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On formation of subnanosecond electron beams in air under atmospheric pressure

V.F. TARASENKO, V.S. SKAKUN, I.D. KOSTYRYA, S.B. ALEKSEEV, AND V.M. ORLOVSKII
High Current Electronics Institute Siberian Branch of Russian Academy of Sciences, Tomsk, Russia

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Abstract

This article reports on experimental studies of subnanosecond electron beams formed in air under atmospheric pressure. An electron beam with an amplitude of ~170 A with a duration at FWHM of ~0.3 ns has been obtained. Based on beam temporal characteristics and discharge spatial characteristics, the critical fields were supposed to be reached at plasma approach to anode. Simultaneously, the sharp high-energy pulse of e-beam current is generated. Of critical importance is the cathode type and occurrence on the cathode of plasma protrusions. It is shown that to get maximum amplitude of the electron beam in the gas diode, the discharge in the gas diode should be volumetric.

Keywords: Atmospheric pressure; Runaway electrons; Subnanosecond e-beam in air

1. INTRODUCTION

Research has been reported on hard X-ray radiation recording under atmospheric pressure of air (Stankevich & Kalinin, 1967) and helium (Noggle *et al.*, 1968). These studies attracted the attention of many investigators and got them to study conditions of fast electrons and X-ray radiation generation in gas-filled diodes under elevated pressures (Babich *et al.*, 1990; Korolev & Mesyats, 1991). However, electron beam (e-beam) current amplitudes obtained in molecular gases under 1 atm did not exceed fractions of an ampere (Babich *et al.*, 1990). In 2002 (Alekseev *et al.*, 2003*a*, 2003*b*, 2003*c*), the possibility of an amplitude increase of the gas diode e-beam formed in atmospheric pressure molecular gases (air, nitrogen), CO_2-N_2-He mixtures (Alekseev *et al.*, 2003*a*, 2003*c*), and helium (Alekseev *et al.*, 2003*b*; 2003*c*) was explored. The high-current e-beam has been obtained under different values of the parameter E/p, where E is the electrical field strength, and p is gas pressure. Under low values of pressure, Alekseev *et al.* (2003*b*) obtained $E/p > 70$ kV/(cm Torr) and high current values (>1 kA) that correspond to the known conditions for formation of the nanosecond electron beams (Zagulov *et al.*, 1989). For all that, the parameter E/p was essentially above the critical values to get a runaway electron effect (Babich *et al.*, 1990; Korolev & Mesyats, 1991); however, with an increase in the pressure of helium, air, and nitrogen up to 1 atm (Alekseev *et al.*, 2003*a*, 2003*b*, 2003*c*; Tarasenko *et al.*, 2003*a*, 2003*b*, 2003*c*) the average values of E/p were lower than the critical ones (Babich *et al.*, 1990; Korolev & Mesyats, 1991) of $E/p < 0.1$ kV/(Torr cm). Alekseev *et al.* (2003*a*, 2003*c*) and Tarasenko *et al.* (2003*a*) considered (later these considerations were developed by Tarasenko *et al.* 2003*b*) that the major amplitude e-beam behind the foil is forming with the critical field reached between the plasma, propagating from cathode to anode, and the anode. It was suggested by Tarasenko *et al.* (2003*a*) that a subnanosecond e-beam with an amplitude in air of tens of amperes is being formed from propagating plasma generated by the volume avalanche discharge subnanosecond avalanche electron beam (SAEB).

The recent results obtained by Tkachyov and Yakovlenko (2003) show that runaway electron generation in gases has a nonlocal character corresponding to the case when electron multiplication length (Townsend inverse coefficient; Raizer, 1992) is comparable to interelectrode distance. The multiplication effect of electrons on the formation of runaway electrons was taken into account at derivation of the nonlocal criterion. That gave an increase of the critical field value sufficient for runaway of the main part of the electrons as compared to the value of the critical field from papers by Babich *et al.* (1990) and Korolev and Mesyats (1991). At high values of E/p (in helium $E/p > 200$ V/(cm Torr)) the Townsend coefficient (impact ionization coefficient) decreases corresponding to the upper branches of the curves characterizing runaway electron criteria (Tkachyov & Yakovlenko, 2003) and discharge ignition criteria, that is

Address correspondence and reprint requests to: V.F. Tarasenko, High Current Electronics Institute, Akademichesky Avenue 4, 634055 Tomsk, Russia. E-mail: vft@loi.hcei.tsc.ru

Paschen's curve (Raizer, 1992). The dependencies of the Townsend coefficient under the high electric fields on the values of the parameter E/p for helium are given by Tkachyov and Yakovlenko (2003).

The goals of this article are to investigate e-beam formation modes necessary to get maximal beam current amplitudes behind the foil in the air diode. Moreover, the article summarizes experimental results of studies devoted to obtaining of electron beams in gas diodes, that were published in 2003 as short reports (Alekseev, 2003*a*, 2003*b*; Tarasenko *et al.*, 2003*a*, 2003*b*, 2003*c*).

