Generation of runaway electron beams in high-pressure nitrogen

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Abstract. In this paper the results of experimental studies of the amplitude-temporal characteristics of a runaway electron beam, as well as breakdown voltage in nitrogen are presented. The voltage pulses with the amplitude in incident wave $\approx 120$ kV and the rise time of $\approx 0.3$ ns was used. The supershort avalanche electron beam (SAEB) was detected by a collector behind the flat anode. The amplitude-time characteristics of the voltage and SAEB current were studied with subnanosecond time resolution. The maximum pressure at which a SAEB is detectable by collector was $\approx 1$ MPa. This pressure increases with decreasing the voltage rise time. The waveforms of the discharge and runaway electron beam currents was synchronized with the voltage pulses. The mechanism of the runaway electron generation in atmospheric-pressure gases is analyzed on the basis of the obtained experimental data.

1. Introduction

The generation of runaway electron beams in high-pressure gases with sharp-ended electrodes or so-called electrodes with a small curvature radius is a fundamental physical phenomenon that determines the delay of breakdowns and the properties of discharges. By now, several scientific groups have managed to detect runaway electron beams with collectors downstream of anode foils in air and other gases at a delay of $\approx 0.1$ MPa [1, 2], and only one scientific group has reported on detection of such a beam with a collector at $\approx 0.2$ MPa and higher and on measurements of the beam current amplitude and its pressure dependence in different gases [3–5]. The highest pressure at which a runaway electron beam was detected with a collector was 0.4 MPa for nitrogen [3], 0.2 MPa for SF$_6$ [4], and 1.2 MPa for helium [5]. There are three main factors that make difficult the detection of a runaway electron beam at a diode pressure higher than 0.2 MPa. First, increasing the gas pressure decreases the beam amplitude. Second, if we increase the gas pressure, we have to complicate the design of an experimental setup. Third, it is required to use generators with a voltage amplitude of hundred kilovolts and rise time shorter than a nanosecond. Note that in some studies, a runaway electron beam in nitrogen at up to 4 MPa was detected from luminescence of a scintillator [6, 7], but neither the beam current amplitude and duration nor their dependence on pressure and other parameters were measured.

Here we investigate the parameters of a supershort avalanche electron beam (SAEB), which is a runaway electron beam downstream of an anode foil [8], in nitrogen at a pressure of 0.2–1 MPa.

2. Experimental setup

The setup with new modification pulser SLEP-150M [9] was used in our experiments. To work at high pressures were reduced to 30 mm inner diameter of transmission line and gas filed diode. The output of
pulser SLEP-150M (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 dividers, (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 FWHM of ~1 ns at 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 AlBe foil 7 60-µm-thickness reinforced with a grid 6 from the side of the collector 3. The collector receiving part 5 was 13 mm in diameter. The time resolution of the collector reached 50 ps. The measuring equipment also included the capacitive voltage dividers 1. The signals from the dividers and collector were transmitted to a DSO-X6004A real-time digital oscilloscope (bandwidth 6 GHz, sampling increment 50 ps) via 5D-FB PEEG high-frequency cables (Radiolab) of length 1 m. For signal of voltage attenuation, we used high-frequency attenuators (Barth Electronics, model 142-NMFP) with a bandwidth of up to 30 GHz.

The voltage and the SAEB current were measured simultaneously in each pulse. The timing accuracy of SAEB and voltage pulses was no worse than 100 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 [10]; the timing accuracy of voltage and SAEB current pulses with a LeCroy WaveMaster 830Zi-A real-time digital oscilloscope (bandwidth 30 GHz, sampling increment 12.5 ps) was no worse than 10 ps.

3. Experimental results and discussion

In our experiments, we studied the generation of a SAEB at a nitrogen pressure of 0.2–1 MPa for three gap widths which were smaller than 12 mm optimal at a nitrogen pressure of 0.1 MPa [11]. 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 nitrogen pressure, and $d$ is the gap width. In the range of nitrogen pressures from 0.2 to 1 MPa, we recorded waveforms of the gap voltage, incident voltage wave in the transmission line, and SAEB current. The results are presented in figures 2, 3, and 4. Figure 2 shows typical waveforms of the voltage from the capacitive divider located near the gas diode and of the SAEB current. The voltage and the SAEB current were synchronized reasoning that the maximum SAEB amplitude under optimum conditions roughly corresponds to the breakdown (maximum) voltage across the gap [10]. It is seen from figure 2 that the SAEB has a FWHM of about 90 ps and that its decay is shorter than the decay of the gap voltage. This is because most of the runaway electrons are produced at the front of an ionization wave moving from the sharp-ended cathode to the anode. Once the ionization front reaches the anode, the electric field in the gap decreases to less than its critical value and the generation of runaway electrons ceases.
Figure 2. Voltage and SAEB current at $p = 0.8$ MPa and $d = 4$ mm.

The breakdown voltage as a function of nitrogen pressure at $d = 8$ mm, 4 mm, and 1 mm is shown in figure 3.

Figure 3. Breakdown voltage vs nitrogen pressure at $d = 1$ mm (1), 4 mm (2), and 8 mm (3).

It is seen from figure 3 that increasing the nitrogen pressure from 0.2 to 1 MPa increases the breakdown voltage at $d = 8$ mm and 4 mm. At $d = 1$ mm, the dependence is different: $U_b$ decreases with increasing the pressure; however, at more than 0.5 MPa, the SAEB is also detected by the collector. As the pressure is increased from 0.2 to 1 MPa, the SAEB amplitude decreases for all three gaps (figure 4).

The presented dependences are rather typical for high pressures [3–6]. Although the breakdown voltage at $d = 4$ mm and 8 mm increases (figure 3), the SAEB amplitude decreases (figure 4). The highest SAEB amplitudes were obtained at $d = 8$ mm and 0.2 MPa, which is the minimum pressure in the 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 electrons with energies less than 40 keV are absorbed by the AlBe foil.
Figure 4. SAEB amplitude vs nitrogen pressure at \( d = 1 \) mm (1), 4 mm (2), and 8 mm (3).

Thus, our experiments demonstrate that at a nitrogen pressure higher than 0.2 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 [8], and this is confirmed by experimental and theoretical data [1, 2].

4. Conclusion

Thus, we studied the generation of a super short avalanche electron beam (SAEB) in nitrogen at a pressure of 0.2–1 MPa for gap widths of 1, 4, and 8 mm. The beam parameters were measured for the first time at a nitrogen pressure higher than 0.5 MPa. It is shown that on the SLEP-150M generator with a transmission line diameter of 30 mm, the SAEB amplitude decreases with increasing the nitrogen pressure from 0.2 to 1 MPa, whereas the breakdown voltage under these conditions increases at \( d = 4 \) mm and 8 mm and decreases at \( d = 1 \) mm.

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4