Study of the ionization processes at the delay stage of the subnanosecond discharge in high-pressure nitrogen

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Abstract. This paper reports on a particle-in-cell and Monte Carlo simulations of the development of a pulsed breakdown in a high-pressure (40 atm) nitrogen-filled diode at an initially homogeneous electric field. The simulation shows that even during the formation of a conducting plasma channel, the diode can experience a current flow capable of greatly decreasing the diode voltage compared to its value in idle mode.

1. Introduction

In the case of a pulsed breakdown of gases between the instant of application of the voltage to the discharge gap and the beginning of the breakdown, which is usually fixed by a sharp drop in voltage (figure 1), some time passes, called the breakdown delay time \( t_d \) [1]. Phenomena in the delay stage are usually characterized as prebreakdowns, in contrast to the stage of direct breakdown development, when an irreversible sharp current growth and a voltage drop at the electrodes occur. Then the time of voltage drop on the electrodes, i.e. the time of transition to the high-current stage of the gas discharge is often called the switching time \( t_{br} \). In fact, \( t_d \) is determined, firstly, by the rate of ionization processes in the gas, and, secondly, by the nature of the initiation of the initial electrons in the discharge gap [1]. In the subnanosecond range, including in the experiments analyzed in this article, the breakdown, as a rule, occurs at the voltage pulse front (see figure 1) [2-9]. In this case, the pulse breakdown voltage \( U_{br} \) exceeds the static breakdown voltage \( U_{stbr} \), that is, the discharge gap is overvoltage.

It was shown in [6-9] that in the range of pressures \( p \) 5-40 atm in nitrogen [6, 7, 9] and 5-50 atm in hydrogen [8, 9] in the subnanosecond range, two mechanisms of initiation of a self-sustained discharge operate simultaneously: initiation of a discharge due to field emission from micro protrusions at the cathode surface (this mechanism is described in details in [1, 10]) and multi-electron initiation of a discharge in the bulk of a gas by runaway electrons (RAE). At the pressure range of 10-40 atm in nitrogen and 20-50 atm in hydrogen, the multi-electron initiation of the discharge in the bulk of the gas by RAEs dominates, and completely determines \( t_{br} \) and \( U_{br} \) (reducing them), and the spatial structure of the discharge. The experiments in [6-9] were carried out in an initially homogeneous electric field. The length of the discharge gap varied from 0.25 mm to several mm. The breakdown of the discharge gap occurred at the front of the applied high-voltage pulse. The reduced average electric field strength \( E/p \) in the discharge gap at the moment of the breakdown beginning,
that is, estimated at the upper limit, at a pressure of 40 atm was 36-66 V/(cm Torr). This is significantly lower than required by the criterion for the transition of electrons to runaway mode [1, 11, 12].

\[ U_{stbr} \]

Figure 1. Voltage at the discharge gap G in the prebreakdown stage and in the stage of breakdown \( U(t) \). \( U_d(t) \) – front of the voltage pulse applied to the gas discharge gap; \( U_{be} \) – pulse breakdown voltage; \( U_0 \) – double amplitude of the voltage pulse applied to the discharge gap; \( U_{stbr} \) – static breakdown voltage; \( U_{br} \) – breakdown delay time; \( t_{stbr} \) – the time for which the voltage across the discharge gap reaches the level of the static breakdown voltage.

In [13-16], a new mechanism was proposed for the generation of RAEs at high (from units to tens of atmospheres) gas pressures. It was shown that the electrons go into a runaway mode in the forming cathode layer. At the stage of formation of the cathode layer, a region of enhanced electric field for a short time is formed near the cathode. The electric field strength in this region is at least an order of magnitude higher than the average electric field strength in the discharge gap and its value is sufficient for the realization of the runaway electron mode. In this region, the electron has time to gain the energy required to maintain runaway movement within the weak average field. The formation of an enhanced field region requires some time. During this time, the anode-directed ionization wave (IW), which arises during drift multiplication of field emission electrons, moves away from the cathode for a short, about a dozen microns, distance. Then, the RAEs beam outruns the front of this IW and pre-ionized gaseous medium. This pre-ionization is nonuniform. The maximum ionizations due to the RAEs will be near the boundary of the IW front, since the energy of RAEs in this region is the smallest (units of keV), since they continue to accelerate even in a relatively weak average electric field. Further movement of the IW front is caused by the development of electron avalanches from the secondary electrons arising in the gas volume due to pre-ionization of the gas by RAEs, which leads to a significant increase in the velocity of propagation of the IW front. As a result, a dynamic capacitance arises: the front of the IW - the anode. In the case of high velocities of propagation of the IW, the charging current of this capacitance (bias current) can substantially limit the growth of voltage across the discharge gap, that is, commutation will begin earlier than the plasma reaches the anode. In the nanosecond time range such a regime was not detected experimentally: commutation always began after the discharge gap was covered by plasma [1]. The second factor that can limit the pulse breakdown voltage, this is the flow of current due to ionization multiplication of electrons that have arisen in the gas volume due to the ionization by the RAEs. If the value of this current becomes comparable with the maximum output current of the pulse voltage generator used in the experiments, then the restriction of \( U_{br} \) of the gas diode will be observed. Most likely, both of the above factors affect \( t_d \) and \( U_{br} \).

