Laser and Particle Beams (2005), *23*, 545–551. Printed in the USA.

DOI: 10.1017/S0263034605050731

Supershort electron beam from air filled diode at atmospheric pressure

V.F. TARASENKO,[1] S.A. SHUNAILOV,[2] V.G. SHPAK,[2] AND I.D. KOSTYRYA[1]
[1]High Current Electronics Institute Siberian Branch of Russian Academy of Sciences, Tomsk, Russia
[2]Institute of Electrophysics the Ural Department of Russian Academy of Sciences, Ekaterinburg, Russia

(Received 25 May, 2005; Accepted 8 June 2005)

Abstract

The properties of an electron beam (e-beam) formed in air under atmospheric pressure are reported. The nanosecond generators RADAN-303 (two devices) and RADAN-220, producing nanosecond voltage pulses with amplitude of up to 400 kV and subnanosecond rise time were used in the experiments. It was shown for the first time that the duration of e-beam current of gas diode behind the foil does not exceed 0.1 ns. The maximum amplitude of current of a supershort avalanche electron beam (SAEB) behind the foil was ~400 A. The data on the influence of various parameters on e-beam current amplitude measured behind the foil were obtained. An electron beam with energy less than 60 keV and powerful X-ray radiation were formed in discharge gap simultaneously with SAEB.

Keywords: Fast electrons; Runaway electrons; SAEB; Subnanosecond e-beam in air

1. INTRODUCTION

High intensity electron beams of short time duration have a wide range of applications (Mesyats, 2003; Ozur *et al.*, 2003), and different methods to generate such beams by high intensity laser radiation were presented and discussed recently (Panchenko *et al.*, 2003; Malka & Fritzler, 2004; Baiwen *et al.*, 2004). Recording of X-ray radiation at a nanosecond discharge in air under atmospheric pressure was first proposed by Stankevich and Kalinin (1967), being viable for the further studies aimed at generation of e-beams and X-ray radiation in air-filled diodes under high pressure. The most important results was summarized in reviews (Babich *et al.*, 1990; Tarasenko & Yakovlenko, 2004*b*), as well as reported in papers (Alekseev *et al.*, 2004; Buranov *et al.*, 1991; Repin & Rep'ev, 2004; Tarasenko *et al.*, 2004*a*). The most essential experimental results are:

1. Beams of fast electrons are generated in air under atmospheric pressure or other gases in a gap with a non-uniform electric field at application of high-voltage nanosecond pulses with short rise time. A small–curvature radius cathode and a flat anode used in these experiments provide recording of X-ray radiation either from a gas gap (discharge plasma) or anode.
2. With duration of a voltage pulse rise time of several nanoseconds or more, only soft X-ray radiation is recorded at gas gap breakdown with maximum energies of 5–10 keV (Buranov *et al.*, 1991; Repin & Rep'ev, 2004). The main source of such radiation is the discharge plasma. The current of fast electrons has not been registered (Buranov *et al.*, 1991; Repin & Rep'ev, 2004).
3. It was reported (Tarasova *et al.*, 1974; Babich & Loiko, 1985; Babich *et al.*, 1990) from recordings of runaway electrons generated in atmospheric air pressure, with energies higher than the gap voltage. At the voltage pulse rise time of ~1 ns in atmospheric air pressure, the electron energy distribution maximum corresponded to the electron energies exceeding the gap voltage by 1.5–1.7 times (Babich & Loiko, 1985). It was proposed in (Babich *et al.*, 1990) that the runaway electrons with high (anomalous) energies are generated due to polarization self–acceleration of electrons at the head streamer forming near a cathode. The effect of polarization self–acceleration was predicted theoretically by Askarayn (1973). At e-beam extraction behind the foil in the works reviewed in Babich *et al.* (1990), the amplitude of current of runaway

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Address correspondence and reprint requests to: V.F. Tarasenko, High Current Electronics Institute, 2/3 Akademichesky Avenue, 634055 Tomsk, Russia. E-mail: vft@loi.hcei.tsc.ru

electron beams in atmospheric air pressure was not above fractions of an ampere. It is worth noting that in the work by Babich and Kutsyk (1995), the electron energy distribution maximum at high electron energies was missing. A maximum of electron energy distribution with anomalous electron energy exceeding gas gap voltage is meant.

