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IONIZATION WAVES DURING THE SUBNANOSECOND BREAKDOWN INITIATED BY RUNAWAY ELECTRONS IN HIGH-PRESSURE NITROGEN AND AIR

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The experimental investigations of a subnanosecond breakdown initiated by runaway electrons in air and nitrogen at the pressures within 0.013–0.4 MPa are performed. The temporal development patterns of the discharge plasma glow in different regions of the discharge gap are registered with a fast photodiode, a four-channel ICCD-camera, and an ultrafast streak camera. It is shown that the breakdown occurs in the form of ionization waves propagating from the electrode with a small radius of curvature. It is found that a runaway electron beam behind the anode foil at the nitrogen and air pressure ~0.1 MPa is detected with the collector at the point of time corresponding to the maximum gap voltage.

Keywords: subnanosecond breakdown, runaway electrons, high pressure, ionization wave.

INTRODUCTION

Within the recent years there has been an increased interest in the study of a high-voltage, nanosecond breakdown in high-pressure gases, which is initiated by runaway electrons and X-ray radiation [1–3]. It is well known that a breakdown in a nonuniform electric field occurs due to the formation of an ionization wave (IW), whose front propagates from an electrode with a small radius of curvature [4–11]. The motion of the IW front during the breakdown in air and nitrogen is generally detected as an emission of the second positive system of a nitrogen molecule [7, 9, 10]. The previous investigations of a nanosecond breakdown at the voltage pulse amplitudes from a few to tens of kilovolts demonstrated that the IW-front propagation velocity does not exceed several centimeters per nanosecond. No beams of runaway electrons or X-ray radiation were reported at these voltages [5–7, 11]. At the voltage pulse amplitudes of hundreds of kilovolts, the IW-front propagation velocity reaches ~10 cm/ns, and the beams of runaway electrons and (or) X-rays have been detected in a number of studies [1–4, 9, 10]. However, the data on the formation and propagation of an IW under the conditions of a subnanosecond breakdown initiated by runaway electrons in the gaps with nonuniform electric field strength distribution at the pressures ≥0.1 MPa are insufficient. This is due to the extremely short times of the development of ionization processes in the gap and to the complexity of timing the measuring instrumentation with the start of a breakdown. Furthermore, the authors of most publications did not aim at measuring the runaway electron beam parameters.

The purpose of this study is to obtain a data set on the formation and propagation of ionization waves in air and nitrogen at the pressures of 0.1 MPa and higher under conditions of a subnanosecond breakdown initiated by runaway electrons.

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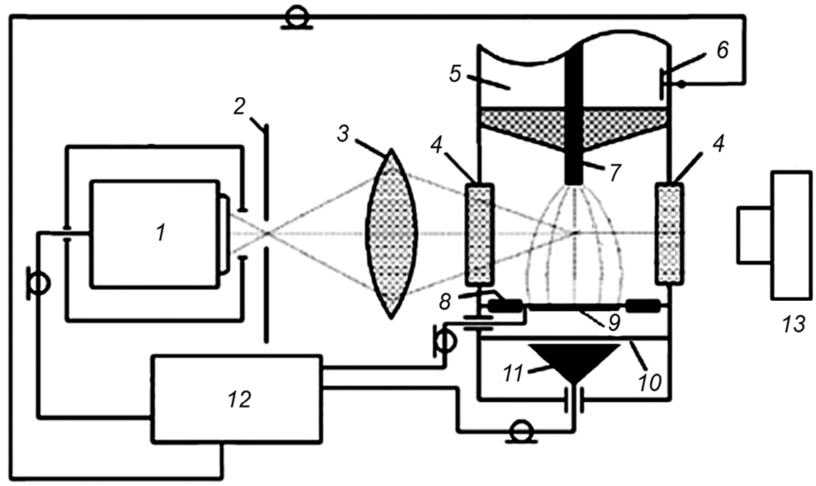

Fig. 1. Schematics of the experimental setup: *1* – PD025 photo diode in a metal screen, *2* – shield with a 1 mm slit, *3* – lens, *4* – side windows, *5* – generator transmission line, *6* – capacitive voltage divider, *7* – high-voltage electrode, *8* – current shunt, *9* – grounded mesh/foil electrode, *10* – foil, *11* – collector, *12* – oscilloscope, *13* – SONY A100 photo camera or spectrometer, or Hamamatsu C10910-05 streak camera, or HSFC-PROICCD-camera.