The situation described above has never been investigated numerically. In the present paper, for the first time, we studied numerically in 2D approximation the development of ionization processes leading to the breakdown under these conditions. We do not aim to investigate the entire range of experimental conditions of papers [6-9], but we shall confine ourselves in our analysis only one point (nitrogen, 40 atm, gap length 0.75 mm), in which the volume initiation mechanism by RAEs, as shown in [9] most noticeable. We were mainly interested in the question of why the breakdown voltage
drops. Whether it is just a consequence of a faster overlap of the gap by the plasma or it is due to the limitation of the voltage on the gap by the charging current of the dynamic capacitance.

2. Experimental setup
The operating mode of the gas discharge gap \( G \) is illustrated in figure 2. The forming line \( L_F \) of the pulse generator (PG) RADAN-303A [17] is charged to the voltage \( U_0 \). The output current of the PG on a 50-Ohm load was 3.6 kA. When the switch \( S \) at the output of the PG is triggered, the high-voltage pulse with amplitude \( U_1=U_0/2 \) propagates along the coaxial line \( L_1 \) towards the discharge gap \( G \). At the prebreakdown stage, the amplitude of pulse \( U_1 \) doubles at the cathode of the gap \( G \). If the gap breakdown did not occur, the voltage at the discharge gap \( U(t) \) would correspond to the dashed line \( U_g(t) \) (figure 1) and would achieve in the end the level of the charging voltage of PG \( U_0 \). In our experiment, the breakdown always occurred at the front of the high voltage pulse applied to the gas discharge gap (figure 1). The method of reflectometry was used in the measurements: the incident \( (U_1) \) and the reflected from the discharge gap \( (U_2=U(t)/2) \) voltage waves were recorded. After the breakdown of the gap, the part of the pulse \( U_1 \) that did not reflected at the prebreakdown stage begins to propagate along the loading coaxial line \( L_2 \), the double run time of which is much longer than the duration of pulse \( U_1 \), and comes back to the discharge gap at the time when \( U_{br} \) and \( t_d \) are already measured. The equivalent wave resistance of the discharge circuit in our experiment was 100 \( \Omega \).

![Figure 2. Equivalent discharge circuit: \( L_F \) – PG forming line; \( L_1 \) – coaxial transmission line (\( R = 50 \) \( \Omega \)); \( L_2 \) – coaxial loading line (\( R = 50 \) \( \Omega \)); \( G \) – discharge gap; \( S \) – switch at the output of the PG.](image-url)

3. Numerical simulation of ionization processes
The simulation was carried out in cylindrical coordinates in 2D geometry. The electrodes were represented by two disks with infinite radii. It was assumed that the emission of electrons occurred from the center of the cathode \( (r=0) \). The length of the cathode-anode gap was 0.75 mm. The nitrogen pressure was 40 atm. The voltage was set in the form of an electromagnetic wave from the boundary located at a distance of 400 \( \mu m \) from the axis of symmetry, with a linearly increasing infinite front. The rate of voltage rise was \( 7 \times 10^7 \) V/s. In [16], the time \( (t_c) \) of injection into the gap of the RAEs beam was analytically determined for the same experimental conditions. In the analysis [16] it was assumed that the initiating electrons appear as a result of field emission from the micro protrusion at the cathode, the geometry of which provides the field enhancement factor \( \beta =25 \). It was analytically shown that the generation of the RAEs beam occurs in the developing cathode layer at a time \( t_c=270 \) ps since the beginning of the voltage growth. By this time, the IW, which develops during the avalanche multiplication of field emission electrons, has time to move away from the cathode by several tens of microns, that is, practically the whole gap is filled with a neutral gas. In this case, in the developing cathode layer at 40 atm, the RA can receive energy \( \varepsilon=\left(6.5–8.5\right) \) keV. The RA will lose some of this energy passes through the space-charge region, formed near the micro protrusion – the source of initiating field emission electrons. The analysis of available reference data on the electron energy losses in the plasma showed that the average energy of RAes in the beam would be \( \approx 3.8 \) keV when entering the neutral gas. In numerical analysis, we artificially launched at the time 270 ps from
the beginning of the voltage raise the RAEs beam with duration from 1 to 3 ps with this energy. The amount of RAEs in the beam was 100 or $6 \times 10^7$ pieces, which corresponded to the beam current $I_1=5 \times 10^{-6}$ A or $I_2=3$ A, respectively. For accurate determination of the RAEs number, it is necessary to fulfil a numerical simulation of the cathode layer formation dynamics, which is a rather complex separate task, the solution of which is planned by us in the nearest future.

