

METHODOLOGICAL NOTES

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Nanosecond volume discharge in air initiated by a picosecond runaway electron beam

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Contents

Abstract. **A voltage pulse with an amplitude of 250 kV and duration of 1ns was used to study discharge in atmospheric air. The discharge commences with the emergence of a field emission current from a cathode field enhancer. Next, a beam of runaway electrons with an amplitude of 0.5 – 1 A and duration of 10^{-11} s appears. Interaction between the beam and the voltage pulse was investigated using the reflectometry method. The discharge event was identified by the reversal of the reflected pulse polarity. If the emergence of the runaway electron beam is delayed by a time interval Δt_1, polarity inversion is delayed by the time $\Delta t_2 = \Delta t_1 = 200$ ps. This is due to the small discharge formation time, 33 ps, as a result of the large number (about 10^8) of runaway electrons that initiate the discharge. The time interval between the beginning of the discharge and the voltage inversion is no longer than 100 ps. This process is theoretically estimated based on the concept of multielectron initiation of discharge. It is shown that what is observed in the experiment is the nanosecond multielectron-initiation discharge produced by runaway electrons of the discharge itself.**

Keywords: voltage pulse, field emission, field enhancer, runaway electron, reflectogram, multi-electron initiation, discharge

1. Introduction

The investigation of nanosecond electric discharges in atmospheric air was initially aimed at verifying the applicability of the streamer theory under conditions of a double overvoltage across the gap [1]. The overvoltage is defined as $\Delta = E/E_s$, where E is the discharge initiation electric field strength and E_s is the static breakdown field strength defined by the Paschen law. Practical interest in these discharges was related to the development of techniques for generating high-voltage nanosecond pulses [2, 3] required for investigations in the areas of dielectric physics, plasma physics, laser physics, nuclear physics, microwave (MW) electronics, and gas discharge physics.

This research led to the discovery of several new physical effects that were not observed in the microsecond range. For instance, in the nanosecond range, the discharge formation time can be shorter than the time of the avalanche growth to the critical size and the deexcitation time of gas atoms and molecules. In this case, the streamer discharge mechanism does not exist in its classical form, and the current of initiating electrons starts playing an important role in the discharge. There comes a time when the total current of these electron avalanches becomes higher than in the streamer formation. The initiating electrons are usually produced by the ultraviolet irradiation of the cathode and the gap [1, 4–6]. The discharge is then said to occur under multielectron initiation. The overwhelming majority of nano- and subnanosecond gas-discharge investigations were carried out in precisely these conditions [1, 4–6]. Disregard for these factors led Fletcher [1] to the wrong conclusion that the streamer discharge theory in atmospheric air for millimeter-wide gaps is valid for the reduced electric field E/p (p is the gas pressure) as high as 160 V (cm Torr)$^{-1}$. In the experiments in Ref. [1], the number of initial electrons in the cathode region was 10^4 and the discharge followed the multielectron initiation scenario, first proved in Ref. [5].

This scenario is realized even when the entire gas in the cathode–anode gap is preliminarily ionized. This process is similar to a microwave discharge during its first half-wave [4]. Efficient discharge initiation also occurs under X-ray gap irradiation or direct electron-beam injection into the gas [6, 7]. We emphasize that multielectron initiation gives rise to a volume nature of the discharge [6], which is sometimes called diffuse. The discovery of such discharges came to be the most

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significant achievement of investigations involving high-voltage nanosecond technology [5–7]. For instance, the development of gas lasers reliant on such discharges became a major breakthrough in laser engineering.

For a high overvoltage across the gap, which is the case in the nanosecond range, there is the effect of electron avalanche self-braking, when the electron number growth rate decreases after reaching a certain value. Furthermore, with an increase in the electric field strength in the gap, the field emission from microspikes on the cathode surface begins to exert a significant effect on the discharge development. When the average field strength in the gap reaches 10^6 V cm^{-1}, the field strength at the tips of the microspikes ranges up to 10^8 V cm^{-1}. The time taken by the electric explosion of these spikes, for instance, on a tungsten cathode, is $< 10^{-9}$ s, after which explosive electron emission occurs [3].

