Generation of runaway electrons beams during the breakdown of high-pressure gases

V F Tarasenko¹,², A G Burachenko¹ and E Kh Baksht¹

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

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

Abstract. Generation of run-away electrons in SF₆, CO₂, argon and nitrogen at high and super high pressures is studied. Super-short avalanches electron beams (SAEB) was obtained and measured with a collector at pressures up to 0.3, 0.7, 1.0 and 1.2 MPa in SF₆, CO₂, argon and nitrogen, respectively. The SAEB duration was shown to be ~60 ps (FWHM) and gas composition has only minor effect on the duration. It was found that in a gap of 4 mm in SF₆, CO₂, argon and nitrogen at pressure up to 0.3, 0.7, 1.0 и 1.2 MPa the voltage pulse duration (FWHM) and amplitude increase with pressure.

1. Introduction

By now it is shown that in high electric field generation of run-away electrons and x-rays due to electron action on an anode and ambient gas is a fundamental physical process, see reviews [1, 2] and monographs [3, 4], and references therein. Due to the run-away electrons and x-rays diffuse discharges can be formed in non-uniform electric fields at high gas pressure [5, 6]. Beams of run-away electrons are used for investigation of cathodoluminescence [7]. However, on many issues concerning the mechanism of runaway electron generation and parameters of runaway electron beams, the results obtained in different scientific groups differ substantially [1-6]. Besides, only two scientific groups have recorded the generation of beams of runaway electrons in various gases at pressures significantly exceeding the atmospheric one (>0.1 MPa). By now, only one scientific group have managed to detect runaway electron beams with collectors downstream of anode foils in helium [8] and for nitrogen [10]. Three main factors make difficult the detection of a runaway electron beam at a diode pressure higher than 1.0 MPa. First, increasing the gas pressure decreases the beam amplitude. Second, if we increase the gas pressure, we have to complicate the design of a gas diode. Third, it is required to use generators with a voltage amplitude of hundreds kilovolts and rise time shorter than one ns. Note that in work [11] of second scientific group, a runaway electron beam in nitrogen at pressure up to 4 MPa was detected from a scintillator luminescence, but neither the beam current amplitude and nor its duration dependence on pressure and other parameters were measured.

In this work, we present the SAEB parameters measured with collectors downstream of anode behind foils in SF₆, CO₂, argon and nitrogen at a pressure of 0.1–1.2 MPa. The SAEB parameters were measured with temporal resolution of ±50 ps.
2. Experimental setup

The setup with new modification pulser SLEP-150M [9, 10] was used in our experiments. Inner diameter of the transmission line and gas filed diode were reduced to 30 mm, which allows to work at high pressures. The output of the SLEP-150M pulser (part of transmission line), a gas filed diode, and a collector are shown on the figure 1.

Figure 1. Schematic of the output of the SLEP-150M pulser, gas filed diode, and collector with the 13-mm-diameter receiving area: (1) capacitive voltage divider, (2) transmission line of the pulser, (3) housing of the collector, (4) connection for gas pumping, (5) receiver part of the collector, (6) mesh, (7) foil, (8) tubular cathode in gas filed diode, (9) insulator.

SLEP-150M formed a voltage pulse with a duration of ~1 ns (FWHM) on a matched load. The voltage rise time was ~ 250 ps at a level of 0.1-0.9. The wave impedance of transmission line 2 was 100 Ohm. The voltage amplitude of incident wave in the transmission line was ~120 kV. The parameters of a SAEB were measured with the cathode that was made as a stainless steel foil tube of diameter 6 mm and thickness 100 μm. The anode of the gas diode was formed by 60-μm AlBe foil 7, reinforced with a grid 6 from the side of the collector 5. The collector receiving part 5 was 13 mm in diameter. The measuring equipment also included the capacitive voltage dividers 1. The signals from the dividers and collector were transmitted to a LeCroy WaveMaster 830Zi-A real-time digital oscilloscope (bandwidth 30 GHz, sampling increment 12.5 ps) via 5D-FB PEEG high-frequency cables (Radiolab) of length 1 m. High-frequency attenuators (Barth Electronics, model 142-NMFP) with a bandwidth of up to 30 GHz were used in measurements. The voltage and the SAEB current were measured simultaneously in each pulse. The time accuracy of SAEB was no worse than 50 ps. The SAEB generation time with respect to the voltage pulse was determined from capacitive current of collector for revealing one the foil was removed. This procedure is described in detail in [12].

