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F I A N

On the nature of nanosecond diffusion-channel discharges in air

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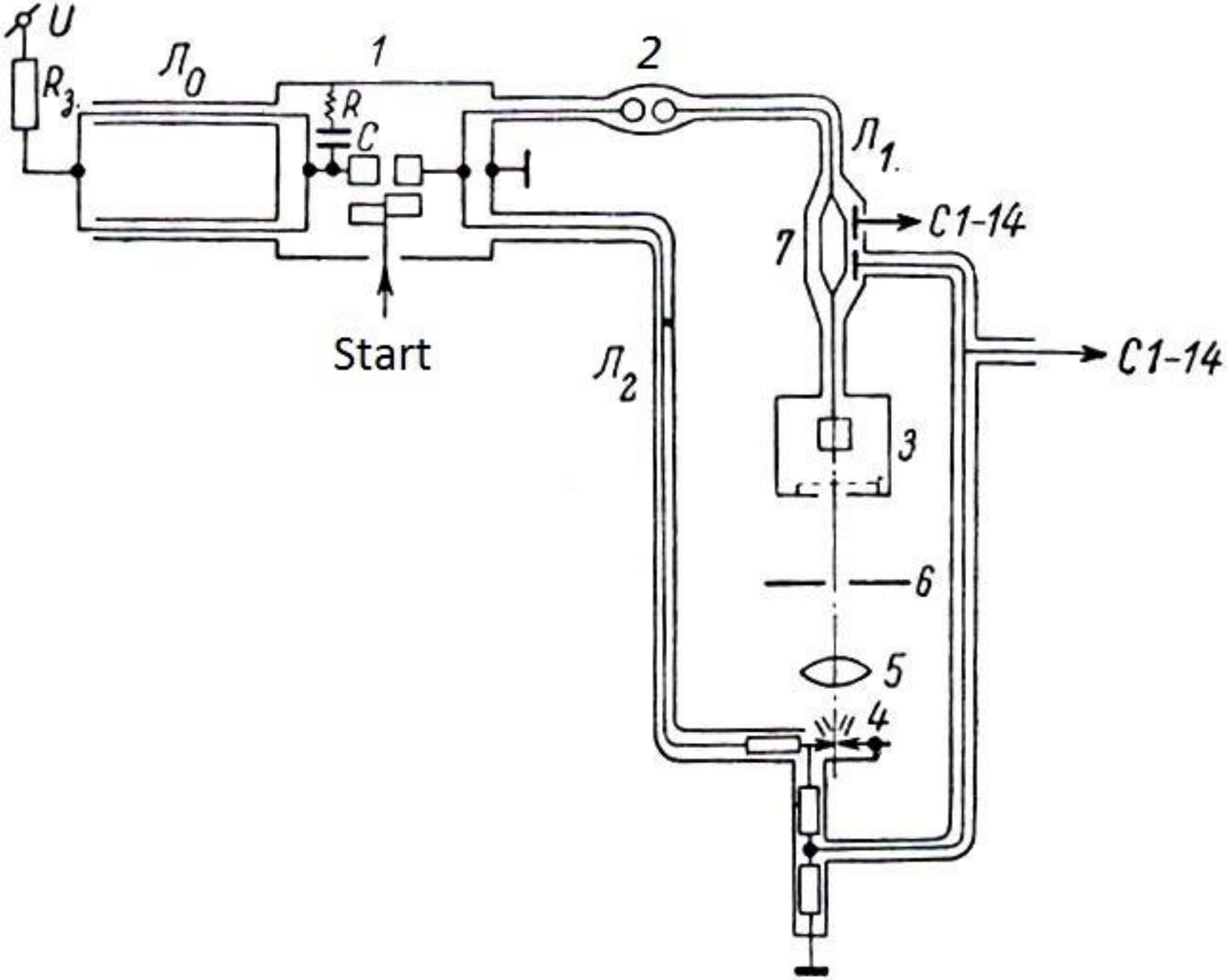
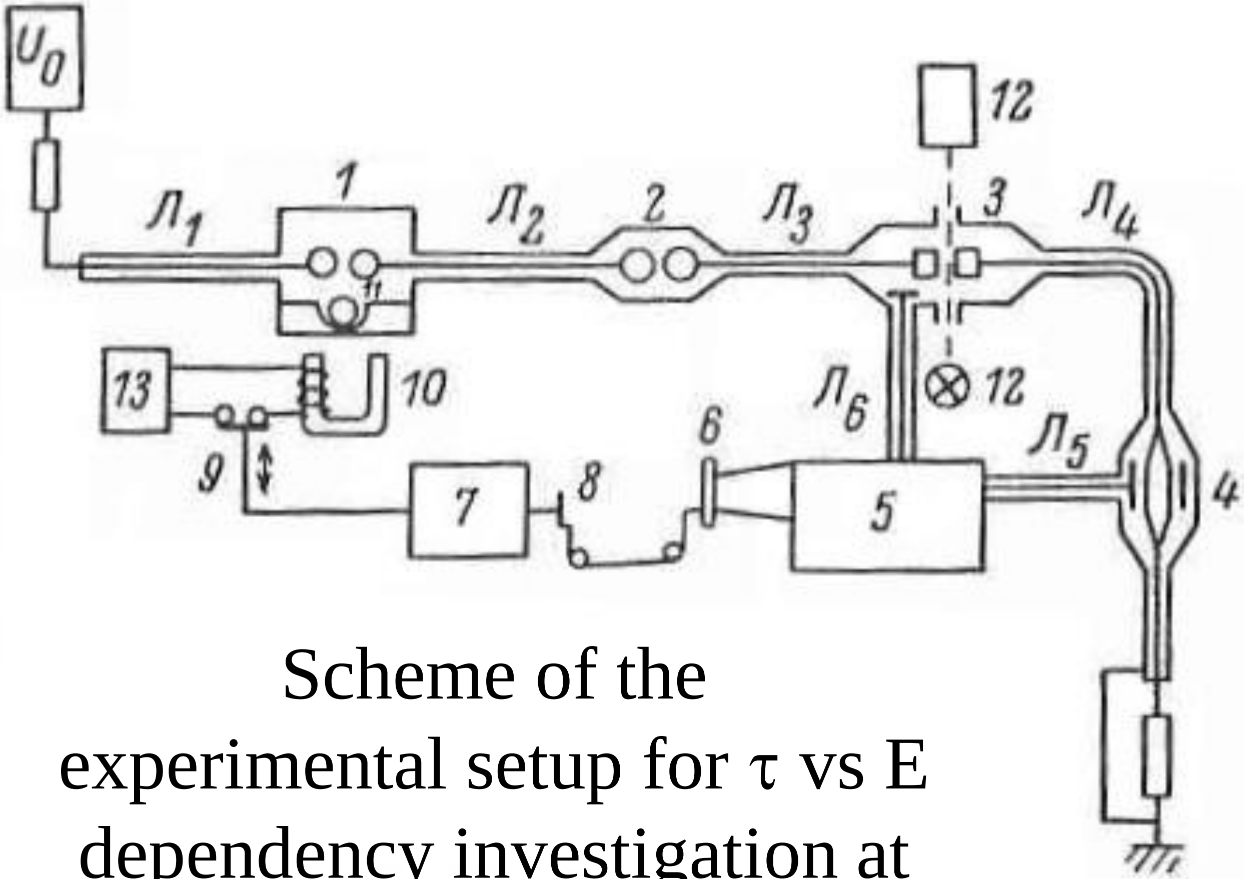
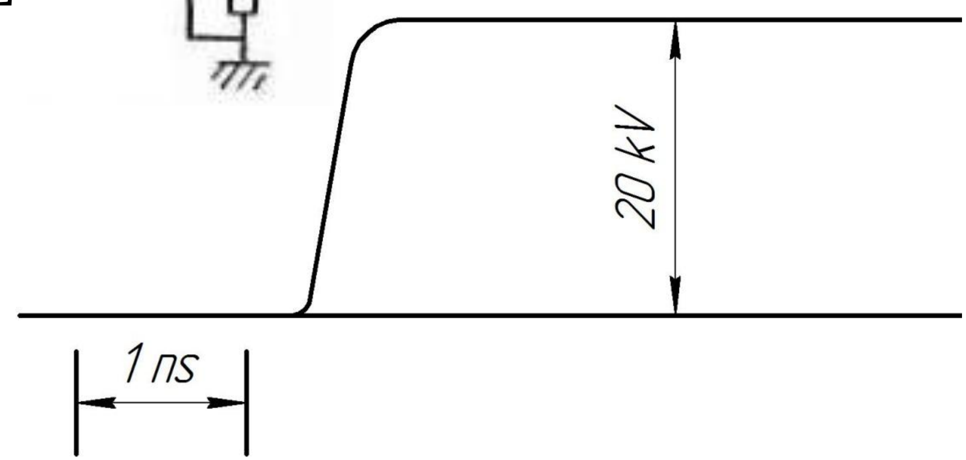
Scheme of the experimental setup for τ vs E dependency investigation at the multi-electron initiation





