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Modelling of argon/dust pulsed plasma

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We analyze how properties of an argon/dust pulsed plasma depend on the shape of the electron energy probability function (EEPF) and the pulsing frequency. The study is carried out using a spatially averaged model, which assumes that the plasma has R = 15 cm radius and L = 7 cm height and consists of electrons with density n_e, singly charged positive ions (Ar^+) with density n_i, dust particles with density $n_d = 3.0\times10^7$ cm^{-3}, radius a_d = 50 nm and negative charge eZ_d (e is the elementary charge), ground-state argon atoms (Ar_0) with density n_a, metastable argon atoms (Ar_m) with density n_m, argon atoms in the resonance 4s states ($^3P_1$ and $^1P_1$) as well as argon atoms in 4p states. The neutral gas pressure P is 10 Pa, and the EEPF is described as $F(\varepsilon) = A_1 \exp(-A_2 \varepsilon^{x_F})$, where ε is the electron energy and x_F takes different values according to the shape of EEPF: x_F = 1 and x_F = 2 for Maxwellian and Druyvesteyn electron energy distributions, respectively. The coefficients A_1 and A_2 are functions of x_F and the average electron energy [1]. We also assume that ions and dust particles are at gas temperature T_g and ions have Maxwellian distribution.

The density of a species Y (electrons and argon atoms in excited states) as a function of time t is found from the following balance equation

$$\frac{\partial n^{(Y)}}{\partial t} = \sum_i R_{G,i}^{(Y)} - \sum_i R_{L,i}^{(Y)}, \qquad (1)$$

where $R_{G,i}^{(Y)}$ and $R_{L,i}^{(Y)}$ are, respectively, the rates for reactions of the various generation and loss processes of the species Y. We assume that in both pure argon and dusty pulsed plasmas, electrons are generated in collisions of electrons with argon atoms in the ground and excited states (4p and 4s states), as well as in metastable–metastable collisions. In the dusty plasma, we assume that electrons can be additionally produced at interaction of excited argon atoms with acetylene molecules [2]. It is assumed that acetylene molecules are present with the very low density (~10^{11} cm^{-3}) in the pulsed dusty plasma since the experimental procedure of making the dust plasma involves the use of acetylene as a precursor [2]. Electrons and ions are lost from the discharge because of their diffusion to the walls and by deposition on dust particles. The plasma is assumed to be quasineutral ($n_i - n_e + n_d Z_d = 0$). The effective electron temperature, $T_{\text{eff}} = (2/3e)\int_0^\infty \varepsilon F(\varepsilon)\sqrt{\varepsilon} d\varepsilon$), as a function of time was found from the power balance equation [3], assuming that the effective electron temperature cannot be smaller than the afterglow temperature T_{aft}, i.e. after its decay to reach T_{aft}, T_{eff} becomes time-independent. Here, T_{aft} =0.15 eV and T_{aft} =0.1 eV for the dust-free and dusty cases, respectively. It is also assumed that the absorbed power is modulated by an ideal rectangular waveform

$$P_{\text{abs}} = \begin{cases} P_{\max} & \text{for } (k-1)\tau \le t < (k-1)\tau + \eta\tau, \\ 0 & \text{for } (k-1)\tau + \eta\tau \le t < k\tau, \end{cases} \tag{2}$$

where τ is the full cycle period, η is the duty cycle, and k is a positive integer. $P = P_{\max}$ for the on-period and $P = 0$ for the off-period.

The dust charge as a function of time is found from the following equation:

$$\frac{\partial Z_d}{\partial t} = K_i^d n_i - K_e^d n_e, \tag{3}$$

where K_i^d and K_e^d are the rates describing collection of ions and electrons by dust particles, respectively. More details on the model equations and the reaction rates can be found in [3].

Using the model, we calculated plasma properties (n_e, n_m, T_{eff} and Z_d) as a function of time in dust-free and dusty plasmas for the conditions typical to experiments on pure argon and argon/dust pulsed plasmas [2]. Fig. 1 illustrates the temporal behavior of the line-of-sight averaged electron density [(*a*) and (*c*)] and Ar* 1s$_5$ metastable density [(*b*) and (*d*)] measured at the mid-plane between electrodes and the corresponding simulation results. The results of calculations are in a good qualitative agreement with the experimental data.

