JOURNAL OF APPLIED PHYSICS **113**, 196101 (2013)

Temporal and spatial structure of a runaway electron beam in air at atmospheric pressure

D. Levko,[1,a)] Ya. E. Krasik,[1] V. F. Tarasenko,[2,a)] D. V. Rybka,[2] and A. G. Burachenko[2]
[1]*Physics Department, Technion, Haifa 32000, Israel*
[2]*Institute of High Current Electronics, Russian Academy of Sciences, Tomsk 634055, Russia*

(Received 14 April 2013; accepted 7 May 2013; published online 20 May 2013)

The time- and spatial structure of a runaway electron beam generated in air at atmospheric pressure by a high-voltage pulse with a rise time of ~300 ps is studied experimentally and numerically. It is obtained that the duration of the runaway electron current is a few tens of picoseconds, and it can consist of two or many peaks. It is shown that the many-peak temporal structure of the beam is caused by the non-simultaneous appearance of several emission centers on the cathode edge. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4807403]

During the last two decades, the interest in nano- and subnanosecond high-voltage (HV) gas discharges has increased due to the different applications of these types of discharge.[1–3] Diffuse discharges are realized in the gas-filled diodes with a blade-like cathode and plane anode, which are typically used in these experiments.[2,3] The blade-like geometry of the cathode allows the observation of an enhanced electric field in the vicinity (a few tens of micrometers) of the cathode, exceeding the critical electric field needed for runaway electrons (RAE) generation (for instance, $E_{cr} \approx 4.5 \times 10^7$ V/m in air at $P = 10^5$ Pa). Both experimental and theoretical studies[2–11] showed that the HV nanosecond discharge in pressurized gas accompanied by the formation of plasma is initiated by these RAE, which pre-ionize the gas inside the cathode-anode (CA) gap.

However, in spite of many research studies, some questions related to the generation of RAE remain unanswered. For instance, in the experiments described in Refs. 9 and 10, two or even more peaks of the RAE current (total duration $\tau \leq 70$ ps) were obtained using a collector with picosecond time resolution. It was shown that the number and amplitude of these peaks depend on the CA distance d_{CA}, cathode geometry, and diameter of the collimating hole d_H in the anode. However, the phenomena responsible for the formation of these peaks have not yet been defined. That is, these peaks in the RAE current can be generated due to the non-simultaneous appearance and termination of emission centers on the cathode edge and switching of the field emission to explosive emission.[5] Also, two-peak structure of RAE beam was obtained by Gurevich *et al.*[12] In these experiments, the second peak, having much smaller amplitude than the first peak, was explained by the RAE emission from the boundary of the plasma front propagating towards the anode.

This paper presents the results of experimental research with a time resolution of ~30 ps and of particle-in-cell (PIC) numerical simulations. We explain the phenomenon behind the multi-peak structure of RAE generation in air at atmospheric pressure.

a)Authors to whom correspondence should be addressed. Electronic addresses: dima.levko@gmail.com and VFT@loi.hcei.tsc.ru

The experiments were carried out in air at $P = 10^5$ Pa using an SLEP-150 generator (the voltage amplitude measured by a capacitive voltage divider at the end of a 100 Ω-transmission line is ~200 kV, with a rise time of ~300 ps at matched load) specially designed for the generation of RAE in gas-filled diodes.[6] Four types of cathode were used in the experiments. A cylindrical cathode was made of a stainless steel tube with diameter of 6 mm and thickness of 100 μm mounted on a cathode holder (Fig. 1). Spherical and blade cathodes were made, respectively, of a steel sphere 9.5 mm in diameter and a blade 7 mm long. A disk cathode was formed by five 0.2 mm-diameter stainless steel wires fixed on a 30-mm diameter ring. The electron beam was extracted through 10 μm-thick anode *Al* foil reinforced by the anode *Cu* holder, which was 5 mm thick and had $d_H = 1$ mm. The radial location of the hole in the holder was in the range 0–10 mm. Also, experiments were carried out with a *Cu* holder 0.25 mm thick, and where d_H were 0.5 mm, 1 mm, 2 mm, 4 mm, and 6.5 mm. The d_{CA} was in the range 4–18 mm. The electron beam current was measured by a collector[6,9,10] (time resolution ~20 ps) 3 mm in diameter placed at a distance of 5 mm from the anode holder (Fig. 1). Signals from the collector and capacitive divider were recorded by a LeCroy WaveMaster 830Zi-A digitizing oscilloscope (30 GHz, 80GS/s) via 5D-FB cables ~1.3 m in length providing a time resolution of the whole registration system of ~25 ps.

