Formation of Electron Beam and Volume Discharge in Air under Atmospheric Pressure

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Abstract – This paper reports on experimental studies of sub-nanosecond electron beams formed in air under atmospheric pressure. An electron beam with amplitude of ~ 170 A with duration at FWHM ~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. After beam current ends, the discharge is usually continued in quasi-stationary mode being of a volume character. Within 5 ns during voltage pulse at the gap the anode current density reaches ~3 kA/cm^2, specific input energy in gas is ~1 J/cm^3 and specific input power is ~400 MV/cm^3.

1. Introduction

In 2002, the scope of amplitude increasing of gas diode e-beam formed in atmospheric pressure molecular gases (air, nitrogen), mixture CO_2–N_2–He, and helium was displayed [1, 2]. The high-current e-beam has been obtained under average values of parameter *E*/*p* (*E* is the electrical field strength; *p* is gas pressure) being either above the critical values to get running away electrons effect [2], or relatively low average values, lower than critical one, of parameter *E*/*p* [1–4], it was considered [1, 3] (later those considerations were developed in [4]) that major amplitude e-beam behind the foil is forming with critical field reached between plasma, propagating from cathode to anode, and anode. It was suggested in [3] to call subnanosecond e-beam with amplitude in air of tens amperes being formed from propagating plasma generated by the volume avalanche discharge as SAEB (subnanosecond avalanche electron beam).

The goals of this paper are to investigate e-beam formation mode to get maximal current beam amplitudes behind the foil in air diode, as well as to investigate the volume discharge in gas diode.

2. Experimental Set-up

The experiments were carried out using two nanosecond pulse generators RADAN described in a more detail in the papers [5, 6].

The generator 1 (RADAN-303) with 45-Ohm impedance generated at matched load the voltage pulses from 50 to 170 kV (the no-load voltage was about 340 kV) at voltage pulse duration at FWHM of ~ 5 ns and voltage pulse leading edge of ~ 1 ns [5]. The gas gap voltage smoothly varied with main spark-gap change.

The generator 2 (RADAN-220) with 20-Ohm impedance generated the voltage pulse at the discharge gap with amplitude of up to 220 kV and duration at FWHM of ~2 ns, at the voltage leading edge of ~0.3 ns [6]. Like in most of papers, devoted to X-radiation study and gas diode fast electrons, the flat anode, and small-sized cathode were used in experiments, providing additional amplification of near-cathode electric field.

Four different cathodes were used in the experiments. The cathode No. 1 was made from a 6-mm steel tube with 50-μm wall thickness fixed on the similar diameter metallic rod. The cathode No. 2 was made from 6-mm graphite rod with sharp ends. The cathode No. 3 was made from steel needle running forward metallic rod by 8 mm. The cathode No. 4 was made from steel ball of 9.5 mm in diameter. The flat anode used for e-beam extraction was made from AlBe foil of 40 μm in thickness, or Al-foil of 10 μm in thickness, or the mesh with light transmission of 20–70%. The cathode–anode distance was varied from 5 to 18 mm. At e-beam formation in air in parallel with the gas diode (gap was 16 mm) an additional gap with amount of clearance from 10 to 16 mm was switched on in some experiments.

For taking signals from the capacitive divider, collectors and shunts, the oscilloscope 1 GHz-band TDS-684B with 5 GS/s (5 points on 1 ns), or the oscilloscope 0.3 GHz-band TDS-3034 with 2.5 GS/s (2,5 points on 1 ns), or the oscilloscope S7-19 were used. Recording system resolution was not less 0,3 ns in case of oscilloscope TDS-684B and S7-19, and not less 1 ns in case with TDS-3034. 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 essentially less usually not exceeding 10%.

The discharge illumination data were taken by digital camera.

3. Result and Measurements

The main experimental results are as follows. In the non-uniform electric field with a short voltage leading edge, there exists the discharge regime with which an electron beam with the amplitude of tens of amperes is formed in an air diode under atmospheric pressure. The electron beam appears at the voltage leading edge having duration at FWHM not higher than 0.5 ns, and the amplitude reaches 35 A at extraction through AlBe foil in the case of the generator *1* and 75 A in the case of the generator *2*. From comparison of the experimental results obtained at use of oscilloscopes TDS-684B and TDS-3034 it may be noted that improving of recording system time resolution results in decreasing of e-beam current duration and corresponding increasing in amplitude of current pulses. Nevertheless, product of current amplitude and its duration does not essentially change. The current pulse waveform registered by collector contains some important information (Fig. 1).

