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Effect of emission on subnanosecond breakdown in a gas diode at low pressure

E.Kh. Baksht [a, *], S.Ya. Belomyttsev [a], A.G. Burachenko [a, b], A.A. Grishkov [a], V.A. Shklyaev [a, c, **]

[a] Institute of High Current Electronics, Russian Academy of Sciences, 2/3 Akademichesky Ave., 634055 Tomsk, Russia
[b] Tomsk State University, 36 Lenin Ave., 634050 Tomsk, Russia
[c] Institute of High Technology Physics, National Research Tomsk Polytechnic University, 30 Lenin Avenue, 634050 Tomsk, Russia

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The paper presents experimental and numerical research results on the operation of a gas diode at low pressure. A large scattering in runaway electron beam current (from 20 to 100 A) with regard to the average (~50 A) is observed for a tubular cathode with a working edge radius of 30 μm, nitrogen pressure of 40 mbar, and interelectrode gap of 6 mm. Numerical simulation data show that the low beam current (~20 A) is due to early electron emission from the cathode (at the stage of low-voltage prepulse) in which the runaway electron beam is formed from the boundary of a plasma layer developed early in the breakdown. The high beam current (~100 A) is due to delayed electron emission from the cathode, which increases the diode voltage and the runaway electron beam current. In the latter case, the runaway electron beam is formed directly at the cathode.

1. Introduction

By now, many research papers have been published on the generation of runaway electron beams in gas diodes with a highly inhomogeneous electric field, considering the possibility to obtain such beams in different gases and at different pressures, the mechanisms of their generation and their parameters depending on the interelectrode gap width as well as on the cathode material and design, the range of their possible applications, etc. [1–6]. However, the generation stability of runaway electron beams, which is no less important, is addressed only in [7, 8], paying attention to the onset of cathode operation in the steady-state mode (conditioned cathode) without considering the dependence of the beam current scattering on the gas diode parameters.

In experiments with gas diodes, the current of a runaway electron beam can differ greatly from pulse to pulse under the same operating conditions. The stability of the beam current is influenced by different factors. Our previous studies show that in nitrogen at a pressure of 40 mbar, the duration of the beam current is limited by the anode foil which precludes the passage of electrons with energies below the threshold determined by the foil thickness [9, 10]. In this case, the beam current depends on the maximum voltage across the discharge gap (breakdown voltage), and at the same voltage rise time, it depends, in fact, only on the emission characteristics determined by the state of the cathode surface. Thus, the only factor that can be responsible for the beam current scattering under such conditions is the state of the cathode surface varying from pulse to pulse.

The objective of our experimental and numerical study was to investigate the effect of cathode emission on the generation stability and parameters of a runaway electron beam at the onset of the cathode to a steady-state mode. Clearly, the stability of the beam parameters depends strongly on the voltage rise time, discharge chamber geometry, cathode design, gas pressure, and state of the cathode emitting surface. Whereas most of these parameters can be fixed or recorded on diagnostic equipment, the state of the cathode surface changes from shot to shot, and this can lead to an uncontrollable scattering in the parameters of a runaway electron beam. For studying the influence of cathode emission on the parameters of runaway electron beams, we considered pulses in which the rise time of incident voltage wave and the voltage amplitude were identical. As has been shown [10], the duration of

* Corresponding author.
** Corresponding author. Institute of High Current Electronics, Russian Academy of Sciences, 2/3 Akademichesky Ave., 634055 Tomsk, Russia.
E-mail addresses: beh@loi.hcei.tsc.ru (E.Kh. Baksht), shklyaev@to.hcei.tsc.ru (V.A. Shklyaev).

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the beam current in nitrogen at a pressure of 40 mbar is limited by the foil separating the diode and the beam measuring unit and precluding the passage of electrons with energies below 40 keV; that is, the beam current amplitude at such pressures depends only on the time of onset of emission processes at the cathode.

2. Experiment

In our experiments, we used a SLEP-150 nanosecond generator connected to a transmission line filled with transformer oil and to a gas diode (Fig. 1). The anode was an Al foil of thickness 15 μm (3) and a metal diaphragm of diameter 10 mm (2). The foil at its back was reinforced with grids of total transparency 6.6% which, in addition to reinforcement, provided attenuation of the beam current. The cathode (1) was a stainless steel tube of diameter 7.3 mm with a working edge 30 μm thick. The amplitude of incident voltage wave in the transmission line was ~120 kV with a rise time of ~250 ps at a level of 0.1–0.9, and its FWHM with a matched load was ~1 ns

Fig. 2 presents experiment data on the stability of the runaway electron beam current in a sample of 300 pulses. It is seen that the beam current ranges from 20 A to 100 A. Reasoning that all pulses were produced in a single series at a pressure of 40 mbar, it can be stated with confidence that it is the state of the emission surface which influences the beam current under these conditions.