4. The peak current of fast electrons behind the foil is essentially greater at realization of supershort avalanche electron beam (SAEB) conditions, when the critical electric field is reached between plasma and an anode (Alekseev *et al*., 2003*a*, 2003*b*, 2004; Tarasenko *et al*., 2003*a*, 2003*b*, 2003*c*, 2004*a*, 2004*b*). In Alekseev *et al*. (2004) and Tarasenko and Yakovlenko (2004) it was reported on e-beam current pulses having amplitudes of hundreds of amperes at duration of a radiation pulse at FWHM of 0.2–0.3 ns. In these conditions the electron energy distribution maximum corresponded to the electron energy lower than the gap voltage.

However, the above-mentioned papers did not contain the data on the beam current measured with sufficient time resolution (in many works it was noted that recording of the beam current duration was restricted by the measuring equipment used). So, the nature of the soft X-ray radiation formed in nanosecond discharges at the use of small–curvature radius cathodes and flat anodes is still the open problem, and the conditions under which electrons occur with anomalous energies higher than the gap voltage were not evident.

The objective of this work was investigation of the conditions of fast electrons formation and their parameters measurement with resolution of registration system not worse than 0.1 ns, as well as determination of the causes for soft and hard X-ray radiation generation. The main attention was paid to the experimental conditions of SAEB formation, since e–beam current amplitude behind the foil in such conditions was maximal. This work is the extension of the cycle of experimental works earlier published in Alekseev *et al*. (2003*a*, 2003*b*, 2004) and Tarasenko *et al*. (2003*a*, 2003*b*, 2003*c*, 2004*a*, 2004*b*, 2004*c*).

2. EXPERIMENTAL SET-UP

Three RADAN nanosecond pulse generators described in a detail by Yalandin and Shpak (2001) and Zagulov *et al*. (1989) were used in the experiments.

The first generator, *A*–modification of RADAN-303, had an impedance of 45 Ohm generating voltage pulses from 50 to 170 kV at the matched load (no-load voltage of about 340 kV) at voltage pulse duration at FWHM up to ~5 ns and voltage rise time of ~1.5 ns in the transmission line (Yalandin & Shpak, 2001). The output voltage smoothly varied with change of the main spark-gap.

The second generator, *B*–modification of RADAN-303, had the similar impedance generating voltage pulses at the matched load from 50 to 200 kV (no-load voltage of about 400 kV) at ~5 ns voltage pulse duration at FWHM and voltage rise time in the transmission line of ~1.2 ns (Yalandin & Shpak, 2001). The output voltage smoothly varied with change of the main spark-gap.

The third generator, RADAN-220 with 20-Ohm impedance provided voltage pulses in a discharge gap with an amplitude of up to 220 kV and duration at FWHM of ~2 ns at voltage rise time in the transmission line of ~0.5 ns (Zagulov *et al*., 1989). It is worth noting that usually duration of the leading edge of a voltage pulse in a gas diode was shorter than duration of voltage pulse leading edge in the transmission line.

Like in the studies carried out on X-ray radiation and gas diode fast electrons, a flat anode and a small-sized cathode were used in the experiments for near-cathode electric field gain.

The generators used the similar construction of a gas diode, earlier used by Alekseev *et al*., (2003*b*) and Tarasenko *et al*. (2003*a*, 2003*b*, 2003*c*, 2004*a*, 2004*b*). Two different cathodes were used in experiments. Cathode number 1 was made of a ~5.5–mm steel tube with a 25–50–μm wall thickness fixed on a metallic rod with 5–mm diameter. Cathode number 2 was made of a 9.5–mm diameter steel ball. A flat anode, made of Al–Be foil of 40–45 μm in thickness or 10-μm Al-foil was used for electron beam extraction. Cathode–anode spacing varied from 5 to 18 mm. Figure 1 shows a gas diode part and collector 1 design used for recording current pulses of the beam behind foil with resolution not worse than 0.1 ns. The beam current was measured in vacuum, 10^{-3} Torr (see Fig. 1).

