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Nanosecond discharge in atmospheric air in submillimeter gaps in a uniform electric field

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Abstract. A nanosecond electric discharge in air in submillimeter gaps at the overvoltages up to 15-fold is under investigation. The initial electric field in such discharges is up to 10^6 V/cm. This field is sufficient for the electrons that initiate the discharge, as well as those obtained during the discharge, to go into the runaway mode. These electrons are called runaway electrons (RE). REs create plasma in the period 10^{-9} s. When the plasma density is reached of 10^4 cm^{-3}, a glow discharge (GD) is initiated. The process of transition of the discharge to the GD mode lasts 10^{-11} s. During this time, about $5 \cdot 10^{10}$ pieces of runaway electrons are formed, which, falling on the anode, lead to the formation of an X-ray beam. This beam is due to a rapid increase in the plasma density during the discharge. In the GD stage, the electric field between the cathode and the anode is divided into two parts: the cathode layer (CL) and the plasma column. The electric field in the CL exceeds 10^6 V/cm. At such a field, field emission (FE) from microprotrusions on the cathode surface takes place on the cathode. It leads to the explosive emission of electrons and the formation of a cathode spot and the transition of the discharge to the arc mode.

Keywords: electron avalanche, runaway electrons, nanosecond discharge, glow discharge, field emission, explosive electron emission

1. Introduction

Two types of discharges are widely known in air and other gases: Townsend and streamer [1, 2]. In both cases, the beginning of the process is due to the formation of electron avalanches, which are initiated by electrons located in the space between the cathode and anode. The Townsend discharge occurs at a static voltage or close to it when the gap is successively filled with plasma of many successive electron avalanches. The streamer discharge occurs at a voltage exceeding the static breakdown voltage. One electron avalanche passing into a streamer is enough for this. In atmospheric air, this excess is 20% or more [3]. These discharges are visually different. In the first of them, a diffuse glow is observed in the gap during the formation of the discharge, and in the second, one can see a brightly glowing plasma channel.

2. Nanosecond Diffuse-Channel Discharge

In addition, at a high overvoltage in the nanosecond range, there is a discharge partially combining the properties of both discharges. We call it a nanosecond diffuse-channel discharge (NDC). For the first time, it was mentioned in [4, 5] when discussing the contradictions in the interpretation of the dependence of the discharge formation time in the nanosecond range in millimeter gaps on the electric field, obtained by Fletcher [6]. He assumed that this discharge was a streamer discharge, which was allegedly initiated by single electrons [3]. However, as shown in [4, 5], the actual number of electrons initiating the discharge was about 10^4. Each of these electrons created its own electron avalanche, and their total current was interpreted in [6] as the streamer current. However, when the discharge did occur upon initiation by single electrons [4, 5], it turned out that the discharge formation time was orders of magnitude longer than that which should be in the case of a streamer breakdown [1, 2]. We proposed to compare these three discharges with each other by the ratio of the gap length d to the length of the critical avalanche x_k, which means an avalanche with an ion space charge field comparable to the external field [7, 8]. If $x_k >> d$, then the discharge will be Townsend; if $x_k \geq d$ – the streamer one, and if $x_k << d$, then the NDC discharge will occur. Recall that $x_k = \ln(N_k/\alpha)$, where N_k is the critical number of electrons in an avalanche, and α is the impact ionization coefficient.

Discharges with $\mu = d/x_k$ is about 10 are considered in [8]. In such discharges, avalanches initiated by external electrons reach a critical size near the cathode surface. The length of this avalanche is much greater than its width, i.e., the radius of the head. As a result, the electric field on this head of the avalanche can be amplified many times over. This leads to the runaway of electrons. Each runaway electron will create a new avalanche of electrons. That is, a streamer-like plasma formation will be created, which is called an avalanche chain (AC) [9]. These ACs fill the gap with plasma, creating a discharge similar to the glow discharge. We are interested to follow what will happen to such a discharge if the value of μ increases significantly. In atmospheric air, this takes place at an electric field of the order of 10^6 V/cm. Such a field is characteristic of a vacuum discharge.

