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Kinetic theory of initial stage of planar vacuum diode operation in pulse-periodic mode of cathode plasma emission

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A simulation of the non-stationary process of formation of an electron beam in a planar vacuum diode with a plasma cathode operating in the mode of pulses with duration of 3 ns and pauses between pulses of 2 ns has been carried out. Plasma is described on the basis of the collisionless kinetics of electrons and singly charged ions in a self-consistent electric field. The movement of the plasma emission boundary towards the anode is due to the formation of a local region of an inverse electric field in the gap. The electron beam current density depends on the cathode plasma density and can be several times higher than the Child−Langmuir current. The field inversion region has a „virtual cathode"structure in the cathode plasma generation mode, and the inversion region has a „potential hump"structure in the pauses between the cathode plasma generation pulses.

Keywords: electron beam, vacuum arc, plasma cathode.

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The present study belongs to the field of theoretical modeling of a vacuum discharge (vacuum arc) with non-stationary plasma emission centers, which are abbreviated as ectons [1,2], emerging at the cathode of a vacuum diode with a certain voltage applied to it. It is known that the emission of electrons from the boundary of plasma formations is initiated in this scenario. Accelerating in an electric field, these electrons form a beam. In the course of beam generation, cathode plasma expands into the gap with characteristic velocities of several cm/μs and alters the diode perveance. It is the process of filling the gap with plasma that sets the duration of an electron-beam current pulse. Therefore, a theoretical description of the mechanism of expansion of plasma generated in the intermittent mode of its emission is of great fundamental and practical interest.

The motion of plasma in vacuum is a process that is difficult to characterize theoretically. One needs to find a mathematically correct description of the continuous transition from dense quasi-neutral plasma (with electric currents flowing in it) to the motion of charged particles (with vastly different masses) in vacuum with non-uniform and non-stationary electric fields generated in the gap taken into account [3–5]. The hydrodynamic plasma model provides only a partial solution to this problem, failing when discontinuous solutions or other types of unstable behavior emerge in the calculation. The methods of physical kinetics of charged particles in combination with Maxwell's equations for a self-consistent electric field [6,7] appear to be more fitting to the examined scenario. The results of application of the kinetic approach to calculating the electron current of a vacuum diode with a pulsed mode of cathode plasma generation, where both „virtual cathode" and „potential hump" effects are manifested naturally, are reported briefly below.

A non-stationary problem was solved for the following system of equations within the simplest (collisionless) kinetic model of two-component plasma (electrons and ions of the same type) with a self-consistent electric field:

$$\frac{\partial f_e}{\partial t} + v\frac{\partial f_e}{\partial x} + \frac{e}{m}\frac{\partial \varphi}{\partial x}\frac{\partial f_e}{\partial v} = 0,$$

$$\frac{\partial f_i}{\partial t} + V\frac{\partial f_i}{\partial x} - \frac{e}{M}\frac{\partial \varphi}{\partial x}\frac{\partial f_i}{\partial V} = 0,$$

$$\varepsilon_0\frac{\partial^2 \varphi}{\partial x^2} = -e\left(\int\limits_{-\infty}^{\infty} f_i(x, V, t)dV - \int\limits_{-\infty}^{\infty} f_e(x, v, t)dv\right). \quad (1)$$

Here, e is the elementary charge; m and M are the electron and ion masses, respectively; $\varphi(x, t)$ is the electric potential; and v and V are the velocities of electrons and ions in ensembles with corresponding velocity distribution functions $f_e(x, v, t)$ and $f_i(x, V, t)$. Numerical algorithms for solving Vlasov's system of equations (1), which were used in the calculation and characterized in detail in [7], provide a high degree of reliability. The vacuum gap was assumed to be empty at the initial moment $t = 0$, $f_e(x, v, 0) = f_i(x, V, 0) = 0$, but constant voltage $\varphi(0, t) = 0$, $\varphi(D, t) = +U_0$ was applied to it. A vacuum discharge was initiated by „switching on" nonequilibrium plasma ($T_e \neq T_i$) in cathode plane $x = 0$ with Maxwell distribution functions

$$f_e(0, v, t) = \chi(t)\frac{n_0}{\sqrt{2\pi m k T_e}}\exp\left(-\frac{mv^2}{2kT_e}\right),$$

$$f_i(0, V, t) = \chi(t)\frac{n_0}{\sqrt{2\pi M k T_i}}\exp\left(-\frac{MV^2}{2kT_i}\right), \quad (2)$$

which were modulated in time by periodic step function $\chi(t)$ shown in Fig. 1, *a*.