A multi-peak structure of RAE was obtained with all four types of the cathode. However, this structure was obtained most often with the cylindrical cathode. Waveforms of the diode voltage and RAE current behind the anode for the cylindrical cathode for different values of d_{CA}, thickness of the anode holder h, and d_H are shown in Fig. 2. In this case, the multi-peak structure of the RAE beam appeared most often when $d_H < 2$ mm and $h = 0.25$ mm. An increase in the d_H or h lead to the disappearance of the multi-peak structure, i.e., only one peak of RAE beam current was obtained. It was obtained that both the amplitude of the RAE current and its structure can be changed from pulse to pulse, even if the front of the voltage remains the same [Figs. 2(b) and 2(c)]. Also, it was obtained that the increase in the h leads to a decrease in the duration of the RAE beam registered by the collector, showing only a beam current with only one peak. Finally, a

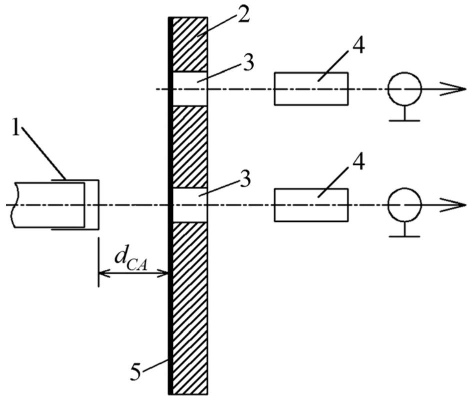

FIG. 1. Experimental set up. (1) Cylindrical cathode; (2) *Cu* anode holder; (3) central and shifted from the central axis holes in the anode holder; (4) collector; (5) *Al* foil.

radial shift of the hole by ~10 mm also results in RAE consisting of only one peak with $\tau \sim 30$ ps.

In addition to the experimental study, two numerical PIC codes were used to explain the experimental results. The 1st code is the 2D PIC WARP code[13] used to study the electron propagation in a vacuum diode consisting of a 6-mm diameter cylindrical cathode with a wall thickness of 100 μm biased by a potential of -140 kV and an anode located at a d_{CA} of 6 mm, 8 mm, 10 mm, and 12 mm. The thickness of the anode was either 0.25 mm or 4 mm, and d_H was 0.5 mm, 1 mm, 2 mm, or 4 mm. The simulation begins with the uniform distributed injection from the cathode edge of an electron bunch with zero velocity.

The 2nd code is a 1D PIC code[5] used to study RAE generation from a single emission center on the cathode surface in a diode filled with nitrogen at $P = 10^5$ Pa. In this code, a 1-cm long emission center with a radius of 3μm and d_{CA} varied in the range of 4–12 mm were considered.