In comparison with the traditional electron accelerators, where the vacuum diodes are used for formation of nanosecond electron beams (Shpak, 1980; Zagulov *et al.*, 1989), the given method of electron beams formation allows a decrease in the duration of an electron beam pulse up to fractions of a nanosecond. The design of an accelerator becomes rather simpler in this case, too. To form subnanosecond electron beam pulses, it is not necessary to form the voltage pulses of subnanosecond duration and to use vacuum diodes.

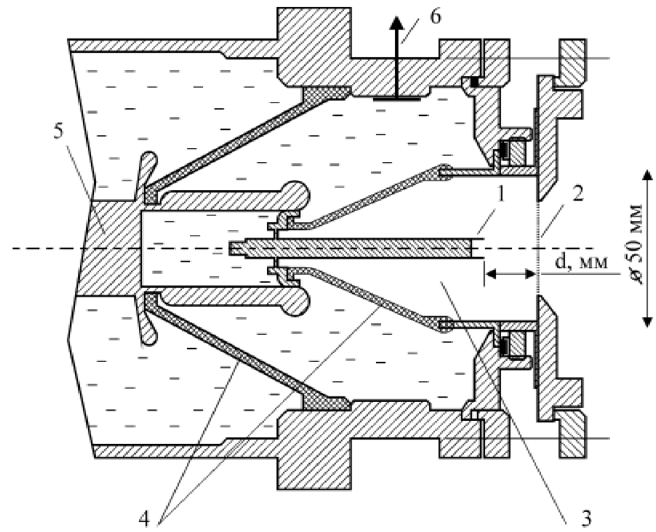

Fig. 1. High-voltage outlet construction of generator and gas diode. 1: cathode, 2: foil or mesh, 3: gas diode, 4: insulators, 5: high voltage electrode of the generator, 6: capacitive potential divider.

2. EXPERIMENTAL SETUP

The experiments were carried out using two nanosecond pulse generators RADAN described in a detail by Yalandin and Shpak (2001) and Zagulov *et al.* (1989).

Generator 1 (RADAN-303) with 45-Ohm impedance generates at the matched load voltage pulses from 50 to 170 kV (the charging voltage was about 340 kV) with a voltage pulse duration at full width at half maximum (FWHM) of ~5 ns and a pulse rise time of ~1 ns (Yalandin & Shpak, 2001). The gas gap voltage smoothly varied with the change of the main spark gap.

Generator 2 (RADAN-220) with 20-Ohm impedance generated voltage pulses at the discharge gap with amplitudes of up to 220 kV and duration at FWHM of ~2 ns with a voltage rise time of ~0.3 ns (Zagulov *et al.*, 1989). As in most papers devoted to X-ray generation studies and gas diode fast electrons, a flat anode and small-sized cathode were used in these experiments, providing additional amplification of the near-cathode electric field.

Both generators used similar construction of the gas diode as shown in Figure 1, earlier used by Alekseev *et al.* (2003*a*, 2003*c*) and Tarasenko *et al.* (2003*a*, 2003*b*, 2003*c*). Four different cathodes were used in experiments. Cathode 1 was made from a 6-mm steel tube with a 50-μm wall thickness fixed on a metallic rod with a similar diameter. Cathode 2 was made from a 6-mm graphite rod with sharp ends. Cathode 3 was made from a steel needle exceeding the end of the metallic rod by 8 mm. Cathode 4 was a steel ball 9.5 mm in diameter. The flat anode used for e-beam extraction was made from an AlBe foil 40 μm thick, or an Al foil 10 μm thick, or a mesh made of stainless steel with a light transmission of 50–70%. The cathode–anode distance was varied from 5 to 18 mm. In some experiments, at the e-beam formation in air, an additional gap with a clearance from 10 to 16 mm was switched on in parallel with the gas diode (the main gap was 16 mm).

The beam current was measured with a copper disk collector, 49 or 20 mm in diameter, spaced 10 mm from the output foil. The collector was loaded with a coaxial cable or with a cable and a low-ohmic shunt. In some experiments, the current was collected on small-area electrodes loaded with coaxial cables or on a graphite electrode connected to a strip line or a Faraday cup. The Faraday cup design allowed the space between the output foil and measuring electrode to be differentially pumped. The electron energy distribution was determined using the foil technique. The measuring electrodes were connected to an oscillograph with wideband coaxial cables and attenuators of the 142-NM type (Barth Electronics) with a bandwidth of 30 GHz (at an ~3 dBN level). This allowed us to measure pulses with a front width of 0.1 ns. The detection circuit was tested using a low-voltage generator of pulses with a front width of up to 70 ps and a 6-GHz stroboscopic oscillograph of the TDS-820 type. At a 100-ps front width, a decrease in the voltage pulse amplitude did not exceed 20%, whereas the amplitude of pulses with a 400-ps front width decreased by no more than 5%. Signals from the capacitive voltage divider and the electron beam collectors (Faraday cylinders) and shunts were measured using a digital oscillograph of the TDS-684B type (1 GHz and 5 G/s), or an 0.3 GHz-band TDS-3034 oscillograph with 2.5 G/s, or an S7-19 oscillograph. The recording system resolution was not less 0.3 ns in case of TDS-684B and S7-19, and not less than 1 ns in the case of the TDS-3034. The conducted studies show that, on the whole, the recording system resolution was determined by the oscillographs used.