EXPERIMENTAL APPARATUS AND MEASUREMENT PROCEDURES

The experiments were carried out in a setup using two high-voltage pulse generators, a discharge chamber (gas diode), and three different systems for the detection of optical radiation. In all the regimes under study, in addition to registration of optical radiation from plasma the beam of runaway electrons behind the foil anode (supershort avalanche electron beam – SAEB [2]) and the gap voltage and current were also recorded. Using a RADAN-220 generator, voltage pulses of positive or negative polarity were applied across the gap at the incident wave amplitude in the transmission line $U_{inc} \approx 110$ kV, FWHM $\tau_{0.5} \approx 2$ ns, and pulse rise time $\tau_{0.1–0.9} \approx 0.5$ ns. A schematic layout of the discharge chamber and system of registration of optical radiation from the regions along the longitudinal axis of the discharge gap is presented in Fig. 1. The radiation from plasma formed in the gas-filled gap excited by the RADAN-220 generator was recorded by a PD025 photodiode.

The high-voltage electrode represented a 100 μm-thick stainless steel foil rolled into a tube (Ø = 6 mm) or a 18 mm-long razor blade made of stainless steel; the grounded electrode was either a metal disk or, in the case where the runaway electron current was recorded, a grid-reinforced foil. The interelectrode gap *d* in the experiments with the RADAN-220 generator was 13 mm. The photo diode recorded the plasma discharge radiation from the region along the longitudinal axis of the gap with a spatial resolution of ~1 mm. In every region, 100 radiation pulses 100 respective voltage and current pulses were recorded, following which the values were averaged. The voltage pulse repetition frequency was 1 Hz or less. A more detailed description of the setup with the RADAN-220 generator is given elsewhere [9, 10]. During the investigations on this experimental setup, a method was used, which allowed identifying the relationship between the radiation intensity of the transition bands $C^3\Pi_u$–$B_3\Pi_g$ of the nitrogen molecule and the relative value of the reduced electric field strength E/p [9, 10]. Within the framework of this method, we experimentally obtained the value of$f(t) = d[dI_D(t)/dt + I_D(t)/\tau_{eff}]/dt$ (I_D – radiation intensity of the bands of the second positive system of nitrogen, τ_{eff} – effective lifetime of the $C^3\Pi_u$ state of a nitrogen molecule), which illustrates the behavior of E/pin the discharge gap.

In the experiments with a HSFC-PRO four-channel ICCD-camera (minimum exposure time – 3 ns) and a Hamamatsu C10910-05 streak camera, equipped with an Acton SpectraPro SP-2300 spectrometer (Princeton