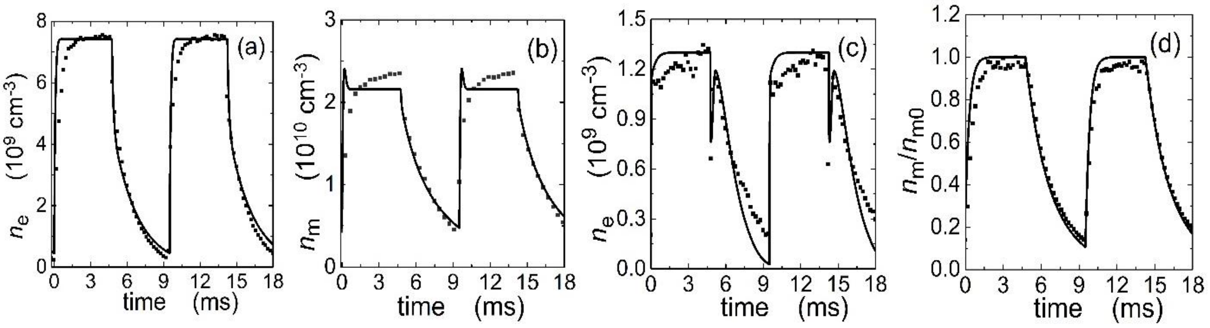

Fig. 1. Electron [(*a*) and (c)] and metastable [(*b*) and (*d*)] densities as a function of time in a pulsed plasma for the dust-free [(*a*) and (*b*)] and dusty [(*c*) and (*d*)] cases. Solid lines — model; black squares — experiment [2]. Zero time indicates the beginning of the on-period. The off-period (afterglow phase) starts at 4.75 ms and ends at 9.5 ms. n_{m0}=9.64×10^{10} cm^{-3} and n_{m0}=1.75×10^{11} cm^{-3} for the model and experiment, respectively. Here, x_F = 2.

The simulations were carried out for different shapes of the EEPF (Fig. 2). It is found that with increasing x_F, the EEPF becomes more convex and the effective electron temperature in the on-period increases [Fig. 2(*a*)]. As a result, the metastable density becomes larger [Fig. 2(*b*)]. The increase of n_m is accompanied by increasing the electron density in the off-period [Fig. 2(*c*)]. At the end of the on-period, the calculated metastable densities for $x_F = 1$ and $x_F = 1.5$ [Fig. 2(*b*)] are much smaller than the measured one (1.75×10^{11} cm^{-3}). Moreover, the time-dependence for n_e in the case $x_F = 1$ [Fig. 2(*c*)] differs essentially from the experimental data [Fig. 1(*c*)]. Thus, the results of theory and experiment agree better if the EEPF has a Druyvesteyn shape instead of a Maxwellian one.

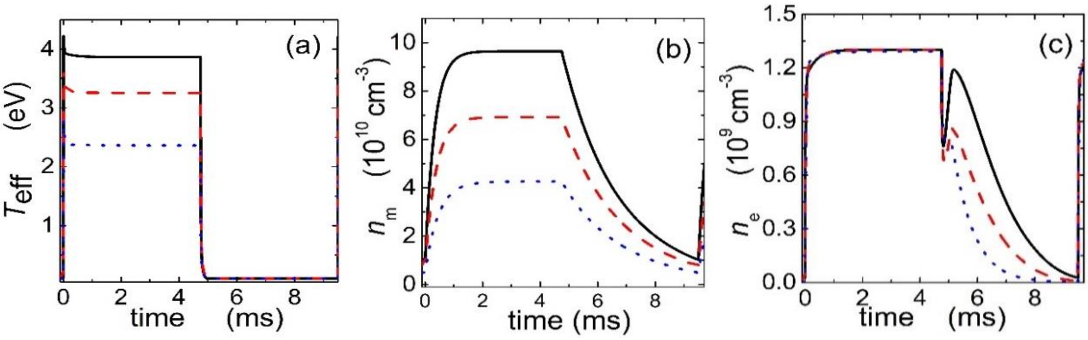

Fig. 2. T_{eff} (*a*), n_m (*b*) and n_e (c) in an argon/dust pulsed plasma for different x_F: 2 (solid line), 1.5 (dashed line) and 1.0 (dotted line). Here, n_e at the end of the on-period is 1.3×10^9 cm^{-3}, as in Fig. 1(*c*).

