The initial phase of breakdown of high-voltage nanosecond discharge initiated with runaway electrons in a nonuniform electric field

M. Lomaev[1,2], D. Beloplotov[1,2], V. Tarasenko[1,2], D. Sorokin[1]

[1]Institute of High Current Electronics, Akademichesky Ave. 2/3, 634055 Tomsk, Russia
[2]National Research Tomsk State University, Lenina Ave. 36, 634050 Tomsk, Russia..

The initial phase of the breakdown during the formation of diffuse discharges initiated by runaway electrons and X-Ray in the pure nitrogen and sulfur hexafluoride with small admixture of nitrogen was investigated. Nanosecond voltage pulses of both polarities with an amplitude up to ~300 kV and rise time of ~0.5 ns were applied across the discharge gap with sharply nonuniform electric field distribution. Estimations of average propagation velocity of the ionization wave in the nitrogen and mixture sulfur hexafluoride with nitrogen were performed on the basis of data on dynamics of radiation of the second positive (2^+) nitrogen system from various areas along of the longitudinal axis of interelectrode gap. Interrelation between the glow dynamics and the local value of the electric field strength has been defined. The results showed that the breakdown is developed in the form of the ionization wave propagating from the potential tubular electrode with the highest concentration of the electric field to the flat-grounded one. In the regions near the grounded electrode the practically simultaneous increasing of emission intensity is registered, that indicates on a possible change of the breakdown mechanism in this part of the discharge gap.

1. Introduction

Currently, increased attention is paid to the pulse and pulse-periodic discharges in the dense gases initiated with runaway electrons under conditions of an inhomogeneous electric field distribution. The main feature of such discharges is a generation in a gap of runaway electrons and X-ray, affected on a breakdown. These processes was shown in [1-5] to provide the formation of diffuse discharges at the excitation of gas medium by high-voltage nanosecond pulses of both polarities.

The increased interest in the study of runaway electron preionized diffuse discharge (REP DD) is due to the presence of a number of unresolved fundamental problems in this area of gas discharge physics. Among them are the process of the breakdown and discharge formation, refinement the mechanism of generation of runaway electrons and others, as well as opportunities of wide practical application of the high-pressure non-equilibrium low-temperature plasma, in particular, for cleaning, oxidation and hardening of metal surfaces [5, 6].

It is known, that the phenomenon of electrical breakdown of gas-filled gaps has a threshold character [7]. The breakdown of long gaps was shown to occur in the form of the ionization wave which characterized by an amplification of electric field strength in a zone of its front [8, 9]. In a case of relatively short gaps, the leading role of runaway electrons in the process of breakdown and subsequent discharge dynamics is noted [1], and the concept of breakdown of the discharge gap under these conditions of excitation in the form of the wave of a background electrons multiplication was presented [10]. The studies of formation and propagation of streamer at breakdown of elevated pressure gases are conducted actively as well [11-14]. The appearance of runaway electrons during streamer propagation was discussed in [14]. At REP DD formation, the overlap of many electrons avalanches occurs and an ionization wave with transverse dimensions of the order of a centimeter forms [3, 5, 6].

The objective of this work is to study the initial phase of a breakdown in an inhomogeneous electric field in the gases at pressure of 0.013-0.7 MPa during the REP DD formation.

2. Experimental setup and measurement

The block-diagram of the experimental setup is presented in Figure 1. The voltage pulse produced with the RADAN-220 pulser was applied through a short transmission line (5) to an electrode with small radius of curvature (7). The potential electrode (7) was a tube (Ø ~ 6 mm) made of 100-μm-thick stainless steel foil, and the grounded electrode (9) was a plate, which located at a distance of 13 mm from the edge of the potential one. The voltage pulse was registered with a capacitive divider (6) located at the end of the transmission line (5). The impedance of transmission line (5) was several times higher than that of the RADAN-220 pulser, making it possible to increase the voltage pulse amplitude across the gap up to ~300 kV. The voltage pulse duration at a matched load was ~2 ns, and the pulse rise time in the

