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Parameters of runaway electron beam generated during excitation by nanosecond voltage pulses in short gaps filled with nitrogen

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Abstract. Parameters of a supershort avalanche electron beam (SAEB) in nitrogen excited by the triangular-shaped voltage pulses with 45kV amplitude in incident wave and full width at half-maximum (FWHM) of ~ 1 ns were investigated. In experiments, cylindrical-shaped cathodes made of aluminum and stainless steel were used. An interelectrode distance in the gas-filled diode was 3, 5, and 8 mm. It was established that the highest values of SAEB's current were registered with an aluminum cathode. It was shown that, in contrast to the case of 8-mm gap length, when the interelectrode distances were 3 and 5 mm, the amplitude of SAEB current pulse in nitrogen began to decrease with high values of the pressure – 100 and 50 kPa, respectively.

1. Introduction

To date, a runaway electron beam (REB) and X-rays which take place during the nanosecond discharges in various gases at atmospheric pressure is registered by many research teams (see the monograph [1] and references therein). Nevertheless, there are relatively few detailed studies on the REB parameters behind the anode foil in a wide range of experimental conditions. Only three research teams have registered the REBs in atmospheric-pressure gases with collectors at the temporal resolution of a registration system not worse than 100 ps [2-4]. As well, there are few data on the REB parameters in gases at pressures ranging from 100 to 1 kPa. Although, still in [5] it had been shown that when the gas pressure was reduced from 100 to ~ 6 kPa, the number of electrons in a beam increases. However, due to the lack of equipment with subnanosecond temporal resolution, duration of the beam current pulse was not measured by the authors of [5]. The result of [5] was later confirmed in [6]. In addition, according to [6], in helium, hydrogen, neon, nitrogen, argon, methane, sulfur hexafluoride, krypton and xenon, the pressure of which ranged from 30 to 100 kPa, the REB had the full width at half-maximum (FWHM) of about 100 ps. More detailed studies of the REB current pulse duration when the pressure of nitrogen, hydrogen, and helium was decreased to those below atmospheric showed that the FWHM values of ~ 100 ps remained up to very low pressures of these gases (1.3, 4 and 8 kPa, respectively) [7].

The aim of this study was to investigate the amplitude and duration of the REB generated in short interelectrode gaps pressured with nitrogen in the range of 1-100 kPa, which was excited by

1-ns-duration triangular-shaped voltage pulses having incident wave's amplitude of 45 kV. According to [8], an electron beam generated in the gas-filled diode and registered behind the anode foil will be called the supershort avalanche electron beam – SAEB.

2. Experimental setup

The experimental setup was assembled of a gas-filled diode, a pulser FPG-100-01 (FID Technology), and a registration system. The pulser formed the triangular-shaped voltage pulses having the FWHM of ≅ 1 ns, the risetime of ≅ 0.7 ns, the falltime of ~ 5 ns, and the amplitude on high-resistance load of 90 kV which was applied to a cathode in the gas-filled diode. The cathode was 6-mm-diameter cylinder with the wall thickness of 1 mm and 100-μm-thickness edge at the end facing towards the anode (i.e., the cathode had a small radius of curvature). The cathodes were made of aluminum and stainless steel. The gas pressure in the diode varied from 1 to 100 kPa. A flat anode of the gas diode was an aluminum foil having thickness of 10 μm. The distance between electrodes in experiments was 3, 5, and 8 mm. The diode was evacuated to ~ $1.3\cdot10^{-4}$ Pa, using the forevacuum pump, and filled with high purity nitrogen containing not more than 0.001 % of impurities. The amplitude and the FWHM of the REB's current pulse were registered behind the anode foil using the collector of 20-mm-diameter receiving part. The signal from the capacitive voltage divider located near the gap was a triggering signal. The pulse repetition rate was 1 Hz. Waveforms of pulses from the capacitive voltage divider and collector were recorded using the digital real-time oscilloscope Agilent Technologies DSO-X6004A (bandwidth was 6 GHz, sampling rate was 20 GS/s). Waveforms were recorded in both the single pulse mode and averaging mode (over 16 pulses).

3. Results and discussion

Dependencies of the SAEB current pulse amplitudes from nitrogen pressure for the values of interelectrode distance d = 3, 5 and 8 mm are presented in Figs. 1, 2, and 3.