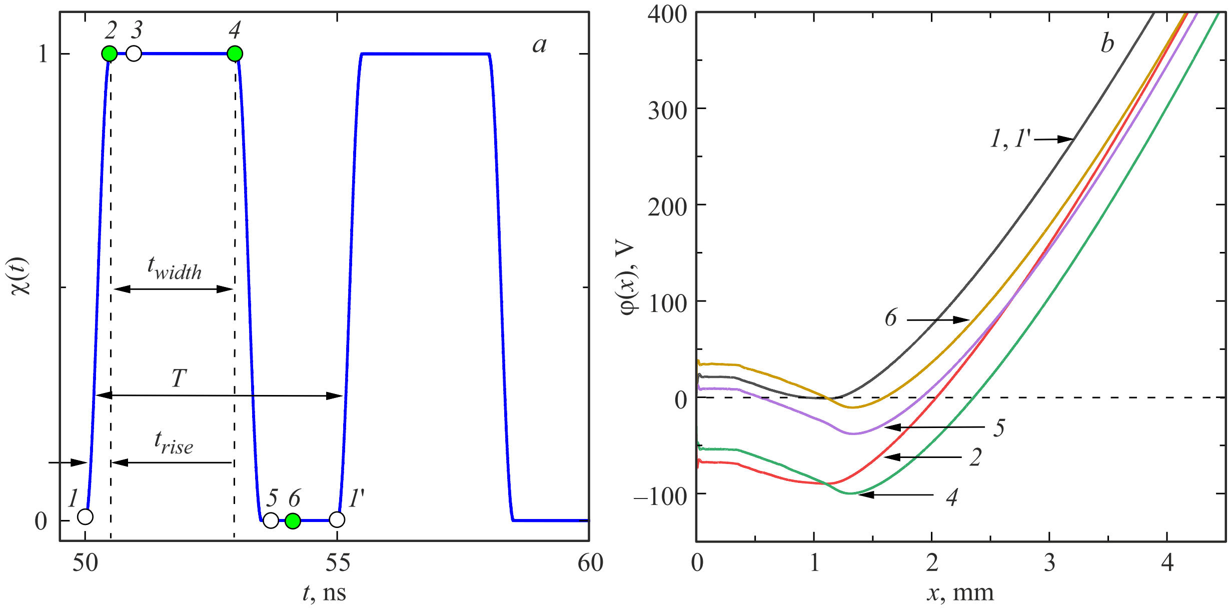

Figure 1. Temporal profile of cathode plasma emission (a) and instantaneous spatial profiles of the electric potential corresponding to characteristic profile points *1–2–4–5–6–1'* (b) for the 11th plasma emission pulse (50–55 ns from the onset of the discharge).

The results of calculation for system (1) with the following parameters are illustrated below: gap length $D = 1$ cm, applied voltage $U_0 = 2$ kV, the plasma-forming metal is antimony ($M = 121$ a.m.u.), cathode plasma density $n_0 = 10^{16}\,\mathrm{cm}^{-3}$, and the temperatures of ensembles in cathode plasma are $T_e = 5$ eV and $T_i = 1$ eV. Modulating function $\chi(t)$ had period $T = 5$ ns, leading and trailing edge time $t_{rise} = 0.1$ ns, and emission duration $t_{width} = 2.9$ ns. Other parameters of the problem (D, n_0, U_0, parameters of function $\chi(t)$) were also tested within a wide range, but the results were qualitatively similar.

Figure 1 illustrates the spatiotemporal dynamics of the electric potential within a single period of cathode plasma operation. The 11th emission pulse was chosen as an example. It is initiated at the 50th nanosecond with a fast emission switch-on; this emission persists to the end of the 53rd nanosecond and is then cut off rapidly for 2 ns (through to the end of the 55th nanosecond). The 11th pulse was chosen to be analyzed in detail, since the plasma boundary has already moved noticeably by this time, but still remained fairly distant from the anode.

