Investigation of Mechanisms of Pulsed Electrical Breakdown of Highly Overvolted Gas Gaps on Subnanosecond (< 1 ns) Scale

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Abstract – Experiments were made on a specially designed setup based on a RADAN303 pulsed power generator. The amplitude and the waveform of the subnanosecond pulsed high voltage applied to the gas gap and the glow accompanying the gas breakdown were recorded. The initial portion (~1 ns) of the streak photographs was of greatest interest. From these photographs it was possible to determine the region of the glow origination in the gas gap and velocities of the glow expansion across the gas gap.

1. Introduction

Investigations of mechanisms of initiation of the pulsed electrical breakdown of gas gaps on the subnanosecond scale present great interest for the physics of gas discharges. Recent pulse generators provide high voltage pulses with fronts up to 200 ps and voltages applied to the gas gap largely exceeding the static breakdown voltage. In these conditions field emission from the cathode surface and subsequent explosions of microscopic inhomogeneities on the cathode surface acquire great significance in the process of the breakdown initiation [1]. Moreover, if the electrostatic intensity to pressure ratios (E/p) are sufficiently high at the stage of the breakdown delay and the initial stage of commutation, some free electrons may switch to a regime when the energy acquired by them on a unit of way is higher than the energy loss in inelastic collisions. This regime is usually called the "regime of continuous acceleration of electrons" and electrons are referred to as "quick" or "running away" [1]. As "quick" electrons move, they strongly ionize the gas and, as a result, the breakdown initiation time may be greatly reduced as compared to the classical streamer discharge [2]. When these electrons are braked at the anode, X-radiation appears [3–6] and initiates new secondary electrons and new avalanches. All the aforementioned processes take a very short time, and, moreover, mutually cross in time. Therefore, the study of subnanosecond breakdown is not a simple task. It should be noted also that the "regime of continuous acceleration of electrons" has been so far analyzed theoretically in the main, because of difficulties encountered in experiments performed on the subnanosecond scale. Only a few papers, in which the very fact of existence of "running away" electrons was proved experimentally, have been published [3–6]. Experimental data concerning the effect of "running away" electrons on the gas breakdown initiation have been absent for today.

In this study an attempt was made to investigate the dynamics of initiation and development of the pulsed electrical breakdown of highly overvolted gas gaps on the subnanosecond (< 1 ns) scale.

2. Experiment

Experiments were made on a specially developed experimental setup based on a RADAN-303A small-sized pulse generator [7]. A pulse (Fig. 1) with FWHM of (0.5–3) ns, a controlled voltage of (70–150) kV, and a voltage rise rate of ($7\cdot10^{13}$–$6\cdot10^{14}$) V/s was applied from a high-voltage pulse generator to the test gas-discharge gap. The breakdown current value and the waveform were recorded. Simultaneously, using a high-speed electron-optical camera, the glow accompanying prebreakdown and breakdown processes in the gap was photographed. Obviously, electron-optical chronography [8] is the only method today, which allows locating the region in the gap where breakdown is initiated. The experimental setup was described comprehensively in [9, 10].

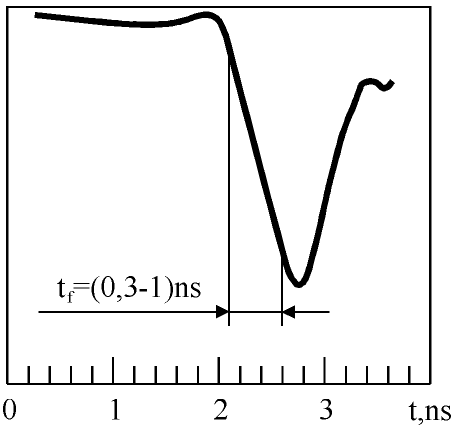

Fig. 1. The pulse at the test gas-discharge gap

The test chamber (Fig. 2) is a piece of a 50-Ohm gas-filled coaxial line with additional peaking and test gas-discharge gaps arranged as breaks in the central electrode. The additional peaking gap is fixed, while the test gap (position 7, Fig. 2) can be smoothly adjusted without depressurization of the case. The sealed-off unit for adjustment of the gap spacing (position 12, Fig. 2) has a scale with graduations of

0.05 mm. The chamber is wave-resistance matched with the load coaxial transmission line whose length is sufficient to provide the required separation in time between the observed discharge processes and the reflections from the short-circuited end of the system. The voltages across the gaps are measured with the use of capacitive voltage dividers built into the coaxial line of the chamber. To calibrate the voltage dividers, a subnanosecond-risetime low-voltage pulse generator built around mercury gercon [11] was used.