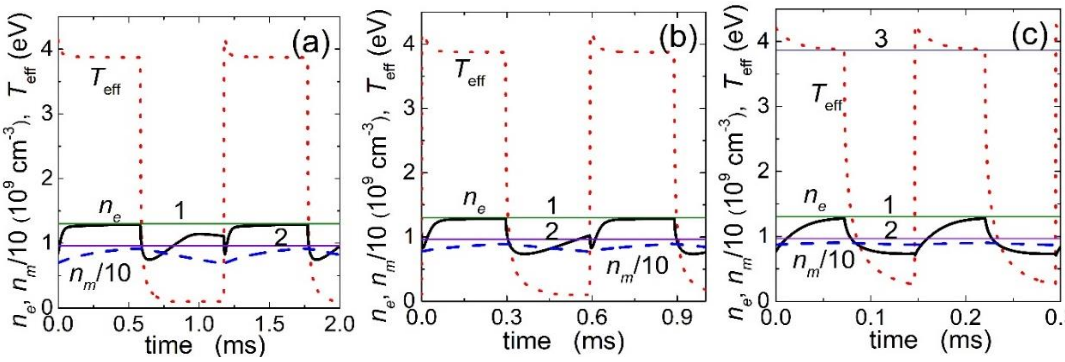

Fig. 3. n_e (solid line), n_m/10 (dashed line) and T_{eff} (dotted line) as a function of time in Ar/dust pulsed plasma at $x_F = 2$ and different ν_p: 840 (*a*), 1680 (*b*) and 6720 (*c*) Hz. The line 1 describes n_e, the line 2 describes n_m/10 and the line 3 (only in (*c*)) T_{eff} for the CW plasma with P_{abs}= 12.6 W (which equals to P_{max} in the pulsed plasma case).

Our model also shows that in the presence of dust and at some pulsing frequencies ν_p the electron density decreases rapidly in the very beginning of the on-period (Fig. 3). In our opinion, this decrease is due to an enhancement of electron collection by dust particles at the beginning of the on-period. Further, variation in the pulsing frequency differently affects the metastable density in a dust-free and in a dusty plasma. For large pulsing frequencies ($\geq$ 840 Hz), the metastable density in presence of dust is smaller than in the continuous-wave (CW) discharge

(Fig. 3), contrary to the dust-free case [3]. In our opinion, this is due to faster variation of the effective electron temperature in the dusty case comparing with the $n_d = 0$ case, because of collection of electrons by dust particles.

Using a 1D model for a dust-free Ar plasma afterglow, we also studied the charge of a dust particle and the forces affecting the dust particle as a function of time and spatial coordinate x. A plasma slab of $L = 5$ cm size was considered. It was assumed that the spatial dependence for n_e is cosines-like, $x_F = 2$, T_{eff} is spatially homogeneous and $T_{aft} = 0.1$ eV. The calculations were carried out for $a_d = 50$ nm, $P = 0.1$ Torr and for the initial electron density in the slab midplane $n_{e0} = 10^{10}$ cm^{-3}. The electron temperature and density were obtained using the ambipolar diffusion approach, and the dust charge was calculated assuming that the ion current to a dust grain equals to that of electrons. The forces affecting the dust grain were calculated in the same manner as in [4].

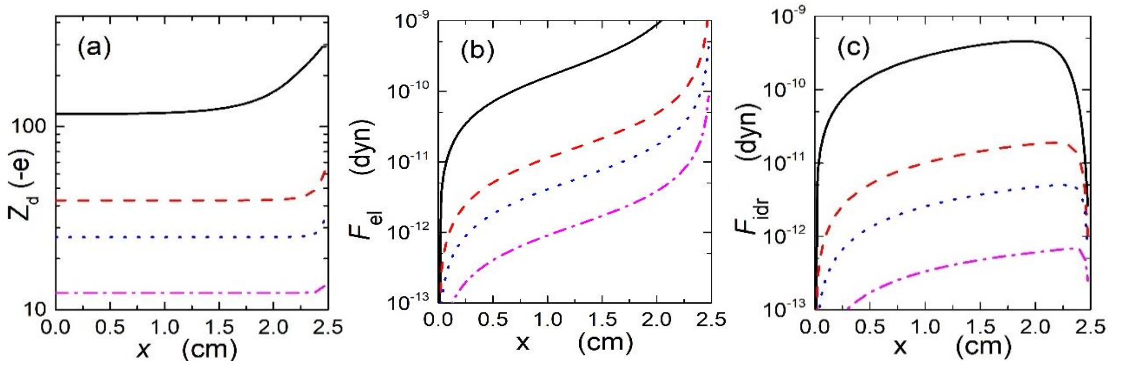

Fig.4. The spatial distributions of dust charge (a) and the electric (b) and ion drag forces affecting a dust grain in an afterglow plasma for $t = 0$ (solid line), 5×10^{-2} ms (dahed line), 0.1 ms (dotted line) and 0.3 ms (dash-dotted line). Here, x=0 and x =2.5 cm correspond to the slab midplane and the slab boundary, respectively.

It was found that the amount of negative charge on the dust particle decreases rapidly in the beginning of the afterglow [Fig. 4(*a*)] because of decreasing the electron temperature, until $T_{eff} = T_{aft}$. The decrease is accompanied by decreasing the electron density and by a decrease of the electric and ion drag forces [Figs. 4(*b*) and 4(*c*)]. At large afterglow times (here, $t \geq 0.3$ ms), the electron temperature becomes time-independent, and, as a result, the dust charge and the electric force are also nearly time-independent. In the late afterglow, the ion drag force is essentially smaller than the electric force [Figs. 4(*b*) and 4(*c*)] because of decreasing n_e.

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