It is evident that the overall shape of the spatial profile of potential remains unchanged throughout the entire process, but near-cathode plasma formed at the previous discharge stages is charged to a positive (in the interval between emission pulses) or negative (in the process of emission) potential. The so-called „potential hump“ (curves *5* and *6* in Fig. 1, b), which has long been the subject of heated scientific debate among specialists in vacuum discharge [1,2,8], is observed precisely in the interval between emission phases. In the phase where dense plasma (its density in our calculations is $10^{16}\,\mathrm{cm}^{-3}$) is generated in the cathode plane ($x = 0$), lower-density plasma of the cathode plume acquires a negative potential value. A potential distribution of the „virtual cathode“ type, which is typical of a vacuum diode, is established here. It is the formation of the region of inversion of the electric field direction in cathode plume plasma that ensures monotonic acceleration of ions (and advancement of the emission boundary of the cathode plume at a rate of $2.6 \cdot 10^6$ cm/s) toward the anode both at the stages of cathode plasma emission and in the intervals between them. The mechanism of this acceleration was discussed in detail in [7]. We note only that rate of advance u_f of the cathode plume front is governed by the self-consistent kinetics of plasma in a non-stationary electric field and may be several times greater than the rate specified by formula $u_f \approx \sqrt{2e|\Delta\varphi|/M}$, where $|\Delta\varphi| = 70{-}100$ V is the approximate value of the potential drop across plume plasma.

Phase portraits of the electron ensemble provide more intriguing data on the mechanism of electron emission from cathode plume plasma. Figure 2 presents the phase portraits of the electron distribution function for three moments in time: $t_2 = 50.1$ ns (the moment a new portion of cathode plasma is introduced; near-cathode plasma acquires a negative potential of -70 V relative to the cathode); $t_4 = 53.0$ ns (completion of the active cathode emission phase; the potential of the bottom of the virtual cathode is -97 V); and $t_6 = 53.4$ ns (the interval between emission pulses; near-cathode plasma is charged to a positive potential of $+37$ V, and a „potential hump“ structure forms near the cathode).

The injection of a portion of electrons with increased energy (up to 70 eV) is seen in the phase portrait right after the moment of „switching on“ the plasma (50.1 ns). These electrons slow down gradually in the virtual cathode field and form a highly heated (with average energy

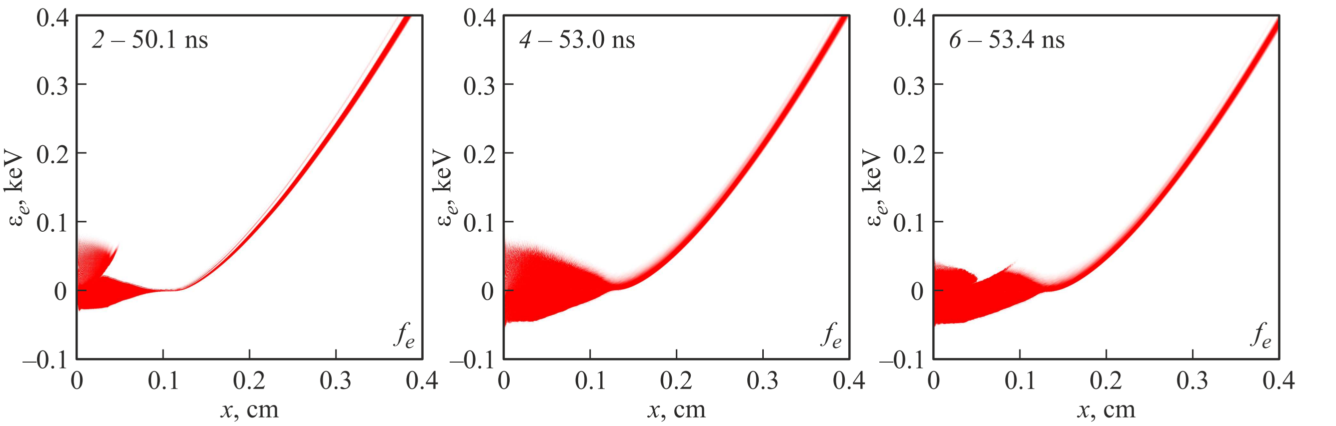

Figure 2. Phase portraits of the electron distribution function at different points within a single (11th from the onset of the discharge) emission pulse at the cathode. These portraits are numbered in accordance with the time points in Fig. 1, *a*.