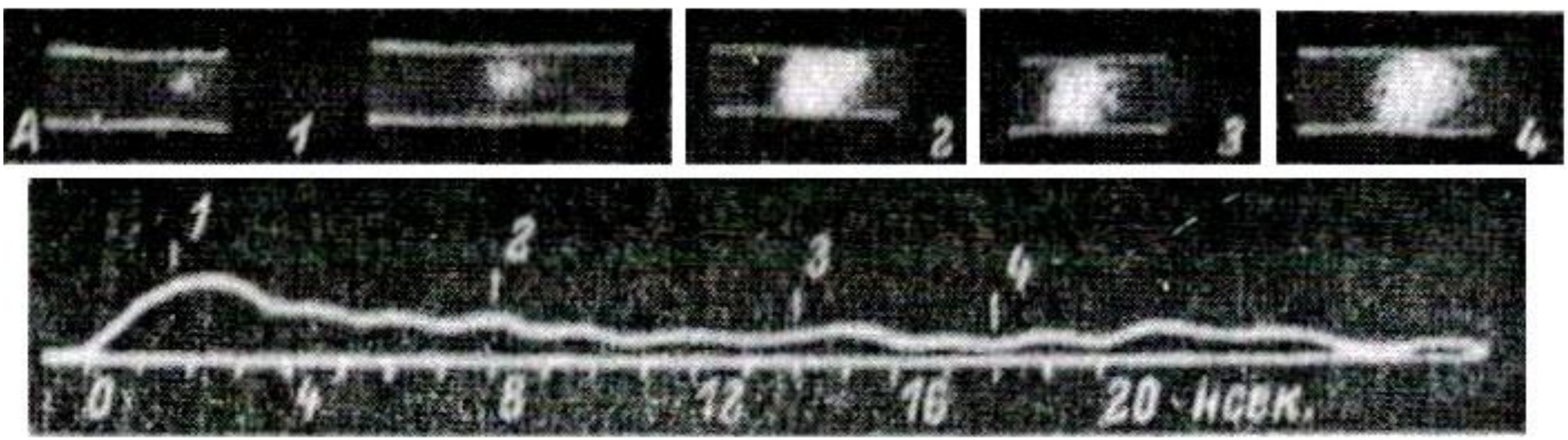
Scheme of the experimental setup for τ vs E dependency investigation at the single-electron initiation



Oscillogram of voltage pulse

Pictures of multi-electron-initiated discharge development in air, obtained by image intensifier.

p = 760 Torr, E=10^5 V·cm^{-1}, d = 0.6 cm



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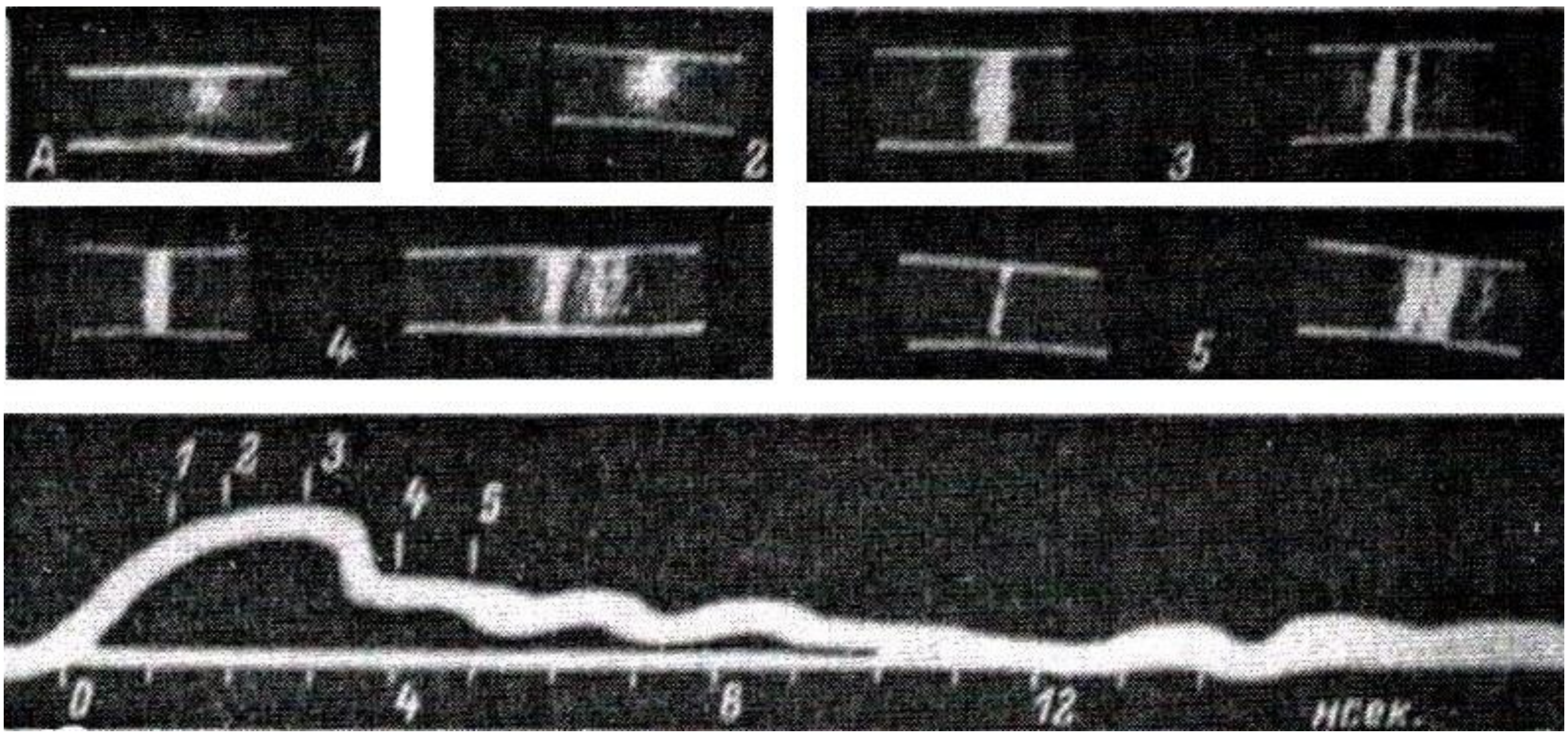
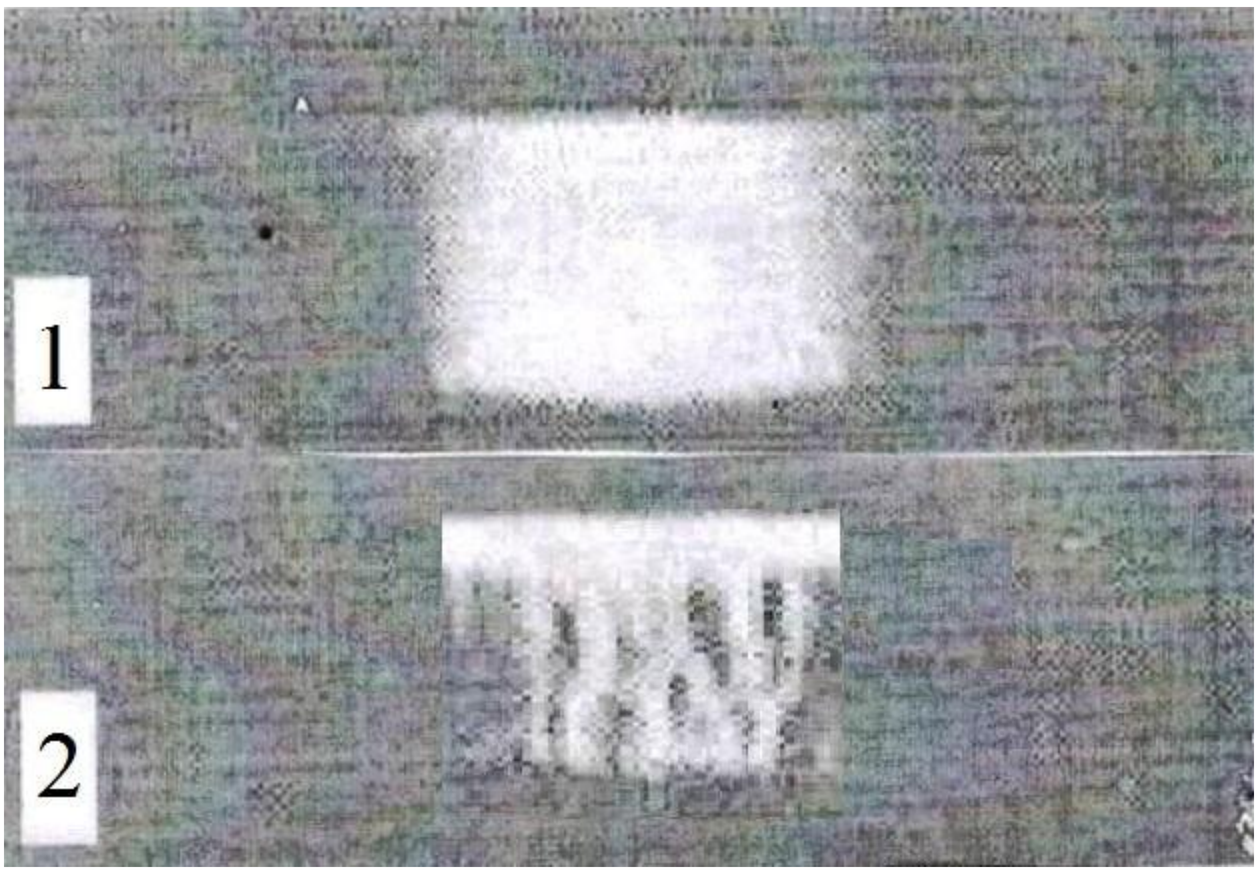


