_{gm} = \sqrt{\omega_{ce}\omega_{ci}}$ is geometric mean frequency. The ion temperature is equal to $T_i = 0.3$ eV, the electron temperature is by an order of magnitude greater, $T_e = 3$ eV. For these parameters the electron-ion collision frequency is $\nu_{ei} = 3.21 \cdot 10^6$. The dependence of the growth rate of the unstable oscillations on the values of longitudinal $k_{\|}\rho_e$ and transversal $k_{\perp}\rho_e$ wave numbers is shown in Fig. 1. The frequency of the unstable oscillations is near ω_{gm} frequency.

As it shown in Fig. 1, in this case the instability takes place in the wave number range, $0.1 \le k_{\perp}\rho_e \le 0.9$, $0.2 \cdot 10^{-3} \le k_{\|}\rho_e \le 5 \cdot 10^{-3}$. The propagation angle of the parametrically unstable ion acoustic oscillations relatively the magnetic field direction vary within wide limits, $2.2 \cdot 10^{-3} \le \cos\theta \le 5 \cdot 10^{-2}$. The maximum growth rate, $\gamma_{\max} \approx 0.14\omega_{gm}$ is reached for the wave number $k_{\perp}\rho_e \approx 0.2$, $k_{\|}\rho_e \approx 7 \cdot 10^{-4}$ and the propagation angle value $\cos\theta \approx 0.35 \cdot 10^{-2}$.

The frequency of the parametrically unstable oscillation in this region of the wave numbers can essentially defer from the frequency of the "pure" ion sound $\omega_s = kV_s$. It is found out that the discrepancy $\Delta\omega$ between ω_s and the frequency of the unstable ion acoustic oscillations for which the maximum growth rate is reached is $\Delta\omega \sim \gamma_{gm} \sim 0.1\omega_{gm}$.

2. SYMULATION RESULTS

For the numerical simulation the following parameters are chosen: the plasma density number $n_0 = 10^{12} cm^{-3}$, the external magnetic field $B_0 = 100G$, the initial temperature of electrons T_{e0} =3 *eV*, the initial temperature of ions $T_{i0} = 0.1 \cdot T_{e0} = 0.3$ *eV*, the pumping field frequency $\omega_0 = 1.2\,\omega_{LH}$. The velocity of electrons oscillations relatively ions equals $5 \cdot V_s$, where V_s is the ion sound velocity. Then the parameter $q = \omega_{pe}/\omega_{ce}$ =32. The operation gas is argon.

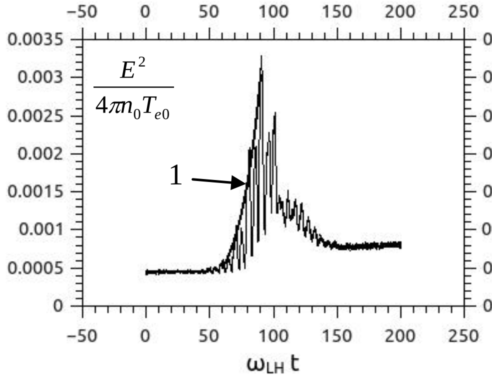

Fig. 2. Electric field energy density

Evolution of the electric field energy density normalized on the initial thermal energy density of electrons is presented in Fig. 2. The electric field energy at first exponentially grows up to the maximum energy level is reached. Then, after the several relaxation oscillations, it decreases together with the value $u/v_s(t)$. The curve 1 in Fig. 2 is proportional to $\exp\left(0.16\,\omega_{LH}\,(t - t_0)\right)$. It corresponds to the growth rate $\gamma = 0.08\,\omega_{LH}$. At the final stage the value $E^2/n_0 T_{e0}$ becomes stable at the quasi stationary level.

Time evolution of the amplitude of the most unstable ($k\rho_e \approx 1.17$) Fourier harmonic of the electric potential is shown in Fig. 3.

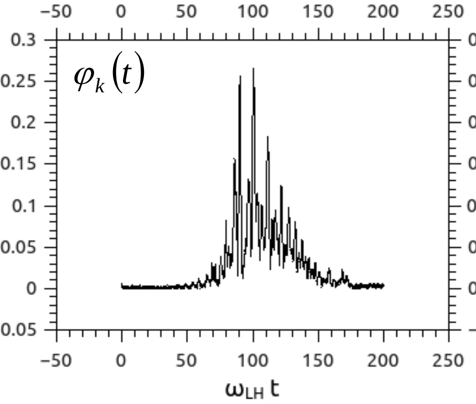

Fig. 3. Most unstable electric field mode

Fig. 4 demonstrates the behavior in time of the longitudinal electron temperature and transversal ion temperature. The transversal ion temperature exceeds the initial temperature of ions more than five times at stationary level. At the same time the longitudinal temperature of ions remains almost fixed. The longitudinal electron temperature exceeds the initial temperature of electrons three times at stationary level and continues father growth.