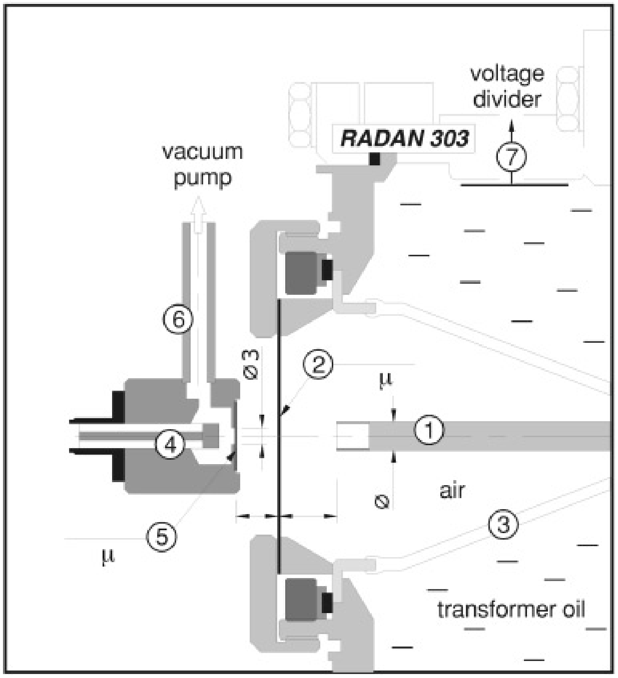

Fig. 1. Gas diode and current collector design. (1) Cathode, (2) foil anode, (3) glass insulator, (4) collector, (5) Al foil, (6) gas pumping tube, (7) output voltage divider.

A 6 GHz-band TDS-6604 oscilloscope with 20 GS/s and a 1 GHz-band TDS-684B oscilloscope with 5 GS/s were used to receive signals from a capacitive divider, collectors, and a shunt. Recording system resolution was not less than 0.05 ns for TDS-6604, and 0.3 ns for TDS-684B. 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 for all regimes. Amplitude instability of gap voltage pulses and gas diode discharge current were low, not exceeding 10%.

A digital camera photographed the discharge light. X-ray radiation was registered by RF–2 film and Direct Reading Dosimeters (Arrow-Tech, Inc. Model 138, and VICTOREEN 541R). Such dosimeters made registration of X-ray radiation with quanta energies higher than 16 and 60 keV, respectively. With the diode geometry shown in Figure 1, and RADAN-303*B* charging voltage of 140 kV at a distance of 50 mm from a 45-μm Al–Be anode, such doze was $\sim$20 μR/pulse as registered by VICTOREEN 541R. Measured by Arrow-Tech, Inc. Model 138 monitor, the doze was $\sim$300 μR/pulse in the case of using RADAN-220 generator, and the similar diode geometry, at a distance of 10 mm from a 45–μm Al–Be anode. The total exposure doze of X-ray radiation to the full angle was essentially higher. However, to define that, it would be necessary to measure distribution of exposure doze by angle, not available in our conditions.

3. EXPERIMENTAL RESULTS

Figures 2 to 8 demonstrate the main experimental results, obtained at volume discharge formation in a discharge gap, corresponding to the conditions of SAEB formation. Some experiments were performed with time resolution of registering equipment of $\sim$0.05 ns. Usually, an electron beam occurs during a voltage rise time (Fig. 2) with duration at FWHM not higher than 0.12 ns (Fig. 3). On recording e-beam current (Fig. 3), test limits of registration system were explored, allowing to establish the values of leading and trailing edges duration of e-beam current pulse not exceeding 0.1 ns. Figure 3b demonstrates the trace of e-beam current with interpoint linear approximation. It is seen that there are two points of registration for leading edge and trailing edge of an e-beam current pulse. That confirms that duration of leading and trailing edges of current pulse does not exceed 0.1 ns. Figure 2 shows that duration of the descending part of the current pulse is increased, that is, connected with the influence of collector number 2 sizing. The sizes of the collector were increased aimed at total current recording.

