THE ABRUPT FORMATION OF LARGE POPULATION OF COLD ELECTRONS WITH CURRENT GROWTH, ACCOMPANIED WITH PLASMA SELF-TRAPPING IN LOW PRESSURE DISCHARGES

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The interest in study of the low-pressure discharges has been invoked by such an interesting physical phenomenon, as a formation of the strongly non-Maxwellian electron distribution function (EDF) which is inherent to this type of discharges. The concave shaped EDF with a strongly pronounced group of low energy electrons was observed experimentally and in the various types of discharges: inductively, capacitively coupled discharges [1], direct current and electron cyclotron resonance ones.

One of the reasons stipulating the interest in study of capacitively coupled plasma (CCP) is the inherent to this type of discharge such physical phenomena as a radical changes of the EDF form with discharge parameters variation. So it is necessary to solve kinetic equation even for a qualitative description. Moreover we have found new principal phenomena in the discharge self-organization – *plasma self-trapping*, due to coupling of EDF profile with ion density profile and vice versa. We have shown that plasma non-uniformity and non-locality of EDF plays the key role in formation of large amount of cold electrons.

For analysis of the complex self-consistent structure of the low pressure discharges the method of fast modeling has been developed [2]. It is based on averaging over fast electron and ion motions and on eliminating a small spatial scale, the Debye radius. As a result, the solution of self-consistent system of electron kinetic equation, the Poisson, and ion continuity equations takes approximately 10min on 486PC.

The full self-consistent system of equations for CCP discharge description is based on the non-local approach [2]. We consider discharge under conditions: $\nu >> \nu^*$; $\omega >> \nu^*$, $\lambda_\varepsilon \sim \sqrt{\lambda\lambda^*/3} > L_0$, where ν, λ and ν^*, λ^* are elastic and inelastic collision frequencies and mean free paths respectively, λ_z is electron energy relaxation length, L_0 is a characteristic system spatial scale. These inequalities hold for radio frequency (RF) discharges under condition PL< 0.3 torr cm, where P is gas pressure, L is halve of discharge gap. In this case

EDF is a quasi-stationary, isotropic, and governed by nonlocal averaged space-time averaged electron kinetic equation [2]:

$$\frac{d}{d\varepsilon}\left(\overline{vD_{\varepsilon}}(\varepsilon)\frac{dF_0(\varepsilon)}{d\varepsilon}\right)=\sum_k \overline{v\nu_k^*}(\varepsilon)\,F_0(\varepsilon)-\sum_k \overline{v\nu_k^*}\left(\varepsilon+\varepsilon_k^*\right)F_0\left(\varepsilon+\varepsilon_k^*\right)-St_{ee}\left(F_0\right). \quad (1)$$

The electron energy diffusion coefficient is given by $vD_{\varepsilon}(v,x,t)=e^2v^3\tilde{E}^2(x,t)\nu/(3(\omega^2+\nu^2))$. The averaging is to be performed over the area available for electron moving in ambipolar potential $e\Phi(x)$ with a given total energy $\varepsilon=\frac{mv^2}{2}+e\Phi(x)$, according to: $\overline{G}(\varepsilon)=\int_0^T\frac{dt}{T}\int_{X_-(\varepsilon,t)}^{X_+(\varepsilon,t)}G\left(\sqrt{\frac{2}{m}[\varepsilon-e\Phi(x)]},x\right)\frac{dx}{2L_0}$, $St_{ee}(F_0)$ is electron-electron collision integral [2].

Under condition $\omega_{0i}<<\sqrt{\nu_i\omega}$, where ω_{0i} is ion plasma frequency, ν_I is ion collision frequency, ion density profile is quasi-stationary. Hence, ion continuity equation averaged over RF period can be used:

$$d\left(n_i u_i\left(<E(x,t)>\right)\right)/dx=<I(x,t)>, \quad (2)$$

where $\langle E(x,t)\rangle=-\frac{d\Phi}{dx}$ in the plasma, and to be found from Poisson equation in the sheath region. Ion velocity u_i as function of electric field is defined by known experimental function $u_i(E/p)$ [2].

In order to complete the set of equations for the CCP, it is necessary to determine electron density, conductivity, and ionization rate via the EDF. The quasineutrality condition determines the ambipolar potential:

$$\frac{4\pi}{m}\int_{e\Phi(x)}^{\infty}F_0(\varepsilon)\sqrt{\frac{2}{m}(\varepsilon-e\Phi(x))}\,d\varepsilon=n_i(x). \quad (3)$$

The RF electric field is given by Ohm law: $j(t)=\sigma(x)\tilde{E}(x,t)$. Ionization rate reads:

$$\langle I(x,t)\rangle=\left(1-\frac{Z(x)}{\pi}\right)\frac{4\pi\sqrt{2}}{m^{3/2}}\int_{e\Phi(x)+I}^{\infty}\left[N_a v\sigma_{ion}(\varepsilon-e\Phi(x))\right]F_0(\varepsilon)\sqrt{\varepsilon-e\Phi(x)}\,d\varepsilon \quad (4)$$

One can see that system of equations (1-4) is a *nonlinear system of integral-differential equations*, of quite complicated structure. The non-linearity of ion continuity equation is due to via self-consistent ambipolar potential, which is determined by the form of EDF (see equation (4)). On contrast to common analysis we account the modification of EDF with change of ion density profile, that results in new physical effect: the abrupt formation of large population of cold electrons with current growth. This paradoxical behavior of CCP plasma is closely related to phenomenon of thermal explosion.