One of the most interesting effects discovered in nanosecond discharges is that of runaway electrons (REs) [8]. The electrons of a gas-discharge plasma acquire the energy of directional motion from the electric field and expend it primarily to ionize and excite neutral particles. For high E/p values, the energy acquired by the electrons per unit length can exceed the energy spent in inelastic collisions, and therefore the electrons enter the mode of continuous acceleration [9]. The study of this effect has been the subject of many papers [5, 6, 10–13]. However, discharge investigations in only the nanosecond range have limitations because it is impossible to attain considerably higher overvoltages. The advent of high-voltage picosecond pulse technology [14] enabled studying new RE beam properties because it has become possible to obtain a nearly ten-fold overvoltage in this case [14–19]. However, the properties of the discharge that gives rise to REs remain unexplored. We therefore endeavor to somehow elucidate this issue with the use of the reflectogram technique [17, 18].

2. Experimental technique

The experiments were carried out using voltage pulses with an amplitude of 250 keV and a half-height duration of 1 ns, which were delivered in a traveling wave mode to a gas-discharge diode via a coaxial line with the wave resistance $Z = 60$ Ohm (Fig. 1a). The gap was formed by an open edge of the central electrode and the closed end of the outer conductor of the coaxial line. Prior to the onset of discharge, the gap voltage was doubled to 500 keV, because the generator was idle. The diode configuration is schematized in Fig. 1b. The gap width is $d = 2$ cm. Built into the cathode is a field enhancer, which is a steel cylinder with rounded edges of the height $h = 1$ mm and radius $R_a = 0.2$ mm. The field enhancement that gives rise to REs occurs in the enhancer zone at a distance of several millimeters from the cathode surface [16]. In the remaining part of the gap, the field is determined by the macroscopic part of the cathode and is equal to 250 kV cm^{-1}. Placed behind the anode foil of the discharge gap is a collector sensor D_e with a picosecond time resolution, which records the runaway electron current. Information about the breakdown mode is obtained by analyzing signals from a voltage sensor D_V (Fig. 1a). The first signal is the voltage signal $V_{in}(t)$ from the pulsed generator and the second is a reflectogram $V_{ref}(t)$, i.e., a pulse reflected from the diode. This pulse is recorded with a 4 ns delay, equal to the double time of wave travel through the transmission line.

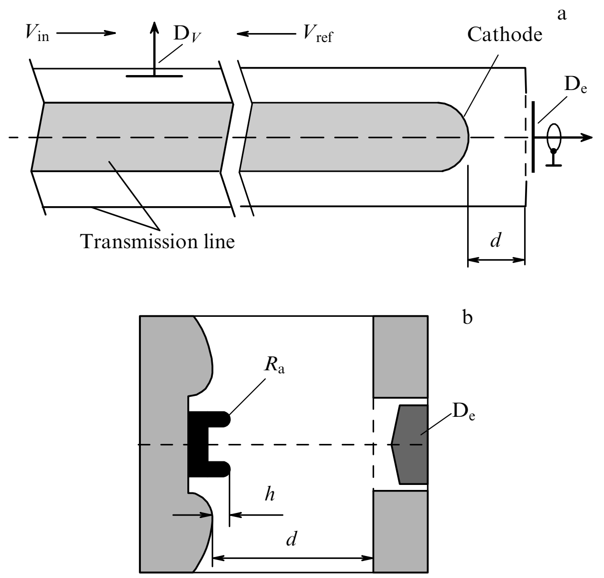

Figure 1. (a) Schematic diagram of the experiment and (b) structure of the discharge gap with a cathode enhancer of the electric field.