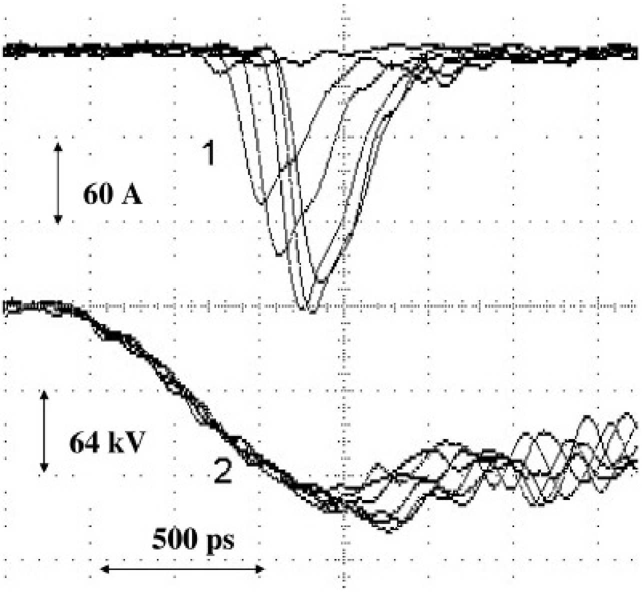

Fig. 2. Oscillograms of e-beam behind 45-μm Al–Be–foil (1) at air pressure in a diode of 1 atm and the diode voltage pulses (2). Cathode-anode gap is 12 mm. Generator 2. Time scale across is 250 ps/sq. Current scale vertical is 60 A/sq. (1), and vertical voltage scale is 64 kV/sq. (2). Recording system resolution is 0.1 ns. Collector number 2.

With the same gap and voltage amplitude applied to it, the maximum amplitude of e-beam current is observed with certain delays. At such delay of e-beam current appearance, decreasing or increasing with respect to the optimal delay, e-beam current amplitude was decreased (Fig. 2). It is also seen from the oscilloscope traces of Figure 2 that after appearance of e-beam current, the gap voltage pulse behavior becomes essentially different from pulse to pulse, as it was before e-beam appearance. This fact testifies that after SAEB formation, discharge gap plasma parameters become different.

On increasing gap voltage, e-beam current amplitude in the optimal gaps is increasing at first and then it is decreas-

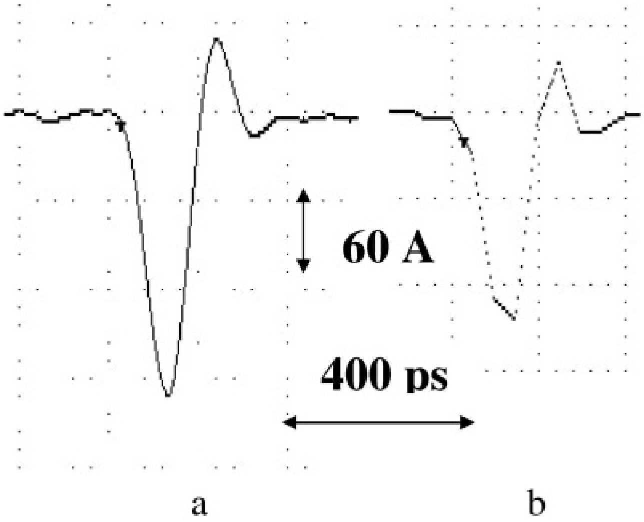

Fig. 3. Oscillograms of e-beam behind 45-μm Al–Be–foil at air pressure in a diode of 1 atm. Cathode–anode gap is 12 mm. Generator 2. Time scale across is 200 ps/sq. Current scale vertical is 60 A/sq. Recording of oscillograms was done at connection of points by sine law (1) and by straight lines (2). Recording system resolution is 0.05 ns. Collector number 1.

ing, Figure 4. The shortening of the voltage pulse front leads to an increase in optimal voltage. For the larger than optimal gaps, the optimal voltage of a generator increases but e-beam current decreases. For the smaller than optimal gaps, the beam current of runaway electrons is also decreasing, as well as decreased is time to e-beam current appearance. With generator 2 at no-load voltage of ~300 kV, it is from ~0.5 ns at a gap of 15.5 mm to ~0.3 ns at a gap of 7.5 mm. That leads to a change in dependence character of e-beam current versus voltage (Fig. 4, curve 4).