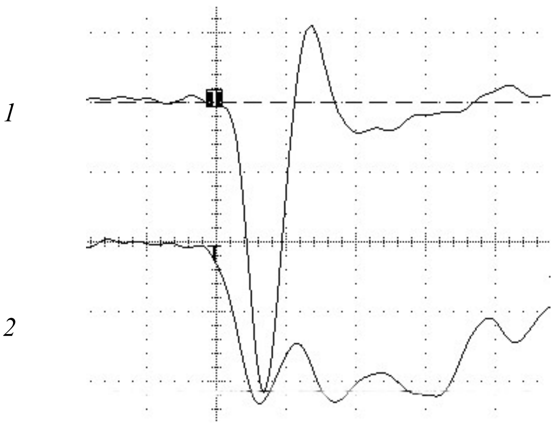

Fig. 1. Electron beam pulse oscilloscope trace (*1*) and voltage pulse on a gas diode (*2*) behind AlBe foil under atmospheric air pressure in a diode. Cathode–anode gap is 17 mm. Generator 1. Cathode No. 1. Time scale across is 1 ns/square. Vertical electron beam scale is 10 A/square (*1*), and vertical voltage scale is 45 kV/square (*2*)

First, at limiting 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 much less with improving of recording system time resolution. Second, the trailing edge of the current beam pulse has subnanosecond duration, whereas the gap voltage is constant. In other words, after the current peak is achieved, the conditions for e-beam formation in a gas diode are sharply broken, though the gap voltage does not change essentially.

The analysis of current beam waveforms behind foils of different thickness has revealed that increasing in foil thickness leads to shift of current beam maximum to voltage pulse start. With 10-μm thickness foil from Al, the current beam maximum was registered after the first voltage pulse maximum, and with the foil of 50-μm thickness (Al) it was registered before the first maximum on the voltage waveform. Usually, with AlBe foil peak current in high-current regime is registered after gap voltage peak is reached. With voltage decreasing, the delay time of e-beam appearance behind the foil increases, and the beam appears after the first peak on the "flat" top of voltage pulse, hence the beam amplitude is essentially diminished. At the fixed optimal interelectrode gap, the amplitude of current beam behind the foil is being dependent on no-load voltage amplitude of generator (generator *1*) having peak at about 210 kV in the case of air. In these conditions, waveforms of gap voltage and discharge current are practically linear despite significant change of beam current amplitude. Note that the voltage amplitude of the second generator was determined by breakdown voltage of uncontrolled gap being about 220 kV that is optimal for obtain of gas diode current beam (Fig. 2). The impedance of the generator *2* was two times lower than of generator *1*, and the beam current behind the foil for generator *2*, as it was mentioned above, was two times higher with similar cathode and cathode-anode gap. Double increase in current beam amplitude may be related to the double decrease of impedance. With replacing foil by mesh, the similar waveforms of current amplitude versus no-load voltage of generators were obtained.

The experiments using generators *1* and *2* with a steel tube cathode (No. 1), devoted to study of the effect of interelectrode gap valuation the current beam in air have shown that the beam behind the foil is observed to decrease with gap increasing from ~16 mm. At the gap above ~18 mm, a partial breakdown to gas diode metallic wall occurred.

Distribution of electron energy of the formed beam is shown in Fig. 2.

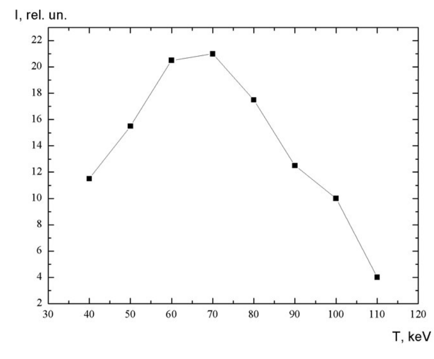

Fig. 2. Electron distribution in a beam by energy at air pressure in a diode of 1 atm, obtained by foils method on generator *1* under no-load voltage of 270 kV

In optimal mode for the cathode No. 1, the beam electrons have average energy of ~60% (65 keV for the generator *1*) with respect to the energy corresponding to the maximal gap voltage. It is seen that energy distribution has major halfwidth. If to take most electrons having average energy, the energies will be from 40 to 100 keV, *i.e.* the beam electrons are forming at different voltages in the gap.