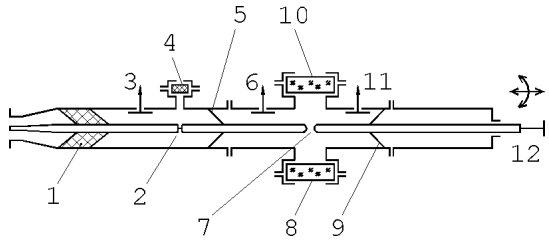

Fig. 2. Test chamber: 1 – input insulator; 2 – peaking gap; 3, 6 and 11 – capacitive voltage dividers; 4 – 6-mm diameter window (organic glass); 5, 9 – bearing insulators; 7 – test gas-discharge gap; 8, 10 – 20-mm diameter windows (glass), and 12 – electrod-moving gear

Dry nitrogen was used as testing gas in all experiments. Electrodes were made from copper. Experiments were carried out only after surface treatment by a few hundred high voltage pulses.

An additional gap was made in the cathode electrode of the test discharge gap (Fig. 3). Along the axis of this gap, a ceramic pin was placed over the surface of which an advance breakdown occurred.

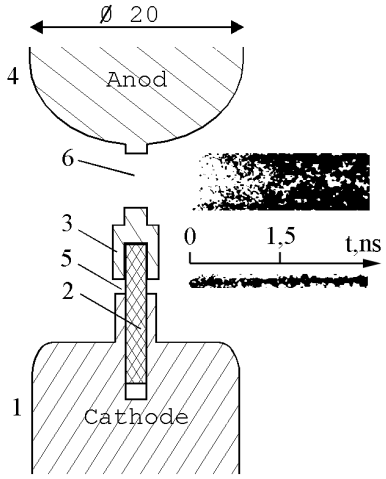

Fig. 3. The test gas discharge gap configuration. 1, 3, and 4 – electrodes; 2 – ceramic pin fixed with epoxy glue; 5 – additional gap; 6 – test gas gap. The negative of streak photograph of glow was scanned

The gap was adjusted so that the flashover of the ceramics took place early in the risetime of the applied pulse at a voltage making up no more than 20% of the peak voltage. The breakdown light was photographed by an electron-optical camera, and these photographs were used to make a reference (zero) mark on the time scale of the streak picture of the breakdown of the main gap. This made it possible to make the time scale of the streak picture of a gas breakdown with that of the high-voltage pulse applied to the gap accurate to 100 ps (for a sweep of 0.5 ns/cm).

The experiments showed that at the first stage of initiation (< 1 ns) the gas breakdown might develop in two ways.

The first type (I) of subnanosecond gas breakdown. In the first series of experiments a pulse with FWHM of 2 ns, an amplitude of 70 kV, and a pulse front of (0.8–1) ns at 0.1–0.9 levels was applied to the test gas-discharge gap (4.5 atm). In this case, the voltage rise rate at the pulse front was $7 \cdot 10^{13}$ V/s. The electric field distribution in the gas gap is shown in Fig. 4. An interactive program [12] designed for calculation of electron guns was used. The cathode edge radius was taken equal to 0.2 mm. In these experiments, calculated values of the normal component of the electric field intensity were $E_1 = 285$ kV/cm on the plane of the most obtrusive part of the cathode and $E_2 = 600$ kV/cm at the cathode edge.