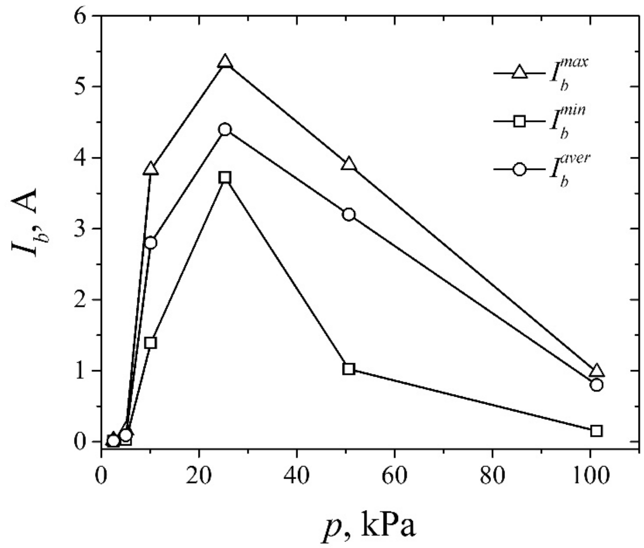

Figure 1. The amplitude I_b of a SAEB's current pulse versus nitrogen pressure p. I_b^{max} – a maximal value of the amplitude; I_b^{min} – a minimal value of the amplitude; I_b^{aver} – a value of the amplitude averaged over 16 pulses. The cathode is a 6-mm-diameter aluminum cylinder. The interelectrode distance is 8 mm.

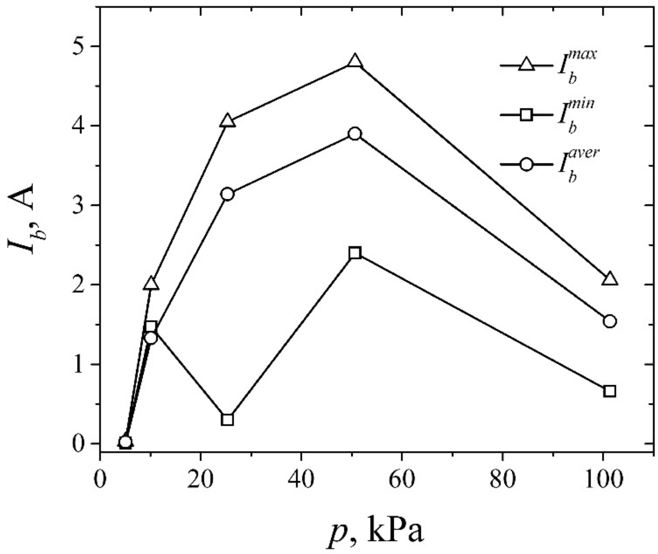

Figure 2. The amplitude I_b of a SAEB's current pulse versus nitrogen pressure p. I_b^{max} – a maximal value of the amplitude; I_b^{min} – a minimal value of the amplitude; I_b^{aver} – a value of the amplitude averaged over 16 pulses. The cathode is a 6-mm-diameter aluminum cylinder. The interelectrode distance is 5 mm.

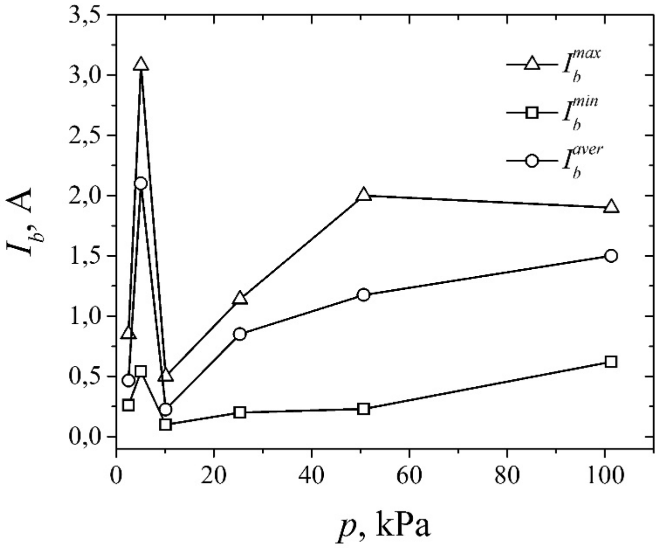

Figure 3. The amplitude I_b of a SAEB's current pulse versus nitrogen pressure p. I_b^{max} – a maximal value of the amplitude; I_b^{min} – a minimal value of the amplitude; I_b^{aver} – a value of the amplitude averaged over 16 pulses. The cathode is a 6-mm-diameter aluminum cylinder. The interelectrode distance is 3 mm.

