IEP UB RAS

Russian Academy of Sciences
Institute of Electrophysics
Physical Electronics Laboratory

Influence of Inhomogeneous Electric Field Geometry Factors on Runaway Electron Generation Conditions

Yuriy I. Mamontov*, Andrey V. Kozyrev,
Natalia S. Semeniuk, Igor V. Uimanov, Nikolay M. Zubarev

*mamontov.ura.1994@yandex.ru

21st International Symposium on High Current Electronics
in 7th International Congress on Radiation Fluxes and Radiation Effects
(EFRE-2020)
Tomsk, Russia
2020

Contents:

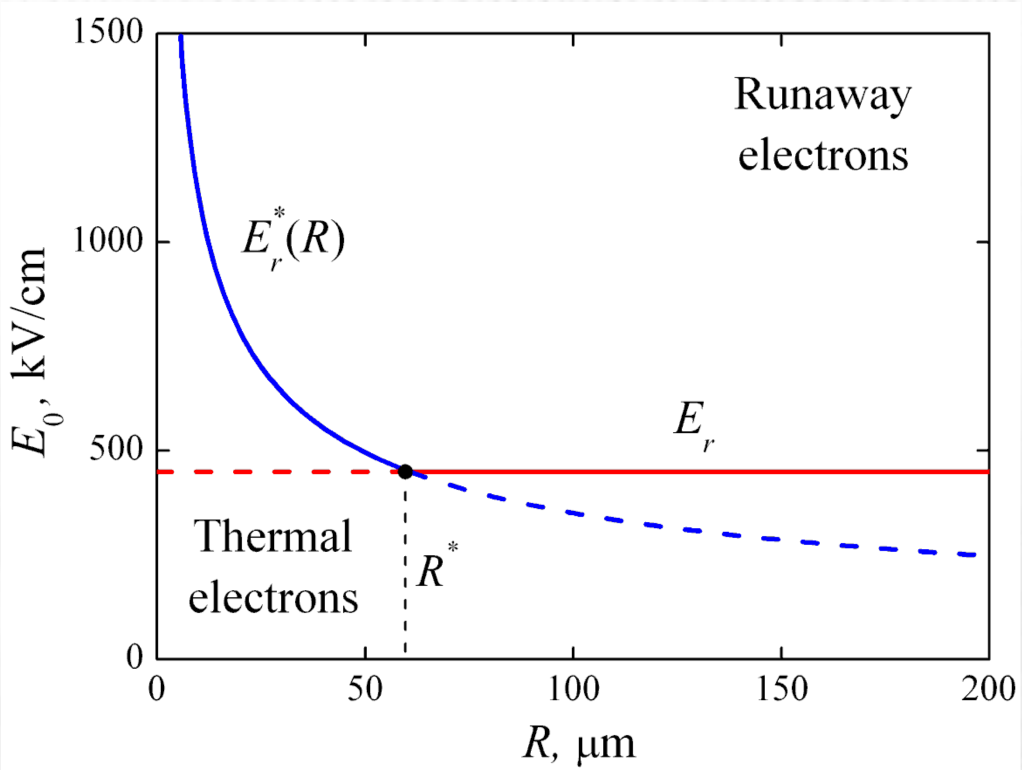
IEP UB RAS

1. **Prerequisites to the Work – slide Nos. 3-5;**
2. **Physical Models Applied – slide Nos. 6-10;**
3. **The Results of Numerical Simulations – slide Nos. 11-15;**
4. **Summary – slide Nos. 16-17.**

1 - Prerequisites to the Work

Previous results

IEP UB RAS



An electric field threshold for electron runaway at the cathode versus an edge radius according to the classical ($E_0 \geq E_r$) and additional ($E_0 \geq E_r^*$) criteria*.

**N.M. Zubarev, G.A. Mesyats, M.I. Yalandin // JETP Lett., vol. 105, no. 8, pp. 537-541*

- RE phenomenon may influence significantly on the discharge gap breakdown process due to pre-ionization of a gas medium
- The classical criterion of RE generation (a critical value of electric field strength E_r near a cathode emitting edge) may not be a sufficient criterion for cathodes of small curvature radius
- The criteria of runaway electron generation in a Nitrogen diode of atmospheric pressure with a strongly non-uniform constant electric field have been investigated by means of an analytical approach*

Aim of the work

Verification of the analytic model [1,2] by means of other theoretical approaches. The 2D Monte-Carlo model and the 1D relativistic kinetic Boltzmann's equation were used independently to study runaway electron generation in a strongly non-uniform electric field.