Note that in some regimes, the value of the current beam amplitude behind the foil could vary from pulse to pulse. Therefore the maximum amplitudes of e-beam current are shown below for all regimes. Amplitude instability of gap voltage pulses and gas diode discharge current was low, usually not exceeding 10%.

The discharge illumination was taken by digital camera.

3. EXPERIMENTAL RESULTS

The main experimental results are discussed in the following. In the nonuniform electric field with a short voltage rise time, a discharge regime occurs in which an electron beam with an amplitude of tens of amperes is formed in an air diode at atmospheric pressure. The electron beam appears at the voltage leading edge with a duration at FWHM not higher than 0.5 ns, and the amplitude reaches 35 A at the extraction through AlBe foil in the case of Generator 1, and 75 A in the case of Generator 2 (Fig. 2). From the comparison of the experimental results obtained by using the oscilloscopes TDS-684B and TDS-3034 it may be noted that improvement of the recording system time resolution leads to decrease of e-beam current duration and an increase of amplitude of the current pulses. Nevertheless, the product of the current amplitude and its duration does not essentially change. The current pulse waveform, shown in Figure 2 (oscilloscope trace 2), registered by the small-sized collector 2 mm in diameter within acquisition system resolution, contains some important information. First, within the time resolution, the current beam duration is observed to be not higher than 0.3 ns. Duration of beam current may be supposed to be considerably smaller with the improvement of the recording system time resolution. Second, the trailing edge of the current beam pulse has a subnanosecond duration, whereas the gap voltage is constant (Fig. 2, oscilloscope trace 4). In other words, after the current peak is achieved, the conditions for e-beam formation in a gas diode are sharply interrupted, although the gap voltage does not change essentially. Note that at an electron beam extraction both in air or vacuum, the form of the current beam did not change, confirming the absence of a breakdown between the collector and foil in the gas ionized by an electron beam. Similar conclusions were made by Shpak (1980) in studies of nanosecond current beams with the same density (tens of amperes per square centimeter).

The analysis of current beam waveforms behind foils of different thicknesses has revealed that increasing the foil thickness leads to a shift of the current beam maximum to the voltage pulse start. For 10-μm-thick Al foil, the current beam maximum was registered after the first voltage pulse maximum, and with 50-μm-thick Al foil it was registered before the first maximum on the voltage waveform. Usually, with the AlBe foil the peak current in the high-current regime is registered after the gap voltage peak is reached. With decreasing voltage, the time delay of e-beam occurrence behind the foil increases. The beam is generated after the first peak on the "flat" top of the voltage pulse; hence, the beam amplitude is essentially diminished. At the fixed optimal interelectrode gap, the amplitude of the current beam behind the foil depends on the no-load voltage amplitude of the generator (Generator 1) having a peak value of about 210 kV in the case of air, as shown in Figure 3. In these conditions, the waveforms of the gap voltage and the discharge current are practically linear despite significant change of the beam current amplitude. Note that the voltage amplitude of the second generator was determined by the breakdown voltage of the uncontrolled gap of about 220 kV that is optimal for the gas diode current beam amplitude (Fig. 3). The impedance of Generator 2 was two times lower than that of Generator 1, and the beam current behind the foil for Generator 2, as was mentioned above, was two times higher with a similar cathode and cathode–anode gap. The doubling of the current beam amplitude may be related to the twice-lower impedance. With replacement of the foil by a mesh, similar waveforms of the current amplitude versus no-load voltage of Generator 1 were obtained.

The experiments using Generators 1 and 2 with a steel tube cathode (No. 1), devoted to the study of the effect of the interelectrode gap on the beam current amplitude in air, have shown that the beam behind the foil decreases with the gap increasing from approximately 16 mm (Fig. 4). At a gap above ~17 mm, a partial breakdown to the gas diode metallic wall occurred.

The distribution of electron energy of the formed beam is shown in Figure 5. In optimal mode for Cathode 1, the beam electrons have an average energy of about 60% with respect to the energy corresponding to the maximum gap voltage (65 keV for Generator 1). It can be noted that energy distribution has a large half width. If we consider that most electrons have the average energy, the electron energies will range from 40 to 100 keV, because the beam electrons are forming at different voltages in the gap.