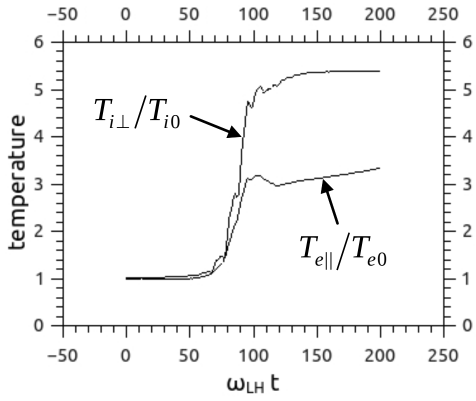

Fig. 4. Growth of the electron and ion temperatures

3. DUST GRAINS CHARGING PROCESS

The dust grains charging process is shown in Figs. 5-8. In the non-equilibrium plasma of the low pressure RF discharge the ions, atoms and dust grains, despite the high energy of electrons, as a rule, remain cold, although the transversal ion energy grows considerably due to parametric ion acoustic instability development. Owing to the considerably greater mobility of electrons their flux greatly exceeds the ions flux. As a result a typical grain of micrometer size obtains the negative charge, collecting several thousands of elementary charges, and creates negative floating potential which repels electrons and attracts ions. The charge of a dust grain grows until the ions flux on their surface comes up with electrons flux. After that the dust grain charge achieves the stationary stage. At this stage it is almost fixed in average, but experiences same fluctuations near the equilibrium value.

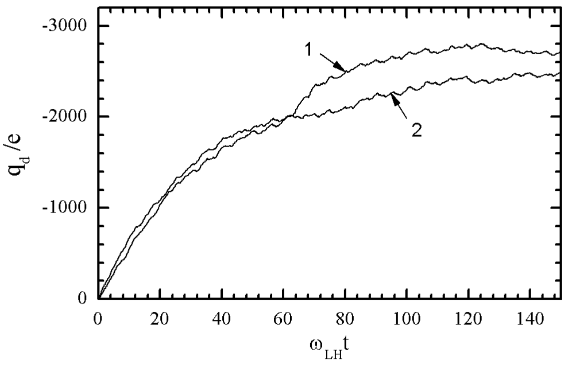

Fig. 5. Time dependence of the charge value of the dust grain 1 and 2

In Fig. 5 the charge varying in time of two dust grains, 1 and 2, located at plasma periphery is presented. At the initial stage of the dust grains charging ($\omega_{LH} t \le 60$) they are charged in correspondence with the ions and electrons fluxes, that fall on their surface.

The computations show that this time interval is about 7 μs . It agrees with the time interval 5 μs , predicted by the "orbital motion limit" (OML) theory. The stationary level of the charge at the plasma periphery is greater than in the bulk plasma. In Fig. 6 the charge fluctuations of the dust grains 1 and 2 near the plasma periphery are shown at the quasi stationary stage.

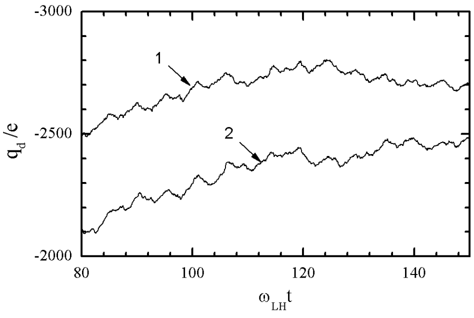

Fig. 6. Charge fluctuations of the dust grains 1 and 2 at the quasi-stationary stage

Most of the dust grains charging in plasma theories are formulated in the terms of continuous variables. But as in a reality, so in the plasma simulation by means of particle-in-cell method (PIC formalism) this process represents a discrete sequence of the events of charged plasma particles absorption by the surface of a dust grain. The sequence and the time intervals between the successive dust grains charging events are described by the stationary stochastic markov process. It gives a possibility to take into account the charge fluctuations of dust grains near an equilibrium value. In the dusty plasma such fluctuations always are present. It makes the properties of the dusty plasma different from the properties of the "usual" multi-component plasma and underlines importance of their taking in account.

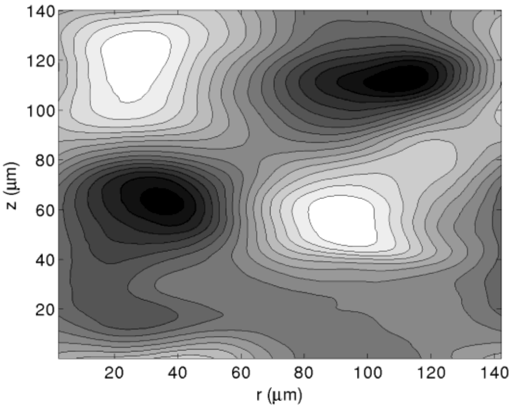

Fig. 7. Plasma potential near the dust grains

The expressions for the amplitude of dusty grain charge fluctuations are obtained in the papers [4-6] on the base of the relation of thermal energy and electrostatic potential at the distance of a dust radius. They give the estimate of the fluctuations at the level of 60 values of elementary charge. However this estimate relies on an assumption of plasma stationarity, but under the instability development it is not the case. Non-stationarity of RF discharge under the ion acoustic parametric instability conditions increases the fluctuations amplitude. Nevertheless, this estimate gives the right order of magnitude of the charge fluctuations of dust grains.