There are maximal, minimal, and average (over 16 pulses) values of the SAEB current pulse amplitude in the figures. The presented data were obtained using aluminum cathode. When the interelectrode distance d decreased below 8 mm and gas pressure - below 100 kPa, it was found that, the SAEB current pulse amplitude started to decrease at relatively high pressure values. So, when d was 8, 5, and 3 mm, the decrease of the SAEB current pulse amplitude was observed at nitrogen pressures of 25, 50 and 100 kPa, respectively. Thus, the highest amplitude values of SAEB current pulses at the interelectrode distance of 3 mm take place at high pressure. The dependencies shown in figures above differ from those obtained earlier in [2], where the interelectrode distance between the cylindrical cathode and the anode was d ≥ 12 mm. The duration of the current pulse of an electron beam generated in the SAEB mode did not change with gas pressure and interelectrode distance and had the value of FWHM of ~ 110 ps. At low pressures, lower than 10 kPa, as in [7], the transition to the vacuum-diode mode of electron beam generation occurred. In this mode, the FWHM of an electron beam current pulse increased. The gas pressure corresponding to change of REB generation mode was depended on the distance between the electrodes and had the maximal value at d = 3 mm. The amplitude of an electron beam current pulse in the transitional mode usually increased. In the vacuum-diode mode (at pressure lower than 0.1 kPa) the amplitude of an electron beam current pulse was lower than that in the transitional mode.

The results obtained for small d can be explained by the delay of SAEB generation increasing with a decrease of the interelectrode distance. The voltage pulse having a triangular shape was used in these experiments for initiation of a breakdown in the gas-filled diode. Therefore, the decrease of pressure at short interelectrode distances led to the breakdown delay, and the SAEB was generated during the voltage pulse falltime. Accordingly, the voltage reduced during SAEB generation. The delay of breakdown and the SAEB generation process had maximal values at the minimal interelectrode distance (d = 3 mm). Therefore, at this interelectrode distance, the amplitude of a beam current pulse began to decrease under 100kPa nitrogen pressure.

Dependencies of the amplitude of SAEB current pulse on the nitrogen pressure at d = 5 mm for the stainless steel cylindrical cathode are demonstrated in Fig. 4.

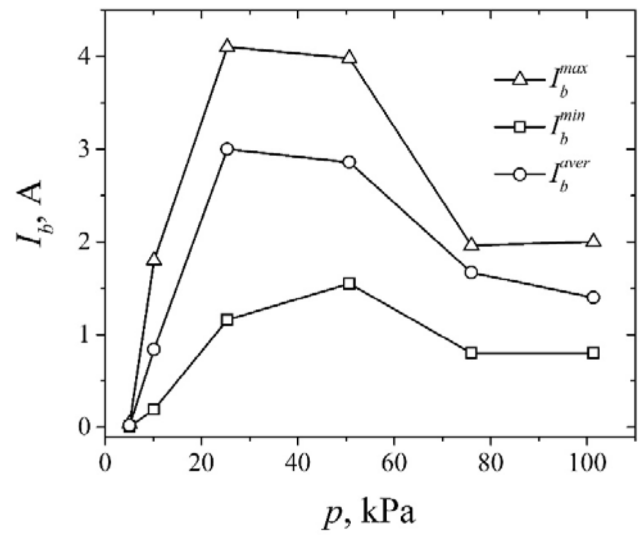

Figure 4. The amplitude I_b of a SAEB current pulse versus nitrogen pressure p. I_b^{max} – a maximal value of the amplitude; I_b^{min} – a minimal value of the amplitude; I_b^{aver} – a value of the amplitude averaged over 16 pulses. The cathode is a 6-mm-diameter stainless steel cylinder. The interelectrode distance is 5 mm.