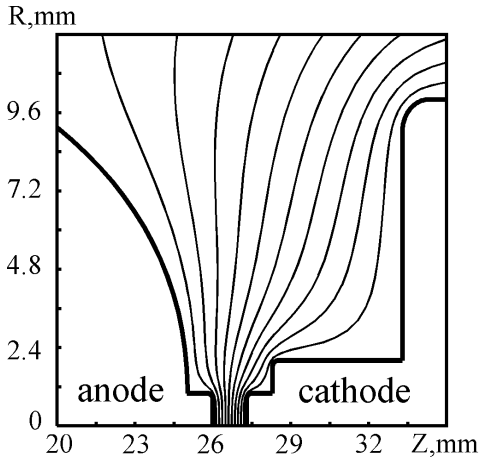

Fig. 4. Distribution of the electric field in the gas gap. Z – axis of symmetry of the system cathode-anode

Figures 5,a and 5,b show typical streak photographs of the glow accompanying breakdown processes, which were time-scanned on the plane parallel to the plane of the electrode surfaces. One can see that the process of the gap covering by the glow was divided into three stages. First stage: relatively pale luminescence appeared in the bulk of the gas, extended towards the surface of the electrodes, and reached the surface in 200–400 ps. Second stage: a bright bridge, which is clearly seen in Fig. 5,a, jumped the gas gap. The lifetime of the bridge was 100–200 ps. Third stage included two simultaneous processes. Label them as stages 3a and 3b. Light emission started from the anode (stage 3a) and reached the cathode surface in about 500 ps. A more intensive glow appeared simultaneously on the surface of the electrodes (we shall refer to this glow as “secondary glow”), which covered the gap in 800–900 ps (stage 3b).

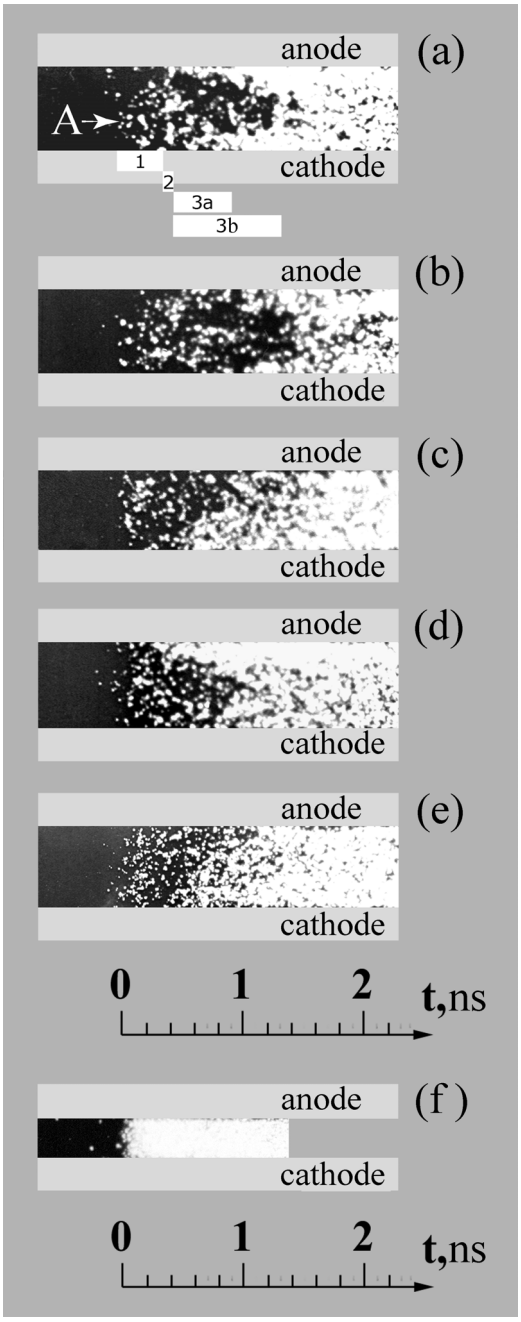

Fig. 5. Streak photographs of the glow accompanying breakdown processes in nitrogen at 4,5 atm, gap width 3,55 mm (a–e) and at 40 atm, gap width 1,42 mm (f)

Notice that the glow at the first stage of the breakdown initiation could start at some local point of the gas gap (Fig. 5,a) or in a large portion of the gas gap (Fig. 5,b). For example, from Fig. 5,a it is seen that the glow originally appeared at the point A, which was separated from the cathode surface by a distance accounting for (30–35)% of the gap width.