Figure 6 shows photographs of the discharge glowing in air, taken from the generator end through the grid with ~50% transparency, on an angle of 0° (a–e) and ~30° (f) from the central axis of cathode. The discharge in the gap is volumetric, and bright spots are seen only in the near-cathode area. In parallel to the discharge gap, there is a chopping gap (Fig. 6a–e), one of its electrodes was the side surface of the metallic rod, and the second electrode (anode) was made conelike. A bright spot is seen on the anode of the chopping gap (Fig. 6a at the bottom of the photo), and the bright spark channels are seen in the Figure 6b–e between the anode and cathode of the chopping gap. By decreasing the chopping gap, the light intensity in the spark channels increases while decreasing in the gas diode. Nevertheless, even at the minimal chopping gap length of 10 mm (Figure 6d), volume glowing in the main gap and bright spots on the cathode were observed. Voltage pulse duration at FWHM for Generator 2 was about 2 ns. Figure 6f shows illumination aside being in the form of diffusive jets with a total diameter of not less than 15 mm near the anode (Fig. 6a–e).

Based on the above-mentioned results, it was supposed that a change in curvature radius and material of the cathode would allow an increase in value of the current beam formed in an air-filled diode. The cathode curvature radius was changed due to the different cathode designs (Cathodes 1, 3, and 4). With the graphite cathode (No. 2) 16 mm from the

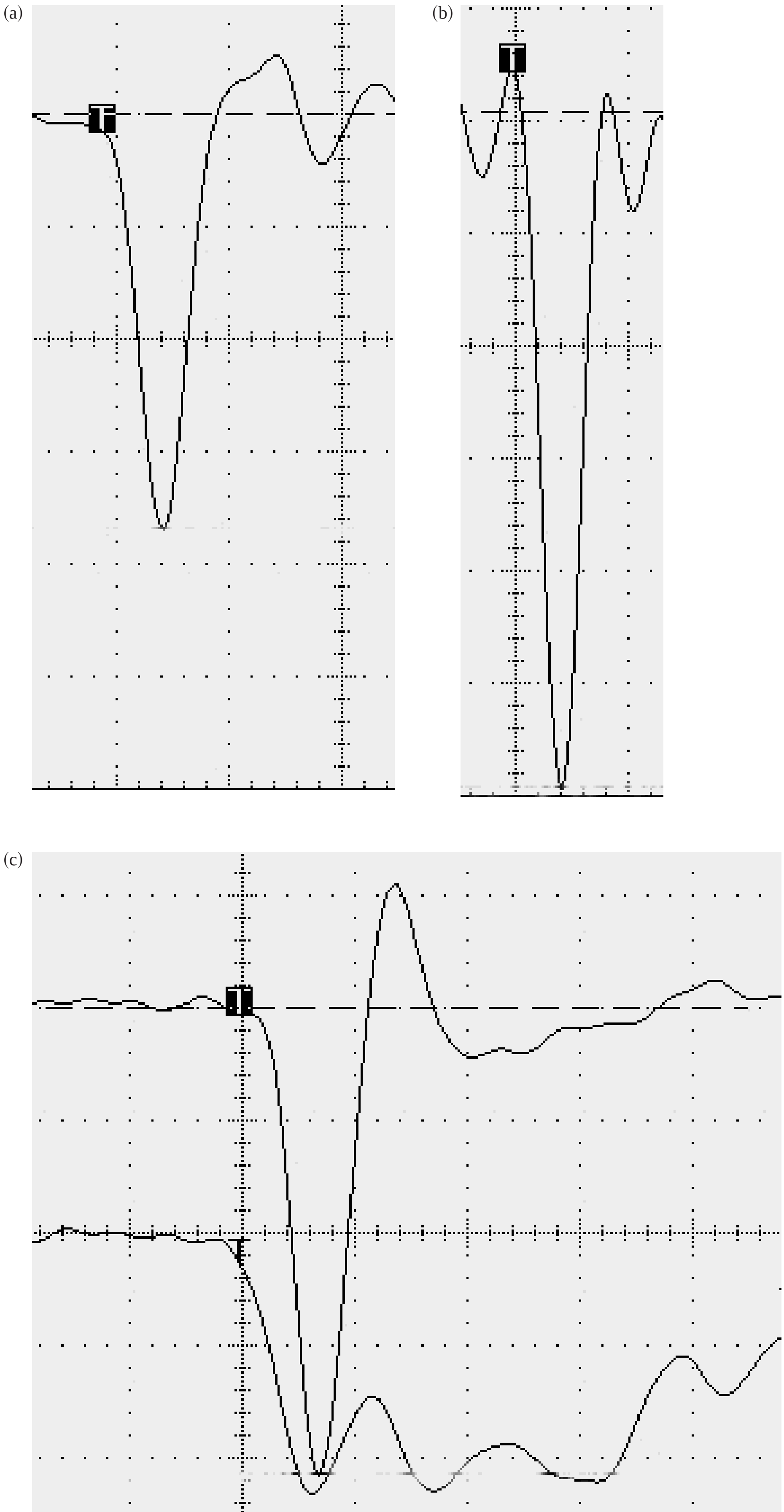

Fig. 2. Electron beam pulse oscilloscope traces (a, b, c (oscilloscope trace above)) behind AlBe foil under atmospheric air pressure in the diode and voltage pulse in the diode (c (oscilloscope trace from bottom)). Cathode-anode gap is 16 (a, b) and 17 (c) mm. Generator 2 oscilloscope traces (a, b) and generator 1 (c). Time scale across is 1 ns/square. Current scale vertical is 20 A/square (a) and 10 A/square (b, c (oscilloscope trace above)), and vertical voltage scale is 45 kV/square (c (oscilloscope trace from bottom)). Recording system resolution is 0.3 ns.

