Time behavior of an electron beam current pulse in the axial and peripheral zones of an anode in vacuum and gas-filled diodes

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Abstract. The study of the time behavior of a current pulse of an electron beam generated during a high-voltage nanosecond discharge in gas-filled and vacuum diodes has been carried out. As follows from the experimental results, in both cases, the distribution of the beam current density in the plane of a grounded anode is non-uniform. The highest beam current density is recorded in the axial part of the anode. It was established that in the case of a gas-filled diode, ~ 2 ns after the onset of the beam current pulse, its shape in the axial anode zone changes relative to that in the peripheral one. It is assumed that the most probable reason for this is the effect of compensation of the charge of the beam electrons by the positive charge of ions arising in the ionization process in the paraxial zone.

1. Introduction
From a practical point of view, the self-focusing effect of an electron beam is attractive, first of all, by the possibility of increasing the beam current density and, accordingly, increasing the power density in a cumulation zone [1–3]. This effect can be used to generate highly ionized plasma and powerful X-ray radiation, in the study of matter at elevated pressure and thermonuclear research [4], in the fields of radiation chemistry and solid state physics [5], to generate powerful radiation in the terahertz frequency range [6], to excite luminescence of artificial and synthetic crystals [7, 8] and in other applications. It was found that at currents of dozens–hundreds of kA, an electron beam is focused by its own magnetic field. At the same time, at currents of no more than 2 kA, the electron beam self-focusing effect is interpreted in different ways. Among the reasons for this effect in various papers are the following: the formation of conductive plasma jets from cathode spots [9]; electrostatic repulsion of electrons [4] formed at the early stage of a discharge; runaway breakdown [10] and others.

In the present study, by recording the time behavior of the beam current in the paraxial and peripheral zones of an anode, the effect of self-focusing of an electron beam formed during a high-voltage nanosecond discharge in gas-filled and vacuum diodes was investigated.

2. Experimental setup and measuring techniques
In the experiments, a RADAN-220 voltage pulse generator [11] was used to form a high-voltage nanosecond discharge. A diode, providing a sharply inhomogeneous distribution of the electric field
strength, was used as a load for this generator. A schematic of the system for recording the electrical parameters of the discharge and the design of a gas-discharge chamber are shown in figure 1.

![Figure 1. Experimental setup](image)

**Figure 1.** Experimental setup: 1 – transmission line of a high-voltage generator RADAN-220; 2 – insulator; 3 – 4-mm-diameter tubular cathode; 4 – foil grounded anode; 5 – capacitive voltage divider; 6 – current shunt; 7 – collector; 8 – digital oscilloscope.

By means of a transmission line 1, a high-voltage pulse was delivered from the RADAN-220 generator to the interelectrode gap formed by a potential cathode 3 and a grounded flat anode 4. The cathode was in the form of a hollow tube with an outer diameter of 4 mm and was made of 100-μm-thickness stainless steel foil. Copper or aluminum foils with the thickness from 15 to 400 μm were used as the anode. A gap width was varied from 1 to 5 mm. The discharge was ignited in air at a pressure from 10 to 10⁻⁵ Torr. Electrical signals from a capacitive voltage divider 5, current shunt 6, and collector 7 were recorded with a Keysight DSO-X6004A digital oscilloscope 8 with a bandwidth of up to 6 GHz and a sampling rate of up to 20 GS/s. The time resolution of the collector was ≈80 ps. Integral images of the discharge plasma glow were captured through the side window of the discharge chamber with a SONY A 100 digital camera.

3. **Experimental results and discussion**

During the experiments, it was found that both in the case of vacuum and gas-filled diodes, the distribution of the electron beam current density in the plane of the grounded anode is non-uniform. The highest beam current density is achieved in the axial zone of the anode. An integral photo of the cathodoluminescence of a 1-mm-thickness Plexiglas plate mounted close to the anode and made of a 15-μm-thickness aluminum foil is presented in figure 2. It can be seen from the figure that the e-beam current flow zone in the anode plane is a combination of radially directed "rays" and a bright spot in the center with a diameter of ≈1.5 mm. This, in turn, indicates the non-uniformity of the distribution of the electron beam current density, both in the radial and azimuthal directions.

An integral image of the discharge plasma glow and the gas-discharge gap with traces of erosion of the grounded anode in the focusing zone of the electron beam are shown in figures 3 (a) and 3 (b), respectively. Figure 3 (a) clearly shows the concentrated discharge glow in the axial zone and bright spots on the anode surface on a circle with a diameter of about 1.5 mm. Figure 3b demonstrates traces
of the electron beam impact on the anode surface. The diameter of the electron beam focusing zone on the anode surface is about 1.5 mm as well. When using an anode made of an aluminum foil with the thickness of 20 µm at the air pressure of 0.2 Torr a through hole with the diameter of ~ 1.5 mm formed in the foil as a result of 3–5 pulses. In the case of a 50-µm-thickness copper foil under optimal conditions for the self-focusing effect, not less than 70 pulses were required for the through hole appearance.

To record the time behavior of the electron beam current pulses in the paraxial zone of the anode, a 15-µm-thickness aluminum foil and a shield installed behind it made of a 400-µm-thickness copper plate with an aperture of 1 mm in diameter on the diode axis were used. When recording a waveform of the beam current at the distance of 2.5 mm from the axis, a shield made of a 400-µm-thickness copper plate with four apertures of 1 mm in diameter located along a circle of 5 mm in diameter at an equal distance from each other was installed behind the foil. Placing the aluminum foil excluded the field signal (electromagnetic noise) from the collector, while the use of screens ensured the registration of the e-beam current that passed through the holes. It was found that, in the case of the gas diode at the pressure of 0.2 Torr, ≈ 2 ns after the onset of the beam current pulse, the self-focusing effect is enhanced. This is manifested in the fact that the time behavior of the current pulses of the beam passing through 1 hole located on the axis, and through 4 holes located at a distance of 2.5 mm
from the axis, differ significantly (figure 4). As can be seen from the figure, the beam current pulse in the axial zone (curve 1) has a slightly longer duration (FWHM), as well as a higher intensity of the 2nd and 3rd pulse peaks. The difference in the shape of the pulses begins ≈ 2 ns after the onset of the beam current pulse. We assume that the probable cause of the effect of additional self-focusing of an e-beam in the case of the gas diode is the compensation of the charge of the beam electrons by the positive charge of ions arising in the process of air ionization.

![Figure 4](image-url)  
**Figure 4.** Waveforms of the e-beam current in absolute (a) and relative (b) units in the axial zone (1) and at the distance of 2.5 mm from the axis (2).

4. Conclusion
The time behavior of the electron beam current pulse under conditions of the high-voltage nanosecond discharge in gas-filled and vacuum diodes was studied experimentally. It was shown that the e-beam current density distribution in the plane of a grounded anode is non-uniform and its highest value is recorded in the axial part of the anode. When the diode filled with gas (air), the e-beam current pulse shape in the axial anode zone changes after some time (≈ 2 ns) in comparison with the peripheral anode zone. This effect, in our opinion, can be associated with the compensation of the charge of the beam electrons by the charge of positive ions produced in the paraxial zone of the diode due to ionization processes.

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