The "secondary" bright luminescence at the gas diode electrodes appeared practically simultaneously or with a 100–150 ps delay at the anode. But some streak photos (a few percent of all the photos taken) show that the "secondary" bright luminescence could appear only at one of the electrodes (Fig. 5,c–d) and then at the second electrode with a delay of a few hundred ps. In this case, the "secondary" bright glow, which appeared at the second electrode, propagated in the volume of the gas gap 2–2.5 times faster than the glow, which appeared first. There was a photograph showing the "secondary" bright glow only from the cathode (Fig. 5,e). In Figs. 5,c–e the first stage of the breakdown initiation is not observed and the full time of the breakdown initiation was reduced by about 400 ps.

Experiments were repeated at pressures from 4 to 10 atm. A pulse with FWHM of 2 ns, a pulse front of (0.5–0.9) ns at the 0.1–0.9 level and a maximum voltage rise rate at the front of the pulse equal to $2 \cdot 10^{14}$ V/s was applied to the test gas-discharge gap. In this case, the normal component of the electric field intensity was E_1 = (280–600) kV/cm on the plane of the most obtrusive part of the cathode and E_2 = = (0.6–1.1) MV/cm at the cathode edge. In these conditions the full time of the breakdown initiation was reduced to 400–500 ps. The "secondary" bright glow bridged the gap with a maximum velocity of up to $(7–8) \cdot 10^8$ cm/s. However, qualitative changes in the breakdown initiation dynamics were not observed.

The second type (II) of subnanosecond gas breakdown. Investigations of breakdown initiation mechanisms at high pressures (tens of atm) present a special interest. It was noted [13] that the shortest fronts of high voltage pulses were obtained exactly with high-pressure gas commutators.

The experiments were carried out at nitrogen pressures of the test chamber equal to (30–40) atm. A pulse with FWHM of 1–2 ns, a front (300–400) ps long at the 0.1–0.9 level and a voltage rise rate at the pulse front of $(4–5) \cdot 10^{14}$ V/s was applied to the test gas-discharge gap. The calculated value of the normal component of the electric field intensity was E_1 = (0.9–1.4) MV/cm on the plane of the most obtrusive portion of the cathode and E_2 = (1.7–2.4) MV/cm at the edge of the cathode. A streak photograph of the light accompanying the pulsed electrical breakdown of the gas is given in Fig. 5,f. In this case, the glow bridged the gas gap differently. Relatively pale luminescence, which was observed at the initial stage of the breakdown initiation in the previous series of experiments, was not registered. A bright glow very quickly (in less than 100 ps) covered all the volume of the gas gap. The glow velocity was over $1.4 \cdot 10^9$ cm/s. However, we cannot see in detail the initial stage of the breakdown because the AGAT SF3M streak camera, which was used in the experiments, had a limited time resolution.

3. Discussion

The first type (I) of subnanosecond gas breakdown. Relatively pale luminescence, which was observed at the first stage (stage 1) of the breakdown, probably

resulted from gas ionization caused by a diffusive electron avalanche. The avalanche might appear due to both free electrons, which are always present in the gas volume, and electrons emitted from the cathode surface. Already 200–300 ps after the instant the applied voltage pulse arrived to the test gap, the normal component of the electric field intensity at the edge of the cathode was over 200 kV/cm. The surface of even a trained cathode certainly has a sufficient number of microscopic inhomogeneities with the electric field strengthening factor of about 40–50 [14], which are centers of field emission.

Several electron avalanches, which initiate the electrical breakdown, may occur simultaneously. Sometimes we cannot determine exactly the point in the gas gap, at which the glow begins. Such points may be several in number at a time. As a result, we observe a superimposition of images of several electron avalanches in the streak photographs and smearing of the initial portion of the streak photographs (Fig. 5,b). An electron avalanche distorts the electric field in the gap. This leads to appearance of secondary electrons owing to ionization of the gas in zones of a large field. Plasma formations or cathode and anode streamers spread towards the electrode surfaces. The velocity of the cathode streamer was $3.1 \cdot 10^8$ cm/s (all calculations in this paragraph were made for Fig. 5,a) and the velocity of the anode streamer was $5.8 \cdot 10^8$ cm/s. When the cathode and the anode streamers reached the surface of the electrodes, a bright straight arch or a spark channel appeared across the gap (stage 2). The velocity of the spark channel was $(2–4) \cdot 10^9$ cm/s. The spark channel produced a new wave of ionization (stage 3a), which bridged the gap from anode to cathode at an average velocity of about $7 \cdot 10^8$ cm/s. The "secondary" bright glow (stage 3b) most probably resulted from explosions of microscopic inhomogeneities on the surface of the electrodes. This assumption is confirmed by the fact that in some streak photographs we observed a bright light, which appeared first at one of the electrodes only (Figs. 5,c–e). That is, this was a random process. The metal vapor, which was formed during explosions, actively ionized the gas, leading to a strong increase in the glow brightness. This glow bridged the gap at an average velocity of about $2 \cdot 10^8$ cm/s. In our experiments the end of the stage 3b corresponded to a breakdown current in the gas gap equal to ~1.4 kA or higher.

