Amplitude-time characteristics of runaway electron beams during the breakdown phase in high-pressure gases

V F Tarasenko

Institute of High Current Electronics SB RAS, 2/3 Akademichesky, Tomsk, 634055, Russia

E-mail: VFT@loi.hcei.tsc.ru

Abstract. Results of experimental studies of the amplitude-temporal characteristics of a supershort avalanche electron beam (SAEB) with a picosecond time resolution are presented. It is shown that the maximum SAEB current and the voltage drop in the gap are timed to tens of picoseconds and that the use of sharp-ended cathode improves the stability of SAEB generation.

1. Introduction

The generation of runaway electrons in high-pressure gases is a fundamental physical phenomenon. Now, many papers dealing with the runaway electron beams and X-rays, which are produced at 1 atm pressure and higher are available. In the last ten years, the greatest progress was reached in this field due to the development of high-voltage pulses and optimum gas diode designs, subnanosecond and picosecond current sensors, and high-resolution real-time oscilloscopes. There are also theoretical models of the processes occurring in gas diodes within several and split picoseconds. The latest results of experimental and theoretical research in runaway electrons and in diffuse discharges are summarized elsewhere [1, 2]. Analysis of these results shows that the parameters of runaway electron beams obtained by researchers differ greatly. It seems to be a consequence of different experimental and measurement conditions, as well as due to the limited number of studies, in which the oscilloscopes operating at ~30 GHz and 100 GS/s are used. We know about only several studies, in which the time resolution was close to the maximum one of those available today. They are applied by the Institute of High Current Electronics, Tomsk [3, 4], and the Institute of Electrophysics, Ekaterinburg [5].

Here, we report the experimental study of a picosecond resolution allowing further researches in the field of runaway electron beams generated in subnanosecond breakdowns in the air of an atmospheric pressure. In the study, we measured the amplitude-time characteristics of runaway electron beams and the breakdown voltage, as well as followed the time correlation between the maximum supershort avalanche electron beam current and the voltage drop across the gap.

2. Experimental setup

The setup shown in figure 1 was used in our experiments. It assembled a SLEP-150 pulser, a gas diode, and a measuring system. The collector receiving part was 3 mm in diameter. One of the electrodes of high-voltage line 1 was the peaking switch 2, allowing us to decrease the line length and
to form a voltage pulse of about $\approx 1$ ns FWHM at a matched load. The voltage rise time was determined by the peaking switch and was about $\approx 250$ ps at a level of 0.1–0.9 of the switch optimum operation. The gas diode 5 was connected to a high-voltage line 1 via a short transmission line 3 with a wave impedance of 100 Ohm. The voltage amplitude in the transmission line depended on the breakdown voltage of peaking switch 2 and could range from 120 to 200 kV. In our experiments, the breakdown voltage of the switch was $\sim 180$ kV.

![Figure 1. Schematic of the output of the SLEP-150 pulser, gas diode, and collector with the 3-mm-diameter receiving area: (1) high-voltage line of the pulser, (2) peaking spark gap, (3) transmission line, (4) capacitive voltage divider, (5) gas diode, (6) tubular cathode, (7) receiver part of the collector, (8) foil, (9) 5-mm-thick collimator with a 1-mm-diameter hole, and (10) collector case.](image)

The parameters of a SAEB were measured with two cathodes, one of which was a stainless steel foil tube of 6 mm diameter and 100 $\mu$m thickness (cathode 1). Another one was a stainless steel ball of 9.5 mm diameter (cathode 2). The anode of gas diode was an aluminum foil 8 of 10 $\mu$m thickness, which was reinforced with a grid or a collimator 9 from the collector side. In a series of experiments, the foil was removed, and the collimator served as the anode. Thus, the SAEB was measured through 1-mm collimator hole without any attenuation by aluminum foil. The time resolution of collector reached 20 ps [4].