Figure 3 shows photos of discharge, taken from the generator end through the grid with ~50% transparency, and at angle of the central cathode axis.

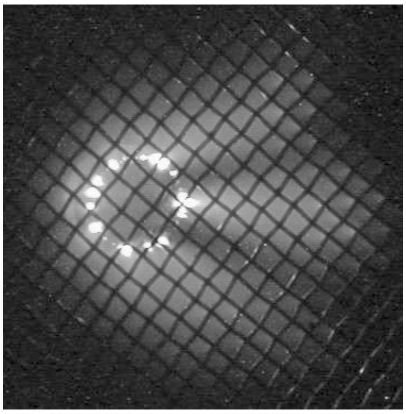

Fig. 3. Photo of discharge glowing in air. Screen opening of mesh is 1 mm. Diode gap is d = 16 mm. Generator *2*

The gap discharge is volume, and the bright spots are seen only in the near-cathode area. Figure 3 shows illumination aside being in the form of diffusive jets of the total diameter not less than 15 mm near the anode. In some experiments in parallel to the discharge gap, there was a chopping gap placed transversely. At decreasing of chopping gap, the lighting intensity in it increases being decreasing in the gas diode. Nevertheless, even at the minimal chopping gap length of 10 mm the volume glowing in the main gap and bright spots on the cathode were observed.

Based on the above-mentioned results, it was supposed that change in curvature radius and material of cathode would allow increase in current beam value formed in air filled diode. With graphite cathode (No. 2) 16 mm distant from the foil having short delay time of cathode spot formation, the beam current decreased several times. The use of the cathode in the form of a needle (No. 3) with electric field at the tip being essentially enhanced than on the first two cathodes, leaded to much decreasing of the beam current. In other words, too quick formation of plasma at the cathode results in 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 1,5 – fold increase in current amplitude behind the foil as compared with current amplitude with cathode No. 1 used.

Further increase in beam current behind the foil was reached at decreasing of gas diode inductance due to diminishing its sizes. The gap between cathode No. 4 and anode was 5 mm. With such assembly, the maximal amplitude of beam current behind the foil was ~170 A at pulse duration of ~0.3 ns (recording system resolution is ~0.3 ns) or ~58 A at pulse duration of ~1 ns (recording system resolution is ~1 ns).

4. Interpretations

On the basis of the experimental data obtained in our papers [1–4] and simulations [4], the following dynamics of breakdown evolution in a gas diode is observed in e-beam formation conditions.

Firstly, of great importance in discharge formation and gap closing during ~ 1 ns is the electric field enhancement on the edge cathode. At high-voltage pulse applied, the cathode spots appear due to explosive emission at short times. These spots are well seen on the photos (see Fig. 3), and their intensity depends on the chopping gap response time. At plasma boundary of small-sized cathode spots (luminous area of every spot is not above 0,2 mm in diameter) there is also the enhanced electric field due to which speed electrons possessing the energy higher than the energy corresponding to maximum losses at collisions might appear.

