On the influence of a cathode shape on the parameters of current pulses of runaway electron beams in a gas discharge when applying voltage pulses with a rise time of 200 ns

D V Beloplotov\(^1\) and V F Tarasenko\(^{1,2}\)

1 Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia
2 National Research Tomsk Polytechnic University, 30 Lenin Ave., Tomsk, 634050, Russia

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

Abstract. The influence of the shape of a cathode on the duration and amplitude of a supershort avalanches electron beam (SAEB) current pulses was experimentally studied. Three cathodes were used in experiments: tube, needle, and ball. Voltage pulses with a rise time of 200 ns were applied across an 8.5 mm gap filled with air and nitrogen at various pressures (12.5–100 kPa). It was found that at an air pressure of 12.5 kPa and a rise time of voltage pulses 200 ns, the largest amplitudes of SAEB current pulses (90 mA) were observed with the tubular cathode. The SAEB current pulse duration was \( \tau_{0.5} \sim 130 \) ps. Two pulses with different duration, amplitude and energy of electrons were observed with the needle cathode at same pressure. When using the ball cathode, the duration and amplitude of the beam current pulses were \( \tau_{0.5} \sim 250 \) ps and \~4\ mA, respectively.

1. Introduction

Runaway electron beams generated during the breakdown of gaps with a cathode having a small radius of curvature are currently obtained in various gases at pressures from units to thousands of kPa (see [1–4] and references in the ones). In some works [4–10], their parameters were measured using collectors with a high temporal resolution. Much attention was paid to determining the duration and amplitude of runaway electron beam current pulses [1–11].

After improving the design of collectors in order to more accurately measure the parameters of the beam current, it was found that the duration of the SAEB current pulses, measured over the entire surface of the anode, is \~100\ ps [5, 9, 11]. This result was first obtained in [11] with a resolution of the measuring system of \~100\ ps, and then confirmed in [3–7, 9] with a higher temporal resolution. When measuring the parameters of SAEB from only a small area of the anode surface, its duration was \~20\ ps [6, 7, 9]. Studies show that the duration of SAEB current pulses depends on many parameters. In particular, it was found that with an increase in gap distance, the SAEB current pulse duration increases [7]. However, such measurements were carried out under conditions of high overvoltages when applying voltage pulses with a subnanosecond and nanosecond rise time.

In practical applications, voltage pulses with a rise time of \(10^{-7}–10^{-6}\) s are widely used [12]. However, there are very few data on direct measurements of the parameters of runaway electron beams under these conditions. Noteworthy is the works [13–16], in which studies of SAEB were
carried out with the long rise time. Moreover, these studies were performed with a discharge in air at atmospheric pressure.

The main purpose of this work is to study the influence of the cathode design on amplitude-time parameters of runaway electron beams in air at a pressure 12.5–100 kPa and at applying voltage pulses with the rise time of 200 ns.

2. Experimental setups
The experiments were carried out on setups which allow studying the breakdown development and measuring subnanosecond runaway electron beam current pulses with temporal resolution up to 100 ps (figure 1).

![Experimental setups diagram](image)

**Figure 1.** (a) – Setup 1 for studying the discharge formation. (b) – Setup 2 for measuring runaway electron beam current.

A GIN-35NP homemade generator produced voltage pulses. Three different cathodes were used. The first one was made of a needle with a length of 5 mm, a base diameter of 1 mm, and a rounding radius of its tip of 75 μm. The second one was a tube with a diameter of 6 mm and a wall thickness of 100 μm. The third one was made of a ball with a diameter of 14 mm. The grounded electrode was a plane. The gap width was 8.5 mm. The generator produces negative voltage pulses with an amplitude of up to 35 kV, the rise time of 200 ns, and a pulse duration \( \tau_{0.5} \sim 270 \) ns. To measure the parameters of SAEB, the grounded plane electrode was made a copper disk having a 1-cm hole where a grid or a 2 μm kimfol (C_{16}H_{14}O_{3}) film coated with a 0.2 μm thickness aluminum layer were placed. The SAEB current was measured with a 20-mm collector placed behind the grounded electrode. The grid had a mesh size of 400 μm ×400 μm and a transparency of 62%. To exclude the influence of the electric field from the gap on the collector, two grids were used too. In this case, the total transparency was 38%. The kimfol film passes electrons with an energy of 10 keV and higher. A capacitive voltage divider (CVD) and a current shunt were applied to measure voltage and discharge current. The electrical signals from CVD and a current shunt were recorded with a Tektronix TDS3054B digital oscilloscope (0.5 GHz, 5 GS-s\(^{-1}\)). The electrical signals from the collector and CVD on the second setup (figure 1b) were recorded with a Keysight Tech MSOS804A digital oscilloscope (8 GHz, 20 GS-s\(^{-1}\)). The bandwidths of a current shunt made of chip resistors and the 20 mm collector were no higher than 4–5 and 6 GHz, respectively.