The measuring equipment also included a capacitive voltage divider and a current shunt. The signals from the divider, shunt, and collector were transmitted to a LeCroy WaveMaster 830Zi-A real-time digital oscilloscope (the bandwidth 30 GHz, the sampling increment 12.5 ps) via RG58-A/U high-frequency cables (Radiolab) of 1 m length with N-type (Suhner 11 N-50-3-28/133 NE) and SMA-type connectors (Radiall R125.075.000). To register the signal of voltage attenuation, we used 142-NM high-frequency attenuators (Barth Electronics) with a bandwidth of up to 30 GHz. The signal from the collector was transmitted to the oscilloscope without attenuators, either with or without anode foil. The voltage and the SAEB current were measured simultaneously in each pulse. The timing accuracy of SAEB and voltage pulses were not worse than 10 ps. The SAEB generation time with respect to the voltage pulse was determined from the capacitive current fed to the collector. For this purpose, the collimator was removed, and the foil was replaced by a grid of 64 % transparency. This procedure is described in details elsewhere [6]; the voltage timing accuracy and SAEB pulses were not worse than 50 ps. The SAEB and X-rays were detected using the blackening of RF-3 film, in a black paper envelope of 120 $\mu$m thickness placed downstream to Al foil anode. The discharge plasma glow in the gap was photographed using Sony A100 camera.

3. Results and discussion
The nanosecond voltage pulse applied to the gap with the sharp-ended cathode, in an inhomogeneous electric field, gives rise to a discharge, in which runaway electrons are generated [1, 2]. The discharge form depends on the gap width $d$. At large gap widths $d$ or small voltage amplitudes of the sharp-
ended cathode, a corona discharge is formed. As far as the gap width \( d \) decreases, the corona discharge during the voltage pulse life transforms to a diffuse discharge, the plasma of which fills the entire gap. This discharge mode is termed a runaway electron preionized diffuse discharge or REP DD [7] and is described in detail elsewhere [1]. The glow of diffuse discharge is much brighter than that of the corona. As far as \( d \) is further decreasing, we observed the sequence of three discharge forms in the gap: a corona discharge (detected by high-resolution CCD camera), a REP DD, and a spark, into which the REP DD was transformed during the voltage pulse. The duration of diffuse and spark discharges as well as the energy deposited in the gas by every discharge depends on the gap width, cathode design, air pressure, and voltage pulse parameters. In the course of the REP DD formation, an ionization wave starts from the sharp-ended electrode. When the wave front reaches the opposite electrode, the runaway electron beam of the highest amplitude is detected downstream of the thin foil anode.

In our experiments, the SAEB parameters were studied when the cathode 1 was at an interelectrode gap of 4–35 mm and when the cathode 2 was at the gap of 4.6 and 8.5 mm. The imprint left on the film by the electron beam downstream to the anode foil without the collimator was 54 mm in diameter, i.e. covering the entire foil surface. The maximum film exposure was observed when we applied the tubular cathode 1 at a gap of 12 mm or less, near the sharp end of the cathode. Near the central axis the exposure decreased. The decrease of film exposure was more noticeable at small interelectrode gaps and when the distance from the central region of the foil increased.

Waveforms of the voltage and SAEB current for the cathode 1 at \( d = 12 \) mm are presented in figure 2.

![Figure 2. Waveforms of the voltage (a,c) and the SAEB current (b,d) pulses. The SAEB was registered by a collector with the 3-mm-diameter receiving area, which was located behind a collimator with 1-mm-diameter hole and 10-\( \mu \)m-thick aluminium foil (a,b) and behind a collimator without a foil (c,d). The gap width is \( d = 12 \) mm. The cathode is a tube of 6-mm-diameter.](image)

The runaway electron current was measured through the collimator hole (1 mm diameter) with and without anode foil of 10 \( \mu \)m thickness. The FWHM and the amplitude of the SAEB without foil changed insignificantly, which indicated that the collector did not detect electrons of an energy higher than 32 keV. However, the SAEB pulse rise times in these two cases differed. With no anode foil, there was a prepulse (figure 2(d), symbol \( P \)), whereas the beam current measured with the anode foil rose steeper (figure 2(b)). Hence, the energy of runaway electrons that contribute to the prepulse is no greater than 32 keV. It is seen from the figures for the timed SAEB pulse and the voltage drop.

Waveforms of the voltage and SAEB current for the cathode 1 at \( d = 4 \) mm and \( d = 18 \) mm are
presented in figure 3.

![Figure 3](image_url)

**Figure 3.** Waveforms of the voltage (a,c) and the SAEB current (b,d) pulses. The SAEB was registered by a collector with the 3-mm-diameter receiving area, located behind a collimator with 1-mm-diameter hole and 10-μm-thick aluminum foil (a,b) and behind a collimator without foil (c,d). The gap width was \(d = 4\) (a,b) and 18 (c,d) mm. The cathode is a tube of 6-mm-diameter.