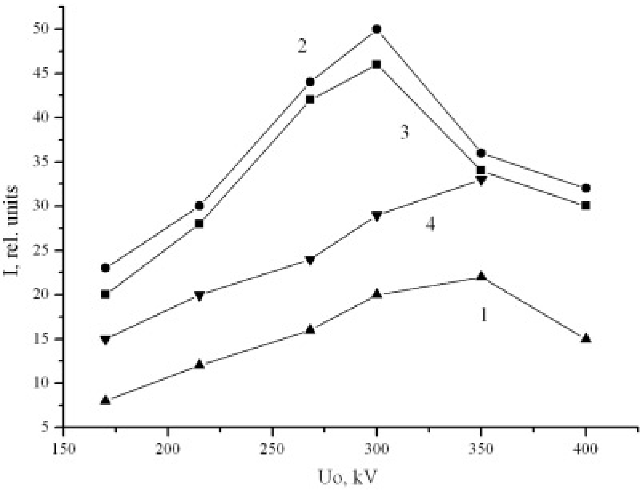

Fig. 4. e-beam current amplitude behind 45 μm-Al–Be foil for various anode-cathode gaps *d* as function of no–load voltage with using generator 2. Cathode number 1, air pressure is 1 atm. Recording system resolution is 0.1 ns. *d* = 17.5 (1), 15.5 (2), 12 (3) and 7.5 (4) mm.

Figure 5 demonstrates e-beam current amplitude as a function of interelectrode gap obtained with RADAN-220 generator. In other equal conditions, the cathodes with the smaller curvature radii need the use of major interelectrode gaps; therefore the optimal interelectrode gap with cathode number 2 is less. As it was earlier noted (Tarasenko *et al.*, 2004*a*), it is necessary to have a gas diode with reduced sizing (inductance), in order to have the maximal e-beam current amplitude. Point 3 in Figure 5 shows e-beam current amplitude, measured at the minimal sizing of a gas diode. A foil was moved to gas diode isolator by 15 mm, and the optimal interelectrode gap and cathode type were the same. That provided to have approximately double e-beam current amplitude increasing.

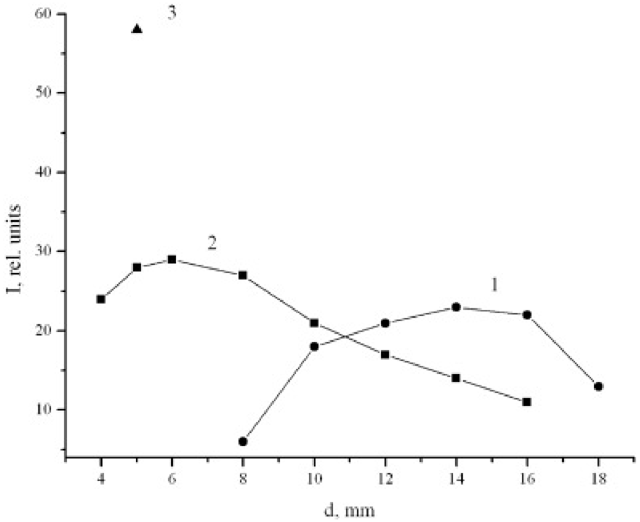

Fig. 5. e-beam current amplitude behind 45 μm-Al–Be foil for various cathodes as function of anode-cathode gaps. Generator 3, cathode number 1 (1), cathode number 2 (2, 3), air pressure is 1 atm.

The estimates of e-beam current amplitude for RADAN generators with a gas diode filled in with atmospheric air pressure gave the value of 100–400 A. The beam current was defined by e-beam energy measured by a calorimeter, e-beam duration, and electron energy distribution. It was noted earlier (Tarasenko *et al.*, 2004*a*) that duration of e-beam current is less at proportionally higher amplitude with an oscilloscope having the better resolution. In the experiments with RADAN-220 generator, the maximal current amplitude was ~400 A at current pulse duration at FWHM not above 0.1 ns. In case of RADAN-303*B*, the current amplitude by our estimates reached ~200 A.

