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The role of ectons in the vacuum breakdown process

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Abstract. This paper presents a valuable addition to the kinetic theory regarding vacuum breakdown formation in a planar vacuum gap, specifically focusing on the cathode plasma emission known as the 'ectonic' (pulse-periodic quasi-particle) nature. We investigate the contributions of ectonic and continuous types of emission from the cathode in terms of their effects on the mechanism of anomalous ion acceleration and cathode plasma expansion during a short-term switching of the emission current corresponding to the death and birth of ectons.

Keywords: vacuum breakdown, Vlasov-Poisson equations, ectons

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Материалы конференции
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Роль эктонов в процессе вакуумного пробоя

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Аннотация. Статья представляет собой дополнение кинетической теории образования вакуумного пробоя в плоском вакуумном зазоре, в котором особое внимание уделяется эмиссии катодной плазмы в т.н. эктонном (импульсно-периодическом) режиме. Исследовано влияние эктонной эмиссии на механизм аномального ускорения ионов и расширения двухкомпонентной катодной плазмы.

Ключевые слова: вакуумный пробой, уравнения Власова-Пуассона, эктоны

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Introduction

Between 2021 and 2023, in a series of theoretical papers by the Laboratory of Theoretical Physics of the Institute of High-Current Electronics SB RAS employees, the first self-consistent collisionless kinetic theory of cathode plasma expansion was formulated [1–3]. It opened up the possibility to explain the physical nature of the plasma expansion phenomenon in vacuum discharge in detail. It allowed us to predict the average speed of a cathode plasma expansion in the vacuum diodes of various designs. It was shown that in a vacuum gap, the key physical mechanism for the plasma expansion, regardless of the diode geometry and the connected electrical circuit, is the collisionless electrodynamic mechanism. It lies in the fact that the peripheral region of a dense cathode plasma in an external electric field acquires an excess negative volume charge, leading to the appearance of a "virtual cathode" of amplitude $\Delta\varphi < 0$. The presence of this region ensures the influence of accelerating electrodynamic forces on ions near the emission center at the cathode, due to which the ions start to move towards the anode and acquire "anomalously" high values of kinetic energy $\varepsilon_i > qU_0$. The possibility of the so-called "deep potential well" near the cathode $|\Delta\varphi| > U_0$ existence has also been predicted by the proposed theory. This effect is entirely assured by the emission center parameters and does not depend on the voltage amplitude U_0 applied to the diode.

In this study, we expand our research experience to investigate the influence of the ectonic mechanism of cathode plasma emission on the phenomenon of anomalous ion acceleration, which results in the expansion of the cathode plasma. Building upon the kinetic theory established previously, we elucidate the mechanism of plasma emission from the cathode and present the results of numerical solutions of the kinetic equations for the model of a planar vacuum diode, considering the periodic variation in the emission current density. Our proposed approach demonstrates that the previously identified collisionless mechanism remains fundamentally significant even when the emission operates in a pulsed regime. Specifically, one ecton's death is followed by another's emergence, leading to the interception of the discharge current throughout the vacuum discharge.

Materials and Methods

As a basic version of the calculations in this work, we use a mathematical model described in more detail in [1]. Here, we also consider a flat one-dimensional vacuum diode formed by a vacuum gap of length D with a cross-sectional area S. Three independent variables parameterize the electron distribution functions (EDF) and ions (IDF): the Cartesian coordinate x, the collinear momentum component p_x and time t. The EDF/IDF parameterized in this way also obeys the collisionless nonrelativistic kinetic equations:

$$\begin{cases} \dfrac{\partial f_e}{\partial t} + \dfrac{p_x}{m_e}\dfrac{\partial f_e}{\partial x} - qE_x\dfrac{\partial f_e}{\partial p_x} = 0, \\ \dfrac{\partial f_i^+}{\partial t} + \dfrac{p_x}{m_i}\dfrac{\partial f_i^+}{\partial x} + qE_x\dfrac{\partial f_i^+}{\partial p_x} = 0, \end{cases} \tag{1}$$

where q is the elementary charge, E_x is the component of the electric field strength along the x-coordinate axis, and m_e and m_i are the rest of the mass of the electron and ion, respectively. Following the methodology [1–3], the model is collisionless, i.e., on the right side of equations (1), there are no integrals of elastic and inelastic collisions. For simplicity of analysis, we will assume that the cathode plasma consists only of electrons and ions of the same type. This is a reasonable assumption for lithium, carbon, bismuth cathodes and some other materials [4]. The modeling proposed below assumes that the cathode material is antimony Sb (m_i = 121 a.m.u.), for which a two-component plasma is also justified.