Further for the study of ionization processes, self-consistent calculations were carried out, taking into account the kinetics of electrons, including runaways, and the dynamics of the electromagnetic field in the gas discharge gap in 2D approximation. The dynamics of both runaway and slow electrons was calculated by the particle-in-cell method using the open-source code XOOPIC optimized for gas discharge problems [18], which makes it possible to simulate the development of a breakdown in a complete electromagnetic formulation. The simulation of collisions was carried out using the Monte Carlo method. In this case, all the main channels of energy loss by electrons were taken into account, such as excitation of an atom or a gas molecule, single ionization, and elastic scattering. The dynamics of the electromagnetic field in a gas diode was calculated using the Maxwell equations system. An analysis of the dynamics of the ionization processes development in the gap was carried out by two methods: firstly, from the change in the distribution of the electric field strength in the gap; secondly, from the change in the distribution of ion concentrations $n_i$. The breakdown voltage $U_z$ during simulation was calculated as the integral of the $z$-component of the electric field strength from the emitting point on the cathode to the flat anode $U_z = \frac{A}{C} \int E_z dz$. Earlier, using a similar technique, a number of problems were solved in modeling the development of a subnanosecond discharge with participation of RAEs [19-24].

![Figure 3](image3.png) **Figure 3.** Distribution of electric field strength $E_z$ in the discharge gap along $z$ axis at different moments of time: curve 1 – 10 ps; curve 2 – 12.5 ps; curve 3 – 14 ps.

![Figure 4](image4.png) **Figure 4.** Distribution of ion concentrations $n_i$ in the discharge gap along $z$ axis at different moments of time: curve 1 – 10 ps; curve 2 – 12.5 ps; curve 3 – 14 ps.

The first method is more convenient to use at the initial stage of the IW development. Before the front of the IW directed to the anode, the electric field intensifies (figure 3). By the velocity of the point at which the electric field intensity reaches the maximum value, it is possible to estimate the velocity of IW at the initial stage of its development (during the first 10 ps after the emission into the gap of the RAEs beam) as $V_{IW}=\frac{(2\div3)\times10^9}{cm/s}$ (in the case of the discharge initiation by the RAE beam with a current $I_2=3$ A). Estimation of the velocity of IW in this way seems to be the most correct, but it is difficult to carry it out at later stages of the breakdown development. From the free electrons that appeared as a result of RAEs ionization, a large number of electron avalanches began to develop, strongly distorting the initially homogeneous electric field in the gap. As a result, it is not possible to
determine the position of the point with maximum electric field strength with sufficient accuracy. Therefore, at the later stages of breakdown, we estimated the velocity of IW from the change in the distribution of ion concentrations in the gap (figure 4). By the motion of the front of the ion concentration change, it is possible to determine the velocity of the IW at a later stages (at $t>10$ ps after the emission of the RAE beam with a current $I_2=3$ A) as $V_{IW}=(0.4\div1)\times10^{10}$ cm/s.

In figure 5 the spatial distribution of electrons in the gap at different moments of time when the RAES beam with $I_2$ current initiates the discharge is shown. In figure 6 the voltage at the discharge gap at the prebreakdown stage and the stage of breakdown when the RAES beam of different intensities initiates the discharge is shown. In the case of discharge initiation by the RAES beam with a current $I_1$, the voltage drop begins 24 ps after the injection of the RAES beam into the discharge gap, and with a current of $I_2$, after 10 ps. The rate of voltage drop in both cases is approximately the same. Let us discuss in more details the initiation of a discharge by the RAES beam with current $I_2$. At the beginning of the voltage drop ($t=280$ ps), IW has departed from the cathode for a distance of 200 μm (see figure 5a). That is, the IW passed only 26% of the discharge gap width.