Thermal explosion arises, when the heat flux, which is proportional to temperature T at the center of the gap can not carry away heat released with the rate Q(T). Stationary equation of heat conduction is $\frac{d}{dx}\left(\chi(T)\frac{d}{dx}T(x)\right)+Q(T)=0$; T(x=0, L) = 0. The thermal explosion implies that, for L above a certain critical size L_{cr}, there are no stationary solutions of this equation. For example for $Q(T)=Q_0\exp(\alpha T)$ and χ = const., the critical size is $L_{cr}=1.88\sqrt{\chi/(Q_0\alpha)}$.

Heat conduction equation with a nonlinear thermal conductivity $\chi(T)$ can possess the same property. For homogeneous heat release $Q=Q_0$=const., the heat flux is $-\chi(T)\frac{dT}{dx}=\int_0^x Q(x')dx'$, and we have $\int_{T_w}^{T_0}\chi(T)dT=Q_0L^2/8$, where T_w, T_0 are the wall and the central temperatures, respectively. Integral in the left-hand side can converge even when central temperature goes to infinity $T_0\to\infty$. For example, for $\chi=X(T+T_1)^{-\beta}$, where $\beta>1$, T_1, X are constants, there are no solutions for $X/[(\beta-1)(T_1+T_w)^{\beta-1}]<Q_0L^2/8$.

Similar processes are possible in low-pressure discharges. The higher is plasma density the lower is the amplitude of the oscillatory field and correspondingly mean electron energy. Hence, the ambipolar electric field and the coefficient of ambipolar diffusion decrease too. The plasma self-trapping is possible, if the ion flux (which is roughly proportional to $D_{amb}n$) has a maximum with increase of n. If the integral from the ion source exceeds the ion flux Γ_i, the stationary solution is absent and the transition to plasma with large amount of cold electrons arises. This is the main mechanism of abrupt formation of cold electrons in low-pressure discharges.

To demonstrate this effect we present the results of calculations for non self-sustaining discharge in argon for p = 0.1 torr, j_0 = 0.3 mA/cm^2, L_0 = 3.35 cm, and $\omega = 2\pi$ 13.56 MHz. The fixed ionization-source power corresponds to the doubled ionization-source power taken from the results of self-consistent simulation for the same parameters. Time evolution of (a) the ion flux, (b) ion velocity, (c) average electron energy, and (d) plasma density at the point x* = 0.3 cm are depicted in Figure 1. Solid lines represent the results of calculation, when *e-e* collisions are not taken into account. Dashed lines represent the results of calculations including *e-e* collisions. The thick line corresponds to $\int_0^{x^*} dx \langle I(x,t) \rangle$.

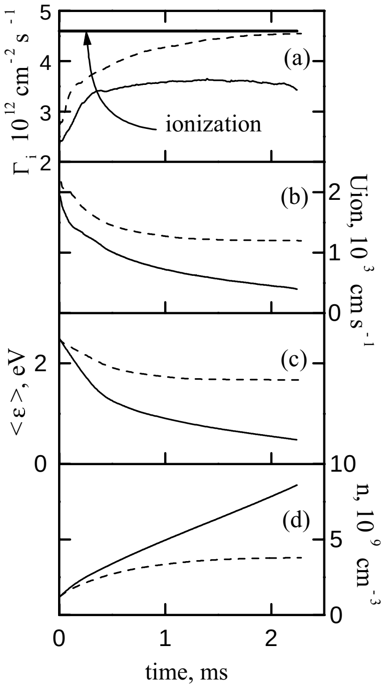

Figure 1. Time evolution of plasma parameters

If *e-e* collisions are not taken into account, then, for $x < |L_p|$, the steady-state solution of the equation of continuity for ions is absent. One can see that the increase of plasma density does not result in increase of ion flux, ion flux saturate at maximal value about $\Gamma_{cr} = 3.410^{12}\,cm^{-2}s^{-1}$, and even can decrease afterwards. Thus, for sufficiently large values of ionization rate $\int_0^{x^*} I(x)dx > \Gamma_{cr}$, ion continuity equation has no steady-state solutions at $x < |L_p|$.

Electron-electron collisions start to be important for a sufficiently high plasma density, and lead to the heating of cold electrons due to their energy exchange with the fast ones. Thereby, account for electron-electron collisions prevent a decrease of the average energy of the cold electrons with density growth. As a result ion flux does not saturate and stationary solution exist.

For real discharges it means that at critical current *radical rearrangement of EDF* exists. The plasma density jumps with current, average electron energy strongly decreases.

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