Figures 6 and 7 show the electron energy distribution behind the foil (a) and before the foil (without foil losses) (b), obtained with generators 1 and 2. Three electron groups were registered. The first group electron energy was 60–80 keV. Correlation of the data obtained with the generators having different duration of voltage pulse rise time has shown that at decreased duration of voltage pulse rise time and other equal conditions, the maximal energy of such electron group is greater. The electron energy distribution behind foil (a), and without foil losses (b), obtained with the generator 1 is shown in Figure 6. Figure 7 demonstrates the same obtained with the generator 2. The values of duration of voltage pulse leading edge produced by transmission line generator were ~1.2 and ~1.5 ns, respectively. It is seen that with increasing of duration of the voltage pulse rise time, the place of sharp bend on e–beam current dependence on electron energy is moved to the lower energies (Figs. 6b, 7b). Such a tendency is also confirmed by the experiments carried out at the greater duration of a voltage pulse rise time (Buranov *et al.*, 1991; Repin & Rep'ev, 2004) with fast electrons energy above 20 keV. Note that at increased duration of a voltage pulse rise time, a share of the first group of fast electrons was greater as compared with SAEB, Figures 6b and 7b. With duration of voltage pulse rise time of several nanoseconds, SAEB beams are usually not recorded.

The second electron group corresponds to SAEB formed when the dense plasma approaches the anode. In the moment of SAEB formation, the electron energy distribution maximum is lower than the gap voltage, being for RADAN-303 and RADAN-220 behind the foil of 65–100 keV. Figure 8 demonstrates autographs of an electron beam and X-ray radiation obtained with the generator 3 behind Al–foil of

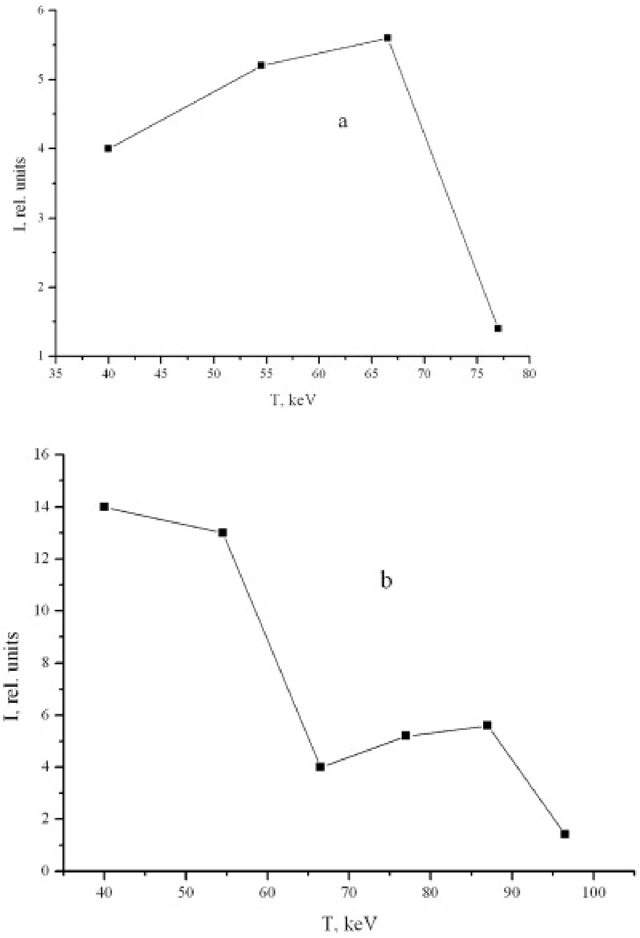

Fig. 6. Electron energy distribution of e-beam in a diode under air pressure of 1 atm, obtained by foils method on generator 1 with no-load voltage of 270 kV. $d = 17$ mm, cathode number 1. (**a**) electron distribution behind 45 μm–Al–Be foil, (**b**) electron energy distribution before foil.