3. Experimental results and discussion

We studied the SAEB generation for gap width \(d=4\) mm. The gap was decreased for increasing the parameter \(U_b/pd\), where \(U_b\) is the maximum (breakdown) voltage across the gap, \(p\) is the gas pressure. In the range of pressures from 0.1 to 1.2 MPa, we recorded waveforms of the gap voltage from the capacitive divider located near the gas diode, incident voltage wave in the transmission line, and SAEB current. The results are presented in figures 2, 3, 4, and 5. Figure 2 shows the breakdown voltage as a function of gas pressure. The breakdown voltage increases with pressure for all gases under study. The parameter values for each gas in figures 2, 3, 4 and 5 are presented for pressure range wherein the collector measured SAEB behind the foil. The voltage pulses duration (FWHM) for different gas pressures are presented in figure 3. The voltage pulse duration increases with the gas pressure. Peak duration in conditions of the SAEB current registration was obtained in \(N_2\) at 1.2 MPa. It is it follows from curves in figure 3 that during initial stage of gas breakdown a diffuse discharge is formed in the gap. In spark discharge the voltage pulse duration becomes shorter [9, 10].
Figure 2. Breakdown voltage versus gas pressure for N$_2$, CO$_2$, Ar and SF$_6$, $d = 4$ mm.

Figure 3. Voltage pulse duration (FWHM) as functions of gas pressure for N$_2$, CO$_2$, Ar and SF$_6$, $d = 4$ mm.

The SAEB current amplitudes and its durations (FWHM) for different gases and its pressures up to 1.2 MPa are shown in figure 4 and figure 5, respectively. The SAEB current amplitudes in N$_2$ and CO$_2$ at 0.1 MPa were similar. At higher pressures, maximal SAEB amplitudes were obtained in nitrogen. The SAEB amplitude was minimal in Ar, probably due to low breakdown voltage, see figure 2. However, at 0.2-0.3 MPa minimal SAEB amplitude was measured in heavy gas SF$_6$ when the breakdown voltage is relatively high. The SAEB current and the voltage were synchronized reasoning
that the maximum SAEB amplitude under optimum conditions roughly corresponds to the breakdown (maximum) voltage across the gap [9, 10, 12]. It is seen from figure 5 that the SAEB has duration (FWHM) of about 60 ps and that its decay is shorter than the decay of the gap voltage. This is because most of the runaway electrons are produced on the front of an ionization wave moving from the sharp-ended cathode to the anode [13, 14]. Once the ionization front reaches the anode, the electric field in the gap becomes lower its critical value, and the generation of runaway electrons ceases.

Figure 4. SAEB amplitude vs different gases pressure at $d = 4$ mm.

Figure 5. SAEB pulse duration (FWHM) vs different gases pressure at $d = 4$ mm.

The presented dependences are rather typical for high pressures [8–10]. Although the breakdown voltage at $d = 4$ mm increases (figure 2), the SAEB amplitude decreases (figure 4). The highest SAEB
amplitudes were obtained in nitrogen at $p = 0.1-0.2$ MPa, which is the minimum pressure in this experiments. Note that the collector detects only part of the runaway electrons, i.e., those arriving at its receiving area of diameter 13 mm. Moreover, the AlBe foil absorbs the electrons with energies less than 40 keV.

4. Conclusion
Thus, we studied the generation of a supershort avalanche electron beam (SAEB) in different gases (SF$_6$, CO$_2$, argon and nitrogen) at high pressures. The beam parameters were measured with a collector for the first time at an argon pressure up to 1.0 MPa, at a CO$_2$ up to 0.8 MPa and at a SF$_6$ up to 0.3 MPa. Our experiments demonstrate that at SF$_6$, CO$_2$, argon and nitrogen pressure higher than 0.1 MPa, the mechanism of SAEB generation remains the same. Most of the runaway electrons are produced between the ionization front, which bridges the gap, and the anode, and this is in the agreement with experimental [1, 13, 14] and theoretical data [15].

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