3. Numerical simulation

For elucidating the effect of the emission surface on the beam current amplitude, we simulated the breakdown developing under the experimental conditions using the 2.5D (2D3V) axisymmetric PIC-code XOOPIC [11].

The computational domain included the diode with part of the transmission line and beam current measuring unit.

The emission was described using a model [10] covering both field emission (early breakdown stage) and transition to explosive emission (unlimited emission ability of the cathode). The field emission was described by a modified Fowler–Nordheim formula for a cathode covered with microprotrusions having different amplification factors β. The above-mentioned formula includes an average amplification factor $<\beta>$ characterizing the state of its emission surface:

$$\langle j_{FN}\rangle(E) = \sqrt{\pi}AB^2\varphi^2\cdot\exp\left(-\frac{2}{\alpha}\right)\cdot\left\{1+2\sqrt{\frac{\alpha}{\pi}}+\frac{\alpha}{2}\right\}, \quad (1)$$

where $\alpha = \sqrt{\frac{\langle\beta\cdot E_{macro}\rangle}{B\varphi^{3/2}}}$; $\langle\beta\rangle$ is the average electric field amplification at the microprotrusions: $\langle\beta\rangle = 4-8$ [12].

The average current density estimated by formula (1) was multiplied by the total surface area $I_{FN} = \langle j_{FN}\rangle\cdot S_C$ with calculation of the coefficient K for field-to-explosive emission transition:

$$\eta_t = \sum_t I_{FN}(t)^2\cdot\Delta t, \quad (2)$$

$$K = \frac{\eta_t}{\eta_0}, \quad (3)$$

where η_0 is equivalent to h being the specific action for explosion [13] but, unlike h calculated for the current density, η_0 is selected for the total current from the cathode. This is because in the axisymmetric approximation used, we can not describe individual microprotrusions, and experiments give only a general idea about emission properties of the cathode. The emission current was calculated by the expression

$$I_{em} = (1-K)\cdot I_{FN} + K\cdot I_{ex} \quad (4)$$

where I_{ex} is the explosive emission current calculated using the Gauss theorem [11]. The electron emission form the cathode was specified by two parameters: $\langle\beta\rangle$ for the onset of emission early in the breakdown and η_0 for the time of field-to-explosive emission transition.

The emission parameters $\langle\beta\rangle$ and η_0 were varied so that the beam current measured by the collector and the voltage at the third divider would coincide with their experimental values corresponding to the highest and lowest currents on the histogram in Fig. 2, because the generation of runaway electrons and the breakdown dynamics at these values can differ greatly.

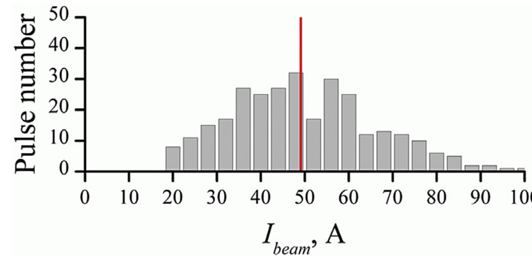

Fig. 2. Histogram of the runaway electron beam current (gap width 6 mm, cathode rounding-off radius 30 μm, nitrogen pressure 40 mbar).

4. Simulation results

Fig. 3 presents experimental waveforms of the voltage from divider U_3 in the transmission line (grey solid curves) and respective waveforms calculated by integrating the r-component of the

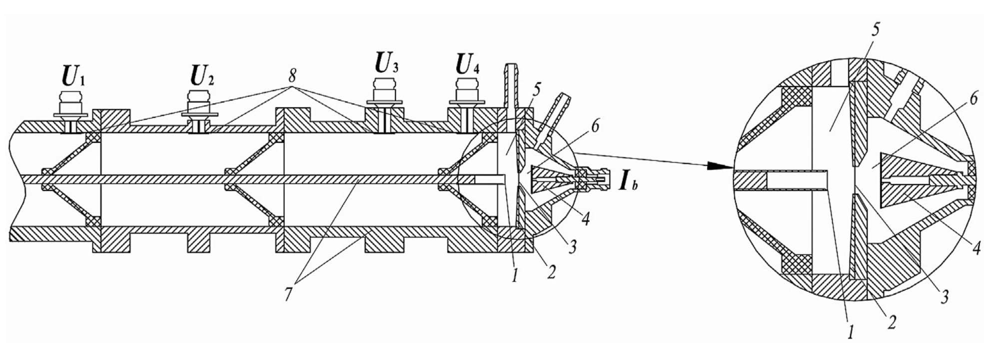

Fig. 1. Transmission line and gas diode: 1 – cathode; 2 – diaphragm; 3 – Al foil; 4 – collector; 5 – gas diode; 6 – drift space; 7 – transmission line; 8 – capacitive dividers.