3. Radiation from NDC-discharge

Let us briefly consider some results of earlier work with such high fields. In [10], the discharge formation time τ in atmospheric air was measured in a uniform electric field between flat copper electrodes 5 mm in diameter. The statistical method of research was used. Rectangular voltage pulses had an amplitude of up to 20 kV, a duration of 20 ns, and a rise time of 0.3 ns. The time τ was measured from the moment the voltage appeared across the gap until the spark current began to rise. To reduce the effect of field emission (FE) from the cathode surface, the electrodes were cleaned, polished to grade 13, washed with acetone, and dried. The first 50 discharges were not considered in the studies to eliminate random irregularities on the surface of the electrodes. One took 100 oscillograms for each voltage amplitude, and two types of statistical distributions based on them were constructed: $\bar{m} = \Delta m / m_0$ and $|\ln(m_t/m_0)| = f(t)$, where m_t is the number of discharges with a formation time of t or more, m_0 is the total number of discharges. Fig.1 shows two distributions with a gap length $d = 0.1$ mm and an electric field $E_0 = 1.4 \cdot 10^6$ V/cm. Fig.1, a reveals distribution after 100 discharges, and Fig.1b after 600. As we can see, these dependences are almost the same. This means that the state of the cathode surface remains virtually unmodified during the experiments. The FE current from the surface of cathode micropoints (CMPs) was $i_e = 5 \cdot 10^9$ e/s [10].

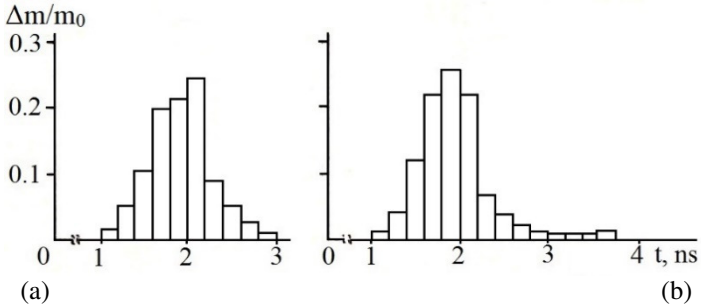

Fig.1. Histograms of breakdown time delay distributions in air at $d = 0.01$ cm, $E = 1.4 \cdot 10^6$ V/cm. (a) – 100 breakdowns, (b) – 600 breakdowns).

Distribution curves $|\ln(m_t/m_0)| = f(t)$ in all experiments were qualitatively the same (Fig.2). For a long time τ they go in a straight line, and for a short time they have a bend. All distributions have the shortest time τ_M; at constant values of the electric field E, gas pressure p, and gap length d, it does not change. At the largest field used, $1.4 \cdot 10^6$ V/cm, the time τ_M was close to a nanosecond (Fig.1). Therefore, the number of electrons initiating the discharge was $\tau_M \cdot i_e \approx 5$ pieces, i.e., the discharge was initiated by single electrons. During rough treatment of the cathode surface, when the scratch depth exceeded 0.5 μm, as well as when the cathode surface was illuminated with ultraviolet from a closely spaced spark, the time τ_M sharply decreased to 10^{-10} s, i.e., the discharge occurs at the front of the voltage pulse. This meant that in both cases a multielectron discharge initiation takes place [11]. In the presence of scratches, initiating electrons appear due to field electron emission from microprotrusions at the scratch boundary, and when the cathode is illuminated, due to photoemission

of electrons from the cathode surface. Careful inspection of the cathode surface after exposure to single pulses showed the presence of craters from cathode spots. Their number varied and could reach 10 pieces per discharge. This suggests that the final phase of the discharge is an electric arc with many spark channels.

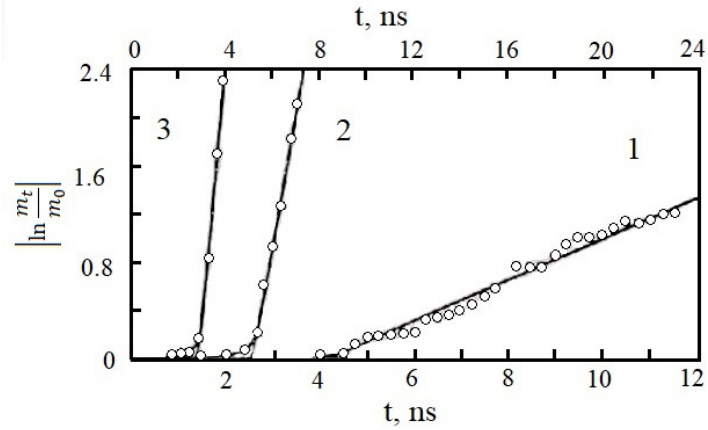

Fig.2. Distribution $\left|\ln(m_t/m_0)\right| = f(t)$ of the field E at $m_0 = 100$, $d = 0.3$ mm for copper electrodes. 1 – $E = 3.3 \cdot 10^5$ V/cm (top X-axis); 2 – $E = 4.7 \cdot 10^5$ V/cm; 3 – $E = 6 \cdot 10^5$ V/cm.