The runaway electron current was measured through the collimator hole (1 mm diameter). A decrease of the gap width \(d\) decreased the voltage amplitude, as well as the SAEB amplitude and FWHM. The interelectrode gap \(d = 12\) mm was optimal for the cathode 1. At \(d = 18\) mm, the voltage amplitude increased but the SAEB amplitude decreased. An increase of the interelectrode gap increased the FWHM of SAEB, which can be explained by the longer time of ionization wave transition through the gap at large \(d\). As the distance to the anode foil increased, the prepulse was detected (figure 3(d), symbol \(P\)). Figure 3 shows that the SAEB pulses and the voltage drop are timed, similar to the case when the gap was equal to 12 mm.

Figure 4 shows waveforms of the voltage and SAEB for the cathode 2 at \(d = 6\) mm.

![Figure 4](image_url)

**Figure 4.** Waveforms of the voltage (a) and the SAEB current (b) pulses. The SAEB was registered by a collector with the 3-mm-diameter receiving area, located behind a collimator with a 1-mm-diameter hole and a 10-μm-thick aluminium foil. The gap width is \(d = 6\) mm. The cathode is a stainless steel ball of 9.5 mm diameter.
The average electric field strength at the surface of cathode 2 was lower than that at the sharp end of the cathode 1, and the breakdown voltage increased. The spread of breakdown delay times and breakdown voltage amplitudes became larger. The beam current measured through the collimator hole decreased. However, the SAEB generation and the voltage drop in the gap were timed as before (figures 2 and 3). The increase of breakdown delay time proportionally increased with delay time of the SAEB generation.

Analyzing the oscilloscope traces obtained with high time resolution, we can distinguish the following features. First, the maximum of the SAEB current and the voltage drop in the gap are timed to high accuracy for both cathodes. At the moment when the collector records the maximum SAEB current, the voltage across the small and optimal gaps decreases steeply. In air of an atmospheric pressure, when the voltage amplitude is of hundred kilovolts, the FWHM of SAEB current measured through the collimator holes of small diameters, with the cathode 2 and $d = 4 \text{ mm}$ can be $\approx 25 \text{ ps}$. Downstream to the entire anode foil surface, the FWHM of SAEB is $\approx 100 \text{ ps}$.

4. Conclusion

Thus, the experimental research of the amplitude-time characteristics of runaway electron beams with picosecond resolution and the discharge characteristics in air of an atmospheric pressure allows the following conclusions.

1. The maximum SAEB current and the voltage drop in the gap are timed to an accuracy of tens of picoseconds.
2. As far as the gap with cathode foil tube of 6 mm diameter and 100 $\mu$m thickness increases, we detect electrons, the energy of which was less than 32 keV before the main beam current pulse.
3. The use of sharp-ended cathode 1 stabilizes the breakdown delay time and voltage, ensuring better stability of SAEB generation.

The amplitude-time characteristics of runaway electron can be calculated using new hybrid mathematical model [8]. Detailed results will be given in the nearest future.

Acknowledgments

I am grateful to I.D. Kostyrya and D.V. Rybka for their help in performing these experiments. The work is performed in the framework of the Russian Science Foundation (the project #14-29-00052).

References

[1] Edited by Tarasenko V F 2014 Runaway Electrons Preionized Diffuse Discharges (New York, USA: Nova Science Publishers, Inc)
[2] Edited by Tarasenko V F 2015 Generation of Runaway Electrons and X-rays in the Discharges of High Pressure (Tomsk: STS) in Russian
[3] Tarasenko V F, Rybka D V, Burachenko A G, Lomaev M I, Balzovsky E V. 2012 Rev. Sci. Instrum. 83 086106
[4] Balzovsky E V, Rybka D V, Tarasenko V F 2015 Instruments and Experimental Techniques. 58 (5) 640-645
[5] Sharypov K A, Shpak V G, Shunailov S A, Ul'masculov M R, Yalandin M I 2013 Rev. Sci. Instrum. 84 055110
[6] Burachenko A G, Tarasenko V F 2010 Technical Physics Letters 35 1185-1194
[7] Baksht E Kh, Burachenko A G, Kostyrya I D, Lomaev M I, Rybka D V, Shulepov M A, Tarasenko V F 2009 J. Phys. D: Appl. Phys. 42 185201
[8] Kozyrev A V, Kozhevnikov V Yu, Lomaev M I, Sorokin D A, Semeniuk N S, Tarasenko V F 2016 EPL 114, 45001