Russian Physics Journal, Vol. 62, No. 6, October, 2019 (Russian Original No. 6, June, 2019)

CUMULATION OF A HIGH-CURRENT ELECTRON BEAM DURING A NANOSECOND HIGH-VOLTAGE DISCHARGE IN A LOW-PRESSURE DIODE

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UDC 537.533.79

The results of an experimental investigation of the effect of cumulation of a beam of runaway electrons formed in a high-voltage nanosecond discharge at a reduced air pressure are presented. The optimal conditions of this effect in a discharge gap in a tubular cathode – grounded planar anode geometry were achieved at an air pressure of ≈5 Pa and an interelectrode gap of 2.75 mm. An electron-beam current pulse is recorded with a high time resolution (up to about 80 ps) behind the flat foil anode. It is found out that due to this effect a through hole is formed in a 20 μm-thick aluminum foil after 2–3 discharge pulses. The results obtained suggest that the electron energy in the second part of the beam current pulse is lower than that in its first part.

Keywords: electron beam cumulation effect, runaway electrons, high-voltage nanosecond discharge**.**

INTRODUCTION

The phenomenon of cumulation of relativistic electron beams (REBs) has been known for quite a long time [1]. This effect was observed at the currents exceeding the Alfven current: $I_A = 17\beta\cdot\gamma$, where $\beta = \upsilon/c$, $\gamma = 1/(1-\beta^2)^{1/2}$ – relativistic factor, υ – electron beam velocity, and c – velocity of light. In the experiments with REBs, the beam currents were generally within the range 100–200 kA, so they considerably exceeded the Alfven current (~20 kA). It has been found out that the beam is focused by its self-magnetic field, in which case the plasma formed in the cathode-anode gap plays an important role [1]. On the other hand, it is well known that the beam density inhomogeneities under the conditions of a vacuum breakdown give rise to the anode erosion at the currents lower than 500 A [2, 3].

Recently there is an increased interest in the study of filamentation and self-focusing of electron beams in vacuum and gas diodes at comparatively low electron accelerator currents (~1 kA) [4–9]. A distinguishing feature of these experiments is the fact that the accelerator currents were much lower than the Alfven current. On the other hand, in a number of studies at the voltage pulse durations of tens – hundreds of nanoseconds holes were observed in thick foils [6, 9]. For the voltage pulse durations of a few nanoseconds, the investigations of self-focusing were performed only in gas diodes at the pressures of hundreds – thousands of Pascals [4, 9]. Under these conditions no considerable damage of the foil was observed.

This study aims at investigating the influence of air pressure on electron beam cumulation at the voltage pulse duration of a few nanoseconds and determining the conditions at which the foil suffers the largest damage.

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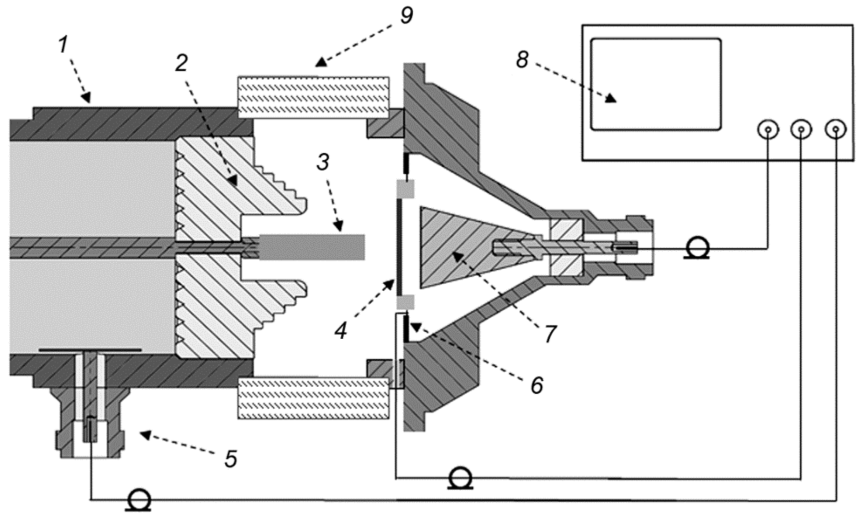

Fig. 1. Gas-discharge chamber design and scheme of discharge parameter diagnostics: *1* – transmission line of a RADAN-220 generator, *2* – insulator, *3* – cathode, *4* – anode, *5* – capacitive voltage divider, *6* – current shunt chip-resistors, *7* – collector, *8* – oscilloscope, *9* – quartz side window.

EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

In the experiment a RADAN-220 high-voltage pulsed generator was used [10] with a gas diode switched to it. The gas chamber design and the schematics of the discharge electrical parameter diagnostics are presented in Fig. 1. The generator produced voltage pulses of negative polarity with an amplitude in the incident wave of up to about 120 kV with FWHM on the matched load and pulse-front duration ≈2 and ≈0.5 ns, respectively. The energy store of the generator pulse-forming line was ≈2 J. The voltage pulse was supplied from the generator to the electrodes of the gas-discharge chamber via the transmission line *1*. The discharge was initiated in the gap between the potential cathode *3*, made in the form of a hollow tube with the outer diameter 4 mm and was grounded by a flat anode *4*. The tube was made from a stainless steel foil 100 μm in thickness. The anode was a copper or aluminum foil with a thickness from 20 to 100 μm. The interelectrode length was varied from 1 to 5 mm. The discharge was ignited in air at the pressure from 10^5 to 3 Pa. The evacuation of the chamber and the residual pressure measurements were carried out with a 2NVR form-vacuum pump and a VO vacuum gage within the range of pressures from 10^5 to 100 Pa and by a PMT-4M thermocouple gage-head at a pressure below 100 Pa.

The discharge electrical parameters were registered with a capacitive voltage divider *5*, and a current shunt *6*, based on the low-inductance chip-resistors with the typical size 1206. The time variation of the current of a beam of runaway electrons behind the anode plane *4*, which were generated in the discharge gap, were registered by a collector *7* with the receiver portion diameter 20 mm. The collector time resolution was ≈80 ps. For the registration of electric pulses we used the 5D-FB high-power coaxial cables and N-type connectors, 142-NM Barth high-voltage pulse attenuators, and a KeySight DSO-X6004A oscilloscope with the band pass range up to 6 GHz and the discretization rate up to 20 GS/s. The form of the discharge was photographed through a side window *9* using a Sony A 100 camera.

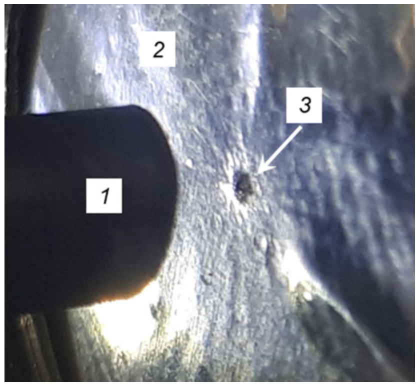

Fig. 2

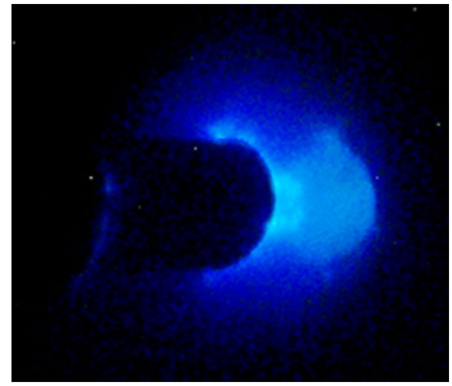

Fig. 3

Fig. 2. Discharge gap photo: *1* – cathode, *2* – anode made of a 20 μm-thick aluminum foil, *3* – ≈1 mm-thick through-hole in the foil, formed after 3 discharge pulses. Interelectrode gap length – 2.75 mm, residual air pressure in the chamber ≈5 Pa.

Fig. 3. Discharge photo. Experimental conditions the same as those in Fig. 2.

RESULTS AND DISCUSSION

The phenomenon of the beam electrons has been investigated in a wide range of residual air pressures in the discharge chamber from 10^5 to 3 Pa and interelectrode gap lengths from 1 to 5 mm. The beam electron cumulation effect was most conspicuous at the pressure ≈5 Pa and interelectrode gap 2.75 mm. A through hole appeared on the 20 μm-thick aluminum-foil grounded electrode surface after 2–3 pulses (Fig. 2). An integral photograph of the discharge under these conditions in presented in Fig. 3. The hole diameter increased with the number of pulses, and after 100 pulses was found to be ≈1.5 mm. When a thicker foil, or a copper foil of the same thickness, was used instead of the aluminum one, more pulses were necessary for the hole to appear. For instance, in a 50 μm copper foil under the optimal beam electron cumulation conditions more than 70 pulses were necessary for the through hole to appear. A decrease in the foil thickness, the formation of a through hole in the point of the beam incidence on the foil surface, and an increase in the hole diameter with the number of pulses led to a change in the beam current amplitude and temporal pulse shape of the beam current recorded behind the foil plane.

Figure 4*a* presents the voltage, discharge current, and beam current pulses recorded after installation of a 50 μm aluminum foil for the first 5 pulses. As the number of pulses is increased, the amplitude and the time variation of the beam current pulse, recorded on the collector, change (Fig. 4*b*). The beam current pulse amplitude is monotonically increasing as the number of pulses is increased and the foil thickness is decreased in the point of the beam incidence and a subsequent formation of a through hole, which suggests a considerable weakening of the electron beam during its penetration through the foil metal. At the same time, an increase in the beam current pulse duration with the number of discharge pulses indicates lower electron energy in the stage of the discharge current decreasing. In particular, the conditions of beam current registration, which correspond to Curves *1*, *2* and *3* in Fig. 4*b* differ only in the foil surface states in the area of the beam incidence: Curve *1* corresponds to the initial foil state, and Curves *2* and *3* – passage of a part of the electron beam through a metal layer of lesser thickness, and the remaining part of the beam – via the through hole. The form of the curves suggests that when the electron beam penetrates through the foil of the initial thickness, the beam current pulse duration in the base is ≈4 ns, and after a hole appears in the foil – ≈8 ns. It follows from this that the beam electron energy in the second part of the pulse is insufficient for the beam to penetrate

