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Kinetics of Electrons in Transient Mode of Current Switching in Planar Vacuum Diode

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Introduction

Recent development of high voltage technology for generating nanosecond and subnanosecond pulses has led to the discovery of new effects existing in pulsed vacuum electronic devices operating at ultra-short timescales. One of the novel physical phenomena regarding vacuum diodes became the effect of **fast electrons generation with energies ε exceeding the maximum voltage U_{max} applied to the diode** (multiplied by an elementary charge *q*)

These electrons are known to be the electrons having anomalously-high energies or simply the **anomalous electrons.**

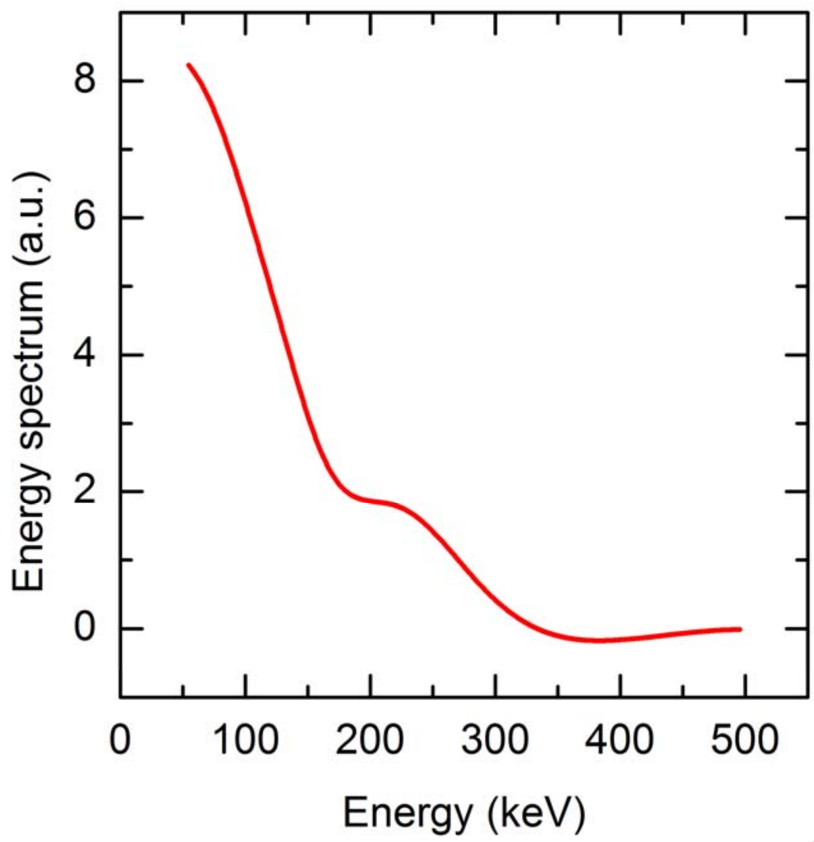
It was shown in various experiments that anomalous electrons exist as in gas discharges as well as in vacuum discharge.

Vacuum diode: an experimental backgrounds

- ✓ Setup example: RADAN-220 (250kV 2ns FWHM pulse) connected to IMAZ-150E sealed-off vacuum tube through 20 Ω ballast load

- ✓ Spectrum consists of two groups of electrons: low-energy with energies below 200 keV and high-energy with enegies up to 320 keV

Electrons energy spectrum



*A. V. Kozyrev et al. // Russian Physics Journal, vol. 53, no. 4, pp. 361–368, 2010

Hypotheses of origin, motivation & problem formulation

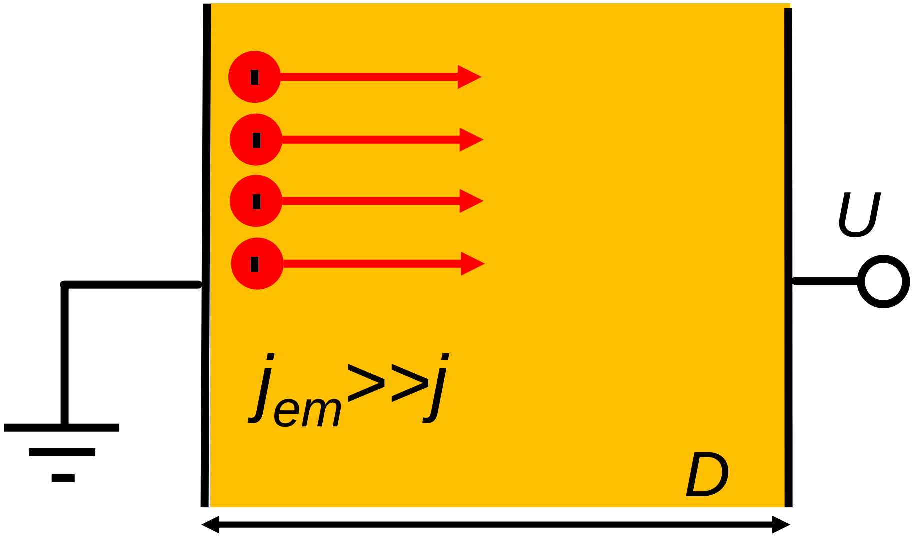
Probable origin of the anomalous electrons is connected with:

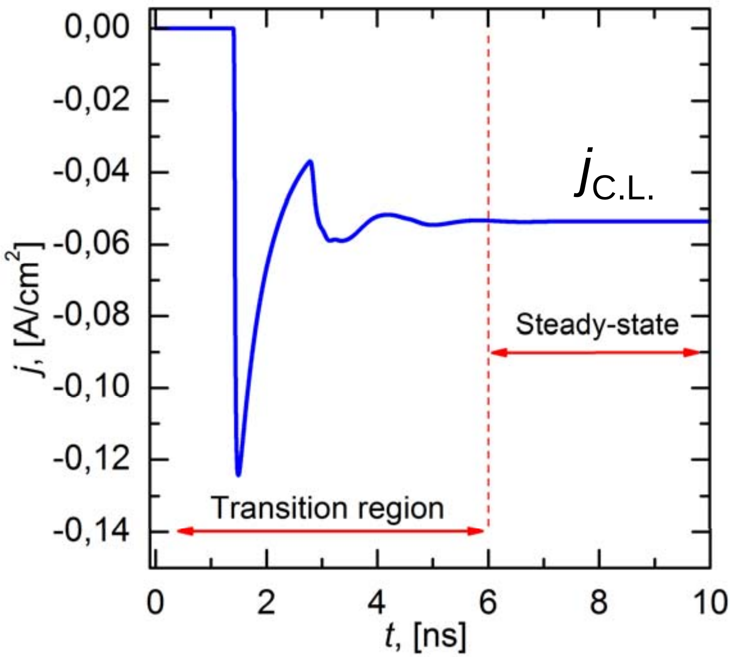
- Geometrical non-uniformities of vacuum diode electrodes;
- The excess of the actual value of idle voltage of the measured;
- Vacuum impurities;
- Measurements errors of collector currents, e.g. caused by gas ionization between anode and collector;
- …

Actual questions:

- Do anomalous electrons exist in planar vacuum diode?
- What is the percent fraction of anomalous electrons in this case?
- What is the mechanism of anomalous electrons generation?
- …

Planar vacuum diode (Child-Langmuir)





- Steady-state current in nonrelativistic case is equal to Child-Langmuir value (Child 1911; Langmuir 1913; Fay 1938)

$$j_{C.L.} = 2.33 \cdot 10^{-6} \frac{U^{3/2}}{D^2} \ [\mathrm{A/m^2}]$$

- Initial current burst (~ 2.75$j_{C.L.}$) and relaxation oscillations to steady-state current values (Kadish 1985; Airapetov, Feoktistov 1990)

Vlasov-Poisson kinetic theory

1D Vlasov-Poisson PDE system:

$$\begin{cases} \dfrac{\partial f}{\partial t} + \dfrac{p_x}{m\gamma\left(p_x\right)}\dfrac{\partial f}{\partial x} - qE_x\dfrac{\partial f}{\partial p_x} = 0 \\ \dfrac{\partial^2 \varphi}{\partial x^2} = -\dfrac{q}{\varepsilon_0}\displaystyle\int_{-\infty}^{\infty} f dp_x, \quad E_x = -\dfrac{\partial \varphi}{\partial x} \end{cases}$$

Boundary conditions:

continuous emission from cathode & transparent anode (collector):

$$f\Big|_{x=0} = f\left(x=0, p_x, t\right) = \frac{n_0}{\sqrt{2\pi m W_0}} e^{-\frac{p_x^2}{2mW_0}}$$