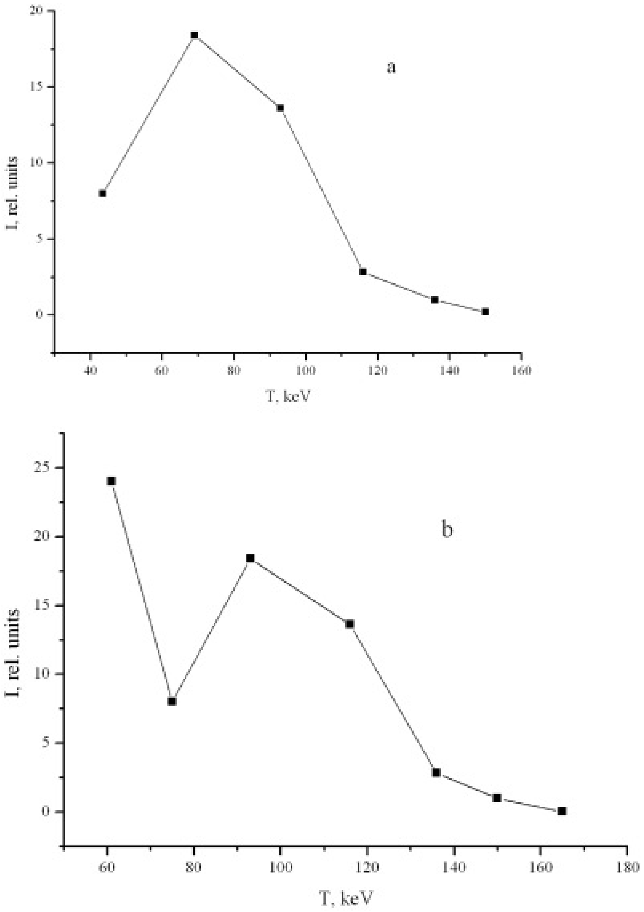

Fig. 7. Electron energy distribution of e-beam in a diode under air pressure of 1 atm, obtained by foils method using the generator 2 with no–load voltage of 250 kV. $d = 11$ mm, cathode number 1. Recording system resolution is 0.1 ns. (**a**) Electron distribution behind 45 μm-Al–Be foil, (**b**) electron energy distribution before the foil.

20 μm in thickness per impulse. The film was 8 mm distant from the foil. The foil window diameter was 47 mm, and an autograph diameter was equal to 6 cm. Note that with the minor thickness of the foil, the film illumination was sufficiently uniform.

The third electron group had no marked maximum, and the energies of recorded electrons slightly exceeded the gap voltage being equal to ~150 kV shown in Figure 7b. These measurements do not match with Babich and Loiko (1985) and Babich *et al*. (1990), reporting on obtaining the fast electrons possessing anomalous energies. Such maximal energies considerably exceeded the gap voltage, and the electron energy distribution maximum exceeded the maximal gap voltage by 1.5–1.7 times (Babich & Loiko, 1985).

3. RESULTS INTERPRETATION

On the basis of these results and earlier obtained experimental data (Alekseev *et al*., 2003*a*, 2003*b*, 2004; Tarasenko *et al*., 2003*a*, 2003*b*, 2003*c*, 2004*a*, 2004*b*), as well as simulation results (Tkachev & Yakovlenko, 2004) the following dynamics of e-beam formation may be considered.

1. First of all, of great importance is gap volume discharge formation. The volume discharge dense plasma should be formed near the cathode, expanding to anode. That is realized automatically at nanosecond duration of high voltage pulse rise time by using a flat anode

Fig. 8. Darkening of RF–2 film with size 23 × 86 mm placed in an envelope made of black paper of 100 μm in thickness 8 mm distant from 20 μm-Al foil within an impulse. Generator 3. Diode gap is $d = 16$ mm, cathode number 1.

and a small–curvature radius cathode. Fast electrons with the energies of ~1 keV and above are being formed due to electric field gain on cathode micro– and macro protrusions. Electric field gain and formation of fast electrons are also observed at the boundaries of dense plasma formations. Fast electrons ionize gas, and initiating electrons form in the near-cathode area, providing origination of electron avalanches at electric field increasing. Formation of a volume discharge in a gap confirms that initiating electrons density in the near-cathode area is sufficient for separate avalanches to overlap and reach their critical sizing, and form a streamer.

Due to gap voltage rapid increasing and high electric field near plasma boundary expanding from the cathode, high-density electron cloud occurs at the plasma boundary. The negative charge of the electron cloud, formed and moving to anode, contributes to acceleration of a part electrons at cloud boundary up to the energies of units-tens keV. Such electrons create the new initiating electrons, providing development of electron avalanches. The heads of the newly developed avalanches are also overlapped until they attain the critical sizes. The analysis of these experimental data has shown that for formation of fast electrons which presence was defined by discharges of soft X-ray radiation, it is enough to form relatively dense volume discharge plasma propagating to anode. The X-ray radiation produced by the fast electrons originates from the discharge gap, with the X-ray quanta effective energies equal over the gap (Repin & Rep'ev, 2004). With the gap voltage rise time and its amplitude increasing, the maximal energies of the fast electrons are increased too (Figs. 6 and 7), allowing registration of parts such electrons behind the foil.