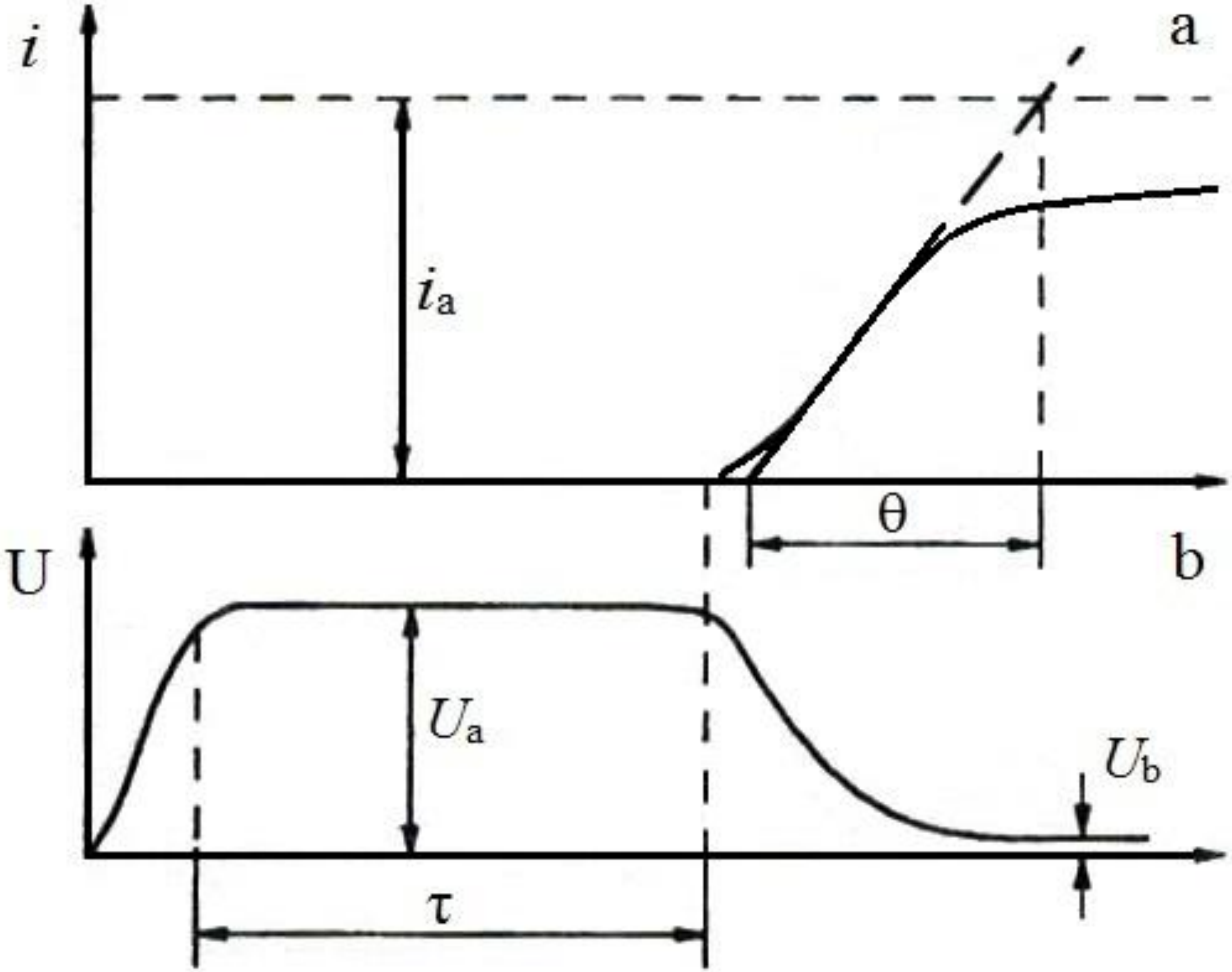
Pictures of the gap glow at the formative stage of breakdown in argon.

U_0=18 kV, p=760 Torr, d=1 cm, t_p= 20 ns.