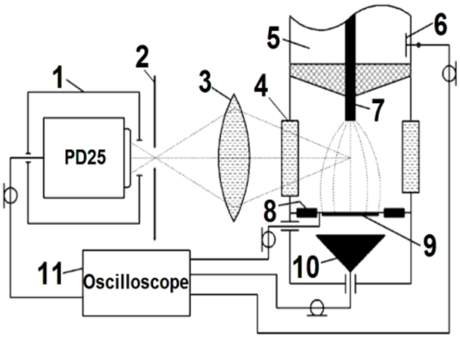

Figure 1. Block-diagram of experimental: 1 – photodetector PD025 in metal box; 2 – screen with slit; 3 – lens; 4 – side window; 5 – transmission line of RADAN-220 pulser; 6 – capacitive voltage divider; 7 – high voltage electrode; 8 – current shunt; 9 - ground electrode made of thin foil; 10 – collector; 11 – oscilloscope.

transmission line was ~0.5 ns. The current through the gap was measured with a shunt (8) made of thin-film chip-resistors. The chip-resistors were connected in series with the flat electrode (9). The current of runaway electrons beam (RAE beam current) was measured with a collector (10) simultaneously with the discharge current and voltage pulse across the gap at the negative polarity of a voltage pulse. For the registration of RAE beam current the anode (9) made of AlMg foil with diameter of 1 cm and thickness of 50 µm was used. A forevacuum pump was used for discharge chamber pumping. By means of the lens (3) 2 times magnified discharge images are formed on screen (2) with 1 mm width split. Thus, the plasma radiation from different discharge gap areas was selected. When the plasma filled this region, the photodiode PD025 (cathode is LNS20, Photek company, the pulse rise time is ~ 80 ps) (1) recorded the waveform of radiation intensity from this area. The spatial resolution of this system was ~ 1 mm in the direction of the longitudinal gap axis. Signals from the capacitive voltage divider, shunt, collector, and photodiode were recorded with Tektronix DPO70604 digital oscilloscope (6 GHz, 25 GS/s) (11). The time synchronization of voltage across the gap, discharge current, RAE beam current and discharge plasma radiation intensity pulses was no more than 200 ps.

Investigation of breakdown was carried out by means of registration of waveforms of discharge plasma radiation intensity from different areas along of the longitudinal axis of discharge gap, voltage pulses and current through the gap. Discharge chamber was filled with pure nitrogen (N_2) or mixture of sulfur hexafluoride (SF_6) with 2.5% N_2 admixture. The arguments in favour of these gases are following. Firstly, the radiation of the nitrogen second positive system (2^+) is easily excited in nitrogen and nitrogen-containing mixtures in the gas discharge plasma. Secondly, the $C^3\Pi_u$ state of nitrogen molecule – the upper state of the transitions of (2^+) nitrogen system is effectively populated at high values of the reduced electric field strength, which are realized in the area of the ionization wave front during the breakdown of the discharge gap. Third, the effective lifetime of the $C^3\Pi_u$ state of nitrogen molecule τ_{eff}, which is determined by radiative and collisional quenching, is less than 1 ns at pressures higher than atmospheric. Thus, from the foregoing it follows, that the radiation of (2^+) system of nitrogen is a convenient spatial-time indicator of the ionization and the excitation processes at breakdown of a gap during REP DD formation. Time resolution of the registration system of radiation is ~100 ps. The duration of breakdown stage depending on the gas pressure can vary from tens to several hundred picoseconds. Therefore, high-pressure gases were used to increase the breakdown stage duration and decrease the effective lifetime of the $C^3\Pi_u$ state. It permitted to obtain more accurate information about the time evolution of radiation intensity from different discharge gap areas

3. Relation between the emission intensity of (2^+) system of nitrogen and local value of the reduced electric field strength

The breakdown phenomena that occur in the discharge gap, when a voltage pulse of sufficient amplitude is applied across the gap are accompanied by increasing in a medium of degree of excitation and ionization. Therefore, the emission dynamics during the initial stage of discharge formation can serve as a source of information for the analysis of the breakdown process in the gap.