In line with the comprehensive analogy with work [1], the kinetic equations system (1) is enhanced with the Poisson equation to compute a vacuum diode's electrostatic potential φ and

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electric field E_x. This enables us to control the dynamics of the space charge of ions and electrons, offering exciting possibilities for innovation and advancement.

$$\frac{\partial^2 \varphi}{\partial x^2} = -\frac{q}{\varepsilon_0}\left(n_+ - n_e\right), \quad E_x = -\frac{\partial \varphi}{\partial x}, \tag{2}$$

where ε_0 is the dielectric constant of vacuum, n_+ is the ion number density, and n_e is the electron number density:

$$n_e(x,t) = \int_{-\infty}^{\infty} f_e(x, p_x, t)\,dp_x, \quad n_+(x,t) = \int_{-\infty}^{\infty} f_i^+(x, p_x, t)\,dp_x. \tag{3}$$

At the initial time $t = 0$, we assume that the vacuum gap is empty $f_e(t=0) = f_i^+(t=0) \equiv 0$. However, in contrast to the boundary conditions of continuous emission used in [10] to model ectonic periodic processes, in this work, the following boundary conditions for EDF/FRI are used:

$$f_e(x=0, p_x, t) = \frac{n_0 \chi(t)}{\sqrt{2\pi m_e T_e}} e^{-\frac{p_x^2}{2m_e T_e}}, \quad f_i^+(x=0, p_x, t) = \frac{n_o \chi(t)}{\sqrt{2\pi m_i T_i}} e^{-\frac{p_x^2}{2m_i T_i}}, \tag{4}$$

where T_e and T_i are the thermodynamic temperatures of electrons and ions of the cathode plasma, respectively, the values of which are close to the parameters of the explosive emission plasma $T_e \sim 5$ eV and $T_i \sim 1$ eV [5], n_0 is the quasineutral plasma number density at the emission center. The function of a pulse-periodic signal with unit amplitude $\chi(t)$ characterizing non-stationary emission is shown in Fig. 1, where t_{rise} is the duration of the rising/falling edge of the signal, t_{width} is the duration of the signal at the base, T is the period of the signal.

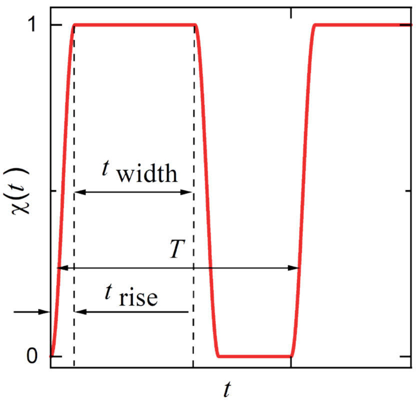

Fig. 1 Cathode plasma number density time profile for the ecton emission regime

The numerical algorithm used in this study is based on the approach described in [6]. To solve the Vlasov equations, we employed the semi-Lagrangian numerical method for solving kinetic equations (semi-Lagrangian method), which utilizes high-order interpolation by cubic splines. The computational algorithm was programmed using the OpenMP and GNU Scientific Library libraries in GNU C language.

Results and Discussion

To investigate the vacuum breakdown of a planar gap, a scenario was modeled (Fig. 2) in which a voltage $U(t)$ from an external source with a rise time of $t_{rise} = 0.1$ ns and an amplitude of $U_0 = 2$ kV is applied through a ballast resistor. The interelectrode distance was chosen to be $D = 1$ cm, and the product of the ballast resistance R and the cross-sectional area S was $RS = 200\ \Omega\cdot\text{cm}^2$. The significant difference was that a pulsed-periodic function with a baseline plasma number density of $n_0 = 10^{22}$ m^{-3} was chosen as the boundary condition for plasma emission.

