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The phenomenon of “anomalous electrons” in pulsed high-current vacuum discharges

V.Yu. Kozhevnikov [1] ✉, A.V. Kozyrev [1]

[1] Institute of High Current Electronics, Siberian Branch, RAS, Tomsk, Russia

✉ Vasily.Y.Kozhevnikov@ieee.org

Abstract. This paper presents the first comprehensive theoretical explanation, based on computational physical kinetics, for the phenomenon of electrons attaining energies exceeding the amplitude of the applied voltage (in eV units) in a vacuum diode. The proposed theory thoroughly elucidates the existence of so-called “anomalous electrons”, detailing their generation dynamics and underlying mechanisms. Additionally, the work calculates the integral energy spectra of these anomalous electrons in a high-current pulsed vacuum discharge and quantifies their contribution to the total current flow. The main tool used for numerical calculations is the latest meshless method for solving Vlasov-Poisson equation systems, known as the numerical flow iteration method (NuFI). The findings provide critical insights into non-equilibrium electron behaviour under extreme conditions, advancing the understanding of electron transport in vacuum-based high-power devices.

Keywords: vacuum electronics, anomalous electrons, physical kinetics

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Явление «аномальных электронов» в импульсных сильноточных вакуумных разрядах

В.Ю. Кожевников [1] ✉, А.В. Козырев [1]

[1] Институт сильноточной электроники Сибирского отделения РАН, г. Томск, Россия

✉ Vasily.Y.Kozhevnikov@ieee.org

Аннотация. В работе впервые представлено теоретическое объяснение явления, при котором электроны в вакуумном диоде приобретают энергии, превышающие амплитуду приложенного напряжения (в единицах эВ). Исследуются динамика формирования «аномальных электронов», их энергетические спектры и их вклад в общий токоперенос в импульсных сильноточных вакуумных разрядах.

Ключевые слова: вакуумная электроника, аномальные электроны, физическая кинетика

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Introduction

"Anomalous electrons" is the name given to a group of electrons in a vacuum discharge whose average kinetic energy ε exceeds the maximum value qU_0, where q is the electron charge and U_0 is the voltage amplitude across the vacuum gap. The existence of such electrons has been discussed in some experimental studies, for example in [1], but the reasons for their appearance were considered unclear for a long time. In [1] the electron energy distributions were calculated using Tikhonov regularization for a Fredholm integral equation, minimizing a priori assumptions about the spectral shape. The reconstructed electron spectra, obtained experimentally in a vacuum diode, revealed two distinctive groups in the beam incident on the collector filter: a low-energy component with a monotonic decrease up to 200 keV ($\varepsilon \leq qU_0$) and an anomalous high-energy component peaking at 220 keV, followed by an extended tail reaching energies of 320 keV, i.e. $\varepsilon > qU_0$.

For a long time, experiments indicating the existence of electrons with anomalously high energies in vacuum discharges were met with considerable scepticism. Some researchers attributed the observation of such electrons to various experimental artefacts or to inaccuracies in the methods used to reconstruct the energy characteristics of electron beams beyond the anode, given the practical impossibility of performing direct measurements within the interelectrode gap. The first explanation for the emergence of anomalous electrons was provided in [2], where the solution of kinetic equations was studied for a low-current vacuum diode with an unlimited cathode emission capacity. This work presents a more detailed investigation of the fundamental physical mechanisms responsible for the formation of electrons with anomalously high energies in pulsed high-current vacuum diodes.

Materials and Methods

As it is supposed, the phenomenon of anomalous electron generation is a general manifestation in vacuum devices, so the configuration without geometric features was chosen as the starting point of the theory – it is a planar vacuum diode formed by a gap D between two plane-parallel electrodes. The coordinate axis x is located normally to the electrode's surface, where point $x = 0$ corresponds to the cathode position. It is the source of electron emission, which can be specified in terms of corresponding boundary condition for the EDF (electron distribution function) f_e as follow:

$$f_e\left(x=0,v,t\right)=\frac{n_0}{\sqrt{2\pi m_e T_e}}e^{-\frac{m_e v^2}{2T_e}},$$

where x и v – phase coordinates (coordinate and velocity), t – time variable, n_0 – emission number density, T_e – the electron temperature in eV, m_e – electron rest mass. The type of emission in this modeling is not essential, but the value of n_0 is determined by the condition of unlimited electron emission from the cathode – $j_{em} \gg j_{CL}$, where the emission current density and the Child-Langmuir current are determined by the following relationships, respectively