[1] N.M. Zubarev, G.A. Mesyats, M.I. Yalandin // JETP Lett., vol. 105, no. 8, pp. 537-541
[2] N.M. Zubarev et. al. // J. Phys. D: Appl. Phys., vol. 51, no. 28, 284003

IEP UB RAS

2 - Physical Models Applied

The Monte-Carlo algorithm description

IEP UB RAS

The electron motion equation solution:

$$m_e \frac{d\mathbf{V}(x,z,t)}{dt} = -e \cdot \nabla \varphi(x,z)$$

OUTPUT

MAIN LOOP

Initial conditions: voltage applied, initial electron energies, velocities and coordinates

Statistics on electron collision types, electron energies and velocities, electron coordinates etc.

INPUT

Scattering of electrons according to collision cross-section data:

1) Total cross-section data*
2) Differential cross-section data**
3) A double-differential cross-section data***

** Itikawa Y. // J. Phys. Chem. Ref. Data, 2006. - Vol. 35, No. 1. - P. 31.*
*** Phelps A.V. , Pitchford L.C. //Phys. Rev. A, 1985. - Vol. 31, No. 5. - P. 2932.*
**** Opal C.B., Peterson W.K., Beaty E.C.// J. Chem. Phys. - Vol. 55, No. 8. - P. 4100.*

The kinetic approach description

IEP UB RAS

The relativistic 1D Boltzmann's equation:

$$\gamma\left(\frac{\partial f(z,p,t)}{\partial t}+\frac{p}{m_e\gamma}\frac{\partial f(z,p,t)}{\partial z}-eE(z)\frac{\partial f(z,p,t)}{\partial p}\right)=$$

$$=-Q_-+Q_++S_{ec}.$$

A loss of electrons due to ionization* collisions:

$$Q_-=f(z,p,t)n_{gas}\frac{p}{m_e\gamma}\sigma_i$$

The number of electrons which appeared after an ionization* collision:

$$Q_+(p)=Q_-(p'(p))\cdot\left|\frac{\partial p'}{\partial p}\right|$$

Elastic* collisions within the "forward-backward" approximation:

$$S_{ec}=-\left(f(p)-f(-p)\right)\cdot$$
$$\cdot n_{gas}\frac{p}{m_e\gamma}\sigma_{ec}$$

***Cross-sections data:**

Itikawa Y. // J. Phys. Chem. Ref. Data, 2006. - Vol. 35, No. 1. - P. 31.

A discharge system under consideration

IEP UB RAS

- An electric potential distribution:

$$\varphi(x,z)-\varphi_c = a(\sqrt{g(x,z)/2}-\sqrt{R/2})$$

- An auxiliary function *g(x,z)*:

$$g(x,z) = z + R/2 + \sqrt{(z+R/2)^2 + x^2}$$

- A constant parameter *a*:

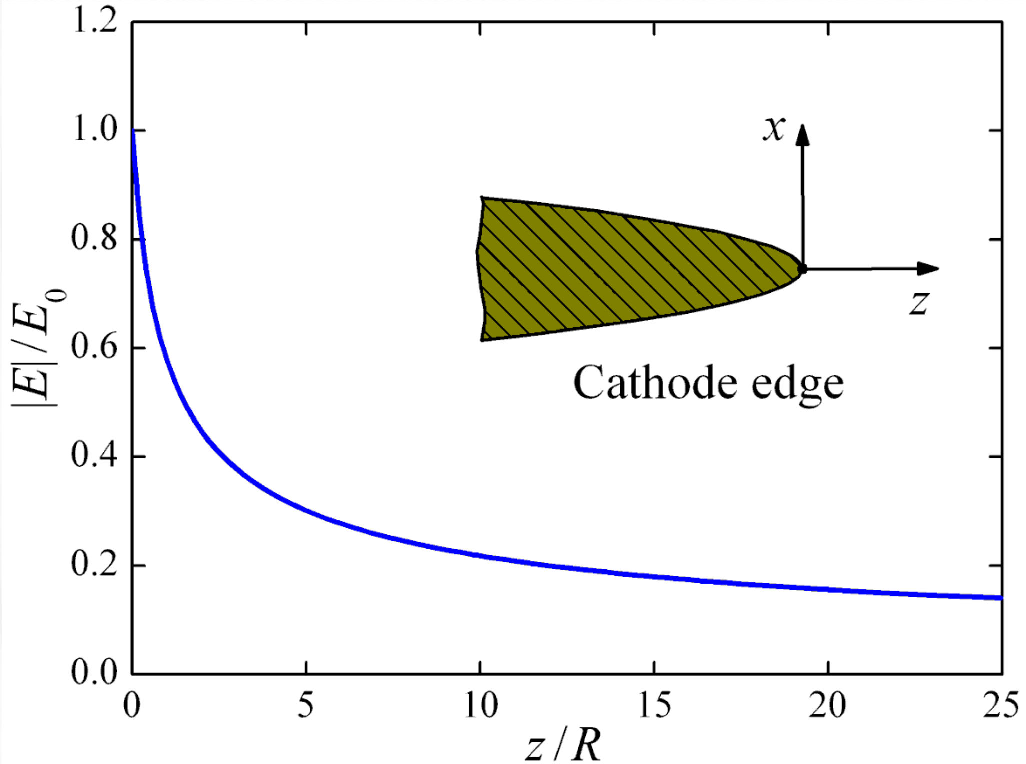
$$a = \frac{\varphi_a - \varphi_c}{\sqrt{g(0,d)/2}-\sqrt{R/2}}$$

- An electric field distribution along the *z*-axis:

$$E(z) = -\frac{E_0}{\sqrt{1+2z/R}}$$

- Electric field strength at the cathode apex:

$$E_0 = \frac{a}{\sqrt{2R}}$$



Distribution of the electric field strength *E* along the *z*-axis. The geometry of the cathode approximated by a parabola is schematically shown in the inset.

A numerical experiment

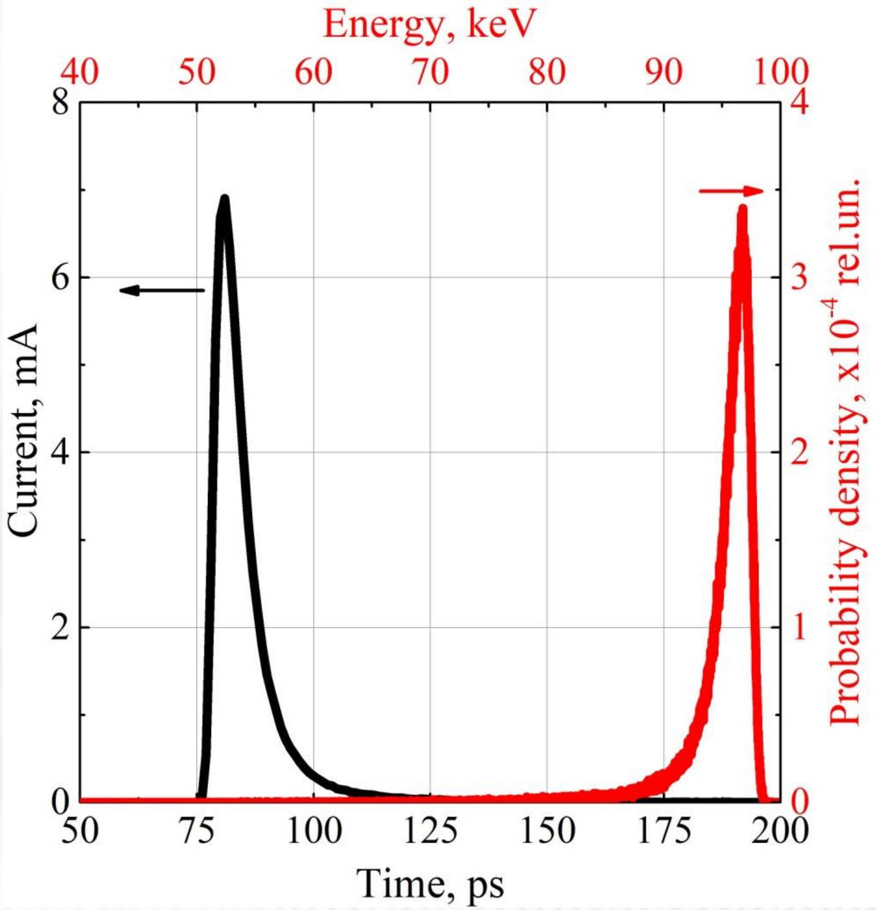
- ✓ Simulation of electron motion through nitrogen of 1 atm pressure in a stationary electric field, $d = 1$ cm
- ✓ Initial quantity of electrons is ~100 000
- ✓ Initial electron coordinate is (0, 0) (the apex of the cathode)
- ✓ Initial electron velocities are about thermal velocities for 300 K
- ✓ The cathode curvature radius range: from 0.5 um up to 150 um
- ✓ The voltage range: from 30 kV up to 150 kV
- ✓ The time range: 200 ps