The results of 1D PIC simulations for CA gaps of 6 mm and 12 mm are shown in Fig. 3. One can see the generation of RAE beam having $\tau \leq 30$ ps during the HV pulse rise time. The termination of RAE generation occurs because a virtual cathode (VC) is formed in the vicinity of the cathode.[5] The difference in the amplitudes of the RAE current shown in Fig. 3 is caused by the difference in the amplitude of the cathode voltage, its rise time, and the value of d_{CA}. Further, simulations showed that there is no generation of RAE from the anode side of the VC propagating toward the anode. The duration of the RAE current agrees with the duration of one peak obtained in experiments (Fig. 2). Thus, the appearance of two peaks in the experiments can be explained by the presence of several emission centers on the cathode surface and cannot be explained by the RAE generation from the boundary of the moving VC. The field emission from different emission centers can start with some time delay with respect to each other, depending on the centers' geometry. Therefore, the termination of RAE generation from these centers would also occur with time delay. In addition, these emission centers can be located randomly on the cathode edge. Thus, RAE generated in the vicinity of the cathode will arrive at the anode at different angles. If the values of d_H or h are small, the RAE beam will not be registered.

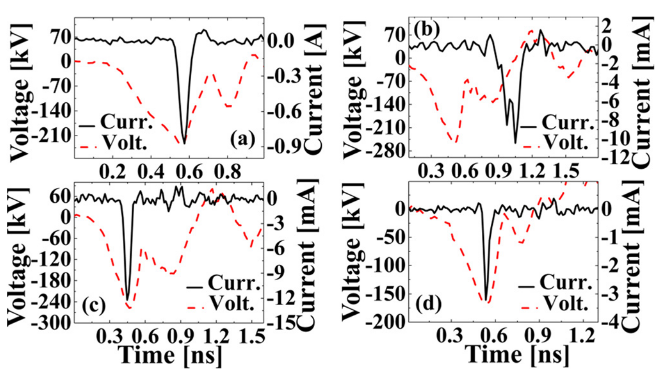

FIG. 2. Waveforms of the diode voltage and RAE current behind the anode for cylindrical cathode. Diameter of the central hole and thickness of the anode holder are, respectively, (a) 6.5 mm and 0.25 mm, $d_{CA} = 12$ mm; (b) 0.5 mm and 0.25 mm, $d_{CA} = 8$ mm; (c) 0.5 mm and 0.25 mm, $d_{CA} = 8$ mm; (d) 1 mm and 5 mm, $d_{CA} = 8$ mm.

In order to study the electron penetration through the anode central hole, 2D PIC simulations for experimental geometry were carried out using the WARP code. Fig. 4 presents the results obtained for $d_{CA} = 8$ mm, $d_H = 0.5$ mm, and $h = 5$ mm. The modeling showed that the electric field $E_C \sim 7 \times 10^7$ V/m at the cathode edge almost does not depend on d_{CA}. This result is to be expected, since the value of E_C at that location is determined by the potential and enhancement factors, which depend on the cathode geometry. The simulations showed that the radius of the electron bunch increases during its propagation toward the anode, and that the larger is the d_{CA}, the larger is the area of the anode that experiences interaction with the electron bunch. These results are explained by the electric field distribution in the cathode vicinity, where the presence of significant radial components of the electric field leads to divergence of the electron bunch in transverse directions. In addition, the fraction of electrons penetrating through the anode hole depends on d_{CA}, d_H, and h. For instance, when $d_{CA} = 6$ mm, one obtains electrons behind the anode only in the case of a thin ($h = 0.25$ mm) anode holder, when the hole $d_H \geq 2$ mm. When $d_{CA} = 8$ mm, a small part of the electron bunch can already been registered behind the anode holder with $h = 5$ mm, when $d_H \geq 1$ mm. Finally, with $d_{CA} = 10$ mm, one obtains electrons behind the anode holder when $d_H = 0.5$ mm or 1 mm and $h = 0.25$ mm and $h = 5$ mm, respectively.