Figure 2 shows oscilloscope traces of the voltage pulses from a pulsed generator and of the RE current. We can see that the runaway electron current initiates the diode discharge. It has been shown that lowering the incident pulse voltage amplitude has the effect that the RE beam is not produced at all beginning with some voltage. When the pulse amplitude is increased such that the RE current appears near the peak of the pulse, a discharge develops, according to the reflectogram in Fig. 2a. This is indicated by the inversion of the reflex polarity during a time period comparable to τ_1 in duration. It is significant that the inverted reflex amplitude turns out to be no less (in modulus) than the near-front part of the incident pulse, which was reflected in the idle mode prior to the breakdown, i.e., was doubled. This is made clear by the short unipolar reflection of duration τ_2.

From the oscilloscope traces plotted in Fig. 2, the discharge event is easiest to detect when the polarity of the trailing edge of the reflected voltage pulse changes sign. When the RE beam formation is delayed by a time Δt_1 (Fig. 2b), the reflex polarity inversion is also delayed by a time Δt_2. In dedicated measurements, it was shown that Δt_1 and Δt_2, which are equal to about 200 ps, coincide to within 10 ps or better. However, we can see that the shift of the instant the RE beam appears toward the instant τ_3 of voltage pulse termination leads to a decrease in the inverted reflex amplitude. Consequently, when the breakdown begins near the trailing edge of the incident pulse, it turns out to be incomplete.

We explain how the discharge voltage and current can be determined from the oscilloscope traces in Figs 2a and 2b. The beginning of discharge current buildup is the point in the reflectogram where the voltage starts to decrease. At the moment the voltage changes sign, the current flowing through the gap exceeds 4 kA. At this point, the discharge gap resistance D is equal to the wave resistance of the coaxial transmission line. The reflectometry data confirm that the discharge in the atmospheric gas gap is initiated by the RE flux and not by the advance gas irradiation by photons from the cathode avalanche region [12].

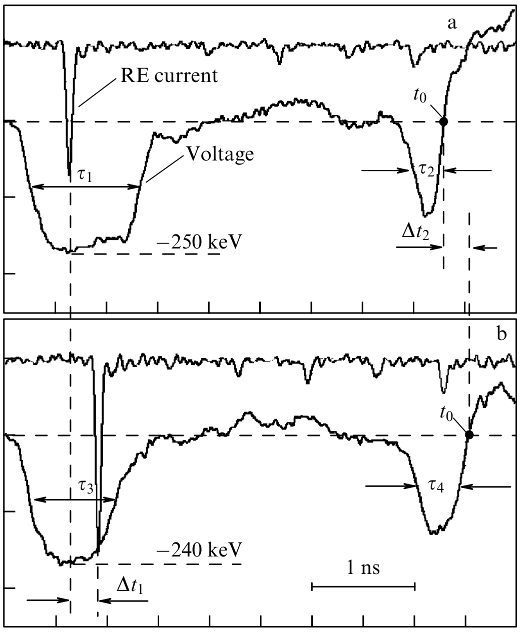

Figure 2. Reflectometry of a voltage pulse delivered to the cathode of the discharge gap and signals from the sensor of runaway electrons emitted at different time instants relative to the voltage pulse.

3. Calculation of discharge parameters

It is well known that a nanosecond gas discharge can be initiated by an electron beam from an external source [7]. In our case, the discharge-initiating electrons make up the RE beam produced in the cathode region of the gap under study. This beam passes through the gas and ionizes it. To estimate the plasma density under this ionization, we have to know the bulk rate ψ [cm^{-3} s^{-1}] of electron–ion pair production in the gap. Rigorous calculations of this quantity invite the use of the Monte Carlo method [20]. For our estimates, it would suffice to consider the simplest situation where an electron beam of the initial energy T_0 enters the gas layer from the cathode side in the x-axis direction through an infinite plane with the coordinate $x = 0$.