IEP UB RAS

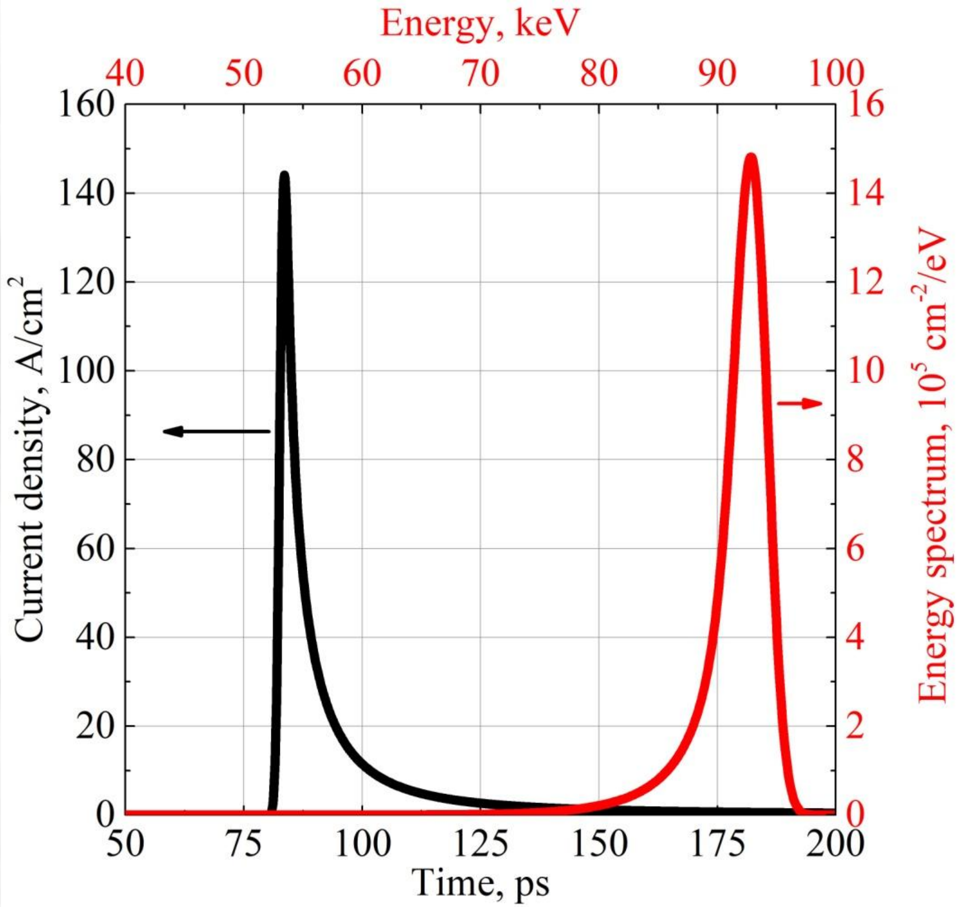
3 - The Results of Numerical Simulations