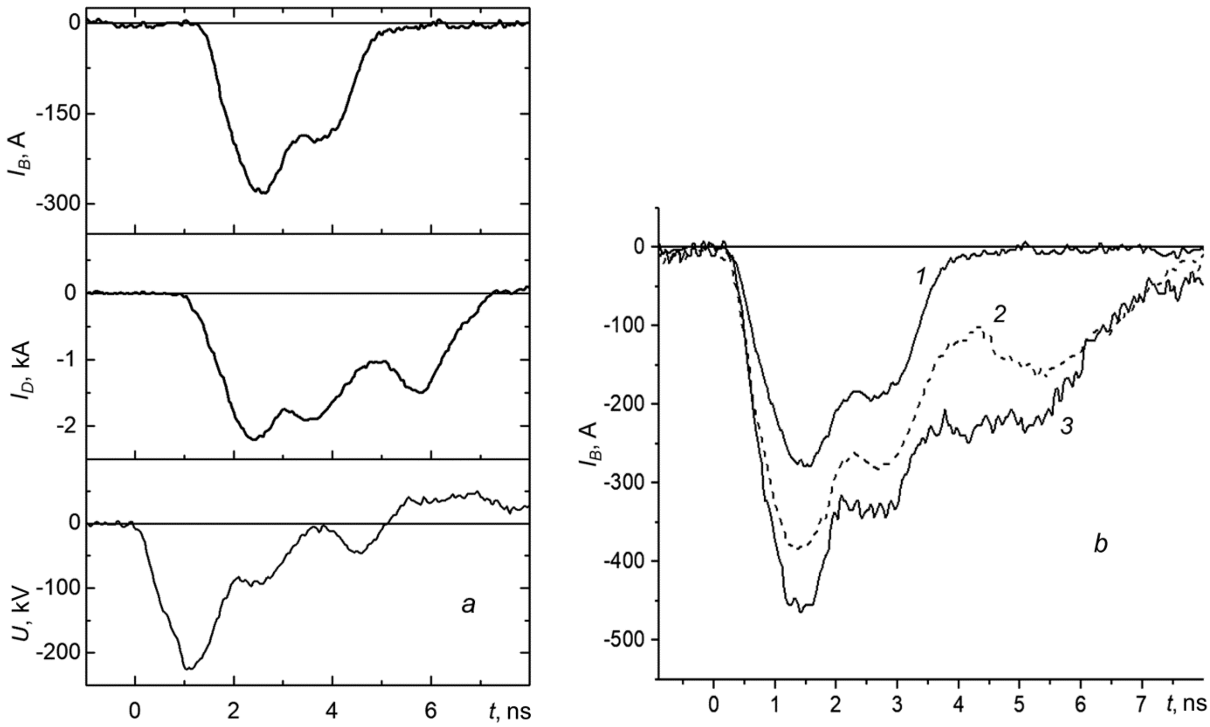

Fig. 4. Pulse waveforms: *a* – voltage from the capacitive voltage divider *U*, discharge current I_D runaway electron beam current I_B, registered behind the 50 µm aluminum foil for first 5 discharge pulses, *b* – beam current I_B after the first 5 (Curve *1*), 25 (Curve 2) and 50 (Curve *3*) discharge pulses. The interelectrode gap length 2.75 mm, air pressure in the chamber ≈5 Pa.

through the foil of the initial thickness. It should be noted that the voltage pulse and discharge current oscilloscope traces were independent of the number of accelerator pulses and foil fracture.

The results obtained in this study can be accounted for by the electron-beam self-focusing, which is enhanced within a certain range of the residual gas pressures due to positive ions generated by the runaway electrons in the discharge gap. An important issue for reaching the self-focusing threshold is electron emission from the cathode spots, resulting in a higher beam current density in local areas. The cathode spots are clearly seen through the window on the accelerator butt end, when the foil is replaced by a grid.

CONCLUSIONS

In this study an experimental investigation of the effect of cumulation of a high-current electron beam has been investigated in a high-voltage nanosecond discharge in air at the pressures from 10^5 to 3 Pa in a discharge gap in a tubular cathode – grounded flat anode geometry and interelectrode gap from 1 to 4 mm. It has been found out that the effect of beam cumulation is most clearly observed at the air pressure ≈5 Pa and the distance between the electrodes 2.75 mm. A through hole was formed on the 20 µm-thick aluminum foil surface in the point of the electron beam incidence on the foil. Its diameter was as large as ≈1.5 mm after 100 discharge pulses. Beam current pulses have been recorded with a high (up to 80 ps) temporal resolution when the electrons passed through the foil of initial thickness, and also when the thickness was reduced and a through hole was formed in it. The results obtained imply a generation of electrons with the duration approximately equal to that of the discharge current under the conditions in question. The electron energy in the first part of the beam current pulse is however essentially higher than that in the second part of the pulse.

The reported study has been funded within the terms of reference of the IHCE SB RAS, research line No. 13.1.4.

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