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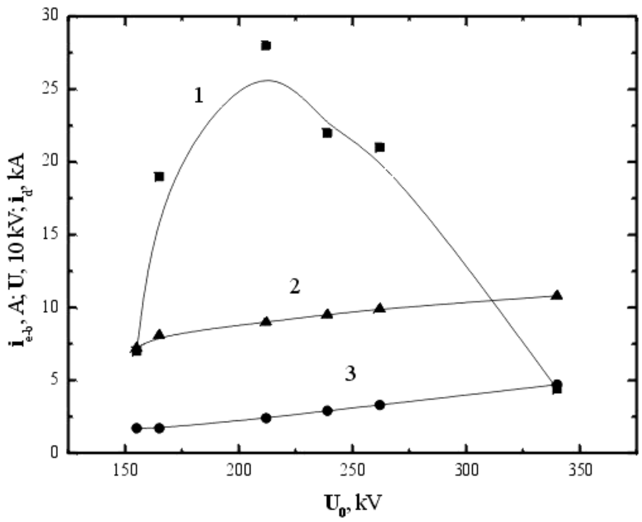

Fig. 3. An amplitude of the e-beam current behind 40-μm AlBe foil (1), gap voltage (2), and discharge current (3) as function of the charging voltage for Generator 1. Recording system resolution is 0.3 ns.

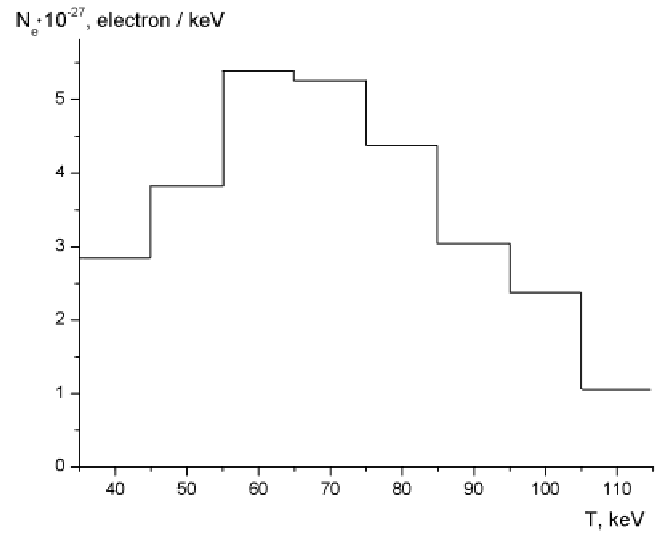

Fig. 5. The electron spectrum in the beam for an air pressure in the diode of 1 atm, obtained by the foils method with Generator 1 under a charging voltage of 270 kV. Diode gap is $d = 17$ mm. Recording system resolution is 0.3 ns.

foil, having a short delay time for cathode spot formation, the beam current decreased several times. The use of the cathode in the form of a needle (No. 3), with the electric field at the tip being essentially enhanced compared to the first two cathodes, led to a considerable decrease of the beam current (Fig. 7). In other words, a too quick formation of plasma at the cathode results in a decrease of beam current behind the foil. Therefore the steel ball-like polished cathode with diameter of 9.5 mm was used in experiments. Such a cathode allowed a 1.5-fold increase in current amplitude behind the foil (Fig. 8) as compared to the current amplitude obtained by using Cathode 1.

A further increase in beam current behind the foil was reached by decreasing the gas diode inductance obtained by minimizing its geometrical dimensions. The length of the metallic rod for cathode support was decreased by 1.5 cm, and the foil was spaced by a similar length in the insulator direction. The diode foil was placed from the other side of the metallic ring in contrast to earlier experiments (Fig. 1), where the foil was situated on the external side of the metallic ring. The gap between Cathode 4 and anode was 5 mm, which was close to optimal in accordance with the dependence shown in Figure 8, obtained with the usual inductance of the gas diode. With such an assembly, the maximal amplitude of the beam current behind the foil was ~170 A for a pulse duration of ~0.3 ns (recording system resolution is ~0.3 ns) or ~58 A for a pulse duration of ~1 ns (recording system resolution is ~1 ns). The current density of the electron beam for a pulse duration of ~0.3 ns was ~100 A/cm^2.