$j_{em} = \frac{qn_0}{4}\sqrt{\frac{8T_e}{\pi m_e}}$, $j_{CL} = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m_e}}\frac{U_0^{3/2}}{D^2}$, where ε_0 – vacuum dielectric permittivity. All variables in this paper are given in SI units.

According to the general methodology of physical kinetics, the dynamics of electron flows in this diode is described in terms of relativistic Vlasov-Poisson equations system

$$\frac{\partial f_e}{\partial t} + \frac{\partial f_e}{\partial x} - \frac{qE_x}{m_e\gamma^3}\frac{\partial f_e}{\partial v} = 0,$$
$$\frac{\partial^2\varphi}{\partial x^2} = -\frac{q}{\varepsilon_0}\int_{-\infty}^{\infty} f_e dx, \quad E_x = -\frac{\partial\varphi}{\partial x}, \tag{1}$$

where E_x – electric field, φ – electrostatic potential, $\gamma = 1/\sqrt{1 - v^2/c^2}$ – relativistic gamma factor.

The system of equations (1) forms a closed mathematical model of the proposed theory. The solution of the system is the electron distribution function f_e, knowing which at an arbitrary time point one can find the velocity, current density, and other "moments" of the distribution function. Initially vacuum diode is supposed to be empty, i.e., $f_e(t = 0) = 0$. The emission boundary condition is established at $x = 0$, simulating the injection of the emission current into an empty vacuum diode.

It is necessary to note only one more point, we assume the vacuum diode to be connected to a pulse voltage source $U(t)$ directly without any ballast load. The voltage pulse $U(t)$ has a trapezoidal shape. It is set by three parameters – the duration of the leading (and trailing) edges t_{rise}, the voltage amplitude U_0, and the total pulse duration by its base t_{width}.

Results and Discussion

To analyze the behavior of the solution of system (1) for a pulsed vacuum diode, a numerical solution was constructed. For the numerical solution of the Vlasov–Poisson system of equations, a modern mesh-free method known as NuFI (Numerical Flow Iterations) was employed. This approach provides an effectively infinite spatial resolution in phase space while maintaining second-order accuracy in time. The method has demonstrated particular efficiency in problems requiring a relatively small number of time steps, which is characteristic of the scenario considered in this study. Unlike the widely used grid-based methods or PIC methods [3], which are significantly affected by numerical diffusion or numerical noise, the NuFI method ensures the strict fulfillment of all conservation laws, which is crucial for the accurate simulation of collisionless processes. In the current one-dimensional case (1), the Poisson equation admits a straightforward solution in quadratures.

Thus, for a planar vacuum gap, we can define the so-called "flight time" for electrons $t_f \equiv \sqrt{2m_e D^2/(qU_0)}$. This estimate is obtained directly from solving the equation of motion for a single electron starting with zero velocity at the cathode, i.e. $m_e x'' = qU_0/D, x(0) = 0, x'(0) = 0$. It determines the characteristic time scale during which electrons from the cathode reach the anode under the action of the accelerating voltage. We consider the numerical solution of (1) for two cases: when a voltage with amplitude U_0 is applied to the diode by a long voltage rise front $t_{rise} \gg t_f$ and a short one $t_{rise} \sim t_f$. In both cases, we plot the time profile of the electron current density through the collector (anode), which is determined by the following moment of the electron distribution function

$$j_{\tilde{n}} = q\int_{-\infty}^{\infty} v \cdot f_e(x = D, v, t)\, dv.$$

Fig. 1 shows the time profiles j_c for these two cases for D = 1 cm, U_0 = 50 kV, j_{em}/j_{CL} = 10 diode parameters. Short rise time for this configuration corresponds to t_{rise} = 100 ps, and the long rise time case here is t_{rise} = 500 ps. The most general case of establishing a steady-state current flow in a diode includes three successive stages: *a*) flight time, *b*) transition region, and *c*) region of steady-state current flow. The second stage occurs only if the voltage is applied fast, i.e., $t_{rise} \sim t_f$. Its key feature is the generation of the limiting value of the diode current. Simplified modeling [3] gives an estimate of the limiting current density as $j_{max} = 2.75 \cdot j_{CL}$, and the actual kinetic theory corrects this value downwards.