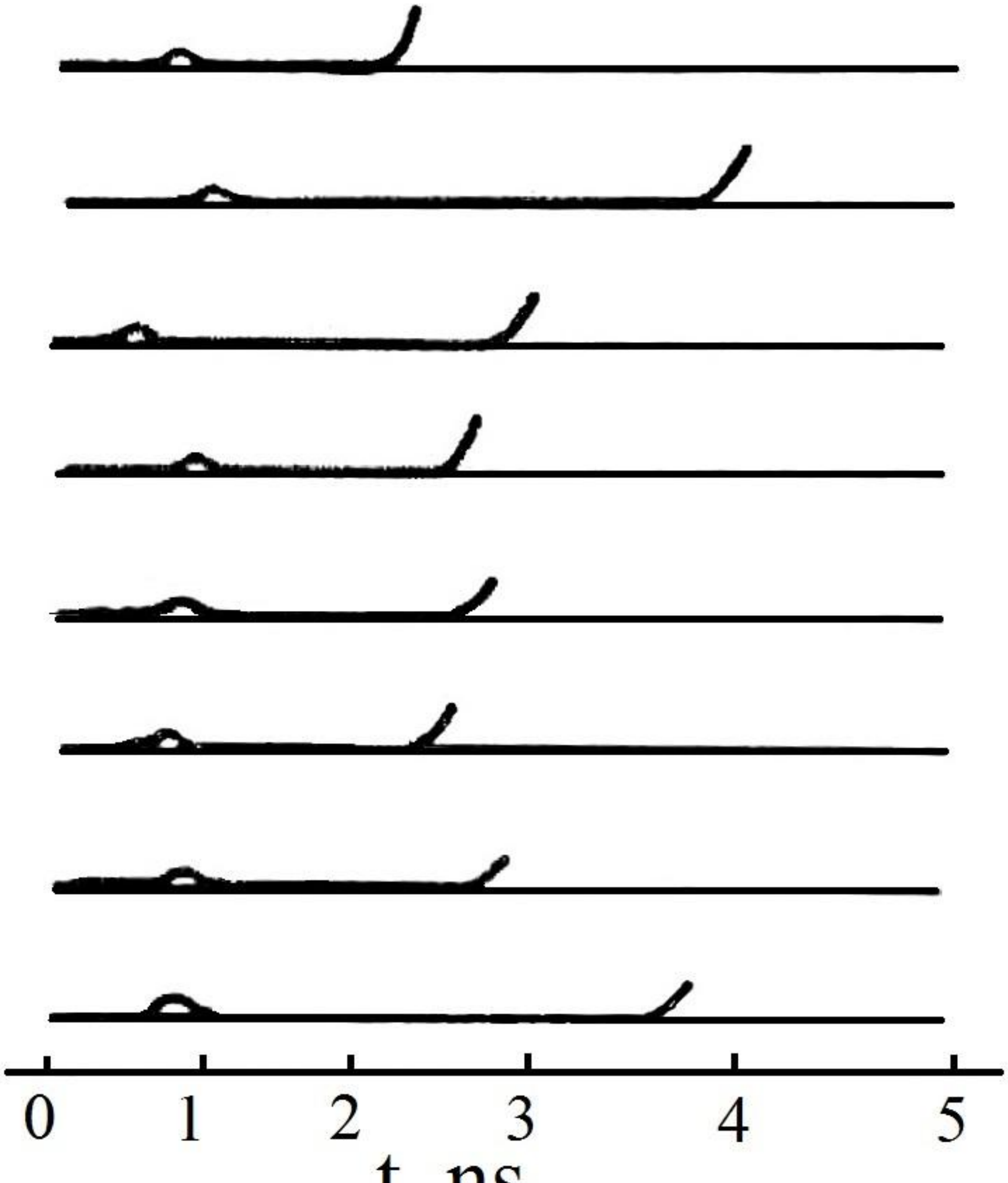
1 – multi-electron initiation,

2 – single-electron initiation





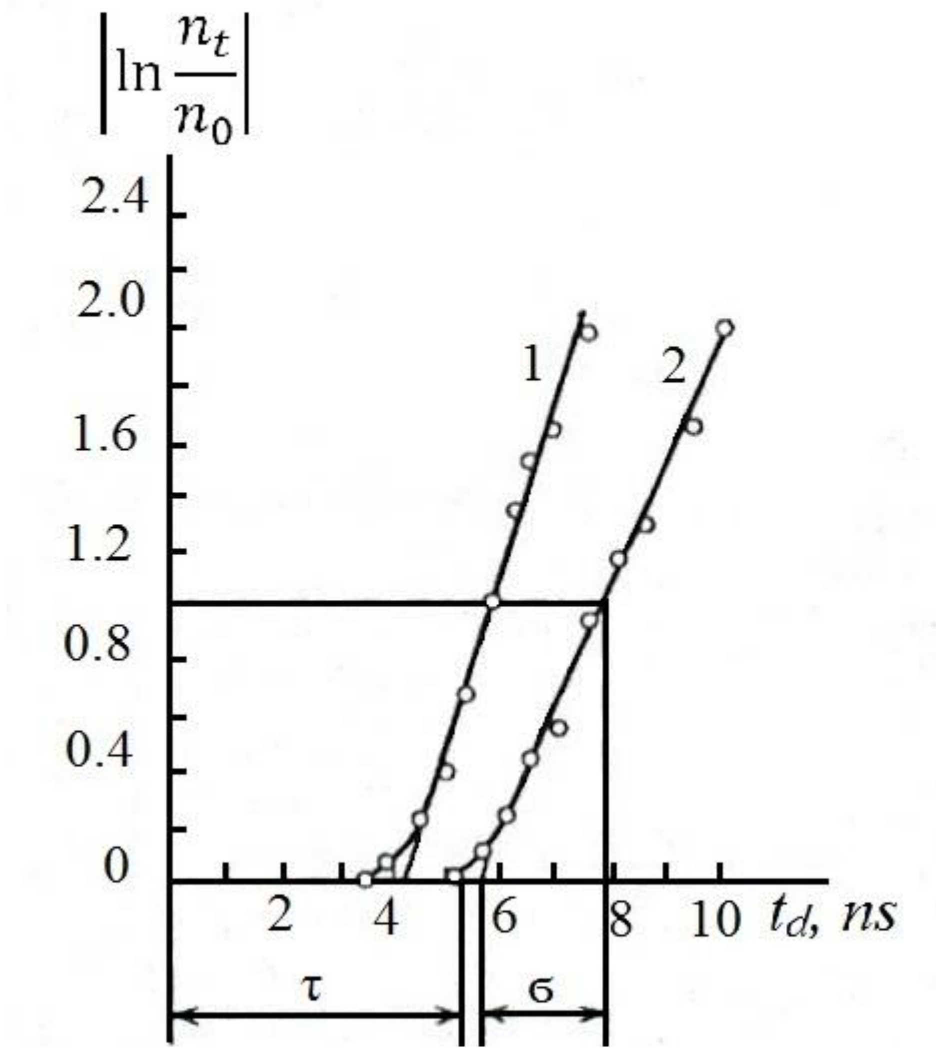
a – Scheme of current oscillogram,
b – scheme of voltage on the discharge gap

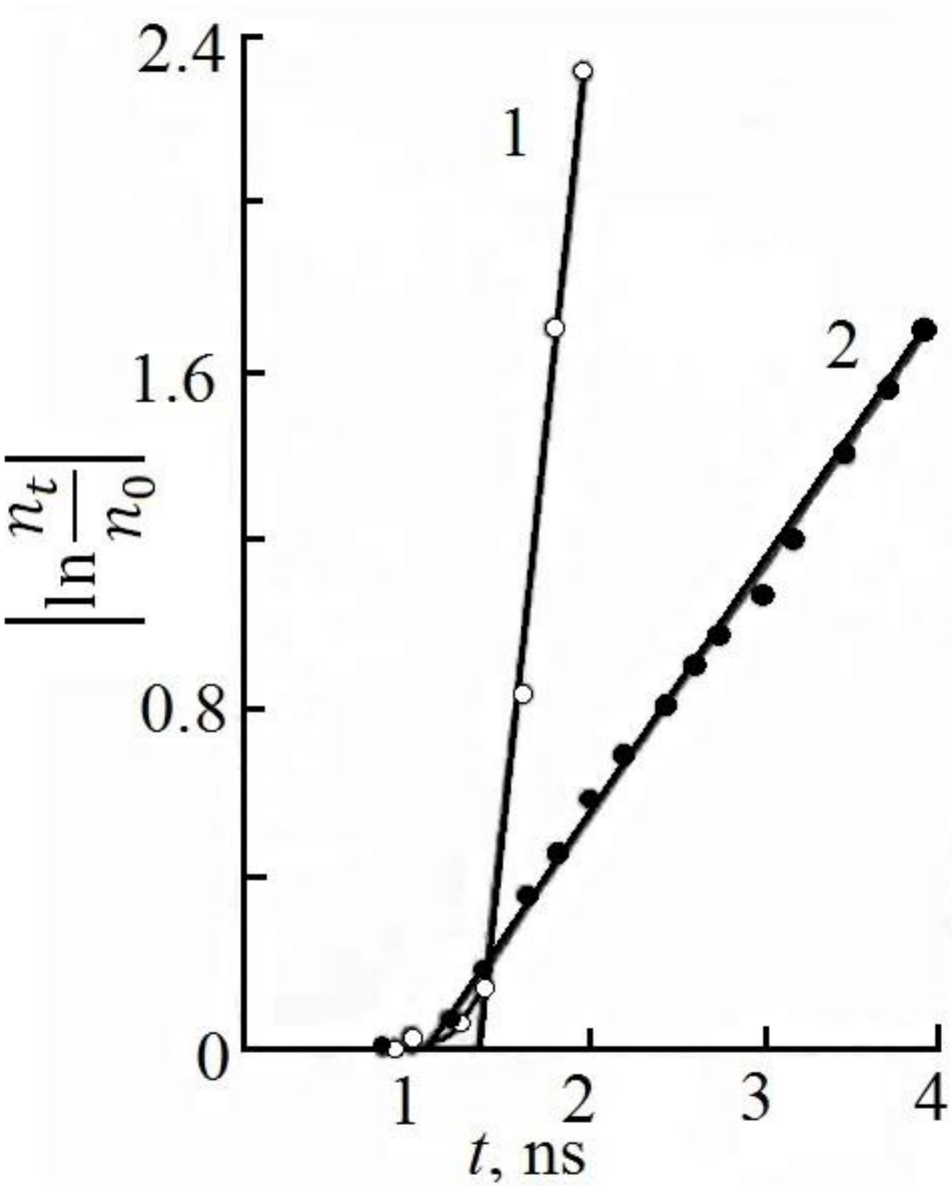


Oscillograms for $|\ln (n_t/n_0)| = f(t)$ distribution

$$\left|\ln\frac{n_t}{n_0}\right| = f(t)$$ distribution for atmospheric air at

d = 2 mm. 1 – E=100 kV·cm^{-1}; 2 – E= 90 kV·cm^{-1}





The influence of the breakdown number on $|\ln(n_t/n_0)| = f(t)$ curve at d= 0.3 mm, E=6·10^5 V·cm^{-1}, n_0=100, copper electrodes.