Runaway electron spectra at the anode

IEP UB RAS



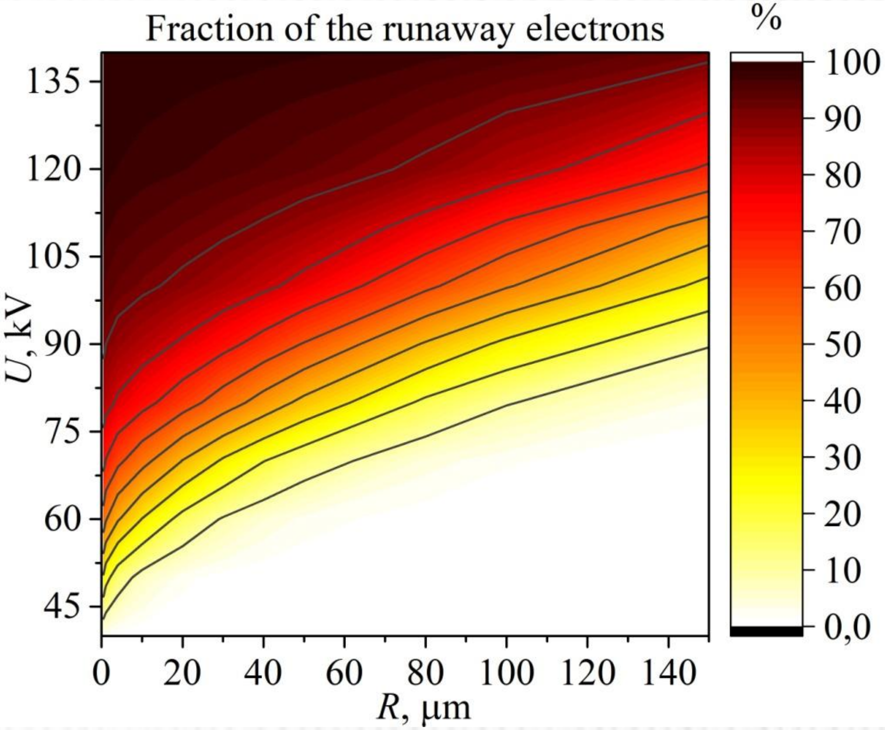
Time dependence of the runaway electron current density and their energy spectrum. Cathode curvature radius 40 μm, voltage 100 kV (the Monte-Carlo simulation)



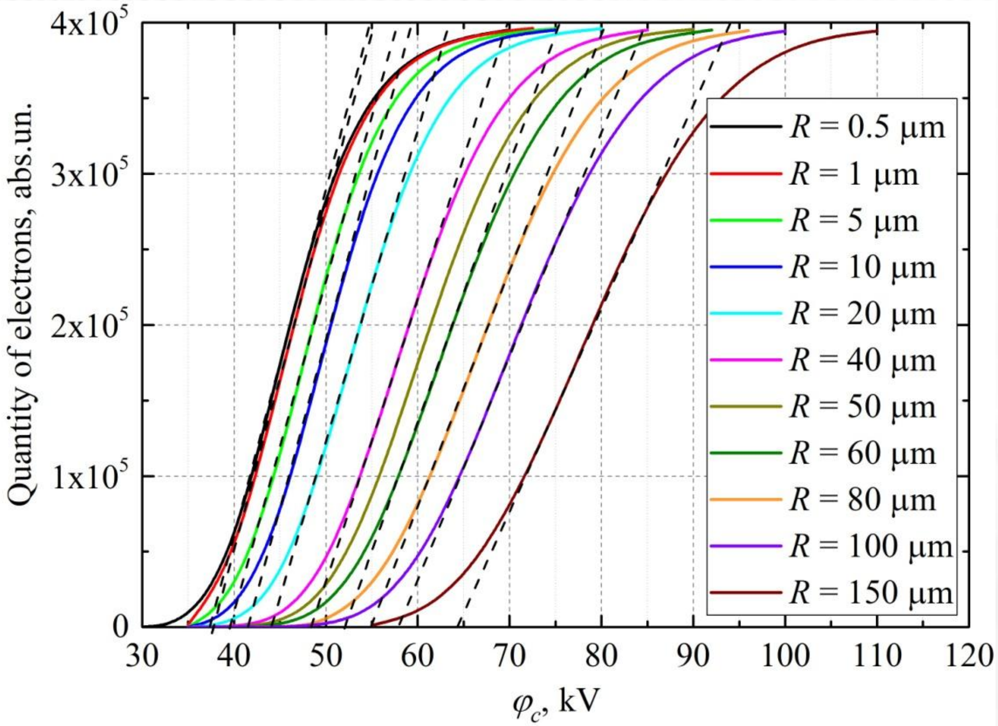
Time dependence of the runaway electron current density and their energy spectrum. Cathode curvature radius 40 μm, voltage 100 kV (the kinetic approach)