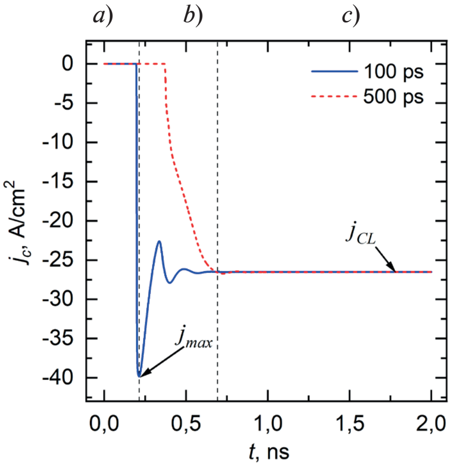

Fig. 1. Collector current density profiles of a planar vacuum diode

The major minimum value of the instant current density is provided by the first electrons that are delivered to the anode in times of the order of t_f, then damped oscillations of the volumetric charge density occur, and the value of the diode current density is established at the level of the stationary value j_{CL}. The key observation of the kinetic theory is the fact that the limiting current $j_{\max}$ is delivered to the collector (anode) precisely by anomalous electrons. This was first noted in the work [2] precisely due to the kinetic description.

Figure 2 shows the electron distribution function at two characteristic time points in the case where the voltage rise time is comparable to the pulse duration ($t_{rise} \sim t_f$): (left plot) when the current density reaches its peak value, and (right plot) when it reaches a steady-state level. At $t = 210$ ps, the current density attains its maximum, and the electrons arriving at the anode have an average energy of 57.8 keV, which exceeds the applied voltage amplitude (multiplied by the electron charge) by 16%. Thus, all electrons reaching the anode at this moment are anomalous, with $\varepsilon > qU_0$. When the current density becomes stationary at $t = 2$ ns, the average kinetic energy of the electrons is $\varepsilon = qU_0$.

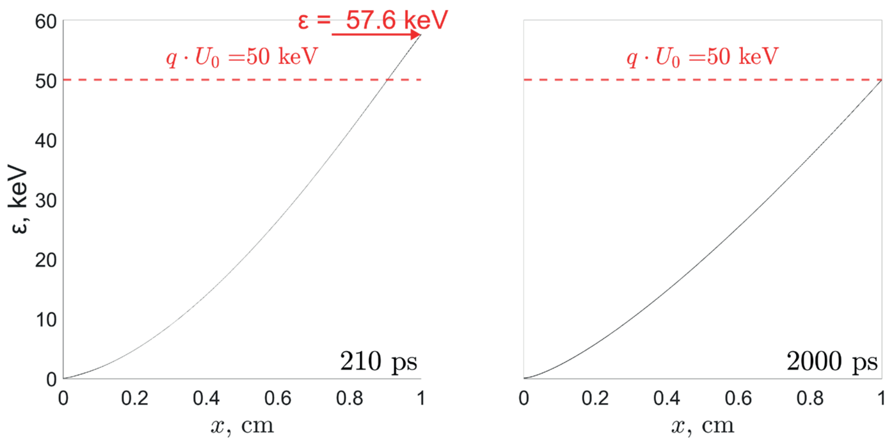

Fig. 2. The collector EDF f_e ($x = D$, ε, t) distribution at selected time points corresponding to the peak collector current density ($t = 210$ ps) and the steady-state collector current density ($t = 2$ ns). The red arrow indicates the instantaneous energy of the electrons at the time point when they reach the anode

An extended voltage pulse rise time ($t_{rise} \gg t_f$) leads to the disappearance of the transient region associated with relaxation oscillations and, consequently, to the vanishing of the anomalous energy component in the spectrum of electrons arriving at the collector.