A nanosecond discharge in air in a uniform field under normal conditions was studied in [12] using spectroscopic equipment. There was no special treatment of the cathode; therefore, the discharge was multielectron. An arrester with iron electrodes and a gap of 0.23 mm was used. Voltage pulses of $7 \cdot 10^3$ V with a duration of 2.5 and 10 ns were applied to it. The study of the glow in the gap showed that already during the first two nanoseconds the discharge was of a diffuse nature. At the beginning, a continuum and several nitrogen lines are excited. The most intense of them are with the energy of the lower level 18.5–20.5 eV. The authors of [12] also observed lines of the FeI cathode material. These lines were recorded already during the first 2 ns of the discharge. The spectral lines of the cathode material (W) were also observed in [13] in a nanosecond discharge in hydrogen and nitrogen. The speed of movement of atoms and ions of tungsten was $2 \cdot 10^6$ cm/s, which corresponds to the speed of expansion of the cathode plasma during explosive electron emission (EEE) [9].

4. Runaway electrons in NDC-discharge

The authors of [14] discovered X-ray emission during a nanosecond discharge in atmospheric air. A voltage pulse with a duration of 23 ns was used. This pulse was applied to a gap 0.4 mm long, because of which, at a pulse amplitude of 46 kV, bremsstrahlung was recorded, which was sufficient to illuminate a 2-mm-thick aluminum plate with attenuation by several times. The electric field at which this effect was observed was 10^6 V/cm. The electrons that are responsible for this radiation are called runaway electrons (REs). In [15], the parameters of such X-ray radiation were measured by the foil method. It was shown that during a discharge in air at a pressure of 80 Torr, a gap length of 4 mm, and a voltage between the electrodes of 40 kV, the maximum energy of X-ray quanta was 16 keV. If we assume that the radiation is caused by electrons with such an energy, then the number of REs per pulse in a discharge in atmospheric air will be equal to $5 \cdot 10^{10}$ pieces [11]. A common feature of the discharges with runaway electrons described above is that the reduced electric field E/p (E is the electric field, p is the gas pressure) in them was higher than that required for electron runaway. This is because at large values of E/p, the energy acquired by electrons per unit path exceeds the energy given up in inelastic collisions. Therefore, such electrons will go into the regime of continuous acceleration. Their energy can be equal to or exceed the potential difference between the cathode and anode [16].

To determine the magnitude of the electric field E_m, at which this phenomenon occurs, the authors of [11] used the theory of runaway electrons in low-temperature plasma developed in [18]. For a nonrelativistic electron, the force of its deceleration in a gas is determined by the expression

$$F(W) = \frac{2\pi e^4 n_0 Z}{W} \ln \frac{2W}{I}, \quad (1)$$

where n_0 is the density of gas molecules, e is the electron charge, Z is the number of electrons in a molecule, $W = mv^2/2$ is the electron energy in plasma, I is the average energy of inelastic losses. The energy balance of an electron moving in a gas at $W > I/2$ can be written as

$$\frac{dW}{dt} = eE - F(W), \quad (2)$$

The function $F(W)$ has a maximum at $W_m = \bar{e}I/2$, where $\bar{e}$ is the base of the natural logarithm. Therefore, if the electric field exceeds the value $E_m = F_m/e$, then the field E_m is determined from the expression

$$E_m = \frac{4\pi e^3 n_0 Z}{\bar{e}I}, \quad (3)$$

Substituting the corresponding numerical constants into this formula, we obtain the condition under which electrons in a gas discharge turn into runaway electrons

$$\frac{E_m}{p} = \frac{3.88 \cdot 10^3 Z}{I}, \quad (4)$$

for example, for nitrogen $Z = 14$, $I_m = 130$ eV, so $E_m/p = 365$ V/(cm·Torr). At atmospheric pressure $E_m = 2.8\ 10^5$ V/cm.