In order that the gap is closed within ~1 ns, it is needed that the electrons with the energy of ~1 keV were arisen, first, on the featheredges of cathode, then on cathode spot boundary, and further on the boundary of moving plasma jets. The electron velocity v_e at the energy ~1 keV is ~$1.9\cdot10^9$ cm/sc, being sufficient to close the gap within the time less than 1 ns. It is known that $v_e = 5.93\cdot10^7\ (\varepsilon)^{1/2}$, where ε is the electron energy. Hence, the electrons with energy of ~1 keV loose their energy rapidly under air atmospheric pressure. That is why there should be some mechanism existing to replenish the energy losses in gas at movement of the electrons with energy of ~1 keV. Allowance for energy waste by the electrons at elastic and non-elastic collisions occurred under rapid rise of electric field at voltage pulse leading edge. Besides, formation of avalanches from the initial electrons created due to gas ionization by speed initial electrons leads to increase in electron concentration at plasma boundary and appearance of the excessive negative charge. It is quite possible that extrusion of the part electrons from the negative charge area at ionization wave leading edge under gap voltage rising can be the explanation both (appearance of the electrons with the energy exceeding charging voltage, and ionization front movement with ~10^9 cm/s). If this were the case that the losses of electrons with the energy of ~1 keV are compensated, they could cross the gap within ~0.8 ns and initiate preliminary ionization of gap. To realize such a situation, the energy of an electron should exceed the energy corresponding to the maximum of non-elastic cross-sections for the gap filling gas. Note that the energy of a part of electrons appeared due to enhancement of the field at cathode and moving plasma front might be essentially higher than ~1 keV. Hence, the number of such electrons must not be so great.

Presence of speed electrons during the initial stage of discharge formation is confirmed by two experimental facts. Firstly, the non-uniform electric field and presence of cathode spots result in formation of volume discharge. Secondly, the voltage pulse passes in quasistationary stage without the phase of rapid voltage drop. The second is realized only with high initial concentration of electrons in the discharge gap, for e.g., at gap preionization by electron beam. Appearance of speed electrons solely on the initial part of the voltage pulse leading edge and gap preionization by those electrons could lead to the observed waveform obtain. Hence, the speed electrons formed due to near cathode electric field enhancement cannot give capital contribution in the beam of current behind the foil at its maximal amplitudes, because of the following reasons:

1. Enhancement of the near-cathode electric field has weak dependence on cathode-anode distance, whereas the current beam amplitude behind the foil in optimal modes is critical to this distance.

2. With needle cathode, when the near-cathode electric field enhancement is maximal, the amplitude of 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 realized, no great amplitudes of the current beam behind the foil are reached.

Note that at plasma cloud expansion, from one side, there is screening of cathode featheredges by the volume charge, and from other side, the positive charge of static ions, after electrons left for anode, strengthens the near-cathode electric field. In order to get exact account for contribution of these processes, as well as for function definition of electrons distribution by velocities and dynamics of electrons distribution over the gap, construction of complex theoretical model is needed. We think, that in these conditions, the plasma cloud should propagate to the anode at a velocity of $1–2\cdot 10^9$ cm/s in order in these experimental conditions to provide gap overlap with reaching to the anode within the time of ~1 ns. Since the area occupied by plasma propagates to anode and it has higher conductivity than other gap part, the electric field between plasma boundary and anode will be constantly enhancing. Propagation of the plasma occupied area results in achievement of critical field between plasma cloud and anode and e-beam formed. The electron beam is recorded in ~0.5 ns after voltage pulse is applied both in the case of grid anode and foil anode. Due to high electric field between the plasma propagation front and anode, with critical field reached the gap becomes to be quickly "overlapped" (in fractions of a nanosecond) determining current beam duration. It is clear, that the average energy of electrons would be less than the energy of accelerated in vacuum electrons at the same gap voltage, since a part voltage drops at resistance of propagating plasma. Under such formation mechanism of electron beam, it will consist of the electrons with different energies. This mode of e-beam formation in gas under elevated pressure rather differs from that described in [7], where under the similar conditions, the beam currents were two orders less, and average energy of electrons essentially exceeded maximal voltage in the gap.

The current beam termination with maximal voltage is conditioned by that after plasma reaches anode the gap electric field is developed and the field gradient is not sufficient for "running away" electrons. In our experiments (Fig. 1), the beam current behind the foil on voltage pulse flat part is recorded only at the beginning of the flat part.

5. Conclusion

From the experiments carried out it is seen that for obtain of maximum current beams in a gas diode the discharge should be volume and the gap voltage rise should stop before the current beam achieves its maximum value. The assumption of run-away electrons generation at the moment of plasma approach to anode allows to make qualitative explanation of the comparatively narrow range of experimental conditions (gap length, cathode construction, generator open-circuit voltage) with which great amplitude and short duration of current beam pulse are realized.

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