The theory enables the simulation of a pulsed process with short leading (and trailing) edges equal to $t_{rise} = 0.1$ ns of the voltage pulse and a total duration of $t_{width} = 1$ ns, and allows the calculation of the integral spectral energy distribution of electrons at the anode according to the formula $g(\varepsilon) \sim \int_0^{t_{width}} f_e(x = D, \varepsilon(v), t)\,dt$. The resulting energy spectrum is shown in Fig. 3. It can be noted that the spectral distribution contains a principal maximum corresponding to the kinetic energy value $\varepsilon = qU_0$, as well as two additional maxima. One of these characterises the low-energy fraction of the electron beam, $\varepsilon < qU_0$, which corresponds to the peak of the diode current curve at time $t = 333$ ps. The second spectral maximum corresponds to a group of anomalous electrons with $\varepsilon > qU_0$ generated at $t = 210$ ps. This integral spectrum has been obtained for the first time based on the proposed kinetic theory. The spectral energy distribution, including the half-widths of the peaks (at $T_e \ll qU_0$), depends nonlinearly on the pulse front duration and the anode voltage amplitude. This issue requires further research regarding to its use in modern high-current electronic devices with the parameters on demand.

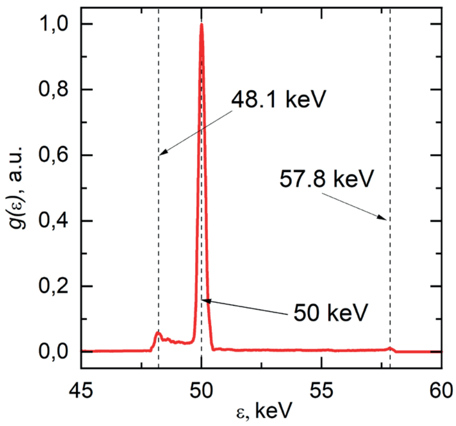

Fig. 3. Integral energy spectrum of the electron beam passing through the anode in a pulsed high-current vacuum discharge of 1 ns duration with a voltage pulse rise time of 0.1 ns

This scenario was simulated for voltage pulses typical of those used in modern nanosecond-scale devices. However, if experimental capabilities allow the generation of subnanosecond pulses with even steeper rise times, it may be possible to achieve conditions under which the electron beam beyond the collector consists exclusively of electrons with anomalously high energies, i.e., with kinetic energies $\varepsilon > qU_0$. This opens up the possibility of using vacuum diodes to generate electron fluxes with energies exceeding the product of the applied voltage and the elementary charge, which is of significant practical interest.

Conclusion

The appearance of anomalous electrons in a vacuum discharge is caused by the imbalance between two physical processes – charged particles entry into the gap (emission current injection) and their absorption at the anode (collector current outflow), which maintains a local space charge oscillations in the gap and the consistent electric field distortion providing the electron acceleration to high kinetic energies $\varepsilon > qU_0$. In this paper, this imbalance is provoked by specific electrophysical conditions (a short front edge of a voltage supply) that are confirmed experimentally [1]. However, in a broader sense, such a space charge imbalance can also be created by other factors inherent in most vacuum electronic devices. For example, the instability of emission current within the “ectonic” mechanism or non-trivial geometrical conditions of the discharge gap can provide short beams of the anomalous electrons, e.g., [4].

Modern vacuum and plasma electronics is an electrophysical technique operating at the nanosecond scales of pulse duration. Further development of high-current electronics is associated with the use of even shorter pulses having subnanosecond durations. For such devices, the influence of anomalous electrons, which inevitably arise in experimental conditions and industrial applications, will become even more significant, since the characteristic voltage rise fronts will be significantly shorter than the flight times of electrons (and ions) in vacuum gaps.

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THE AUTHORS

KOZHEVNIKOV Vasily Yu.
Vasily.Y.Kozhevnikov@ieee.org
ORCID: 0000-0001-7499-0578

KOZYREV Andrey V.
kozyrev@to.hcei.tsc.ru
ORCID: 0000-0002-7078-7991

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