![Figure 5](image.png)

**Figure 5.** Spatial distribution of electrons in the discharge gap at different moments of time.

After 12.5 ps and 14 ps from the moment of injection of the RAES beam ($t=282.5$ ps and 284 ps, see figures 5bc and 6) we have 5.5% and 8.5% voltage drop in comparison with the idle mode, respectively. By this time, the IW had departed from the cathode at 350 μm and 550 μm (i.e. passed 46% or 73% of the discharge gap length), respectively. That is, the voltage drop begins earlier than the IW has reached the anode.

We estimated the instantaneous current flowing through the planes perpendicular to $z$ axis. Such
planes were located at the points $z_1=200 \, \mu m$ and $z_2=700 \, \mu m$ from the cathode. The basis for the analysis was the data on the distributions of the electric field strength and the concentrations of charged particles along $z$ axis (figures 3 and 4), and data on the areas of the cross section of the spatial distribution of electrons in the gap (figure 5), obtained numerically. The evaluation was carried out according to the formula:

$$I = 2 \pi e \int_{0}^{r_p} n_e(r, z = z_{1,2}) v_e(r, z = z_{1,2}) r \, dr$$

(1)

where $r_p$ is the radius of the plasma boundary, $n_e$ is the electron density, and $v_e$ is the drift velocity of the electrons. To estimate the drift velocity, the frequently used approximations were used [1, 25]:

$$v_e = 3 \cdot 10^5 \frac{E_z}{p}$$

(2)

The units of using parameters are following: $E_z/p$ [V/(cm Torr)], $v_e$ [cm/s].

![Figure 6. Voltage at the discharge gap G in the prebreakdown stage and in the stage of breakdown when the RAEs beam of different intensities initiates the discharge.](image)

The estimates have shown that, after 14 ps from the injection of the RAEs beam into the gap through the plane located near the anode (at the point $z_2$) the current $I_{z_2} \approx 100 \, A$ flows. Through the plane coinciding with the maximum of the electric field strength (located at the point $z_1$) the current $I_{z_1} \approx 10 \, kA$ flows. That is, the current flowing in the zone of the amplified field ahead of the ionization wave front is approximately two orders of magnitude greater than the conduction current. The electron drift velocity in the $z_1$ plane is $3.7 \times 10^7$ cm/s. Moving with such velocity, the electrons reach the anode in approximately 1.48 ns. That is, the current $I_{z_1}$ is actually the charging current of the dynamic capacitance: the front of the IW – the anode. And the flow of these current causes a voltage drop across the gap in comparison with the idle mode.

In the numerical calculations, we did not take into account the dynamics of the electromagnetic field in the coaxial lines $L_1$ and $L_2$ (figure 2). In contrast to the previous calculations [19–24], in which the ionization processes were modelled in sufficiently long, on the order of 1 cm, discharge gaps, in the present work in calculations we had to use an order of magnitude denser grid along the $z$ axis. The personal computer productivity did not allow in this case to take into account the processes in the coaxial lines. To describe the experiments in the complete electromagnetic formulation, it is necessary to use a supercomputer and we are planning to solve this problem in the nearest future.

The results obtained during the analysis were compared with the results of the discharge simulation under the same experimental conditions (for the same electrodes configuration, the length of the
discharge gap, the rate of voltage rise at the gap, etc.) but in the absence of the RAEs. In this case, a classical avalanche-streamer discharge [1, 25, 26] develops. The streamer velocity, estimated from the dynamics of the changes in the distribution of the electric field strength in the gap, reaches 1.5×10^8 cm/s. Moving at such a velocity, the plasma will reach the anode in time ~500 ps. As a result, \( U_{br} \) and \( t_d \) will increase significantly. A significant increase in \( t_d \) (by 50%) and \( U_{br} \) (by 70%) with increasing of gas pressure from 50 to 60 atm was observed in experiments [8, 9]. In these experiments, at the pressures less than 50 atm, two mechanisms of discharge initiation acted simultaneously: due to field emission from micro protrusions on the cathode surface and a multi-electron mechanism of initiation in the gas volume by RAEs. At 60 atm, discharge initiation occurred only from the cathode, and the \( t_d \) and \( U_{br} \) measured in the experiment were well described in the framework of the avalanche-streamer model.

The velocities of the IW obtained in numerical analysis are also in good agreement with the results of the streak recording of the glow accompanying a subnanosecond discharge in nitrogen at 40 atm [13, 15, 27].

4. Conclusion

Thus, in the numerical simulation it is shown that at the subnanosecond breakdown in a gas-filled diode of high (40 atm) pressure, the voltage across the diode can be significantly reduced in comparison with the idle mode voltage still at the stage of formation of the conducting channel. The initiation of the discharge by the RAEs will completely determine the discharge delay time and the pulse breakdown voltage.

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