It is known, that radiation of (2^+) system of nitrogen dominates in the emission spectrum of REP DD in nitrogen and nitrogen-containing mixtures [15]. In a pulse discharge in nitrogen the direct electron impact, the radiative and collisional quenching was shown to be the main channels of increasing and decreasing of population of state, respectively [9]:

$$\frac{dN_2[C^3\Pi_u](t)}{dt} = \\ = N_e(t)\cdot N_2[X]\cdot k_{exc}(t) - \frac{N_2[C^3\Pi_u](t)}{\tau_{eff}} \qquad (1).$$

In (1) N_e (t), $N_2[C^3\Pi_u]$, $N_2[X]$, k_{exc} (t) – the electron density, population of $C^3\Pi_u$ and ground states and the rate constant of excitation of $C^3\Pi_u$ state from the ground state by the direct electron impact, respectively. At use (1) interrelation between the glow dynamics and the local value of the electric field strength has been defined:

$$N_e(t)\cdot\left(\frac{d\left(k_{exc}(t)\right)}{dt}+k_i(t)\cdot N_2[X]\cdot k_{exc}(t)\right)= \qquad (2).$$
$$=\frac{\gamma}{N_2[X]}\cdot\frac{d}{dt}\left(\frac{d\left(I_D(t)\right)}{dt}+\frac{I_D(t)}{\tau_{eff}}\right)$$

In (2) $k_i(t)$, γ, $I_D(t)$ - the ionization rate constant from the ground state of nitrogen molecule by direct electron impact and the coefficient of proportionality between a signal from the photodetector I_D(t) and the population of $C^3\Pi_u$ state of nitrogen molecule, respectively. Equation (2) establishes the relation between the values that can be obtained from experimental data (right side of (2)) and the values that depend on the local value of the electric field strength (left side of (2)).

4. Experimental results and discussion

Experiments were carried out at the nitrogen pressure of 0.013-0.7 MPa, as well as in mixture of SF_6 with 2.5% N_2 at the pressure of 0.013-0.25 MPa. Delay of start of the radiation from the grounded electrode area depends on gas pressure and composition of gas mixture. From Figure 2 it is seen, that the delay of start of radiation increases monotonically at increasing of pressure of nitrogen and SF_6 with 2.5% N_2 admixture. The moment when the signal level from the discharge area achieved 5% relative to its maximal value was chosen as the moment of the onset of radiation. At the breakdown in SF_6 with 2.5% N_2 admixture the delay of onset of the radiation from the area near the grounded electrode is higher than that in nitrogen. As well, polarity of voltage pulse influences the one. At a positive polarity of voltage pulse, the delay is smaller than that at the negative polarity (Figure 2). It indicates that at positive polarity the velocity of ionization wave propagation is higher than that at negative polarity.

Based on the data on the delay of onset of the radiation (Figure 2), estimates of average propagation velocity of the ionization wave that passes discharge gap with length of 13 mm were conducted. The range of velocities of ionization wave is ~ (2.1-6.5)·10^7 m/s in mixture of SF_6 with 2.5% N_2 for pressures of 0.05-0.25 MPa and ~ (0.5-1.3)·10^8 m/s in nitrogen at pressures of 0.1-0.3 MPa. The possibility of passage of the front of high-speed ionization wave ((0.1-2) ·10^8 m/s) at the high-voltage (up to 300 kV) breakdown of a long gap (tens of cm), that filled with nitrogen or other gases at pressure of hundreds Torr was shown in [8].