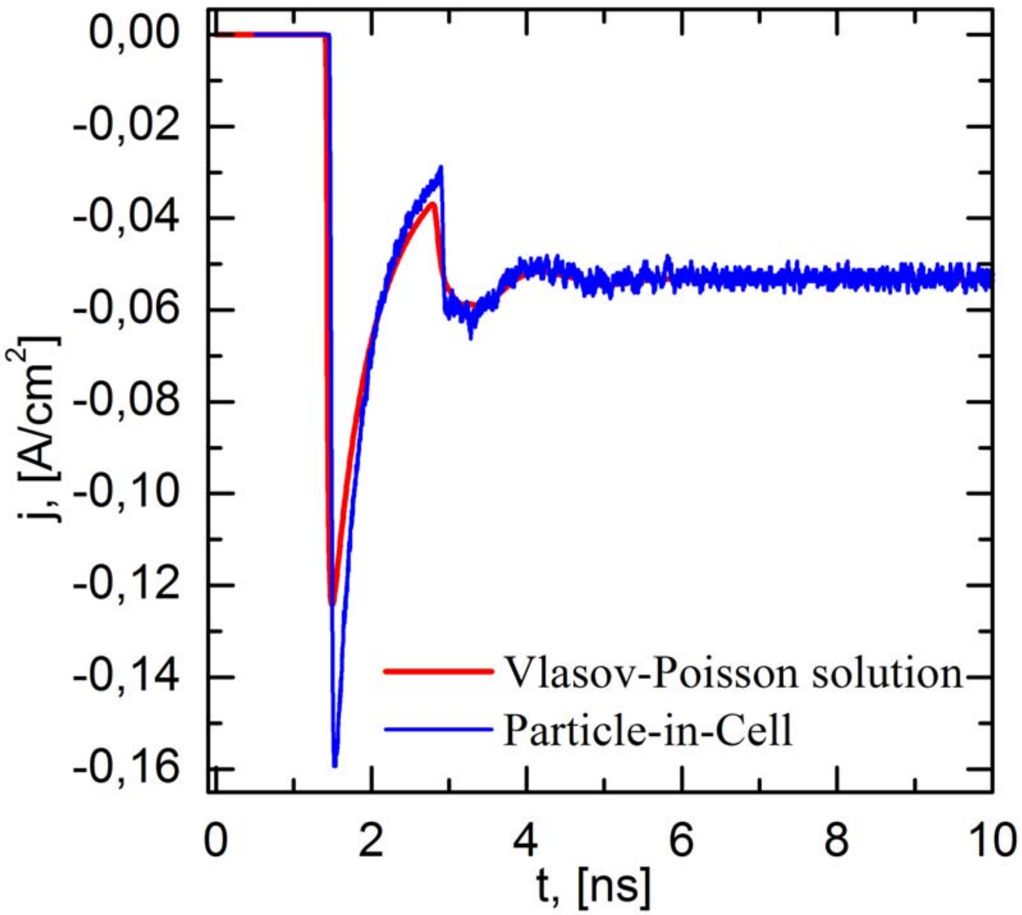
$$\frac{\partial f}{\partial x}\Big|_{x=D} = 0, \quad f\Big|_{|p_x| = p_{\max}} = 0,$$

Used grid-based numerical methods in phase-space*:

- ✓ Semi-Lagrangian method with variable order splitting in time;
- ✓ Various interpolation schemes in use: Cheng-Knorr, WENO-5-SL & PIC3/4;
- ✓ Exact solution of Poisson’s equation in quadrature with high order numerical integration algorithm