1 – after 50,

2 – after 2000 breakdowns

Diffuseness

If electrons initiating the discharge are created on the cathode surface, then the discharge formation time τ is determined from the formula

$$\tau = (\alpha v)^{-1} \ln(i_1 d / e N_0 v), \qquad (1)$$

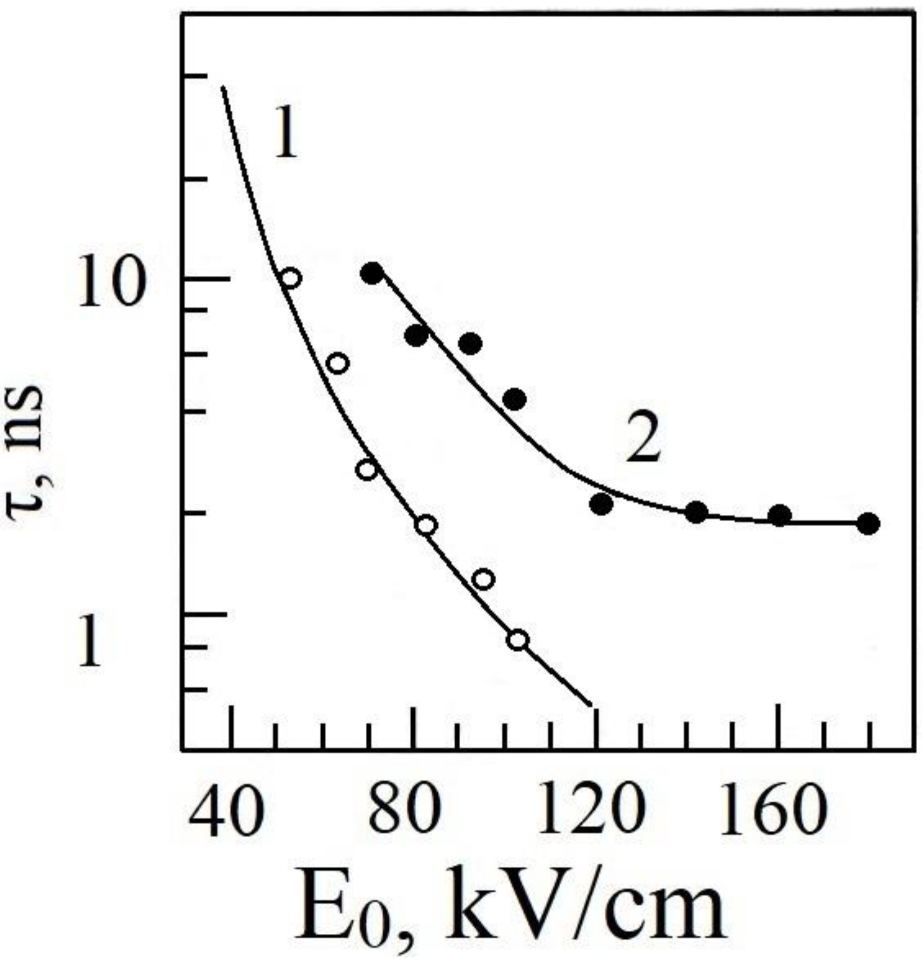
where d – is the gap length, α – is the impact ionization coefficient, v – is the electron drift velocity, e – is the electron charge, i_1 is the current at which the discharge starts, N_0 – is the number of electrons initiating the discharge. $N_0 = 10^4$ is the optimal number of electrons [1,2].

If the initiating electrons are uniformly distributed in the discharge volume, then

$$\tau = (\alpha v)^{-1} \ln(i_1 / e n_e v s), \qquad (1')$$

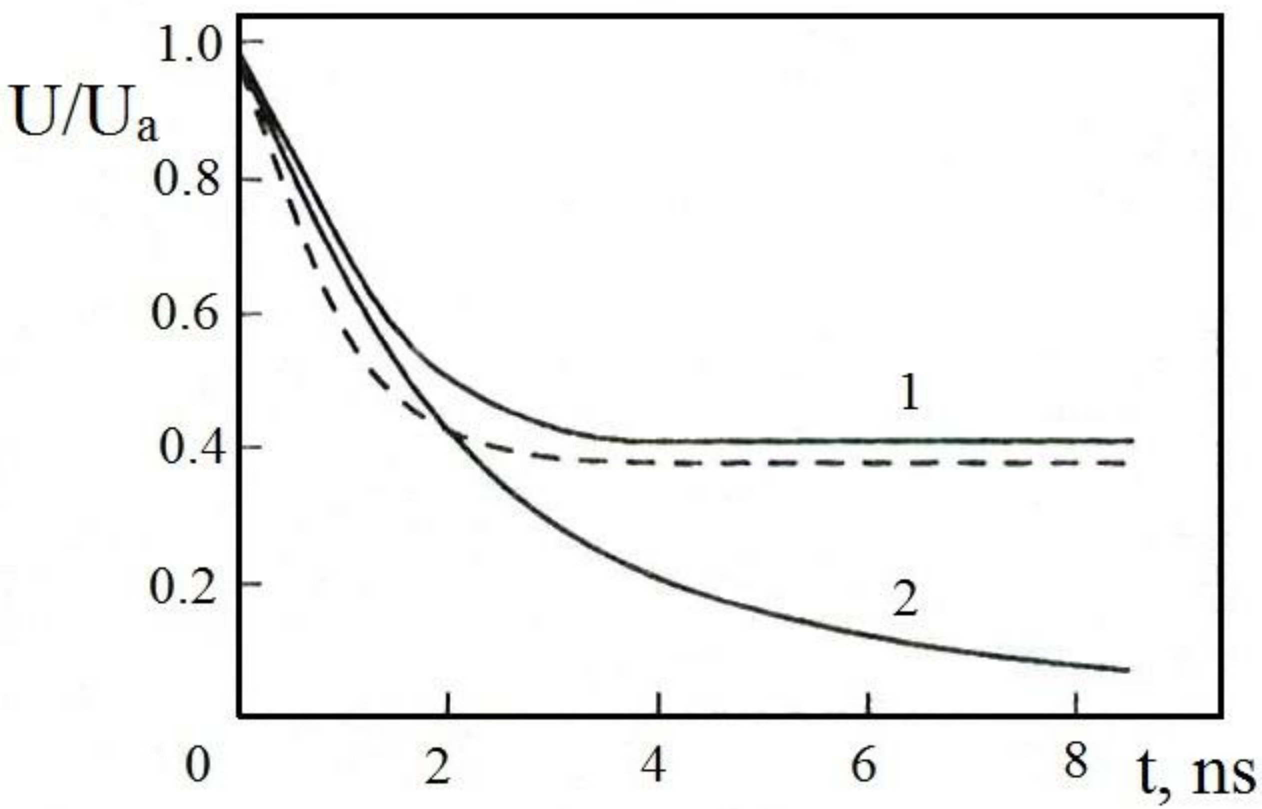
where s – is the cross-sectional area of the plasma column, n_e – is the initial density of initiating electrons. In [3], $n_e \geq 10^6$ cm^{-3} was obtained.

1. G. A. Mesyats, Doctoral Thesis, Tomsk, 1966.
2. G. A. Mesyats, Yu. I. Bychkov, and A. M. Iskoldskii, *Zh. Tekh. Fiz.* **38**, 1281–1287 (1968).
3. P. Felsental, J.M. Proud, *Phys. Rev.*, **139**, 1796 (1965).