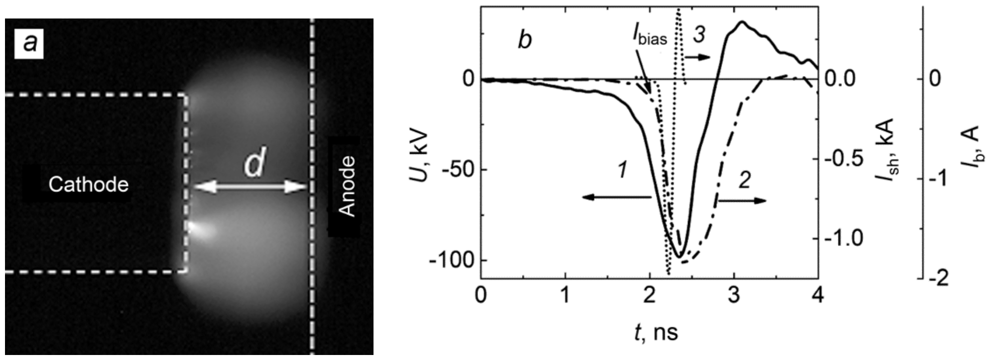

Fig. 2. Integral image of the discharge plasma glow (*a*). Waveforms of the voltage pulses U (curve *1*), discharge current I_{sh} (curve *2*), and super short avalanche electron beam (SAEB) current I_b (curve *3*) (b). I_{bias} – capacitive current from the 'cold cathode' (bias current). Interelectrode spacing $d = 5$ mm. Nitrogen pressure 0.1 MPa. Sleeve potential cathode. Grounded anode – metal disc (*a*) and Al-foil 10 μm in thickness reinforced by the grid with light transmittance 64%) (*b*). Generator – GIN-55-01. Pulse repetition frequency 1 Hz.

Instruments), use was made of a GIN-55-01 voltage pulse generator providing the following parameters of the negative-polarity voltage pulse: $U_{inc} \approx 55$ kV, $\tau_{0.5} \approx 1$ ns, $\tau_{0.1\text{–}0.9} \approx 0.7$ ns, and pulse repetition frequency within 1–100 Hz. In addition, the use of this generator allowed synchronizing the voltage pulses with those actuating the streak- and ICCD-cameras to nanosecond accuracy. The high-voltage cathode in these experiments was shaped as a cone with the cone base diameter 6 mm and the cone apex angle 30°, and the grounded anode was shaped as a disc. During the registration of runaway electrons, both cone and sleeve electrodes were used, and a 10 μm-thick grid-reinforced aluminum foil (light transmittance 64%) served as a grounded electrode. The interelectrode spacing d could be varied from 3 to 8 mm. The experiments with the GIN-55-01 generator were carried out in a single-pulse mode or at the frequency 1 Hz.

Due to a high timing accuracy, the ICCD-camera was actuated 2–3 ns before the voltage pulse arrival time at the discharge gap, which allowed recording the plasma glow in the pre-breakdown stage of the discharge, whose duration was up to 1 ns. The presence of jitter made it possible to register plasma glow at different points of time in the course of the pre-breakdown stage. The camera recorded a large number of pulses ($\sim 10^2$), which allowed us to observe how the gap was filled with the plasma at different gas pressures.

Using a streak camera, the temporal increase in the emission intensity of the plasma of different spectral compositions was measured in several regions along the longitudinal axis of the discharge gap. The measurements were performed by recording the time variation of the emission intensity of the rovibrational band of the second system of nitrogen at the wavelength 337.1 nm. The width and the height of the region from which the emission was recorded were 125 μm and 2 mm, respectively. The final pattern of the time variation in the emission intensity in each region was obtained by averaging over 300 pulses.

The integral image of the discharge plasma glow was photographed by a SONY A100 digital camera. Figure 2*a* presents a typical image of the plasma glow. The signals from the capacitive voltage divider, current shunt, collector, and photodiode were recorded by the DPO 70604 or DSO-X 6004A digital oscilloscopes with the bandwidth 6 GHz and sampling steps 40 and 50 ps, respectively. The waveforms of voltage, discharge current, and SAEB current are presented in Fig. 2*b* for the case where the GIN-55-01 generator was used.

The measurements demonstrate that when the atmospheric-pressure nitrogen is excited by the voltage pulses from the GIN-55-01 generator, the SAEB current amplitude recorded on the collector is found to be units of amperes for the full width at half maximum ~100 ps. In the cases where the RADAN-220 generator and optimal conditions were used, the SAEB current pulse amplitudes reached a few tens of amperes [2]. The time of the SAEB current registration by the collector with respect to the voltage pulse depends on the width of the interelectrode gap and nearly coincides with the point of time where the voltage on the gap reaches its peak value. In the conditions of narrow gaps, the SAEB current is registered with the collector tens of seconds earlier than the above point of time.