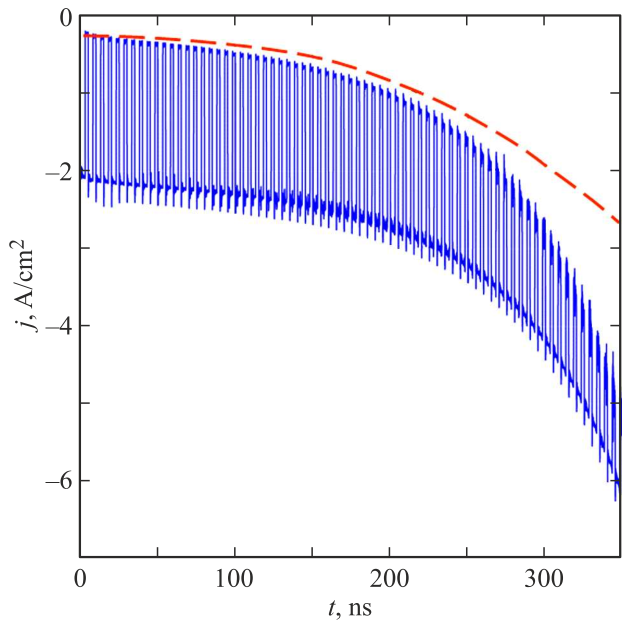

Figure 3. Temporal profile of the electron current in a vacuum diode. The dashed curve corresponds to the calculated Child–Langmuir current.

$\varepsilon_{VC} \sim 20$ eV) near-cathode plasma by the end of the emission stage (53.0 ns). In the interval between emission stages (53.4 ns), cathode plume plasma is charged to a positive potential of +37 V. The „potential hump" ensures continuous transfer of electric current in the cathode section ($x = 0$) by both ions and backward electrons within such intervals. The average density of cathode plume plasma is much lower than the density of cathode plasma ($n_0 = 10^{16}$ cm^{-3}) and decreases monotonically from $\sim 10^{15}$ cm^{-3} near the cathode section to $\sim 10^{11}$ cm^{-3} at the emission boundary of the cathode plume.

Figure 3 shows the time dependence of current density of a vacuum diode, which makes it clear that the current is modulated „rigidly" by the cathode plasma emission regime. It is noteworthy that the electron current density in the cathode emission phase is significantly higher than the Child–Langmuir value, which is $(4\varepsilon_0/9)\sqrt{2e/m}U_0^{3/2}/D^2 \approx 0.21$ A/cm^2 for a gap of 1 cm. This was to be expected, since dense cathode plasma provides efficient neutralization of the space charge in the virtual cathode section. The current density in the diode undergoes just a several-fold reduction in the intervals between emission phases, since the high density of ions in the near-cathode region ($\sim 10^{15}$ cm^{-3}) is more than sufficient to maintain this level. As the cathode plume expands, the diode perveance increases monotonically due to a reduction in length of the „plasma-free" gap between the emission boundary of the plume and the anode (the estimated Child–Langmuir current then grows accordingly; see Fig. 3). The Child–Langmuir formula provides a fine approximation for the electron current in the diode in the intervals between active cathode plasma emission phases, but the electron current within such phases is several times higher than the estimated one.

The following conclusions may be inferred from the results of the study.

1. A model of the process of electron beam formation in a vacuum diode with a plasma cathode was developed. This model simulates the collisionless physical kinetics of charged particles in the threshold current mode.

2. It was found that the electron current density in a diode with a plasma cathode may be an order of magnitude higher than the Child–Langmuir current density at cathode plasma densities at the level of 10^{16}–10^{15} cm^{-3}, which is attributable to efficient neutralization of the space charge in the region of the emission boundary of the plume.

3. It was demonstrated that the longitudinal distribution of electric potential is transformed radically in the process of operation of a diode with a plasma cathode. The virtual cathode mode with cathode plume plasma charged to a negative potential of several tens of volts is established in the active cathode emission phase; in the intervals between

cathode emission stages, plume plasma is charged rapidly to a positive potential of $+(20-30)$ V, and its density decreases smoothly in space to a local minimum at the emission boundary of the plume. It is in the interval between active emission phases that a „potential hump“ forms within cathode plume plasma.

4. In the process of expansion of cathode plasma, a region of electric field inversion forms within it. This region ensures continuous acceleration of ions toward the anode and drives the motion of the emission boundary of the cathode plume with characteristic velocities $(2-5)\cdot 10^6$ cm/s, which were observed experimentally in vacuum discharges [1,2,8,9].

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Conflict of interest

The authors declare that they have no conflict of interest.

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