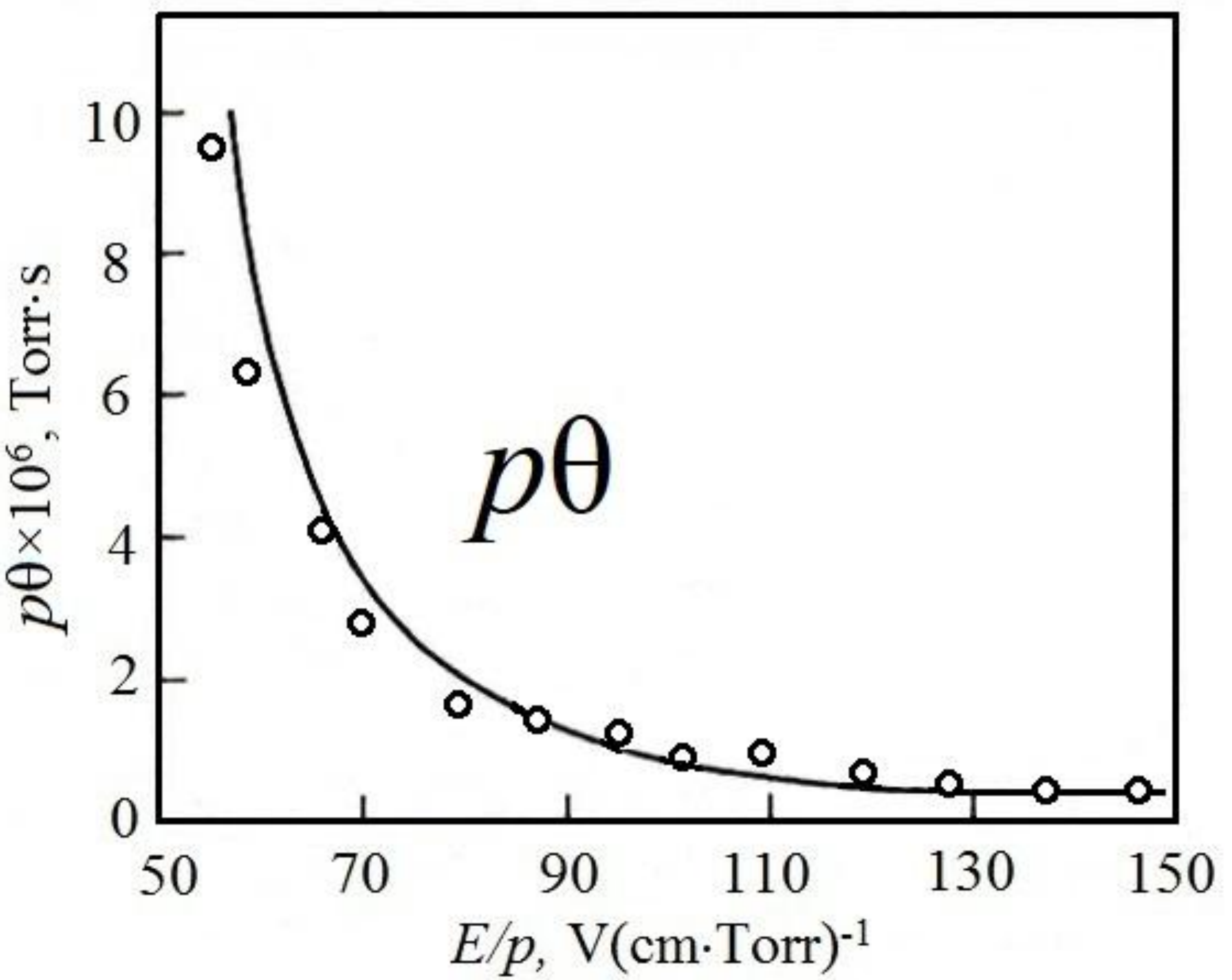


Formative time of breakdown in air (p = 760 Torr) as a function of electric field.
1 –multi-electron-initiated breakdown;
2 –single-electron-initiated breakdown.

Experimental waveforms of gap voltage fall
for a multi-electron-initiated discharge (1)
and for a single-electron-initiated discharge (2) in nitrogen.
Dashed curve – calculation by the avalanche electron multiplication model.
p=760 Torr, *d* = 0.44 cm, E_0=68.5 kV·cm^{-1}



$p\theta$ vs E/p dependence at the multi- and single-electron initiation



Runaway electrons

This phenomenon was discovered in the study of nanosecond discharges in atmospheric air [1]. The critical field E_{cr} at which this takes place is determined by the formula [2]:

$$E_{\mathrm{cr}} = 4\pi e^3 n_m z / 2.72 I \qquad (2)$$

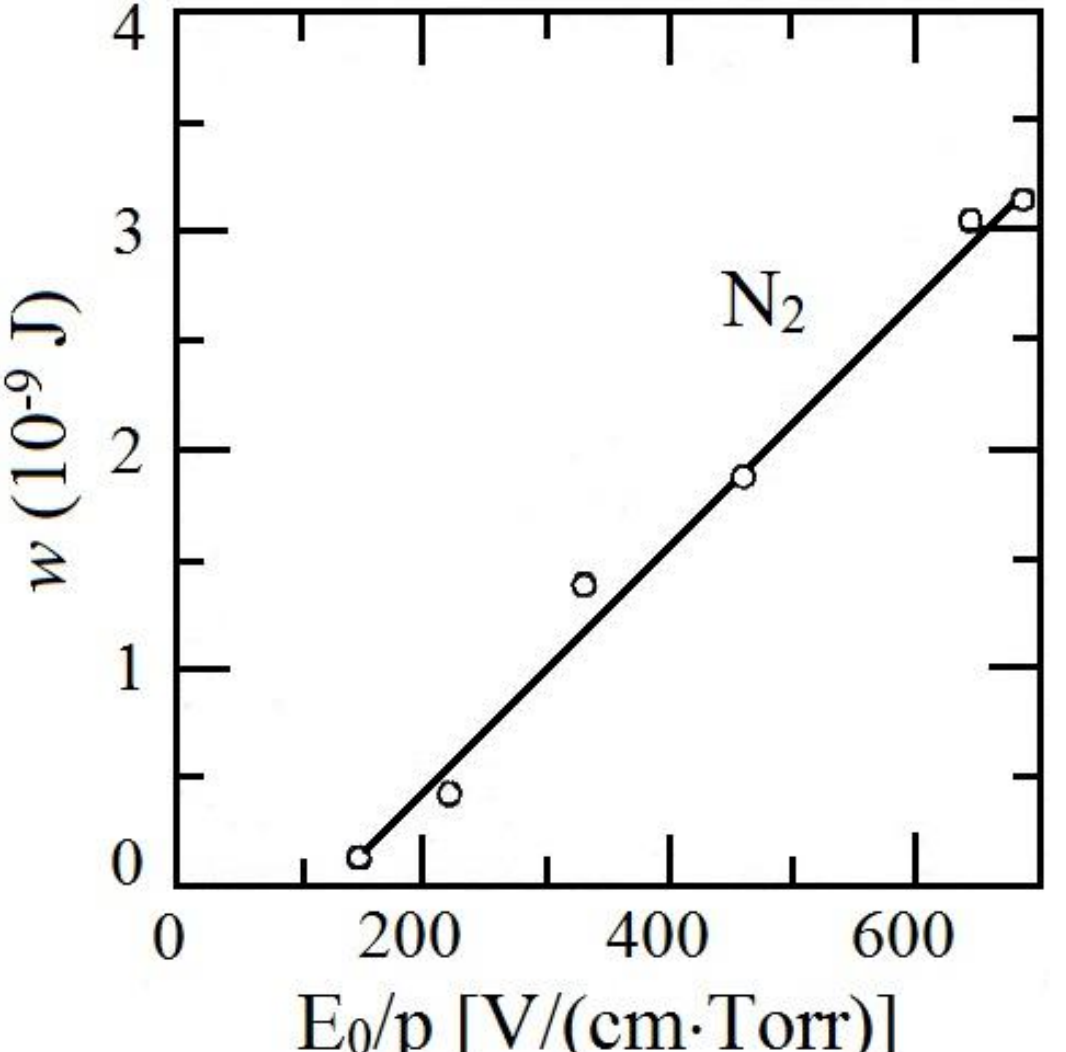
where n_{m} – is the density of the gas molecules, I – is the average energy lost by electrons in inelastic collisions, and z – is the number of electrons in a molecule. From this formula, a condition for electrons in a gas discharge to become runaway electrons can be derived:

$$E_{\mathrm{cr}}/p = 3.38 \cdot 10^3 z/I \; , \qquad (3)$$

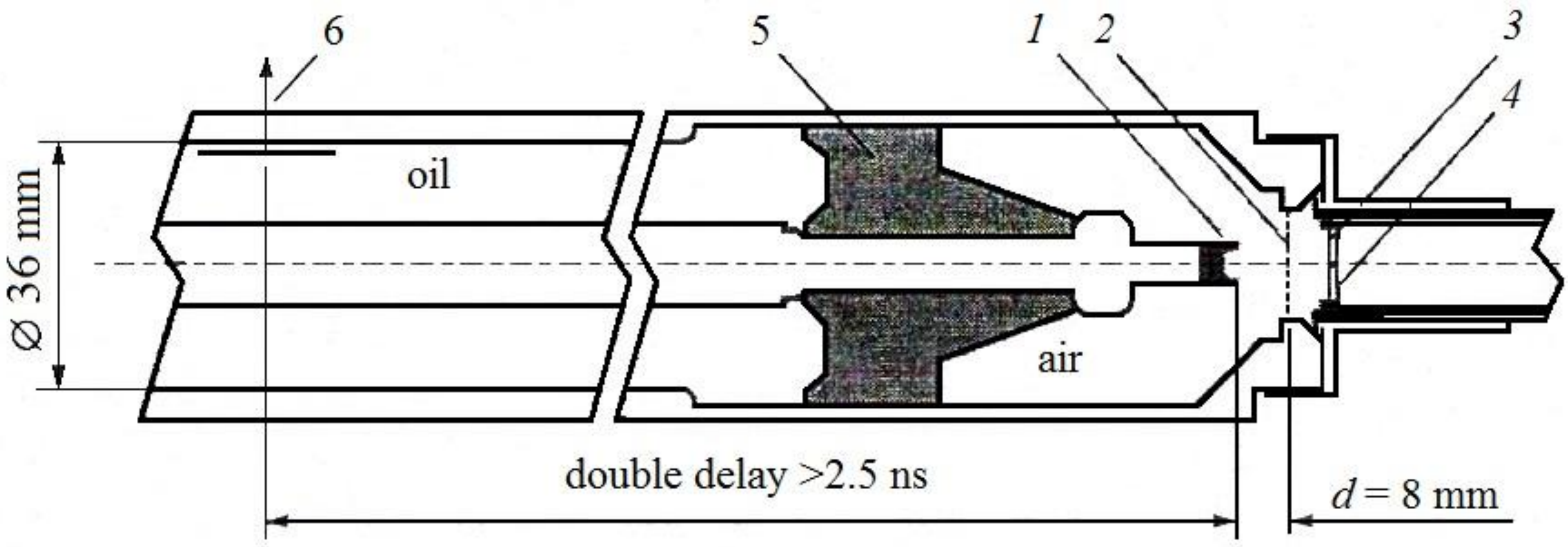
where p – is the gas pressure. For instance, for nitrogen we have $z = 14$, $I = 80$ eV, $E_{\mathrm{cr}}/p = 590$ V·cm^{-1}·Torr^{-1}. For atmospheric pressure, this corresponds to $E_{\mathrm{cr}} = 4.5 \cdot 10^5$ V·cm^{-1}.

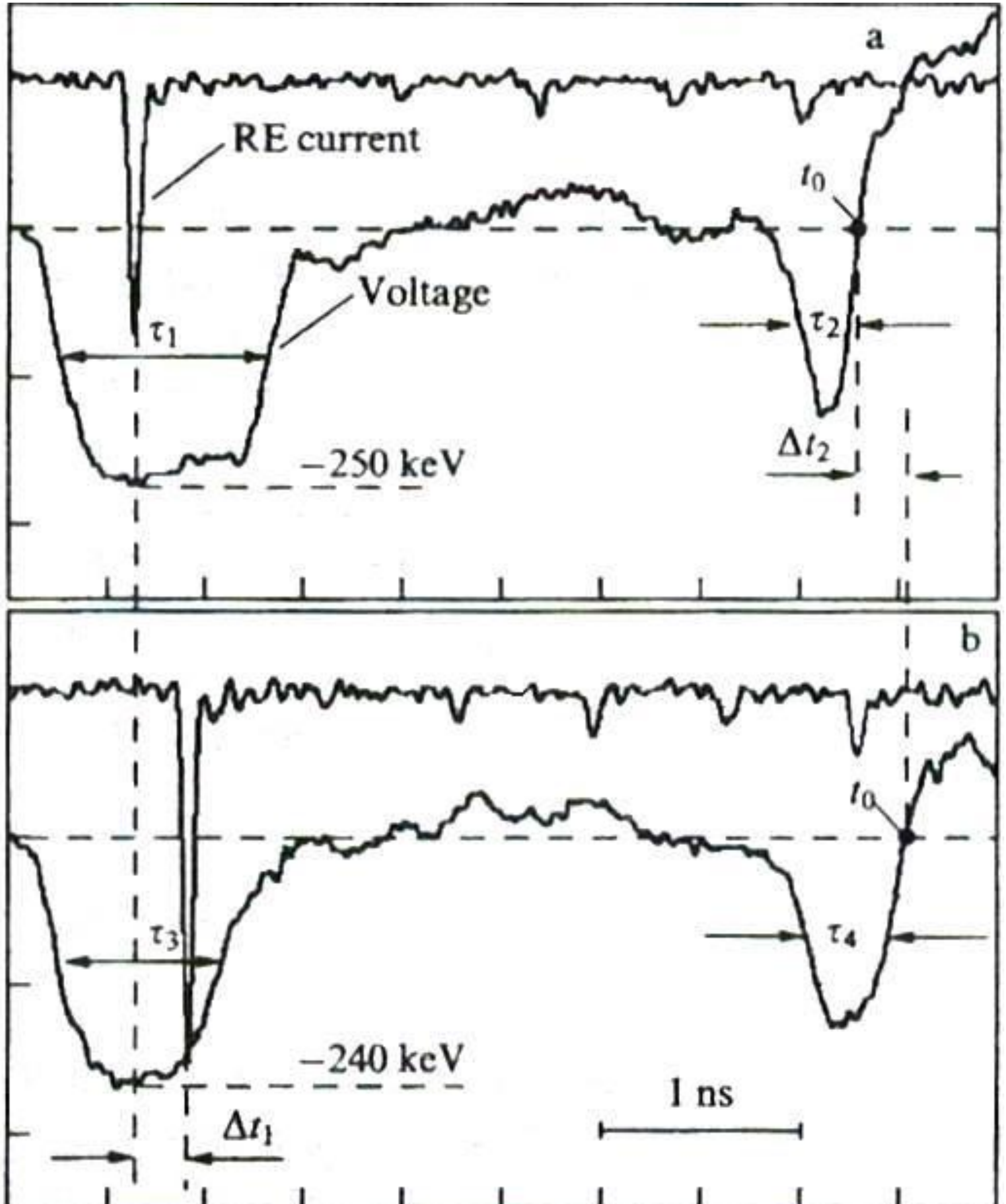
1. Yu. L. Stankevich and V. G. Kalinin, *Dokl. AN SSSR* **177**, 72–74 (1967)
2. A. V. Gurevich, *Zh. Eksp. Teor. Fiz*. **39**, 1296 (1960)

X-ray energy radiated per pulse as a function of E_0/p for discharge in nitrogen



Pulse generator construction.
1 – cathode, 2 – foil, 3 – collector screen, 4 – collector, 5 – insulator, 6 – voltage divider





Reflectometry of a voltage pulse delivered to the cathode of the discharge gap and signals from the sensor of runaway electrons emitted at different time instants relative to the voltage pulse.

$\Delta t_1 = \Delta t_2 = 250$ ps

Electron avalanche propagation

The number of electrons in the avalanche, *N*, increases according to the law

$$N = \exp(\alpha x), \qquad (4)$$

where α – is the impact ionization coefficient and *x* – is the distance covered by the avalanche. We assume that all electrons fly in a group with a drift velocity *v*, and the ions are motionless.