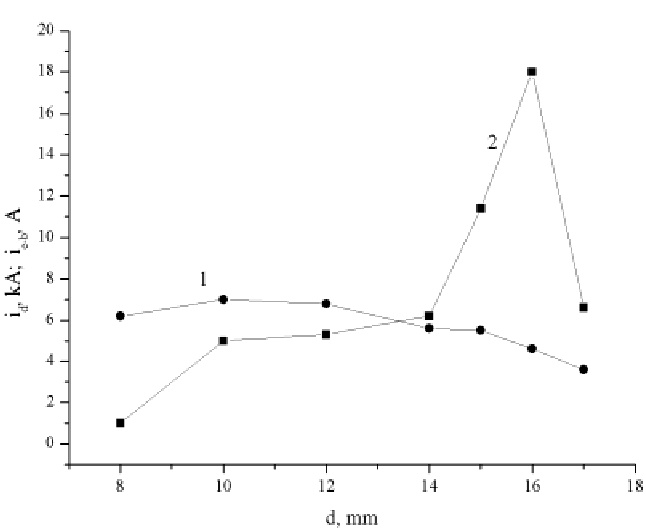

Fig. 4. The amplitude of the discharge current (1) and beam current behind 40-μm AlBe foil (2) as a function of the anode–cathode gap size obtained for Generator 2, Cathode 1, and air pressure of 1 atm. Recording system resolution is 1 ns.

4. INTERPRETATION OF RESULTS

On the basis of the experimental data obtained in our papers (Alekseev *et al.*, 2003*a*, 2003*b*, 2003*c*; Tarasenko *et al.*, 2003*a*; 2003*b*; 2003*c*), we consider that the following dynamics of breakdown evolution in a gas diode is observed in conditions of e-beam formation.

Of great importance in the discharge formation and the gap breakdown during the first ~1 ns is the electric field enhancement on the cathode edge. When the high-voltage pulse is applied, the cathode spots appear due to explosive emission at short times (Korolev & Mesyats, 1991). These spots are easily seen on the photographs shown in Figure 6, and their intensity depends on the chopping gap response time. At the plasma boundary of the small-sized cathode spots (luminous area of every spot is not above 0.2 mm in diameter; Fig. 6d) there is also an enhanced electric field due to which fast electrons possessing energies higher than the energy corresponding to maximum losses at collisions might appear.