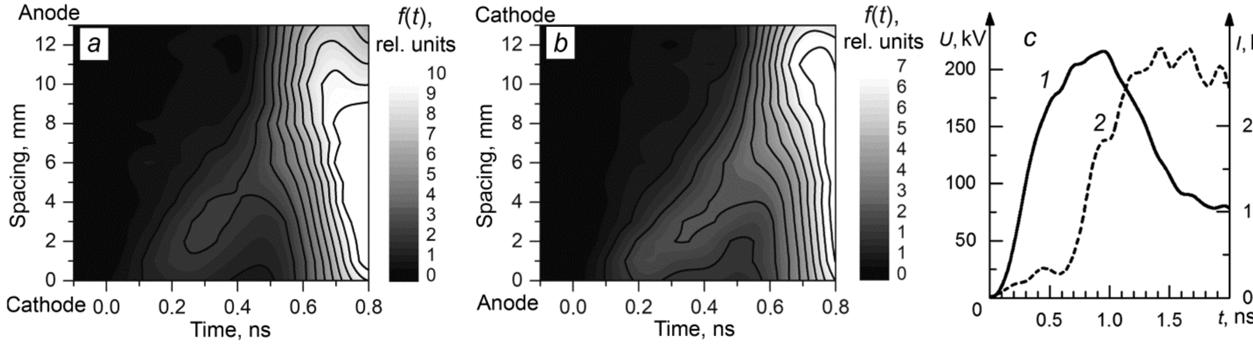

Fig. 3. Behavior of the value of *f*(*t*) in space and time in the cases of the negative (*a*) and positive (*b*) polarities, waveforms of the voltage pulses *U* (curve *1*) and discharge current *I* (curve *2*) in the case of the negative polarity (*c*). Nitrogen pressure 0.4 MPa, "Razor blade – plane" gap. Generator – RADAN-220.

RESULTS AND DISCUSSION

The investigations, performed in the setup with the RADAN-220 generator and the PD025 photodiode (Fig. 1) using a procedure [9, 10] assuming the registration of emission from the regions along the longitudinal axis of the gap, demonstrated that a breakdown in the gap in the case of a nanosecond voltage pulse rise time and a nitrogen pressure of 0.1 MPa and higher occurs as a result of propagation of an IW starting from the electrode with a small radius of curvature (Fig. 3). The IW-front velocity in the gap with a sleeve or a razor-blade cathode is nonuniform over the length of the gap: it is lower in the first half of the gap and becomes higher afterwards. The average rate at which the glow develops in the entire gap with a sleeve cathode at the nitrogen pressure 0.4 MPa was higher and was found to be 3.4 cm/ns. The data within the time interval 0–0.8 ns (Fig. 3*a*, *b*) provide a qualitative illustration of the variation in the value of E/p in space and time, which is due to the electric field redistribution in the gap during its filling with the dense plasma. It is evident that the IW propagates from the electrode with a small radius of curvature in the cases of the voltage pulses of both polarities. Moreover, the IW velocity increases as it approaches the flat grounded electrode. The average values of the IW velocity in these conditions for the negative and positive polarities were found to be ≈2.7 and ≈2.6 cm/ns, respectively. The data obtained also suggest that when the first IW reaches the grounded electrode, a backward propagating IW is formed whose velocity is higher (≈11 and ≈16 cm/ns for the negative and positive polarities, respectively). The voltage across the gap decreases (Fig. 3*c*), when the backward IW reaches the electrode with a small radius of curvature.

The data obtained using an ICCD-camera demonstrate that a diffuse discharge of the duration >1 ns takes place within the ranges of air (0.013–0.1 MPa) and nitrogen (0.013–0.4 MPa) pressures. In the case of low pressures, the transverse dimensions of the plasma formed in the pre-breakdown stage are comparable with its longitudinal size. After the gap is bridged by the IW the discharge plasma glow intensity increases primarily in the area close to the axis. This gives rise to a decrease in the size of the visible discharge region in the integral images. As the gas pressure is increased, the size of the visible glow region in the pre-breakdown stage decreases, which might be due to a decrease in the value of E/p. The images of the discharge plasma glow obtained with an ICCD-camera are given in Fig. 4.