As in the previous figures, there are maximal, minimal, and average (over 16 pulses) values of the SAEB current pulse amplitude in Fig. 4. Comparison of the results obtained for cathodes made of different materials indicates that under conditions of our experiments, the cathode material has a different effect than those reported in [8]. Both our experiments and a number of experiments reported in [8] demonstrated that the voltage pulse risetime did not exceed 1 ns. However, when we used the stainless steel cylindrical cathode, the SAEB current pulse amplitude did not only demonstrate any increase, but even decreased compared to the aluminum cathode. This fact can be explained by differences in the waveform and the amplitude of voltage pulses, which were used in our experiments and reported in [8]. At lower voltage, the stainless steel cathode applied in our experiments did not increase these values during SAEB generation process. It is known that the work function of aluminum electrons is lower than that of the stainless steel. Accordingly, when the voltage applied across the gap is approximately equal, the amplitude of an electron beam current should be higher when we use an aluminum cathode. We observed this in our experiments, see Fig. 2 and 4.

The parameters of runaway electron beams in the gaps with an interelectrode distance of some millimeters can be caclulated using new hybrid mathematical model [9], which allows simulation of the SAEB generation mode. A comparison of calculation results and the experimental data will be reported in the nearest future.

4. Conclusion

The investigation have shown that the parameters of SAEB, which was generated in the diode with an interelectrode distances 3, 5, and 8 mm, filled with nitrogen, and was registered behind the anode foil, depend on the interelectrode distance, parameters of the voltage pulse, and the material of potential cathode with a small radius of curvature (cylindrical cathode in this case). At interelectrode distance of 5 mm and excitation by triangular-shaped voltage pulses having the amplitude in the incident wave of 45 kV, the risetime of ≅ 0.7 ns and the FWHM of ≅ 1 ns the highest amplitudes of the SAEB current pulses is registered when the cathode is made of aluminum. A decrease in the SAEB current pulse amplitude at interelectrode distances 3 and 5 mm with aluminum cathode begins at essentially higher nitrogen pressures (100 and 50 kPa, respectively), than it had been reported in [7]. The obtained dependencies can be explained by a substantial influence of the waveform, duration, and the amplitude of voltage pulse on the value of breakdown voltage for a gap used. It follows from the experimental data that, comparing the SAEB parameters obtained using different experimental equipment, it is necessary to take into account all pulsers parameters, a gas diode design, as well as a design, sizes, and a material of potential cathode with a small radius of curvature.

Acknowledgments
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References

[1] Edited by Tarasenko V F 2015 *Generation of Runaway Electrons and X-rays in the Discharges of High Pressure* (Tomsk, Russia: STS) in Russian
[2] Tarasenko V F, Baksht E Kh, Burachenko A G, Kostyrya I D, Lomaev M I and Rybka D V 2008 *Plasma Dev. Oper*. **16** (4) 267–298
[3] Mesyats G A, Yalandin M I, Reutova A G, Sharypov K A, Shpak V G. and Shunailov S A 2012 *Plasma physics reports* **38** (1) 29-45
[4] Alekseev S B., Lomaev M I, Rybka D V, Tarasenko V F, Shao T, Zhang Ch and Yan P 2013 *High Voltage Engineering* **39** (9) 2112-2118
[5] Tarasova L V, Khudyakova, L N, Loiko T V and Tsukerman V A 1974 *J. Tech. Phys*. **44** (3) 564–568 [in Russian]
[6] Baksht E Kh, Lomaev V I, Rybka D V and Tarasenko V F 2006 *Tech. Phys. Lett*. **32** (11) 948–950
[7] Tarasenko V F, Baksht E Kh, Burachenko A G, Lomaev M I, Sorokin D A and Shut'ko Yu V 2010, *Tech. Phys. Lett*. **36** (4) 375-378
[8] Zhang Ch, Tarasenko V F, Shao T, Baksht E Kh, Burachenko A G, Yan P and Kostyrya I D 2013 *Laser and Particle Beams* **31** 353- 364
[9] Kozyrev A V, Kozhevnikov V Yu, Lomaev M I, Sorokin D A, Semeniuk N S and Tarasenko V F 2016 *EPL* **114**, 45001