In the general case, the lost energy distribution over the gap depth is described by a curve $D(x)$ that depends on the electron deceleration and scattering. Because the energy loss per unit length is proportional to the material density ρ, the quantity $D(x)$ measured in [eV cm^2 g^{-1}] is commonly used. Then the gas ionization rate and the fast-electron current density at the gas input are related by the formula

$$\psi = \frac{j_e D(x)\,\rho}{e\bar{\varepsilon}}\,, \tag{1}$$

where $\bar{\varepsilon}$ is the average electron–ion pair production energy in electronvolts, e is the electron charge, j_e is the RE beam current density, and ρ is the specific weight of the air. To estimate the electron free path in the gas, it is necessary to determine the electron mean path R_0, while to determine $D(x)$, we have to find the electron energy loss B_0 per unit length at the beginning of its motion, i.e., for $x = 0$.

With the electron beam energy spectrum ranging from the suprathermal particle energy to 500 keV, we can assume that the average electron beam energy is $T_0 = 250$ keV. In this case, for air at atmospheric pressure, $B_0 = 2.2 \times 10^6$ eV cm^2 g^{-1} and $R_0 = 71.9\times\ 10^{-3}$ g cm^{-2} [6] (B_0 and R_0 are quantities reduced to the specific gas weight). At atmospheric pressure of the air, $\rho = 1.5 \times 10^{-3}$ g cm^{-3}. For the RE energy we assume, the electron path is $R = R_0/\rho = 47.3$ cm, i.e., $R \gg d$. The extrapolated electron path is also much longer than the gap width d [6]. Consequently, we can assume that $D(x) = B_0 =$ const. The average electron–ion pair production energy is $\bar{\varepsilon} = 35$ eV and the approximate current density in our experiment is $j_e = 0.5$ A cm^{-2}; therefore, $\psi = 2.9\times\ 10^{20}$ cm^{-3} s^{-1}.

We are dealing with a discharge similar to the one with external electron beam ionization proposed in Ref. [7], which is used for pumping gas lasers and triggering high-voltage gas switches [3, 22, 23]. When $R \gg d$, the discharge occurs in a volume [22]. Like a glow discharge, this discharge is characterized by the existence of a cathode region of length l_c and voltage U_c such that $l_c \ll d$ and $U_c \ll U_0$, where U_0 is the voltage pulse amplitude and d is the gap width. Therefore, the main part of the gap is occupied by quasineutral plasma, which is called a positive column by analogy with the glow discharge.

The electron mobility is much higher than the ion mobility, and therefore the discharge current satisfies the relation

$$i = envs\,, \tag{2}$$

where v is the electron drift velocity, n is the plasma electron density, and s is the cross-sectional area of the discharge column. The quantity n is found from the equation

$$\frac{dn}{dt} = \alpha v n + \psi + q\,, \tag{3}$$

where α is the collisional ionization coefficient and q is the thermalized electron production rate per unit gas volume. Because we are dealing with a process of short duration, we ignore the ion drift as well as the electron diffusion and recombination. Furthermore, we ignore the thermalization of electrons, although we are aware of its important role in increasing the field in discharge plasma and, possibly, in the emergence of a second RE beam.

To classify gas discharges with the participation of electron beams, it is common practice to compare the voltage pulse duration t_p and the injected electron beam duration t_e. There are three types of such discharges [6]. For discharges of the first type, $t_e \ll t_p$ and $\Delta \ll 1$, i.e., there is a strong undervoltage. In this case, the discharge current terminates on breaking the electron current. For discharges of the second type, $t_e \approx t_p$ and $\Delta < 1$. These are non-self-sustained high-pressure glow discharges maintained by electron beams. For discharges of the third type, with $\Delta > 1$, the discharge is initiated by the electron beam and becomes self-sustained.