At the pressure 0.1 MPa, first a weak glow is registered near the high-voltage cathode (Fig. 4*a*), then both the glow intensity and the glowing region diameter increase (Fig. 4*b*). Figure 4 *c* presents the discharge plasma glow at the point where an IW arrives at the anode, and Fig. 4*d* – the pulse-integrated glow pattern with a bright spot on the cathode. A similar glow dynamics is also registered in nitrogen.

Using a streak-camera, we performed an investigation of the breakdown phase for different gap dimensions, nitrogen pressures, and cathode shapes and materials. In particular, below we present the data demonstrating that when

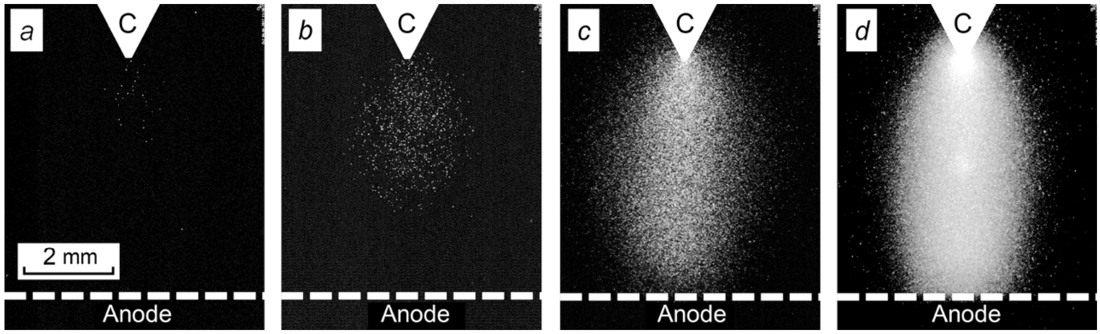

Fig. 4. Images of the discharge plasma glow in the gap filled with atmospheric-pressure air obtained with an ICCD-camera at different points of time: from 0 to 1 ns (*a*–*c*), integral for the pulse (*d*). Generator – GIN-55-01.

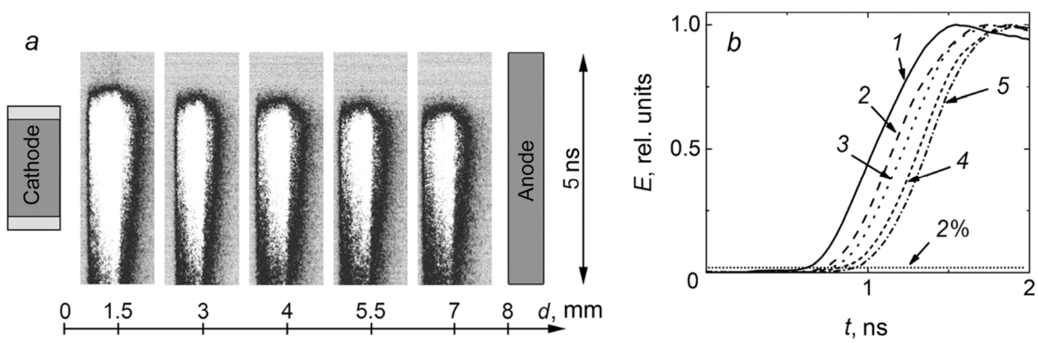

Fig. 5. Illustration of the temporal evolution of the glow of a nitrogen molecule emission band 337.1 nm at the distances 1.5, 3, 4, 5 and 7 mm from the potential cathode along the longitudinal axis of the gap (*a*). Time variation of the emission intensity band 337.1 nm of a nitrogen molecule at the distances 1.5 (curve *1*), 3 (curve *2*), 4 (curve *3*), 5.5 (curve *4*) and 7 mm (curve *5*) from the cathode (*b*). Nitrogen pressure 0.1 MPa. Cathode – stainless steel sleeve (Ø = 6 mm), anode – aluminum flat grounded electrode. Interelectrode spacing *d* = 8 mm. Generator – GIN-55-01.