Polarization self-acceleration of the electrons at a streamer front was predicted by Askarayn (1973). We suppose that one of the main reasons for volume discharge formation at high-voltage pulse with short rise time is the polarization self-acceleration of the electrons at plasma boundary of the avalanche (volume) discharge where streamers have no time to be formed. Thus, a volume discharge can be formed in various gases under elevated pressure without a preionization source at the short front of nanosecond voltage pulses. The fast electrons play the role of a preionization source, being registered behind thin foils as an electron beam at subnanosecond duration of voltage pulses (Figs. 6 and 7). At nanosecond voltage pulse rise time, e-beam is registered by the soft X-ray radiation from the gap (Repin & Rep'ev, 2004). Obviously, there are also conditions for electron polarization self-acceleration at the edge of a streamer, but the number of such electrons was small.

2. It necessary to realize the conditions for SAEB formation in order to have the maximal amplitude of the current beam behind the gas diode foil. As it was earlier suggested and confirmed (Alekseev *et al.*, 2003*a*, 2003*b*, 2004; Tarasenko *et al.*, 2003*a*, 2003*b*, 2003*c*, 2004*a*, 2004*b*), formation of SAEB beams occurs when the dense cathode plasma front approaches the anode. For that, it is needed to use a voltage pulse with a subnanosecond rise time, a gas diode with the minor sizing and inductance, and the optimal voltage amplitude, interelectrode gap, and cathode construction.
3. The presence of the runaway electrons with anomalous energies (being over the gap voltage) could be explained by polarization self-acceleration of the electrons attained at plasma-closed discharge gap. And such polarization self-acceleration in SAEB conditions is basically realized not at the edge of a cathode streamer as it was supposed (Babich *et al.*, 1990), but at the edge of the gap avalanche discharge. As it was shown by the experiments with time resolution of registration system of 0.1 ns and beam extraction through thick foils, the peak current of a beam with the major recorded energy (~160 keV, Fig. 7b) is registered in the same place as in Figure 2, i.e., in 0.6–0.7 ns after the voltage pulse is applied to a gap. It is hard to suppose that streamers occur synchronously with e-beam maximum in the end of voltage pulse rise time. Note that the maximal gap voltage for the conditions of Figure 7 was ~150 keV being less than the energy of a small electron group.

4. CONCLUSION

From the performed experiments it is seen that three groups of electrons with the energies of units-tens-hundreds keV (runaway and fast) are formed in a gap. The energy of these electrons depends on duration of voltage pulse rise time. With decreasing of duration of voltage pulse rise time the number of runaway electrons becomes increased. For the first time it was shown that duration of the current of gas diode e-beam behind the foil does not exceed 0.1 ns.

Besides SAEB beams (runaway electrons), the considerable contribution to e-beam current behind thin foils with a subnanosecond voltage pulse rise time may be done by the electrons with the energies of tens keV (fast electrons). These electrons are formed due to electric field gain on cathode micro– and macro protrusions, and polarization self–acceleration in the volume discharge avalanches. These electrons are formed soft X-ray radiation, which was recorded from discharge plasma.

The electrons with anomalous energies (runaway electrons) do not much contribute to e-beam current. Their part is several percents only. The presence of the runaway electrons with anomalous energies (exceeding the gap voltage) could be also explained by the polarization self-acceleration of electrons realized at the volume discharge plasma boundary closing the discharge gap on its approach to the anode.

In this work, electron energy distribution maximum in the area of energies exceeding the gap voltage was not recorded. It was reported about such a maximum (Babich & Loiko, 1985; Babich *et al*., 1990), and such a maximum was missing on the curve obtained later in the work done by the same team on discharge modeling in helium (Babich & Kutsyk, 1995).

ACKNOWLEDGMENTS

The authors are thankful to V.S. Skakun, V.M. Orlovskii, and V.V. Roctov for their assistance rendered.

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