In our case, we are dealing with a type-three discharge, because the RE beam duration amounts to several dozen picoseconds and the voltage pulse duration in our experiment is $t_p = 10^{-9}$ s. In this case, the overvoltage across the gap is $\Delta = 8$. Because $t_e \ll t_p$, it can be assumed that all RE beam electrons are delivered to the gap simultaneously. The total number of electrons in the beam is $N_e = i_e t_e/e$. In our experiment, N_e is of the order 10^8. The cross-sectional areas of the discharge and RE beam are taken to be equal, $S \approx 1$ cm^2.

The discharge begins with plasma production due to the ionization of gas by the RE beam. The density of this initial plasma is

$$n_0 = \psi t_e \,. \tag{4}$$

Next, the plasma density increases exponentially due to collisional gas ionization by electrons:

$$n = n_0 \exp \int_0^t \alpha v \, dt \,. \tag{5}$$

We substitute expression (5) in formula (2) to obtain the relation among the discharge current i, the electric field E, and the time t,

$$i = i_0 \exp \int_0^t \alpha v \, dt \,, \tag{6}$$

where

$$i_0 = \frac{e B_0 \rho v N_e}{\bar{\varepsilon}} \,. \tag{7}$$

In the calculation of the discharge current $i(t)$, we bear in mind that the field E also depends on the existence of the wave resistance Z of the coaxial line in the discharge circuit. This is taken into account by the Kirchhoff equation for the discharge circuit, which defines a relation between the current i and the voltage U across the gap,

$$i = \frac{U_0 - U}{Z} \,, \tag{8}$$

where U_0 is the amplitude of the voltage pulse. The electron drift velocity v and the collisional ionization coefficient α in the air in the range $E/p = 100-800$ V (cm Torr)$^{-1}$ are determined from the relations [21]

$$v = C \left(\frac{E}{p} \right)^{1/2} , \tag{9}$$

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

where $A = 15$, $B = 365$, and $C = 3.3 \times 10^6$. Solving Eqns (6) and (8) with relations (9) and (10), we can calculate the voltage, the current, and the time of discharge formation.

To determine the discharge current i and the gap voltage U, we use the theory of a pulsed gas discharge with multi-electron initiation [3, 5]. For this, we equate the current from formulas (6) and (8), find the logarithm of the left- and right-hand sides, and then differentiate them. In view of formulas (9) and (10) for α and v, we obtain an equation for the voltage across the discharge gap,

$$\frac{dx}{dt} = -\frac{a(1-x)\,x^{3/2}}{1+x} \exp \left(-\frac{b}{x} \right) , \tag{11}$$

$$a = 2ApC \left(\frac{U_0}{pd} \right)^{1/2} , \quad b = \frac{B}{U_0/pd} , \tag{12}$$

where $x = U/U_0$. It follows from formula (8) that the current i and voltage U are related by the formula $x = 1 - y$, where $y = iZ/U_0$. Therefore, from formula (11), we obtain the equation for the current i:

$$\frac{dy}{dt} = \frac{ay(1-y)^{3/2}}{2-y} \exp \left(\frac{b}{1-y} \right) . \tag{13}$$

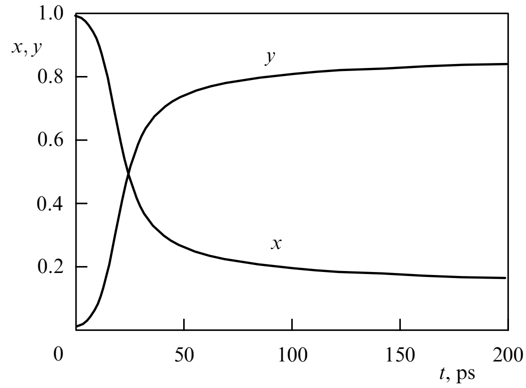

Figure 3. Theoretical time dependences of the relative voltage $x = U/U_0$ and current $y = iZ/U_0$ magnitudes.

For the gap under investigation, $a = 1.37 \times 10^{12}$ and $b = 1.11$. The time dependences of the voltage $x(t)$ and the current $y(t)$ are plotted in Fig. 3.