The plasma glow dynamics was studied using a HSFC PRO four-channel ICCD camera with a minimum gate width of 3 ns. The image of the discharge gap at the ICCD camera entrance was built using a quartz lens with a focal length of 26.7 cm. The diameter of the lens was 5 cm. It should be
noted that precisely due to the presence of four channels in the ICCD camera, it was possible to study the discharge development even with a large breakdown jitter. The trigger signal from the channel C1 of the ICCD camera was recorded on the Tektronix TDS3054B oscilloscope simultaneously with signals from CVD and the current shunt. This allowed us to synchronize ICCD images and the waveforms.

Discharge chamber was filled with atmospheric air with a humidity not higher than 50% or nitrogen with purity 99.99%. The pressure of gases was ranged from 12.5 to 100 kPa.

3. Results and discussion
Typical dynamics of breakdown development in the gap filled with nitrogen at a pressure of 50 kPa is shown in figure 2. Similar dynamics were observed in air. The change in pressure in the above range did not have a qualitative effect on the dynamics of discharge formation.

![Figure 2](image)

**Figure 2.** (a) ICCD images of the discharge in nitrogen at a pressure of 50 kPa. C1–C4 are channel numbers. (b, c) Waveforms of voltage and current pulses. Rectangles show the exposure duration and the moments of switching the ICCD camera channels.

It is seen that the ionization of the gas begins near the needle electrode and the formation of a ball streamer is observed. It bridges the gap in ~ 1 ns. Further the diffuse discharge is ignited. The streamer velocity decreased with increasing pressure and increased with decreasing one. At a gas pressure of 25 kPa and less, the formation time of the streamer was less than 1 ns. Under these conditions, ICCD images were obtained while simultaneously switching ICCD camera channels; however, the channels did not start synchronously due to jitter (~ 0.5 ns), which allowed to get images of a streamer at
different stages per one shot. In such conditions it is better to use streak cameras, which allow to observe the development of a discharge with a picosecond temporal resolution [17].

The formation of several cylindrical streamers was observed when using a tubular cathode, as well as a ball cathode. Studies have shown that the breakdown voltage strongly depends on the shape of the high-voltage electrode. In addition, the breakdown voltage changes greatly from pulse to pulse. Waveforms of voltage as well as SAEB current pulses measured behind the anode made of one grid at using of the needle cathode are shown in figure 3.

![Waveform images](image)

**Figure 3.** Waveforms of (a) voltage as well as (b–d) SAEB current pulses measured behind the anode made of one grid. Needle cathode. Air at a pressure of 100 kPa. 1, 2 – various discharge implementations.

An increase in the breakdown voltage (1 and 2) leads to an increase in the SAEB current pulse amplitude (figure 3b–d, curves 1 and 2). The SAEB current pulse duration was ~ 130 ps. The signal to noise ratio increased with increasing the SAEB current amplitude. When using the tubular cathode, the average breakdown voltage was lower than when using the needle cathode. In addition, the SAEB current amplitude also decreased. There was no breakdown when using the ball cathode at a gas pressures of 50 kPa and above. Thus, the comparison of the SAEB current parameters was performed at low pressures (12.5 and 50 kPa). The parameters were compared preferably at the same breakdown voltage. It was found that the shape of the cathode significantly affects the duration of SAEB current pulse, its amplitude and shape. The largest amplitudes (~ 90 mA) in these conditions were observed with the tubular cathode at a pressure of air of 12.5 kPa. The SAEB current pulse duration was $\tau_{0.5} \sim 150$ ps. Waveforms of voltage pulse and the corresponding SAEB current pulse are shown in figure 4.
Figure 4. Waveforms of (a) voltage as well as (b) SAEB current pulses measured behind the anode made of two grids. Tubular cathode. Air at a pressure of 12.5 kPa.

The SAEB current pulse shape approximately corresponded to that with the needle cathode at a pressure of 100 kPa and a breakdown voltage of 30 kV (figure 3). The SAEB current amplitude increased by more than 20 times due to a decrease in pressure, even with the anode made of two grids. As the pressure increased up to 25 kPa, the shape and duration of the SAEB current pulse did not change, but its amplitude decreased up to ~ 24 mA. Waveforms of voltage pulses and corresponding SAEB current pulses measured behind two grids with the needle cathode at air pressure of 12.5 kPa are shown in figure 5.

Figure 5. Waveforms of (a) voltage as well as (b) SAEB current pulses measured behind the anode made of two grids. Needle cathode. Air at a pressure of 12.5 kPa.