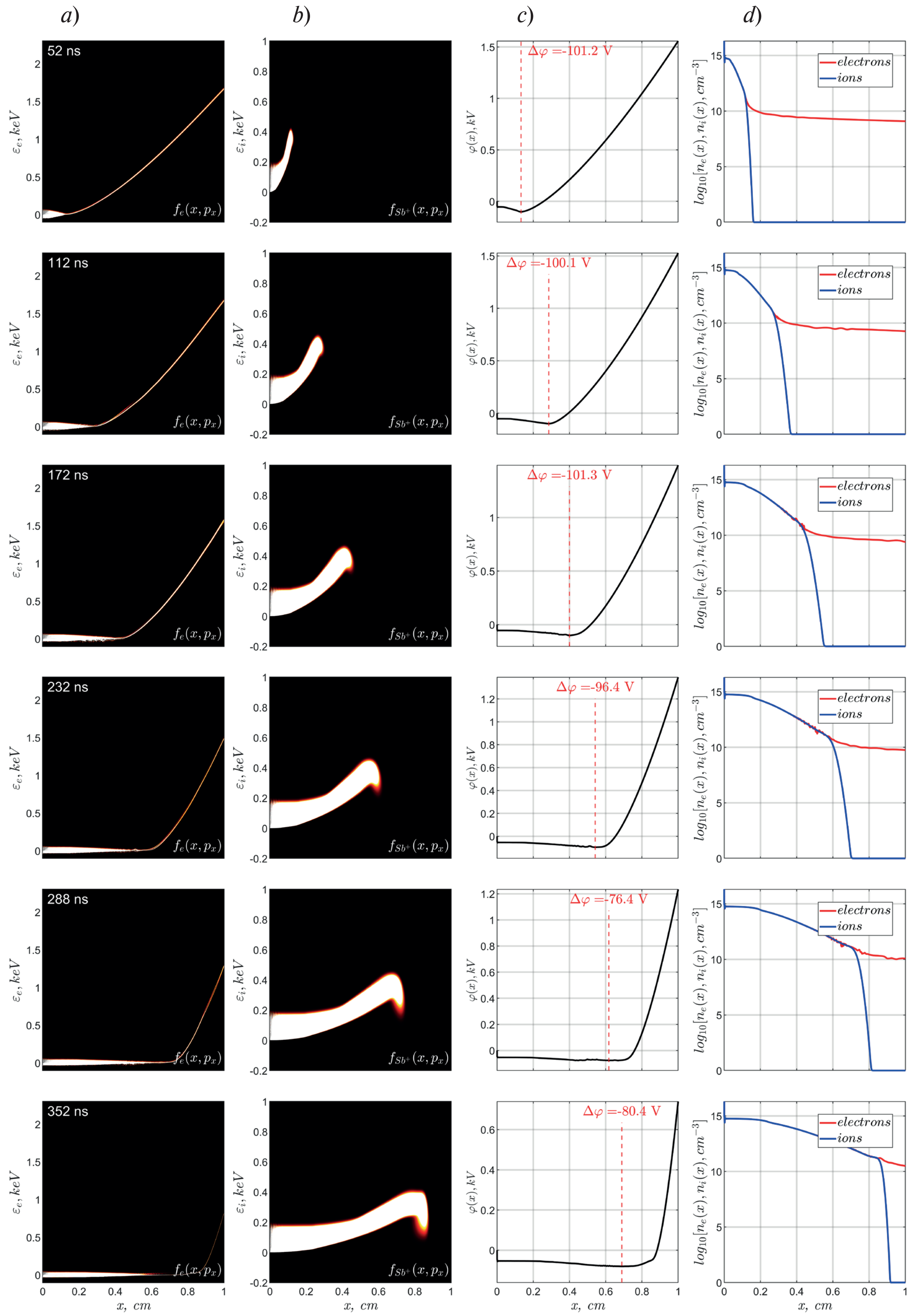

Fig. 2 Temporal dynamics of plasma during the vacuum breakdown stage across a 1 cm gap in the ecton emission mode of plasma from the cathode. (*a*) – EDF, (*b*) – IDF, (*c*) – electrostatic potential distribution, (*d*) – number density distribution of the expanding cathode plasma

The following values were used as parameters for the function: t_{rise} = 0.1 ns, t_{width} = 3 ns, and T = 5 ns. These parameters model the pulsating emission from the cathode so that the average emission current is approximately equivalent to that of continuous emission [1–3], thereby ensuring the high emission capability of the cathode.

The macroscopic picture of plasma expansion in the ecton emission mode does not differ from the case of continuous emission [1]. As lighter and thermalized particles, electrons shift from their initial state even without an external field, forming a negative space charge at the edges of the cluster, the magnitude of which is determined by the number density n_0. Thus, the initial short emission pulse (ecton) at the moment $t = 0$ initiates the expansion mechanism of the cathode plasma. At the time points when the emission current density is at its maximum, the characteristic value of the virtual cathode amplitude, $\Delta\varphi$, reaches −100 V. The shape of the electric potential distribution and the concentrations of charged particles are also approximately the same in both cases. The difference in plasma expansion modes lies in the somewhat lower average velocity of the ion component in the ecton emission mechanism. The average velocity in this case is approximately ~$2.2 \cdot 10^6$ cm/s, which is closer to the parameters of the cathode plume plasma observed in experiments [5]. This is because, during ecton emission, there is typically an interval between two successive pulses during which the cathode completely loses its emission capability.