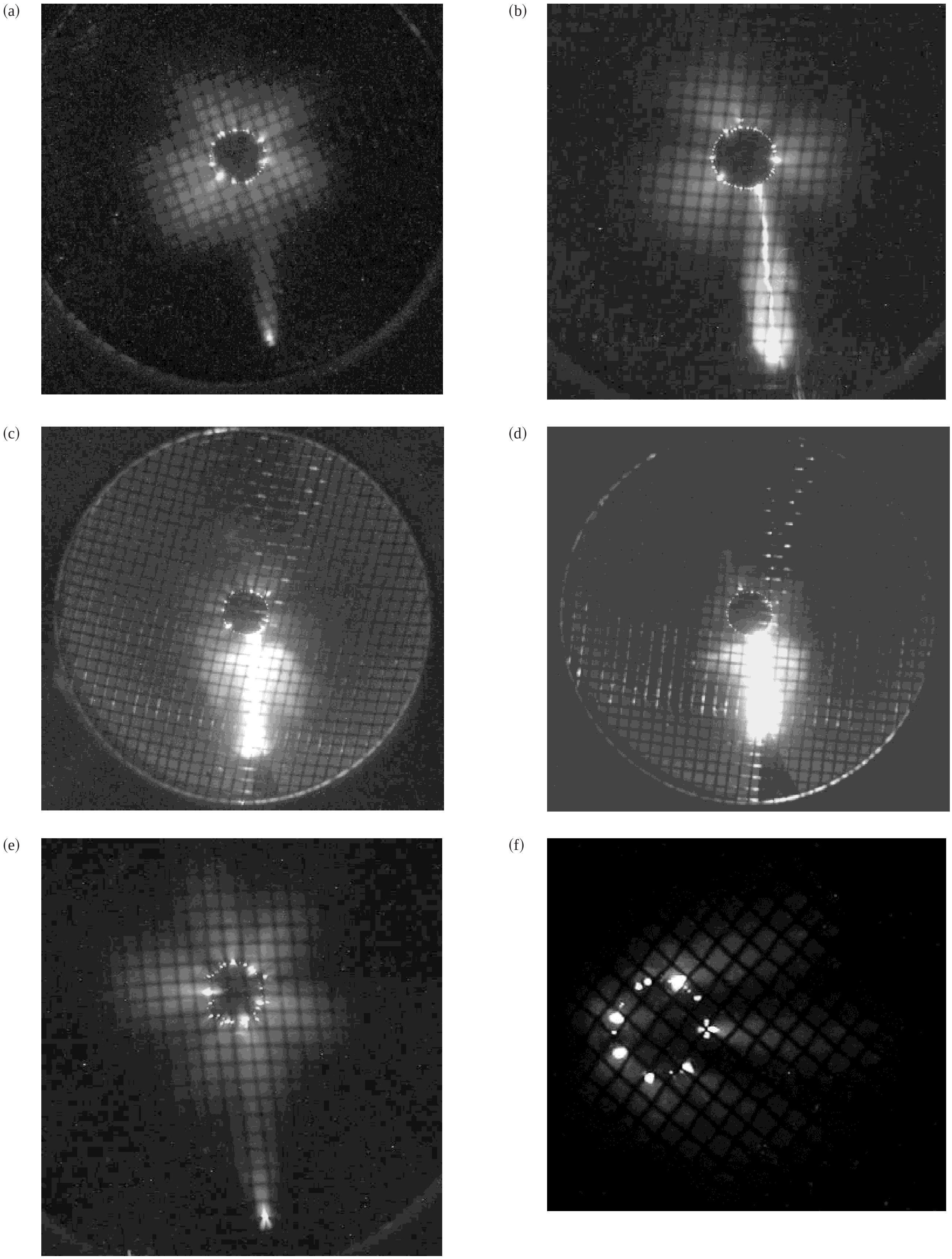

Fig. 6. The pictures of the discharge glowing in the gap at taken-end on (a–e) and under an angle (f). Screen opening of mesh is 1 mm. Diode gap is $d = 16$ mm, interelectrode distance in the chopping gap is 16 (a, e), 14 (b), 12 (c), and 10 (d) mm. Cathode 1 (a, b, c, d, f) and 2 (e). Generator 2.

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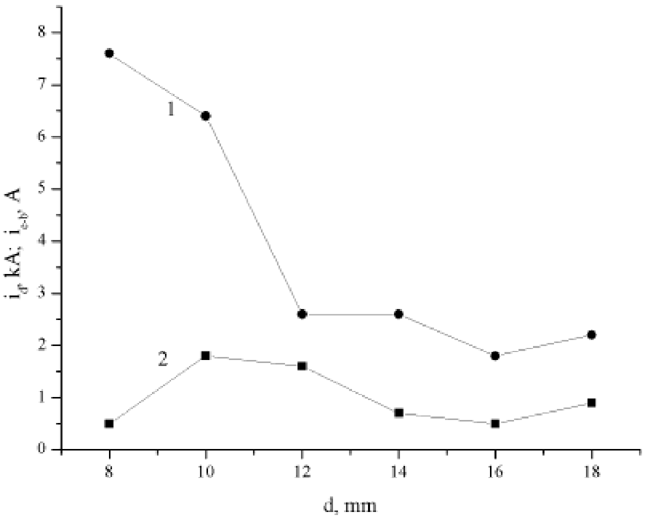

Fig. 7. Discharge current amplitude (1) and beam current behind 40-μm-thick AlBe foil (2) as a function of the anode–cathode gap. Generator 2, Cathode 3, pressure of air is 1 atm. Recording system resolution is 1 ns.

To have a gap breakdown within ~1 ns, electrons with energies of ~1 keV have to lie generated, first, on the feather edges of the cathode, then at the cathode spot boundary, and further at the boundary of the moving plasma jets. The electron velocity v_e at an energy of ~1 keV is ~$1.9 \cdot 10^9$ cm/s, sufficient to close the gap within less than 1 ns. Hence, the electrons with energy of ~1 keV lose their energy rapidly under air atmospheric pressure. That is why there should be some mechanism to replenish the energy losses in gas at the motion of the electrons with energy of ~1 keV. The allowance for energy loss by the electrons at elastic and nonelastic collisions occurs under the rapid rise of the electric field at the voltage pulse leading edge. Besides, formation of avalanches created due to gas ionization by the fast initial electrons leads to an increase in electron concentration at the plasma boundary and the occurrence of the excessive negative charge. It is quite possible that the extrusion of a part of the electrons from the negative charge area at the ionization wave leading edge under gap voltage increases can be the explanation for both the occurrence of the electrons with energies exceeding the charging voltage (Babich *et al.*, 1990; Alekseev *et al.*, 2003*a*) and of the ionization front motion with ~10^9 cm/s. It would explain how the losses of electrons with energies of ~1 keV are compensated; they could cross the gap within ~0.8 ns and initiate preliminary ionization of the gap. As was shown by Babich *et al.* (2002), fast electrons can pass long distances in a gas under a weak electric field. To mate such a situation, the energy of an electron should exceed the energy corresponding to the maximum of nonelastic cross sections for the gap-filling gas. Note that the energy of part of the electrons is generated due to the enhancement of the field at the cathode, and the moving plasma front potential might be essentially higher than ~1 kV. Hence, the number of such electrons must not be so large.