5. Explosive electron emission in NDC-discharge

Therefore, for runaway electrons to appear, it is necessary to have an electric field equal to E_m or more in the gap. For this, cathodes with an electric field amplification are used so that the working part of the cathode has geometric dimensions much smaller than the length of the gap. Points, blades, cones, ends of hollow cylinders, etc. have such properties. In the experiments we have considered above, the electric field was uniform. However, any cathode surface, even a flat one, has cathode micropoints (CMPs), the electric field on which can be amplified up to 100 times or more [9]. Under these conditions, field emission (FE) from the CMP surface begins to play a fundamental role, which then passes into explosive electron emission (EEE). It is assumed that in nanosecond discharges with an inhomogeneous field on the cathode, runaway electrons are initiated by the FE current from the CMP and stop after the appearance of the EEE [20]. Therefore, runaway electrons appear in the form of short-term pulses. The duration of runaway electron pulses was first estimated at several nanoseconds [14]. After the creation of picosecond high-voltage pulse technology [19], it was possible to register runaway electron pulses with a duration of 10^{-11} s [20].

Let us make an approximate estimate of this effect. According to the Fowler and Nordheim formula, the field emission current, depending on the electric field, will be written as follows:

$$j = A_0 E^2 \exp(-\frac{B_0}{E}), \quad (5)$$

where $A_0 = 1.55 \cdot 10^{-6}/\varphi$, $B_0 = 6.85 \cdot 10^7\ \varphi^{3/2}$, φ is the electron work function of a metal. It follows from this formula that for a metal with $\varphi = 4.5$ eV at a field exceeding 10^8 V/cm, the FE current density

reaches 10^{10} A/cm^2. Under these conditions, an electric explosion of the CMP metal occurs. This explosion is accompanied by the appearance of explosive electron emission [21]. For CMPs having a cylindrical shape, the explosion delay time t_d is determined from the formula [21]

$$j^2 t_d = \overline{h}\,, \tag{6}$$

where $\overline{h}$ is the specific action for the electric explosion of a metal. For such metals as Fe, Mo, Cu, Ag, Al, Ni, W, etc., the parameter $\overline{h}$ is about 10^9 A^{2}s/cm^4. For tungsten $\overline{h} = 4\cdot 10^9$ A^{2}s/cm^4. Substituting (5) into (6), we obtain

$$t_d = \frac{\overline{h}\exp\left(-2B_0/E\right)}{A_0^2 E^4}\,, \tag{7}$$

It can be seen from formula (7) for tungsten (φ = 4.5 eV) that when the field at the CMP tip is $E = 1.5\cdot 10^8$ V/cm, the FE current density is $j = 10^{10}$ A/cm^2, and the time $t_d = 2.4\ 10^{-11}$ s.

6. Transition of Glow Discharge into Arc

Using the experimental data and estimates made above, we give a brief description of the physics of a discharge in a submillimeter gap, in which a uniform electric field is 10^6 V/cm at atmospheric air pressure. The nature of the discharge depends on the number of initiating electrons. With a large number of them (about 10^4 pieces [11]), the discharge takes on a diffuse (volume) character already at a time of $t << 10^{-9}$ s, i.e., such a discharge occurs with multielectron initiation. When the discharge is initiated by single electrons, the discharge formation time increases to 10^{-9} s, as in the experiment [10]. This is the time of plasma accumulation within the gap. This plasma is formed by the ionization of gas molecules by runaway electrons. When the electron density in this plasma reaches the critical value n_k, a glow discharge (GD) begins. For example, in a nanosecond discharge in atmospheric air with ultraviolet illumination of the gap, the value of n_k was 10^4 cm^{-3} [22]. The process of gas ionization upon transition to GD can be described by the formula [22]:

$$n = n_k \exp\left(\alpha v t\right), \tag{8}$$

where n is the plasma density during the development of a glow discharge. If we assume that GD occurs at plasma density $n = n_T$, then the transition time t_T to it will be estimated by the formula:

$$t_T = \frac{1}{\alpha v}\ln\frac{n_T}{n_k}\,, \tag{9}$$

In fact, this means that our discharge [10], which began with single-electron initiation, in the process of plasma accumulation in the gap passed into a stage that is similar to multielectron initiation.