*F. Filbert et al. // Comp. Phys. Comm., vol. 150, pp. 247–266, 2003

Typical time-profile of a computed collector current density*



$j_{C.L.}$ = 0.522 A/cm^2

j_{em} ~ 50 $j_{C.L.}$

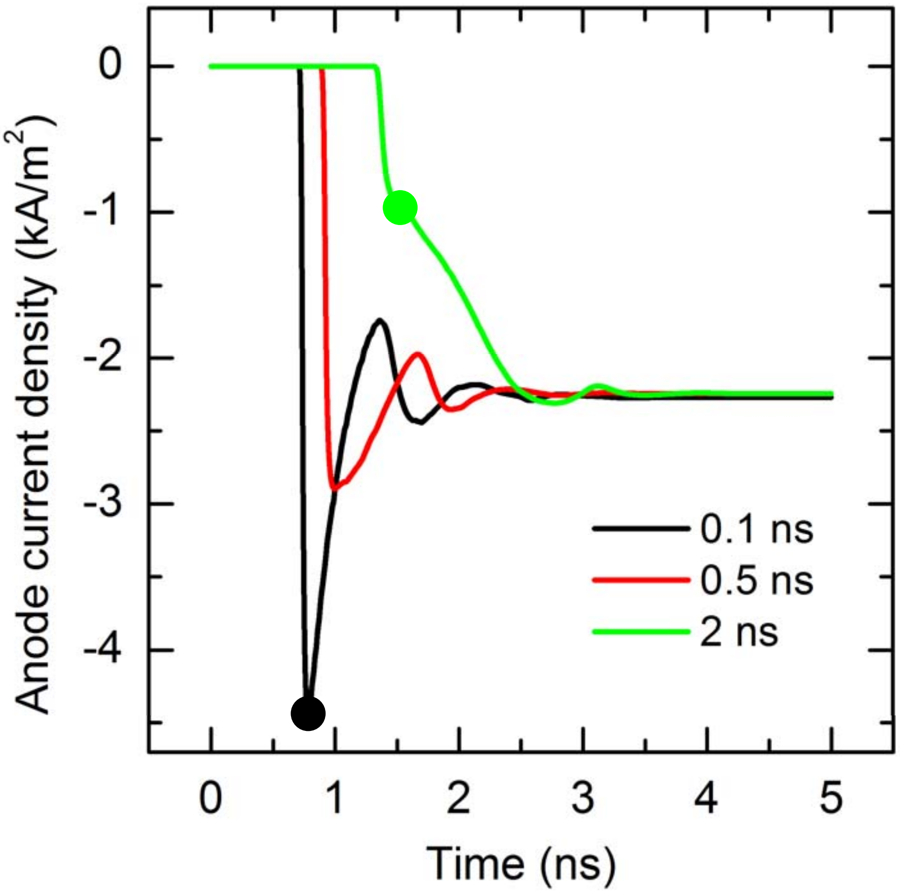
U = 2 kV, D = 2 cm

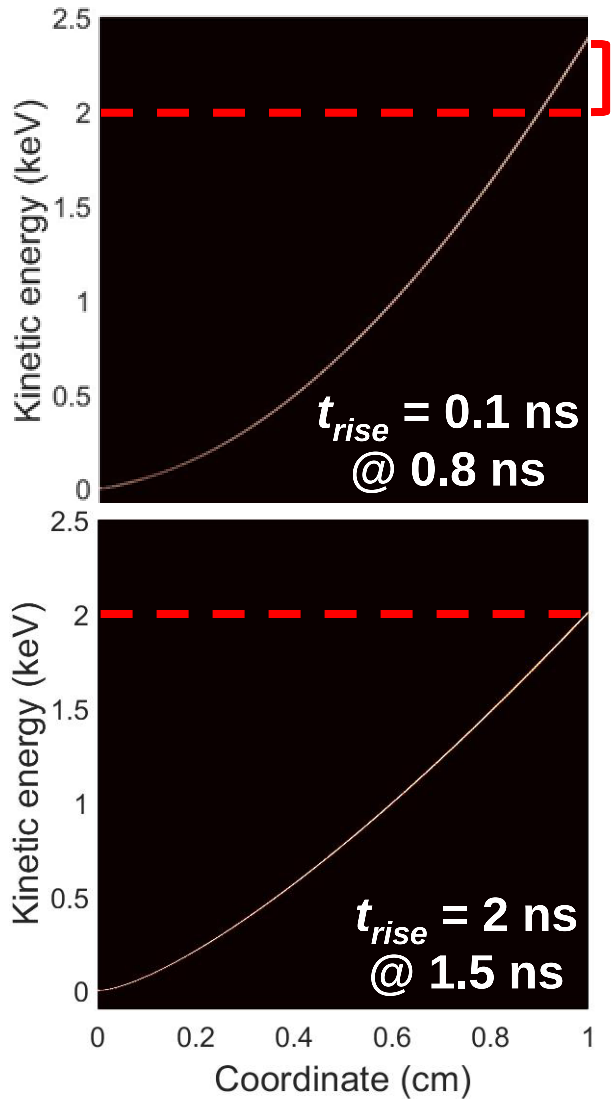
$$j_{em} = qn_0\sqrt{\frac{2qW_0}{m}},$$

*V. Yu. Kozhevnikov et al. // IEEE Trans. on Plas. Sci., Vol. 45, Issue 10, pp. 2762–2766, 2017