4. Discussion of the results

The onset of a nanosecond discharge is taken as the instant at which the discharge current reaches some value $i_1 = \kappa U_0/Z$, where $\kappa \ll 1$. When the pulse front is perfectly steep, the time interval between the arrival of a voltage pulse and the instant the current reaches the value i_1 is taken as the discharge formation time. In the classical case of nano- and subnano-second electric discharges, preionization occurs prior to the arrival of the voltage pulse at the gap. This imposes a limitation on the measurement of the discharge formation time due to the finiteness of the pulse front duration. Because the existing measurements were made for a pulse front duration $\geqslant 3 \times 10^{-10}$ s in atmospheric air, the shortest measured discharge formation time was equal to 5×10^{-10} s [1, 5]. In our experiment (Fig. 2a), this problem can be avoided because the RE beam has a duration of the order of 10^{-11} s and arrives at the gap at the instant the voltage has its amplitude value. This permits measuring significantly shorter times than the previously measured ones.

We estimate the discharge formation time τ using formulas (6) and (7). The time interval between the RE beam appearance and the moment the discharge current becomes $i = i_1$ is taken as the discharge formation time. For an estimate, we consider the oscilloscope trace in Fig. 2a. Because the peak of the pulse is almost flat, it is safe to assume that the electric field is constant in time, $E \approx E_0$. Consequently, the quantities α and v can also be thought of as being constant for $E/p = 330$ V (cm Torr)$^{-1}$. From formula (6), it follows that the discharge formation time is

$$\tau = (\alpha v)^{-1} \ln \frac{i_1}{i_0} \,. \tag{14}$$

Because the current pulse amplitude in the reflectograms is equal to 8.34 kA, for $\kappa = 0.01$ we have the current $i_1 = 83.4$ A. We use formulas (9) and (10) to determine α and v and, for the B_0 and N_e values indicated above, conclude that the discharge formation time in atmospheric air is $\tau = 33$ ps under our experimental conditions. It is less than half that in the case of an ordinary subnanosecond air discharge with multielectron initiation [4, 6]. Interestingly, this shortening of the time τ required an increase in the number of initiating electrons from 10^4 [1, 5] in an ordinary experiment to 10^8 under conditions with runaway electrons. Therefore, when the overvoltage is eight-fold, the discharge formation time becomes so short that the time Δt_1 between the appearance of RE beams in two discharges is exactly equal to the time Δt_2 between two fixed discharge current points in the reflectogram.

As is clear from Fig. 3, according to the theory of multielectron initiation, the current in the gap shows two sections: one with a sharp increase in the current and the other with a slow one. In accordance with formula (8), there also are two sections in the time dependence of the voltage: one fast and the other slow. The transition from one to the other occurs approximately at the instant $t = 100$ ps and the voltage $U \approx 0.2U_0$.

Fast and slow voltage decays are also observed in the reflectogram (Fig. 2a) at about the same voltage level. The slow decay is caused by the decrease in α and v due to the field lowering in the gap, which takes place because of the increase in the voltage drop across the resistor Z with an increase in the discharge current. One of the characteristics of the phase of rapid voltage decay is the instant t_0 at which the voltage reflectogram changes polarity. This occurs at $x = 0.5$. We can see from Fig. 3 that the time $t_0 = 25$ ps. To estimate the total time from the beginning of discharge initiation, the discharge formation time τ should be added to t_0. We then obtain the time interval from the onset of the discharge to the onset of voltage inversion equal to 58 ps. According to the experiment (Fig. 2a), this time is no shorter than 100 ps. This difference is attributable to the existence of intrinsic capacitance of the discharge gap, which is $\sim 10^{-12}$ F, as well as to the transient characteristic of the oscilloscope, which is up to 26 ps in duration. The instant t_0 is in the domain of fastest current increase, and therefore the parameters of the transient response of the circuit have the greatest effect on the time characteristics of reflectograms.