Let us consider that in the experiment [10] the field $E > 10^6$ V/cm, therefore, for the coefficient of impact ionization in atmospheric air and nitrogen, one can use the Pozin formula [17]

$$\frac{\alpha}{p} = \left(B_1\frac{E}{p}\right)^{\frac{1}{2}} - B_2 \tag{10}$$

where $B_1 = 0.21$, $B_2 = 3.65$, and for the electron drift velocity [3]

$$v = B_3\left(\frac{E}{p}\right)^{\frac{1}{2}}, \tag{11}$$

where $B_3 = 3.3 \cdot 10^6$. If we neglect the second term in formula (10) and substitute formulas (10) and (11) into (9), we get

$$t_T = \frac{\ln n_T / n_k}{B_1 B_3 E}, \tag{12}$$

The logarithm in formula (12) according to experiments [3, 11] with a nanosecond discharge in atmospheric air can be taken equal to 10. Then from (12) it follows that the duration of the process of transition to a glow discharge will be $t_T = 1.4 \cdot 10^{-11}$ s. In order of magnitude, this time corresponds to the duration of the pulsed beam of runaway electrons measured in [20] in a nanosecond discharge.

To estimate the number of electrons that will be involved in this discharge, we use the formula accounting the parameters of the experiment [10]:

$$N_e = \frac{2U_0 t_T}{eR}, \tag{13}$$

where U_0 is the charging voltage, R is the wave impedance of the cable. Substituting $U_0 = 1.4 \cdot 10^3$ V, $R = 50$ Ohm and $t_T = 1.4 \cdot 10^{-11}$ s from formula (13), we get $N_e = 5 \cdot 10^{10}$ electrons. This number of electrons coincides with what was obtained in the experiment [11]. Note that the values of the reduced electric field E/p in the experiments [10] and [11] coincided and amounted to 10^3 V/(cm·Torr).

In the GD development process, the electric field will be redistributed in the gap. As a result, a discharge column and a cathode layer (CL) are formed. If this discharge were to become stationary, then the field in the cathode zone E_T can be estimated from the empirical formula [9], which is used for both normal and anomalous glow discharges. For nitrogen, this formula looks like this:

$$\frac{E_T}{p} = 1.1 \cdot 10^5 \left(\frac{j}{p^2}\right)^{0.6}, \tag{14}$$

where j is the glow discharge current density. This formula was obtained experimentally in the study of a large number of discharges in nitrogen. If we assume that the discharge occurs in the entire volume between the electrodes, then $j = 4i_0/\pi D^2$, where D is the diameter of the flat electrodes, and i_0 is the discharge current, p is the gas pressure. As can be seen, this formula obeys the scaling law in a gas discharge. If we substitute the data from [10] into formula (14) current $i_0 = 280$ A, $D = 0.5$ cm, $p = 760$ Torr, then the surface area of the cathode is $S = \pi D^2/4 = 0.2$ cm^2. It is difficult to accurately determine the current density j because it is not known what part of the cathode it occupies. If it occupies the entire surface, then $E_T = 10^6$ V/cm, and if only 10%, then $E_T = 3.4 \cdot 10^6$ V/cm. It is known that when the field at the cathode is $\geq 10^6$ V/cm, the glow discharge transforms into an arc, since due to the field amplification on the CMP, an explosive emission of electrons occurs, which leads to the formation of a cathode spot [9].

7. Conclusion

It should be noted that the NDC discharge in atmospheric air in strong fields at $E \sim 10^6$ V/cm differs little qualitatively from that at medium fields $E \sim 10^5$ V/cm if the discharge is initiated by single electrons. The discharge in both cases consists of the following stages: 1) initiation by external electrons, 2) gas ionization and plasma formation due to runaway electrons, as well as ordinary impact ionization, 3) plasma accumulation, 4) the appearance of a glow discharge, 5) the appearance of FE and EEE and the transition of GD to arc. The difference is only in the second point, when the gas is ionized. In strong fields, REs play the important role in the ionization process, since the external electric field exceeds the field required for the electrons to run away. Therefore, the first electron that appears, initiating the discharge, begins the ionization of the gas with the formation of new electrons. In average fields, runaway electrons appear due to field amplification at the heads of electron

avalanches [7]. Note that in the electric discharge in air we have considered, there are two types of runaway electrons. The first one is when runaway electrons participate in the process of discharge formation. The duration of this process in our case with one-electron initiation is ~10^{-9} s. The second type is runaway electrons in the final stage of the discharge. They appear as a beam with a duration of ~10^{-11} s. These runaway electrons create a short-term X-ray beam.

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