A method of runaway threshold estimation

IEP UB RAS



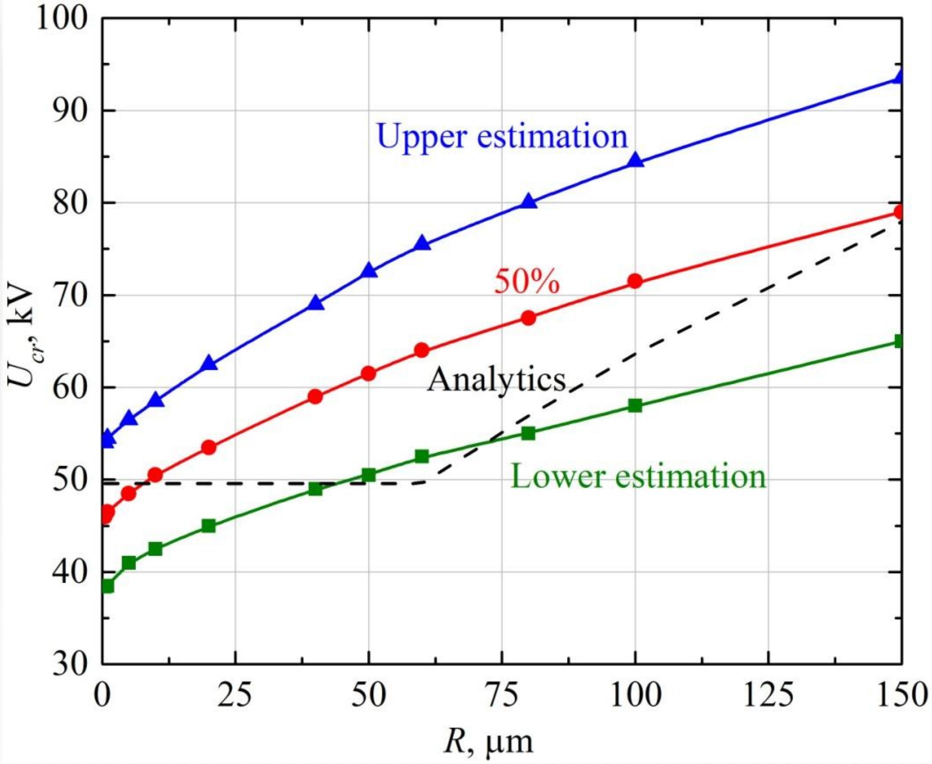
A fraction of runaway electrons depending on the gap voltage *U* and the cathode curvature radius *R* for nitrogen of 1 atm pressure and *d* = 1 cm (the kinetic model)