Planar vacuum diode: EDF in transient mode

Initial current density splash dependence on voltage rise-time





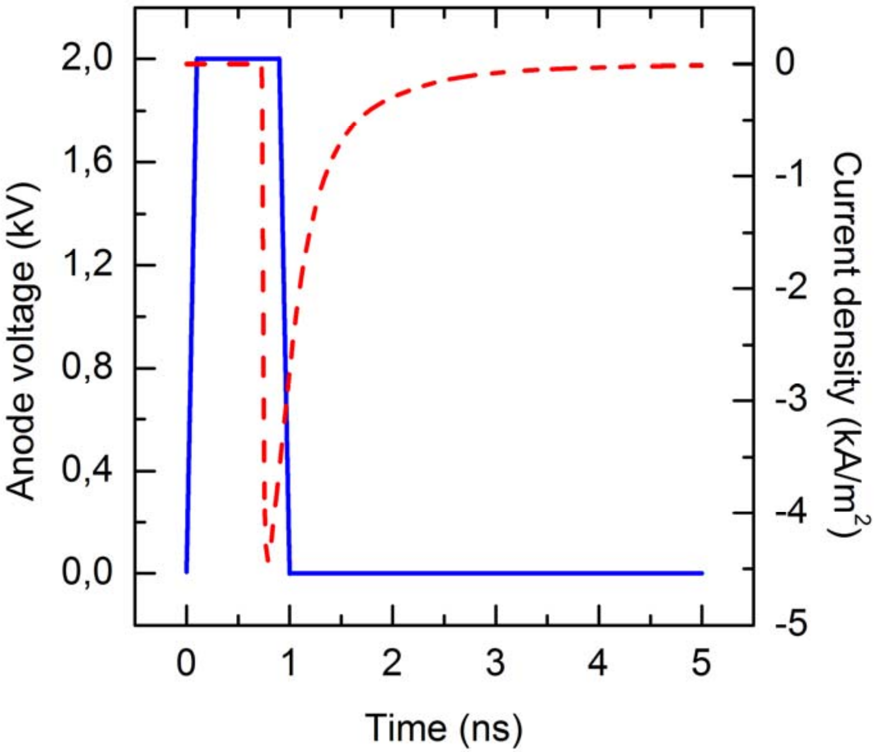
Anomalous electrons are forming the current splash !!!

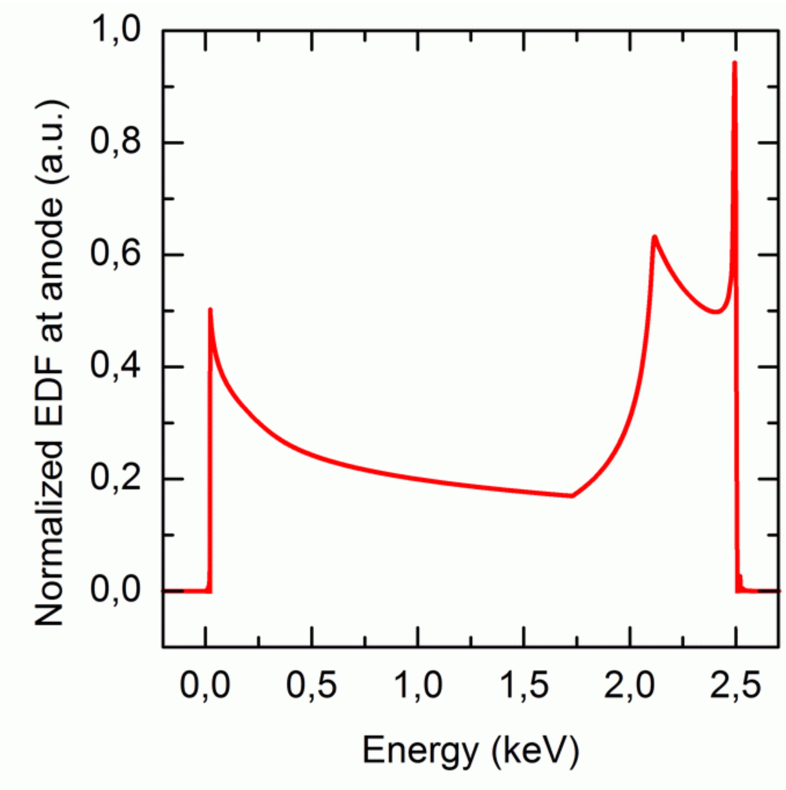
NO current splash – NO anomalous electrons

Diode parameters: D = 1 cm, U_{max} = 2 kV, t_{rise} = 0.1..2 ns

Total electrons spectrum for short rise-time mode

$$E(\varepsilon) = \int_0^{\tau} f\left(x = D, p_x(\varepsilon), t\right) dt.$$





Diode parameters: D = 1 cm, U_{max} = 2 kV, t_{rise} = 0.1 ns

Conclusions

- The so-called “anomalous electrons” exist in planar vacuum diode;
- The fraction of “anomalous electrons” to total electrons significantly depends on the sharpness of the voltage rise-time. It can be as much as 20% for short (subnanosecond) front edges!
- In the transition current flow mode (where the relaxation oscillations are observed) the current density maximum is invoked by the electrons having “anomalous” energies;
- Steady-state current flow mode is free from anomalous electron component;
- In real diodes (with non-uniform electrodes) this effect have to be much stronger w.r.t. planar 1D case.