a sequence of voltage pulses with an interval of 30 ns is applied to the gap and there is no breakdown within the first voltage pulse, during the second voltage pulse the breakdown also occurs in the form of an IW.

Figure 5*a* depicts a high-voltage sleeve cathode and a flat anode, spaced by 8 mm from each other, and the images obtained from the streak-cameras, which illustrate the temporal evolution of the glow at the 337.1 nm in the regions located at the distances 1.5, 3, 4, 5 and 7 mm from the cathode. The curves presented in Fig. 5*b* illustrate the time variation of the emission intensity from the regions corresponding to the images in Fig. 5*a*. It is evident from Fig. 5 that the glow wave (IW) starts from the potential cathode and propagates at the velocity increasing as it approaches the flat grounded anode, which correlates with the results obtained with a photo diode (see Fig. 3). The average velocity of the IW motion at the nitrogen pressure 0.1 MPa, estimated from the time diversity of the plasma glow appearing in different zones at a level of 2% of the amplitude value, was found to be ≈1.8 cm/ns, hence the gap breaks down within hundreds of picoseconds. This result is also supported by the data illustrating the glow evolution in the gap, which were obtained with an ICCD-camera.

CONCLUSIONS

The investigations performed in this study have allowed obtaining a set of experimental data on a breakdown of a gap with a nonunform electric-field distribution at a subnanosecond voltage pulse rise time. It has been demonstrated that the breakdown occurs in the form of ionization waves starting from the electrode with a small radius of curvature at different voltage pulse polarities and nitrogen pressures.

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REFERENCES

1. Runaway Electrons Preionized Diffuse Discharges (Ed. V. F. Tarasenko), Nova Science Publishers, Inc., N. Y. (2014).
2. Generation of Runaway Electrons and X-Ray Radiation in Elevated-Pressure Discharges (Ed. V. F. Tarasenko), Tomsk, STT (2015).
3. Generation of Runaway Electron Beams and X-Rays in High Pressure Gases. V. 1. Techniques and Measurements; Volume 2. Processes and Applications (Ed. V. F. Tarasenko), Nova Science Publishers, Inc., N. Y. (2016).
4. L. M. Vasilyak, S. P. Vetchinin, and D. N. Polyakov, Tech. Phys. Lett., **25**, Iss. 18, 749 (1999).
5. S. Pancheshnyi, M. Nudnova, and A. Starikovskii, Phys. Rev. E, **71**, Iss. 1, 016407 (2005).
6. D. Wang, M. Jikuya, S. Yoshida, *et al*., IEEE Trans. Plasma Sci., **35**., Iss. 4, 1098–1103 (2007).
7. D. Z. Pai, G. D. Stancu, D. A. Lacoste, and C. O. Laux, Plasma Sources Sci. Technol., **18**, Iss. 4, 045030, (2009).
8. S. Yatom, V. Vekselman, J. Z.Gleizer, and Ya. E. Krasik, J. Appl. Phys., **109**, 073312. (2011).
9. M. I. Lomaev, D. V. Beloplotov, V. F. Tarasenko, and D. A. Sorokin, IEEE Trans. Dielectr. Electric. Insulat., **22**, Iss. 4, 1833–1840 (2015).
10. V. F. Tarasenko, D. V. Beloplotov, and M. I. Lomaev, Plasma Phys. Rep., **41**, No. 10, 832–846 (2015).
11. P. Tardiveau, L. Magne, E. Marode, *et al*., Plasma Sources Sci. Technol., **25**, Iss. 5, 054005 (2016).