At the initial stage of the development of an electron avalanche, its radius *r* is controlled only by electron diffusion, and it can be described as

$$r = (6Dt)^{1/2}, \qquad (5)$$

where *D* – is the diffusion coefficient and *t* – is time. As we have

$$t = \frac{x}{v} = \frac{x}{bE_0}, \qquad \frac{D}{b} = \frac{2U_T}{3}, \qquad (6)$$

where E_0 is the electric field, *b* is the electron mobility, and U_T is the thermal energy of the electrons in the avalanche plasma.

Field amplification in the avalanche head

Let us substitute formula (6) in (5), we gain:

$$r^2 = \frac{4U_T x}{E} = \frac{4U_T x^2}{U}, \qquad (7)$$

where $U = xE$ – is the potential difference along the path x traveled by the avalanche. Relation (7) yields

$$\beta = \frac{x}{r} = \frac{1}{2}\left(\frac{U}{U_T}\right)^{\frac{1}{2}} \qquad (8)$$

As the thermal energy of electrons U_T is measured in volts and U in kilovolts, we have $\beta \gg 1$.

The value of β characterizes the enhancement of the electric field in the avalanche head relative to the external field E_0. The electric field enhancement in the head of an electron avalanche is inherent in the mechanism of development of the avalanche. The field enhancement occurs when an avalanche transforms into a streamer. The number of electrons in the discharge plasma during the avalanche-to-streamer transition is determined as $N_s = 10^6$.

Field amplification in the avalanche head

At $E/p = 10^2 \div 10^3$, the factor of field enhancement in an avalanche

$$\beta = Q \exp \frac{B \cdot p}{2E_0}, \qquad (9)$$

where Q ≈3 [1].

For instance, at E_0/p = 150 V·cm^{-1}·Torr^{-1} and atmospheric air pressure, the field enhancement factor β will be 10.4, and the total field at the tip of the avalanche before its transformation into a streamer will be 1.25·10^6 V·cm^{-1}. This field is high enough for electron runaway to occur in nitrogen and in air.

1. G.A. Mesyats, N.M. Zubarev, I.V. Vasenina, *Bulletin of the Lebedev Physics Institute*. **7**, 32-38 (2020)

Field amplification in the avalanche head

The impact ionization coefficient is determined by the Townsend formula

$$\frac{\alpha}{p} = A\exp\left(-\frac{B}{E_0/p}\right), \qquad (10)$$

where A = 15 cm^{-1}·Torr^{-1} and B = 365 V·cm^{-1}·Torr^{-1}. Then we obtain the following relation for the critical avalanche parameters:

$$x_s = \frac{\ln N_S}{Ap}\exp\frac{B}{E_0/p}. \qquad (11)$$

Assuming that the discharge develops in nitrogen, we estimate the thermal electron energy U_T in the avalanche plasma by the Schlumbohm's formula:

$$U_T = c\left(\frac{E_0}{p}\right)^{2/3}, \qquad (12)$$

where c = 0.2 V$^{1/3}$·cm$^{2/3}$·Torr$^{2/3}$. Multiplying the right and left sides of formula (11) by E_0, we obtain for the critical avalanche

$$U = \frac{E_0\ln N_S}{Ap}\exp\frac{B}{E_0/p}. \qquad (13)$$

Streamer formation

The anode-directed streamer under consideration that is formed in an NDC discharge is fundamentally different from classical streamers which are formed in atmospheric air in centimeter gaps at low overvoltages.

As the gap spacing d is much greater than the avalanche critical size x_c, the streamer starts forming in the cathode region rather than in the anode one.

Let us illustrate this by an example. For E_0/p = 150 V·cm^{-1}·Torr^{-1} and p = 760 Torr in a gap of d = 0.2 cm, we have the impact ionization coefficient $\alpha = 10^3$ cm^{-1}, the electron drift velocity $v = 4.0 \cdot 10^7$ cm·s^{-1}, the streamer formation time $t_s = 3.4 \cdot 10^{-10}$ s, and the distance covered by the avalanche before its transformation into a streamer $x_s = vt_s = 13.7 \cdot 10^{-3}$ cm.

Hence, almost **15 electron** avalanches of critical size will fit along the gap.

Streamer formation

Thus, the diffuseness of NDC discharges in air at atmospheric pressure can be due to the runaway electrons emitted by avalanches and streamers.

Runaway electrons also ensure the operation of a streamer and give it a velocity much greater than the electron drift velocity. For nanosecond discharges, as a streamer grows in length, its velocity in a uniform field can reach 10^9 $cm{\cdot}s^{-1}$ [1], and it can be significantly greater in a nonuniform field [2, 3].

The runaway electrons, moving toward the anode, ionize the gas and excite the gas molecules. They also generate X-ray bremsstrahlung at the anode.

1. Yu. I. Bichkov, P. A. Gavrilyuk, Yu. D. Korolev, and G. A. Mesyats, in *Proceedings of the 10th International Conference on Phenomena in Ionized Gases*, *Oxford*,168 (1971)
2. V. F. Tarasenko, *Plasma Sources Sci. Technol*. **29**, 034001 (2020).
3. D. Levko, *J. App. Phys*. **124**, 163302 (2018).

Free electron accumulation

The streamer has a low conductivity, since there will be a small number of electrons N_s in the avalanche head due to the avalanche self-deceleration. In our case, $N_s = 10^6$.

The avalanche emits runaway electrons and ultraviolet photons. Therefore, the streamer will develop in the form of an avalanche chain. The primary avalanche creates a new avalanche ahead of itself at the expense of the RE, which creates new REs, etc.

Due to the photoelectric effect, ultraviolet photons generate new electrons and, accordingly, new avalanche chains. Thus, there is an accumulation of such a number of free electrons that the discharge passes into the multi-electron initiation mode. Therefore, we observe that the times θ of both discharges are the same.

NDC-discharge completion

If the concentration of free electrons is $\geq 10^6$ cm^{-3}, then a volume discharge with multi-electron initiation occurs. The voltage U at such a discharge is described by the equation [1]

$$\frac{dU}{dt} = \left(1 - \frac{U}{U_0}\right) U \alpha v, \qquad (14)$$

From this equation, it is possible to determine the dependence of the voltage U on the time t in the gap, and also to find the time θ, which determines the duration of the initial stage of the discharge. In fact, a glow discharge takes place. In such a discharge, a redistribution of the electric field occurs. At the cathode, it will be [1]

$$E_c/p = 10^5 (j/p^2)^{2/3}, \qquad (15)$$

At a current of 100 A, a cross section of the discharge column of 1 cm^2, and a pressure of 760 Torr, the field is $E_c = 10^6$ V·cm^{-1}. With this field, field emission appears at the cathode, and explosive emission starts from the cathode spots.

1. Yu. D. Korolev, G.A. Mesyats. *Physics of Pulsed Breakdown in Gases*, URO-PRESS, Ekaterinburg, 1998.

Conclusion

- Nanosecond discharges exist at the multi-electron initiation (MEI) and the single-electron initiation (NDC-discharge).
- The NDC-discharge formation time an order of magnitude exceeds the discharge at the multi-electron initiation ($\tau_{NDC} > \tau_{MEI}$).
- NDC-discharge starts from the electron avalanche formation. The avalanches are initiated by the electrons, which are emitted the from microprotrusions on the cathode due to field electron emission (FEE).
- At the number of electrons in the avalanche $N_s < 10^6$, the avalanches transit to the streamer.
- Due to field amplification in the heads of the avalanche and the streamer, they emit runaway electrons (REs).

Conclusion

- Streamer develops in the form of an avalanche chain and emits UV-photons, which produce new electrons, avalanches and streamers due to photoeffect. The process of RE accumulation occurs.
- When the RE concentration $\geq 10^6$ cm^{-3}, the discharge similar to MEI-discharge begins.
- Therefore the initial spark current time θ in both discharges is the same. This period can be considered as a glow discharge.
- This leads to the redistribution of the electric field in the gap, the field amplification at the cathode, the FEE current increase at the cathode's microprotrusions.
- The explosive electron emission starts, which leads to the cathode spot formation in the NDC-discharge.

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Thanks for your attention!