Therefore, in our experiment, we are dealing with a nanosecond multielectron discharge in the air, which is initiated by runaway electrons produced by the discharge itself.

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References

1. Fletcher R C *Phys. Rev.* **76** 1501 (1949)
2. Vorob'ev G A, Mesyats G A *Tekhnika Formirovaniya Vysoko-vol'tnykh Nanosekundnykh Impul'sov* (Techniques of High-Voltage Nanosecond Pulse Formation) (Moscow: Atomizdat, 1963)
3. Mesyats G A *Pulsed Power* (New York: Kluwer Acad. Plenum Publ., 2004)
4. Felsenthal P, Proud J M *Phys. Rev.* **139** A1796 (1965)
5. Mesyats G A, Bychkov Yu I, Iskol'dskii A M *Sov. Phys. Tech. Phys.* **13** 1051 (1969); *Zh. Tekh. Fiz.* **38** 1281 (1968)
6. Korolev Yu D, Mesyats G A *Physics of Pulsed Breakdown in Gases* (Yekaterinburg: URO-Press, 1998)
7. Koval'chuk B M, Kremnev V V, Mesyats G A *Sov. Phys. Dokl.* **15** 267 (1970); *Dokl. Akad. Nauk SSSR* **191** 76 (1970)
8. Stankevich Yu L, Kalinin V G *Sov. Phys. Dokl.* **12** 1042 (1968); *Dokl. Akad. Nauk SSSR* **177** 72 (1967)
9. Gurevich A V *Sov. Phys. JETP* **12** 904 (1961); *Zh. Eksp. Teor. Fiz.* **39** 1296 (1960)
10. Babich L P, Loiko T V, Tsukerman V A *Sov. Phys. Usp.* **33** 521 (1990); *Usp. Fiz. Nauk* **160** (7) 49 (1990)
11. Babich L P *High-Energy Phenomena in Electric Discharges in Dense Gases: Theory, Experiment and Natural Phenomena* (Arlington Va.: Futurepast, 2003)
12. Tarasenko V F (Ed.) *Generation of Runaway Electron Beams and X-Rays in High Pressure Gases* (New York: Nova Science Publ., 2016)
13. Levko D, Yatom S, Krasik Ya E *J. Appl. Phys.* **123** 083303 (2018)
14. Mesyats G A, Yalandin M I *Phys. Usp.* **48** 211 (2005); *Usp. Fiz. Nauk* **175** 225 (2005)
15. Yalandin M I et al. *Tech. Phys. Lett.* **37** 371 (2011); *Pis'ma Zh. Tekh. Fiz.* **37** (8) 56 (2011)
16. Mesyats G A et al. *Plasma Phys. Rep.* **38** 29 (2012); *Fiz. Plazmy* **38** 34 (2012)
17. Gurevich A V et al. *Phys. Rev. Lett.* **109** 085002 (2012)
18. Gurevich A V et al. *Phys. Lett. A* **375** 2845 (2011)
19. Tarasenko V F et al. *Plasma Phys. Rep.* **42** 369 (2016); *Fiz. Plazmy* **42** 376 (2016)
20. Belomyttsev S Ya et al. *J. Appl. Phys.* **123** 043309 (2018)
21. Yalandin M I et al. *IEEE Trans. Dielectr. Electr. Insulator* **17** 34 (2010)
22. Bychkov Yu I, Korolev Yu D, Mesyats G A *Sov. Phys. Usp.* **21** 944 (1978); *Usp. Fiz. Nauk* **126** 451 (1978)
23. Mesyats G A, Osipov V V, Tarasenko V F *Pulsed Gas Lasers* (Bellingham, Wash.: SPIE Optical Engineering Press, 1995)
24. Granovskii V L *Elektricheskii Tok v Gaze* (Electric Current in Gases) (Moscow: Nauka, 1971)