Two pulses with different duration, amplitude, and energy of electrons were observed with the needle cathode. This result was recently discussed in [16]. The pulse durations and their amplitudes were, respectively, ~ 140 and ~ 280 ps, ~ 55 and 110 mA. The first pulse is SAEB generating during the breakdown. This pulse was also observed when using the anode made of the kimfol. This means that the electron energy exceeded 10 keV. The second electron beam was generated after the streamer bridged the gap. Perhaps it was generated during the propagation of the second ionization wave. The electron energy did not exceed 10 keV. At a pressure of 25 kPa and higher, only the first beam was observed. At the same time, the pulse shape did not change, but its amplitude decreased.

When using the ball cathode, the duration and amplitude of the beam current pulses were $\tau_{0.5} \sim 250$ ps and ~ 4 mA, respectively, when applying the anode made of two grids (figure 6).
When using the ball cathode, the breakdown voltage noticeably decreased, which is opposite to expectations. This was observed only at low pressures. As noted above, at pressures of 50 and 100 kPa, there was no breakdown of the gap with the ball cathode.

Figure 6. Waveforms of (a) voltage as well as (b) SAEB current pulses measured behind the anode made of two grids. Ball cathode. Air at a pressure of 12.5 kPa.

4. Conclusion
The experimental studies show the complex dependence of SAEB parameters and breakdown voltages on the cathode design and gas pressures when applying voltage pulses with rise time of hundreds of nanoseconds. The specific feature of the discharge is that the breakdown and generation of runaway electrons occur at sufficiently low voltages. Under these conditions, plasma resistance can be quite high and the voltage across the gap decreases for a relatively long time (several ns). For this reason, the conditions necessary for the generation of runaway electrons can arise in the gap when the electric field in the plasma is redistributed after bridging the gap by a streamer. However, the shape of the cathode has a strong influence on this. Studies performed with the four-channel ICCD camera showed that the breakdown occurs via the development of streamers starting from the cathode. The diameter of the streamer depended on the radius of curvature of the cathode, and was the largest with the smallest radius of curvature (needle cathode).

Acknowledgments
The work is performed in the framework of the State task for HCEI SB RAS (project No. 13.1.4).

References
[1] Babich L P, Loiko T V and Tsukerman V A 1990 Phys. Usp. 33 521
[2] Babich L P 2003 High-Energy Phenomena in Electric Discharges in Dense Gases (Arlington: Futurepast) p 353
[3] Tarasenko V F and Yakovlenko S I 2004 Physics-Uspekhi 47 887
[4] Tarasenko V F 2016 Generation of Runaway Electron Beams and X-rays in High Pressure Gases, vol. 1: Techniques and Measurements, vol. 2: Processes and Applications (New York: Nova Science Publishers, Inc.) p 421
[5] Kostyrya I D, Rybka D V and Tarasenko V F 2012 Instrum. Exp. Tech. 55 72
[6] Rybka D V, Tarasenko V F, Burachenko A G and Balzovskii E V 2012 Tech. Phys. Letters 38 657
[7] Tarasenko V F, Rybka D V, Burachenko A G, Lomaev M I and Balzovsky E V 2012 Rev. Sci. Instrum. 83 086106
[8] Sharypov K A, Ul’masculov M R, Shpak V G, Shunailov S A, Yalandin M I, Mesyats G A, Rostov V V and Kolomiets M D 2014 Rev. Sci. Instrum. 85 125104
[9] Tarasenko V F and Rybka D V 2016 High voltage 1 43
[10] Zubarev N M, Yalandin M I, Mesyats G A, Barengolts S A, Sadykova A G, Sharypov K A,
Shpak V G, Shunailov S A and Zubareva O V 2018 *J. Phys. D: Appl. Phys.* **51** 284003

[11] Tarasenko V F, Shunailov S A, Shpak V G and Kostyrya I D 2005 *Laser Part. Beams* **23** 545

[12] Mesyats G A 2005 *Pulsed power* (New York: Springer) 568 p

[13] Babich L P and Loiko T V 2009 *Doklady Physics* **54** 479

[14] Kostyrya I D and Tarasenko V F 2015 *Plasma Phys. Rep.* **41** 269

[15] Sorokin D A, Tarasenko V F, Zhang C, Kostyrya I D, Qiu J, Yan P, Baksht E Kh and Shao T 2018 *Laser Part. Beams* **36** 186

[16] Tarasenko V F, Beloplotov D, Lomaev M I and Sorokin D 2019 *Plasma Sci. Tech.* **21** 044007

[17] Sorokin D A, Tarasenko V F, Beloplotov D V and Lomaev M I 2019 *J. Appl. Phys.* **125** 143301