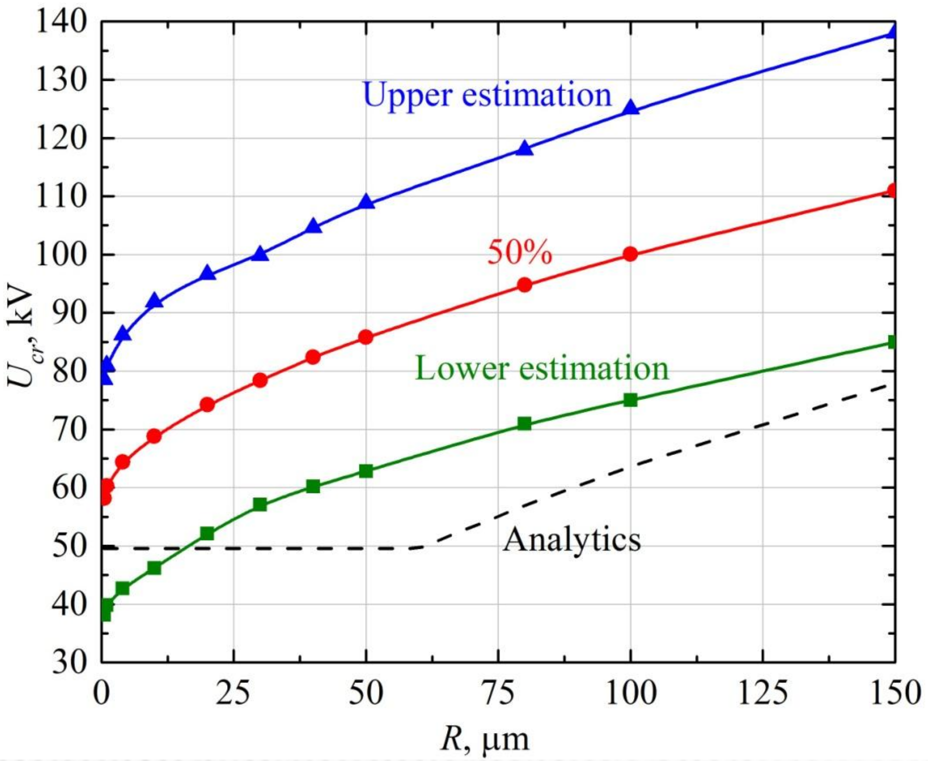
Quantity of runaway electrons having reached the anode at 200 ps depending on the cathode potential and the cathode curvature radius for nitrogen of 1 atm pressure and *d* = 1 cm (the Monte-Carlo model)

Estimation of threshold voltage values $U_{cr}(R)$ for various cathode curvature radii R

IEP UB RAS



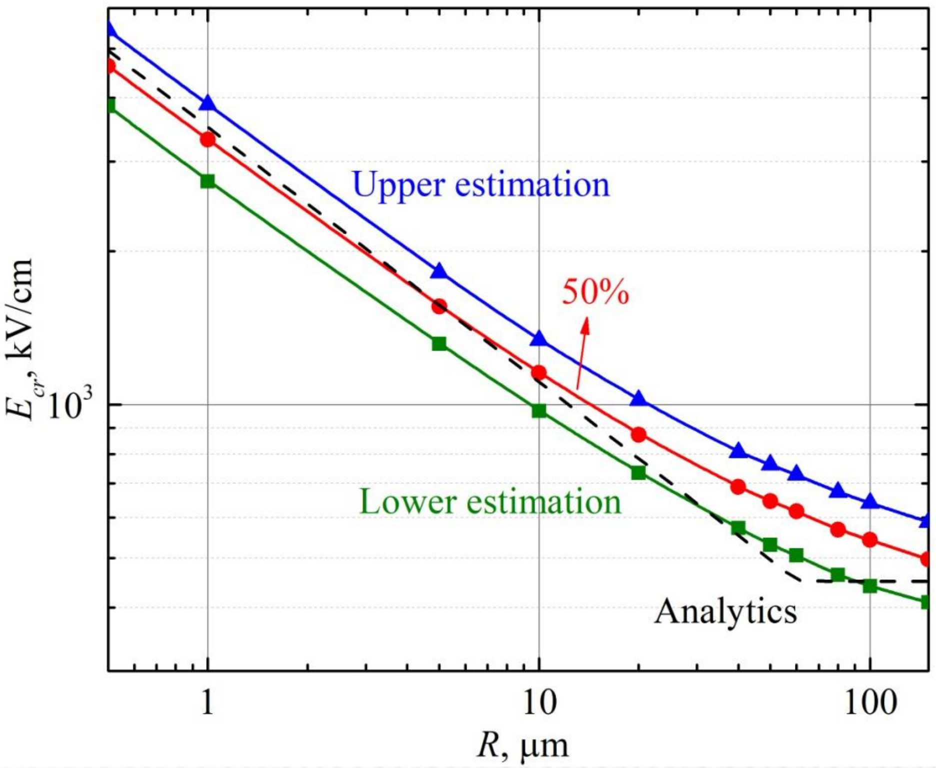
Estimation of $U_{cr}(R)$ corresponding to various R for nitrogen of 1 atm pressure and d = 1 cm (the Monte-Carlo model)