In Fig. 7 the structure of the plasma potential near dust grains is shown. Two dust grains are located in Fig. 7: the first is located in the low left angle (with the coordinates $r = 38\ \mu m$, $z = 60\ \mu m$) and the second is located in the right upper angle (with the coordinates $r = 118\ \mu m$, $z = 117\ \mu m$). The distance between the dust grains is about $100\ \mu m$. They have a negative charge and create a negative potential around itself in plasma.

In Fig. 8 the correspondent density number of ions is presented. As one can see from Fig. 8 the ions concentrate near the dust grains shielding their potential at the distance of the order of $10\ \mu m$.

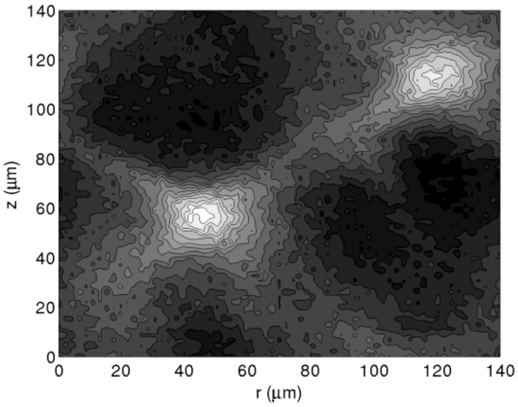

Fig. 8. Ion density number near the charged dusty grains

CONCLUSIONS

At the quasi stationary stage of the ion acoustic parametric instability development the temperature of ions has the considerable anisotropy that depends from the value of the external magnetic field.

For the selfconsistent simulation of the process of dust grains charging, including their finite size effects, the Particle-Particle Particle-Mesh (P3M) numerical model is used, that gives a realistic picture of the interaction of dusty grains with plasma particles, and permits to take into account the short range force between dust grains and plasma particles.

The calculations have shown that the charging time obtained by the numerical simulation agrees with the charging time predicted by the “orbital motion limit” (OML) theory. At that the stationary discharge at the plasma periphery is larger than it is in the bulk plasma.

Nonstationarity of RF discharge under the ion acoustic parametric instability development increases the amplitude of the charge fluctuations of dust grains in comparison with the estimate obtained on the base of the relation of the particles thermal energy and the electrostatic potential value at a distance of the dust grain radius.

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ЗАРЯДКА ПЫЛИНОК НИЗКОТЕМПЕРАТУРНОЙ ПЫЛЕВОЙ ПЛАЗМЫ ПРИ РАЗВИТИИ ИОННО-ЗВУКОВОЙ ПАРАМЕТРИЧЕСКОЙ НЕУСТОЙЧИВОСТИ

В.В. Ольшанский

Рассмотрен процесс зарядки пылинок в низкотемпературной пылевой плазме низкого давления при развитии параметрической ионно-звуковой неустойчивости с учётом вторичной электронной эмиссии с поверхности пылинок и поляризации пылинок под действием самосогласованного электрического поля. Представлены результаты 2D3V-моделирования зарядки пылевой плазмы в ВЧразряде в цилиндрической геометрии. Для самосогласованного моделирования процесса зарядки пылинок используется численная модель, объединяющая три модели: «Particle-in-Cell» (PIC), «Monte Carlo Collisions» (MCC) и «Particle-Particle Particle-Mesh» (P3M).

ЗАРЯДЖАННЯ ПОРОШИНОК НИЗЬКОТЕМПЕРАТУРНОЇ ЗАПОРОШЕНОЇ ПЛАЗМИ ПРИ РОЗВИТКУ ІОННО-ЗВУКОВОЇ ПАРАМЕТРИЧНОЇ НЕСТІЙКОСТІ

В.В. Ольшанський

Розглянуто процес заряджання порошинок в низькотемпературній запорошеній плазмі низького тиску під час розвитку параметричної іонно-звукової нестійкості з урахуванням вторинної електронної емісії з поверхні порошинок і поляризації порошинок під дією самоузгодженого електричного поля. Представлено результати 2D3V-моделювання заряджання запорошеної плазми у ВЧ розряді в циліндричній геометрії. Для самоузгодженого моделювання процесу заряджання порошинок була використана числова модель, яка поєднує в собі три моделі: «Particle-in-Cell» (PIC), «Monte Carlo Collisions» (MCC) та «Particle-Particle Particle-Mesh» (P3M).