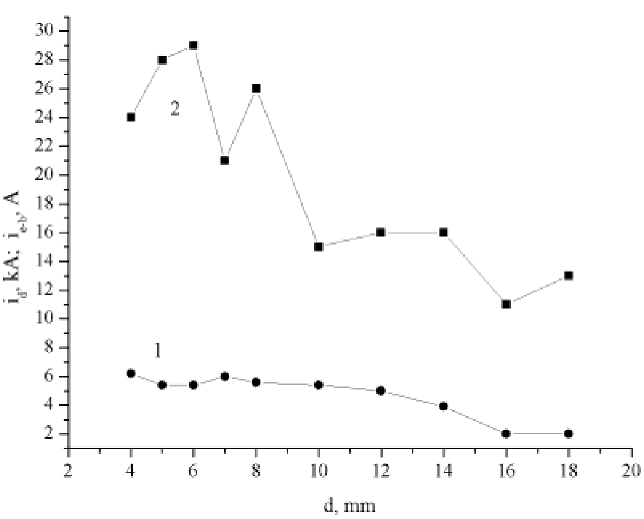

Fig. 8. Discharge current amplitude (1) and beam current behind 40-μm-thick AlBe foil (2) as a function of the anode–cathode gap. Generator 2, Cathode 4, pressure of air is 1 atm. Recording system resolution is 1 ns.

The presence of fast electrons during the initial stage of discharge formation is confirmed by two experimental facts. First, the nonuniform electric field and the presence of cathode spots result in the formation of a volume discharge. Second, the high voltage pulse passes in a quasistationary stage without the phase of a rapid voltage drop (Savin *et al.*, 1976). The second fact is obtained only with a high initial concentration of electrons in the discharge gap at a gap preionization by an electron beam (Mesyats *et al.*, 1995). The occurrence of fast electrons solely during the initial part of the voltage pulse front and gap preionization by those electrons could lead to the observed waveform of the voltage pulse with the highest voltage in a quasistationary stage, $E/p \sim 0.08$ kV/(Torr cm). Hence, the fast electrons formed due to near-cathode electric field enhancement cannot give a major contribution in the beam current behind the foil at its maximal amplitudes for the following reasons:

1. Enhancement of the near-cathode electric field has weak dependence on the cathode–anode distance, whereas the current beam amplitude behind the foil in optimal modes is critical to this distance.
2. With the needle cathode, when the near-cathode electric field enhancement is maximal, the amplitude of the current beam behind the foil is essentially decreased, being weakly dependent on cathode–anode gap length. In other words, when optimal conditions for near-cathode electric field enhancement are heated, no great amplitudes of the current beam behind the foil are reached.

Note that at the plasma cloud expansion, on one hand, there is a screening of the cathode feather edges by the volume charge and, on the other, the positive charge of the static ions, after the electrons left for anode, strengthens the near-cathode electric field. To account correctly for the contribution of these processes, as well as for the function definition of electron distribution by velocities and for the dynamics of the electrons distribution over the gap, a complex theoretical model is needed. We think that in these conditions the plasma cloud should propagate toward the anode at a velocity of $1–2 \cdot 10^9$ cm/s to provide the gap overlap with reaching the anode within the time of ~1 ns in these experimental conditions. Note that the plasma propagation velocity measured in similar conditions (Babich *et al.*, 1990) also reached $\sim 2 \cdot 10^9$ cm/s. Because the area occupied by the plasma propagates to the anode and it has higher conductivity than the rest of the gap, the electric field between the plasma boundary and the anode will be constantly enhanced. The propagation of the plasma results in the achievement of a critical field between the plasma cloud and the anode and formation of an electron beam. The critical field is of 0.8–3.5 kV/(cm·Torr) according to Korolev and Mesyats (1991) or >5 kV/(cm·Torr) (Tkachyov & Yakovlenko, 2003). The electron beam is recorded ~0.5 ns after the voltage pulse is applied both in the case of the grid anode and the foil anode. Due to the high electric field between the plasma propagation front and the anode, after the critical field is reached, the rest of a gap is quickly filled with plasma (fractions of a nanosecond). The electron beam duration is determined by the interval of time between the critical field achievement and the plasma-filled gap. It is clear that the average energy of electrons would be less than the energy of the electrons accelerated in vacuum at the same gap voltage, because a partial voltage drop occurs due to the resistance of the propagating plasma. Under such an electron beam formation mechanism, it will consist of electrons with different energies. This mode of e-beam formation in gas under elevated pressures differs from that described by Babich *et al.* (1990), where, under similar conditions, the beam currents were two orders of magnitude smaller, and the average energy of electrons essentially exceeded maximal voltage in the gap.

The current beam termination with maximal voltage is conditioned by the fact that after the plasma reaches the anode, the gap electric field is formed and the field gradient is not sufficient for runaway electrons. In our experiments (Fig. 2), the beam current behind the foil is recorded only at the beginning of the flat part of the voltage pulse.

5. CONCLUSION

From the performed experiments it is seen that to obtain the maximal gas diode current beam, the discharge should be volumetric and the gap voltage rise should stop before the current beam achieves its maximal value. The assumption of runaway electron generation at the moment when plasma approaches the anode allows us to make a qualitative explanation of the comparatively narrow range of experimental conditions (gap length, cathode construction, generator open-circuit voltage) under which large amplitudes and short duration of current beam pulse are obtained.

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