In Figs. 5,c–e the first stage of the breakdown initiation is not observed. We may assume that in this case the breakdown was initiated mainly due to field emission from the cathode surface and explosions of microscopic inhomogeneities on the surface of the electrodes. The phase of a single electron avalanche (stage 1) was absent.

Thus, it may be inferred that in the first series of experiments we observed a pulsed electrical breakdown, which was initiated by two processes simultaneously: ionization of the gas by electron avalanches and explosive field emission. Sometimes processes of explosive field emission dominated.

The second type (II) of subnanosecond gas breakdown. One of possible explanations why the breakdown started by the second type is formation of a sufficiently large number of "running away" electrons in the test discharge gap. Ionization of the gas with "running away" electrons is faster and more efficient than ionization by recombination radiation or step ionization. As a result, the breakdown forming time can be sharply reduced.

High penetrability of "running away" electrons and brake quanta leads to ionization of the gas far from initial ionization centers. As a result, the breakdown loses its spatial compact form and becomes diffusive or multichannel [15]. The criterion of conversion from the streamer breakdown to the regime of "running away" electrons was formulated [1] as $E_c/p = 3.88 \cdot 10^3 Z/I$, where E_c is a critical field in V/(cm·Torr), Z is the atomic number of the gas, I is an average energy of inelastic losses in electron-volts. For nitrogen $Z = 14$, $I = (75–80)$ eV, $E_c/p = 590$ V/(cm·Torr). The critical field E_c for nitrogen at 40 atm is 17.3 MV/cm. In our experiment the normal component of the electric field intensity at the edge of the cathode was $E_2 = (1.7–2.4)$ MV/cm, i.e. the ratio $E_c/E = (7–10)$. Considering this criterion, "running away" electrons should be absent. However, from the streak photographs it is seen that the breakdown developed differently from the breakdown in the first series of experiments. Furthermore, in the first experiments the ratio $E_c/E = 3$, i.e. the probability that "running away" electrons appear is higher. The experimentally observed increase in the breakdown formation rate to $1.4 \cdot 10^9$ cm/s or higher can be explained as follows. As the highly conductive plasma cloud, which was formed during explosive emission processes at the cathode, was moving from the cathode to the anode, the electric field in the gap was redistributed. For a very short time (probably not more than several tens of ps) an electrical field, whose intensity was higher than the critical value, could appear in some part of the gas gap. As a result, "running away" electrons were formed and the breakdown formation time was reduced. The "second type" of subnanosecond gas breakdown was observed in our experiments only when the front of the pulse applied to the test gas-discharge gap was shorter than 400 ps.

4. Summary and Conclusions

In experiments carried out at voltage rise rates in the test gas-discharge gap lower than $2 \cdot 10^{14}$ V/s and the normal component of the electric field intensity on the cathode surface equal to (0.6–1.1) MV/cm, we observed a pulsed electrical breakdown, which was initiated by two processes simultaneously: ionization of the gas by electron avalanches and explosive field emission. Sometimes explosive field emission proc-

esses dominated. When the voltage rise rate in the test gas-discharge gap was higher than $4 \cdot 10^{14}$ V/s and the normal component of the electric field intensity at the cathode surface was (1.7–2.4) MV/cm, the electrical breakdown mechanism changed and the glow bridged the gap much faster. Probably, in this case the propagation of the breakdown to the anode was determined by the regime of "running away" electrons. The aforementioned processes present interest for designers of subnanosecond pulsed power generators. If optimal conditions are chosen, "running away" electrons may considerably increase the breakdown formation rate. Therefore, it will be possible to develop new types of superfast high-pressure gas commutators.

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