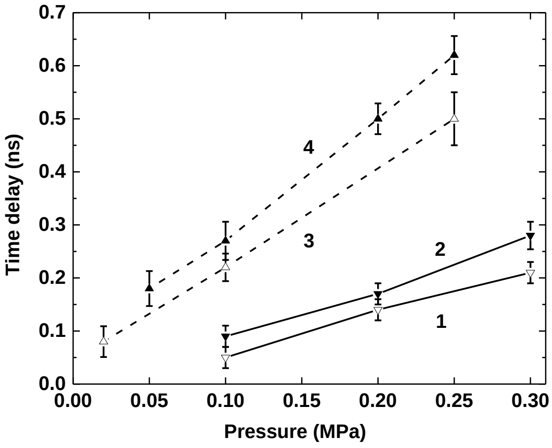

Figure 2. Delays of onset of the radiation emission start from the area near the grounded electrode relatively of the one from the area near the potential electrode in nitrogen (1, 2) and mixture of SF_6 with 2.5% N_2 (3, 4) versus a pressure at positive (1, 3) and negative (2, 4) polarity of the voltage pulse.

Because the duration of breakdown stage increases with pressure, it enhances the accuracy of the information about the time evolution of the intensity of radiation at a given stage of development of the discharge. Therefore, to identify the features of the breakdown at conditions under study the dynamics of radiation from different areas along the axis of the discharge gap with step of 1mm was investigated in nitrogen at a pressure of 0.7 MPa. To

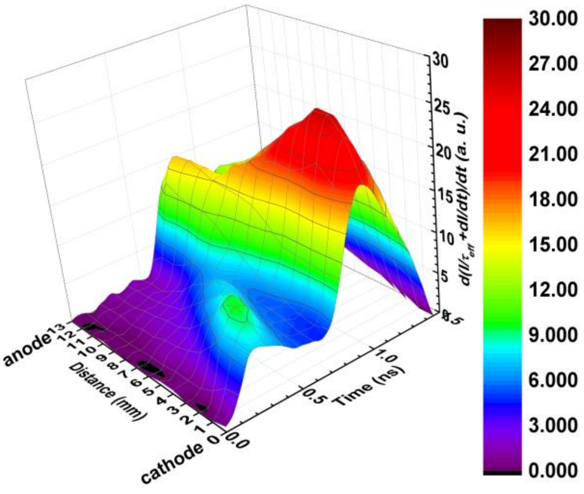

Figure 3. Dependence of the rate of change of $\frac{d\left(I_D(t)\right)}{dt}+\frac{I_D(t)}{\tau_{eff}}$ as a function of time and distance from the potential cathode. Nitrogen pressure of 0.7 MPa

reduce the random error the average of 100 waveforms of radiation pulses were recorded. The calculated values of $\frac{d}{dt}(\frac{d(I_D(t))}{dt}+\frac{I_D(t)}{\tau_{eff}})$ (right part of equation (2), that is equal to the left part of equation (2) to within the constant γ), are presented in Figure 3. It is shown clearly from the figure that this value achieves the local maximum consequently in the areas from the cathode towards the middle of the discharge gap that corresponds to the breakdown stage. It is known, that at the breakdown stage the electrons density increases monotonically with delay relative to growth of electric field strength. That is why the non-monotonically time evolution of value

$$N_e(t)\cdot\left(\frac{d(k_{exc}(t))}{dt}+k_i(t)\cdot N_2[X]\cdot k_{exc}(t)\right) \quad (3)$$

is due to electric field strength increasing before and decreasbehind a front of a wave ionization. At conditions under study both, $\frac{d(k_{exc}(t))}{dt}$ and $k_i(t)\cdot N_2[X]\cdot k_{exc}(t)$, are increasing functions of local electric field strength that influences on the electron energy distribution function. In areas located at a distance of ~10 to 13 mm the time evolution of this value is approximately the same during the breakdown stage.