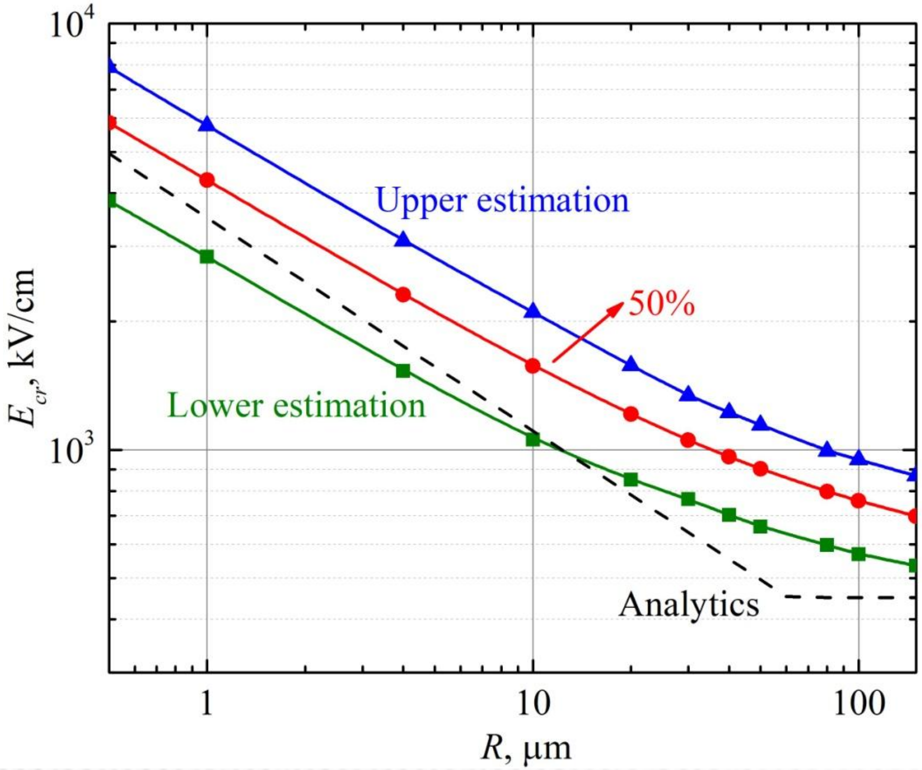
Estimation of $U_{cr}(R)$ corresponding to various R for nitrogen of 1 atm pressure and d = 1 cm (the kinetic model)

Estimation of threshold electric field strength near the cathode apex $E_{cr}(R)$ for various cathode curvature radii R

IEP UB RAS



Estimation of $E_{cr}(R)$ for various R for nitrogen of 1 atm pressure and d = 1 cm (the Monte-Carlo model)



Estimation of $E_{cr}(R)$ for various R for nitrogen of 1 atm pressure and d = 1 cm (the kinetic model)

IEP UB RAS

4 - Summary

Main conclusion

IEP UB RAS

The presence of some constant value of the runaway threshold voltage U_{cr} for cathodes of small curvature radius R was found by both the Monte-Carlo model and the kinetic approach.

Even being accelerated near the cathode of small R in the area of high E, a fast electron may become thermalized one in the region of a weak field at the periphery of the discharge gap.

In strongly non-uniform electric fields, it imposes the additional restrictions on the minimal voltage (or the minimal electric field strength value near the cathode edge) sufficient for generation of runaway electrons.

It confirms the runaway criterion proposed earlier: it is necessary to apply some finite voltage to the discharge gap to prevent deceleration of runaway electrons in a relatively weak field as they approach an anode.

IEP UB RAS

Russian Academy of Sciences
Institute of Electrophysics
Physical Electronics Laboratory

THANK YOU FOR YOUR ATTENTION!

Yuriy I. Mamontov, junior researcher,
mamontov.ura.1994@yandex.ru,
+7 909 004 83 77

21st International Symposium on High Current Electronics
in 7th International Congress on Radiation Fluxes and Radiation Effects
(EFRE-2020)
Tomsk, Russia
2020