More information about the influence of the ecton emission mechanism is provided by the detailed construction of electric potential distributions over one full period T (Fig. 3, *a*). Fig. 3, *b* shows the potential distributions at time points corresponding to points *1–6* and *1'* on the emission pulse's temporal profile. From time point 1, when the emission current begins to enter the gap, until the end of the emission, the potential distribution changes significantly. At time point *4*, the ecton terminates, meaning plasma emission from the cathode completely stops. Therefore, in the subsequent moments *5–6*, corresponding to the "dead time" between pulses, the virtual cathode ($\Delta\varphi = -3.7$ V) rapidly smooths out, the plasma discharges, and then the birth of a new ecton at point 6 (resumption of emission) continues the process described above.

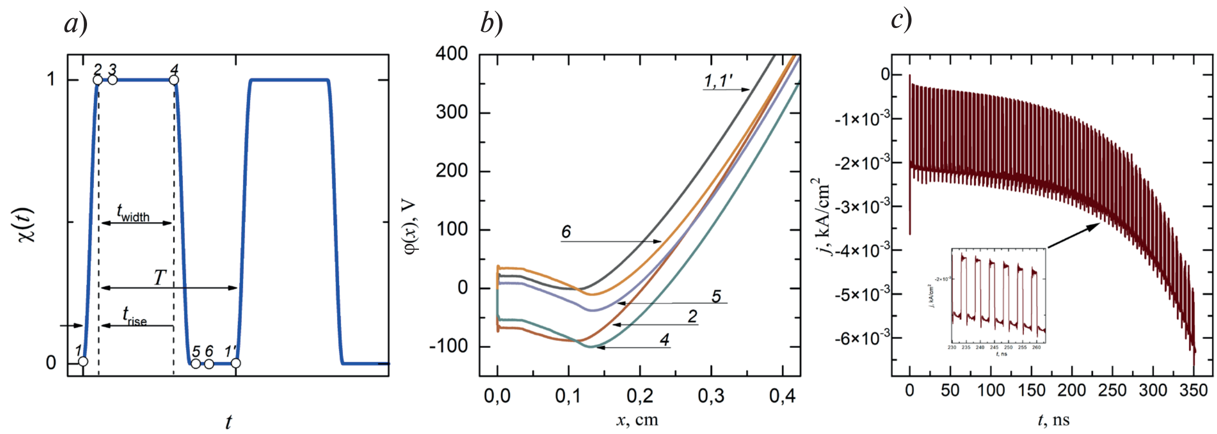

Fig. 3. The emission function profile (*a*), the corresponding electric potential distribution (*b*) and the time-dependent full current density profile in the vacuum diode in the near-to-cathode region

The rise and fall of the emission current due to the birth and death of ectons lead to oscillations of the space charge in the gap. In summary, the fluctuations in space charge caused by pulse-periodic ecton emission are evident in the time-varying current flow through the diode. (Fig. 3, *c*) illustrates the total current density in the vacuum diode within the power supply circuit, which includes a ballast resistance of $R = 200\ \Omega$. It can be seen that throughout the entire vacuum breakdown process, the total current density in the diode exhibits a curve with noticeable frequency modulation. The modulation amplitude (Fig. 3, *c*) is small (< 5%). Still, its presence shows the influence of the ecton emission mechanism on the current flow, as the volume charge oscillations have a period T that matches the modulation period and the period of the $\chi(t)$ function.

Conclusion

When comparing the results of numerical simulations of vacuum breakdown phenomena in a planar diode gap with a continuous cathode emission mechanism to those of a similar breakdown simulation with an ecton emission mechanism, it was demonstrated that in both cases, the mechanism of cathode plasma expansion constitutes an electro-field collisionless process. Detailed kinetic modeling of vacuum breakdown in the simplest one-dimensional configuration of a planar diode utilizing the ecton mechanism revealed the following findings:

- The establishment of the initial cathode potential drop is characterized by durations significantly shorter than the typical ecton nucleation times. Hence, plasma expansion from the cathode jet commences at the first ecton's emergence.
- The cessation of one ecton and the interval preceding the emergence of the subsequent ecton cause a temporary vanishing of the virtual cathode region ($\Delta\varphi \sim 0$), yet it does not impede the plasma expansion from the cathode to the anode.
- Plasma expansion occurs at the outer emission boundary of the quasi-neutral expanding plasma during the intervals between bursts of emission current. For ions, this expansion is fueled by the inertia of the ion component, attributed to its kinetic energy acquired during the ecton existence (emission) periods.
- The appearance of each successive ecton triggers the formation of a new virtual cathode at the outer emission boundary. It accelerates a fresh portion of the plasma's ion component along the declining section of the electrostatic potential.

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