5. Conclusion

In this work, features of the breakdown stage during the formation of discharge initiated by runaway electrons and X-ray in the gap with an inhomogeneous electric field filled with nitrogen or mixture of SF_6 with 2.5% N_2 admixture were investigated. It was shown, that the high-voltage breakdown of the gap with a nonuniform electric field distribution at elevated gas pressures and subnanosecond rise time of voltage pulse is occurred owing to the ionization wave characterized by amplification of the electric field strength in the area of its front. The average velocity of ionization wave is ~(2.1-6.5)·10^7 m/s in mixture of SF_6 with 2.5% N_2 admixture at pressures of 0.05-0.25 MPa and ~(0.5-1.3)·10^8 m/s at nitrogen pressures of 0.1-0.3 MPa at negative polarity of electrode with small radius of curvature. These values of the ionization wave velocity sort well with the ones of the high-speed ionization wave formed at the high-voltage breakdown of long gap. It was established experimentally, that the average ionization wave velocity is decreased, for the both when using of electronegative gas SF_6 and when increasing of pressure of nitrogen and mixture of SF_6 with 2.5% N_2 admixture. One of the features of the breakdown of the discharge gap at the investigated conditions of discharge excitation is to increase of the ionization wave velocity when it moves through the gap. Practically simultaneous increasing of the radiation intensity in areas near the grounded electrode is observed due to the increase of the electron density and increasing the electric field strength. This fact indicates to the possibility of changing the breakdown mechanism in this part of the discharge gap.

Acknowledgment

The work was supported by the grant from the Russian Science Foundation, project №14-29-00052.

6. References

[1] L.P. Babich, T.V. Loiko, V.A. Tsukerman, *Sov. Phys. Usp.* **33**, Iss. 7 (1990) 521.

[2] V.F. Tarasenko, S.I. Yakovlenko, *Physics-Uspekhi* **47**, Iss. 9 (2004) 887.

[3] D. Levko, Y.E. Krasik, V.F. Tarasenko, *International Review of Physics* **6**, No. 2 (2012) 165.

[4] G.A. Mesyats, M.I. Yalandin, A.G. Reutova, K.A. Sharypov, V.G. Shpak, and S.A. Shunailov, *Plasma Physics Reports* **38**, No. 1 (2012) 29.

[5] *Runaway Electrons Preionized Diffuse Discharges*. Ed. by V.F. Tarasenko, Nova Science Publishers, Inc.: New York. USA, 598 p, 2014.

[6] E.H. Baksht, A.G. Burachenko, I.D. Kostyrya, M.I. Lomaev, D.V. Rybka, M.A. Shulepov and V.F. Tarasenko, *J. Phys. D: Appl. Phys.* **42**, (2009) 185201.

[7] Y.P. Raizer, *Gas Discharge Physics*, Springer-Verlag, Berlin Heidelberg, 449 p, 1991.

[8] L.M. Vasilyak, S.V. Kostyuchenko, N.N. Kudryavtsev, I.V. Filyugin, *Physics-Uspekhi* **37**, Iss. 3 (1994) 247.

[9] S.M. Starikovskaia, N.B. Anikin, S.V. Pancheshnyi, D.V. Zatsepin, and A.Yu. Starikovskii, *Plasma Sources Sci. Technol.* **10**, Iss. 2 (2001) 344.

[10] *Beams of runaway electrons and discharges in dense gases, based on a wave of multiplication of background electrons*. Ed. by S.I. Yakovlenko, Proc. of the Prokhorov General Physics Institute, Prokhorov General Physics Inst. -Moscov: Nauka, Vol. 63. 186 p. 2007.

[11] D. Wang, M. Jikuya, S. Yoshida, T. Namihira, S. Katsuki, H. Akiyama, *IEEE Trans. Plasma Science* **35**, (2007) 1098.

[12] G.V. Naidis, *Phys. Rev. E* **79**, (2009) 057401.

[13] S. Nijdam, F.M.J.H. van de Wetering, R. Blanc, E.M. van Veldhuizen, U. Ebert, *J. Phys. D: Appl. Phys.***43**, (2010) 145204.

[14] C. Li, U. Ebert, W. Hundsdorfer, *J. Phys. D: Appl. Phys.* 42 (2009) 202003.

[15] M.I. Lomaev, D.V. Rybka, S.D. A. Sorokin, V.F. Tarasenko, and K.Yu. Krivonogova, *Optics and Spectroscopy* **107**, No. 1 (2009) 33.