Results of simulations showed that $\leq 10\%$ of the emitted electrons penetrate the anode hole. Since electron-neutral collisions were not taken into account in this model, one could expect a smaller number of electrons behind the anode if collisions are taken into account. The scattering angle decreases with the increase in electron energy.[4] Therefore, RAE propagate through the CA gap at an almost constant angle with respect to the diode axis. However, near the cathode, where electron energy is small, electrons can scatter at large angles due to electron-neutral collisions. This leads to RAE propagating and approaching the anode at different angles, which explains the registration of electrons behind the anode in the case of $d_{CA} < 8$ mm. If there are several emission centers at the cathode edge, RAE beams emitted from these centers propagate at different angles with respect

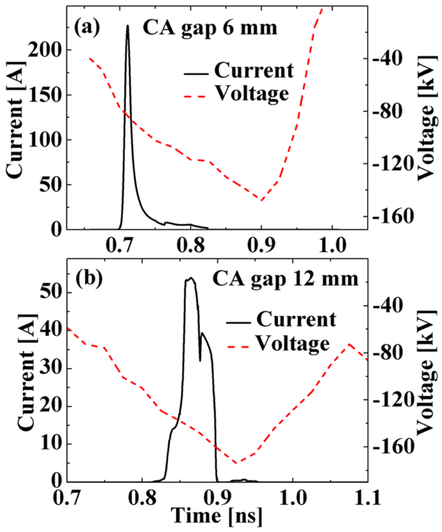

FIG. 3. Time evolution of the RAE current passing through the anode obtained in 1D PIC simulations for a given experimental voltage for d_{CA} of 6 mm (a) and 12 mm (b).

to the diode axis. Therefore, even if electron emission from these centers is started simultaneously, one peak in the RAE will be registered behind the anode hole. Here, let us note that the simulation results showed that when d_H is kept constant, the increase in h leads to a decrease in and the disappearance of the RAE beam behind the anode. Thus, the presence of several peaks in the time evolution of the RAE current indicates the presence of several emission centers appearing non-simultaneously on the cathode surface. It is important to note that only one peak in the RAE current can be registered even for several emission centers, if d_H small and the anode holder is very thick.

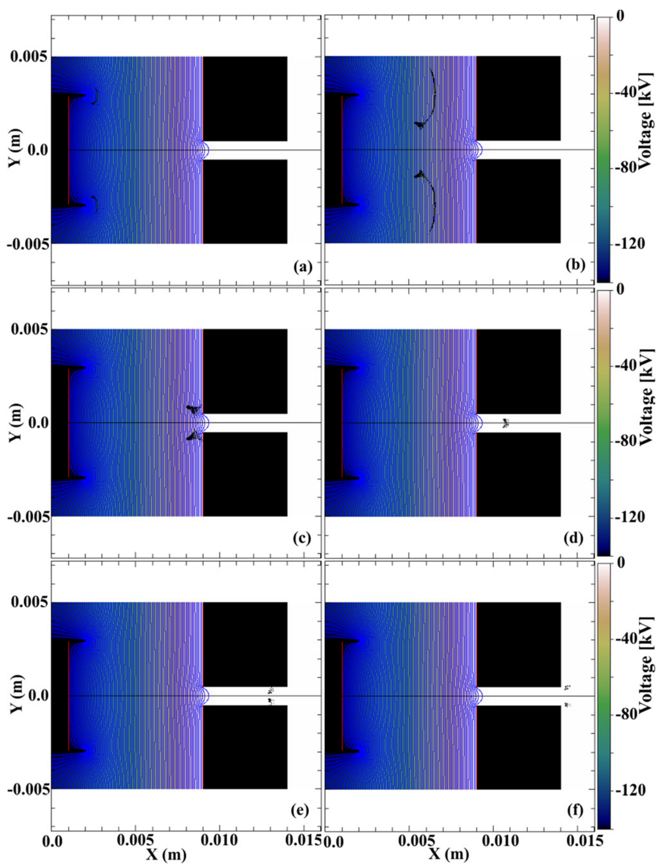

FIG. 4. Electron bunch propagation in the vacuum diode: $d_{CA} = 8$ mm; $d_H = 0.5$ mm; and $h = 5$ mm.

To conclude, the many-peak structure of RAE beams generated in air at atmospheric pressure by an HV pulse with rise time of ~300 ps was studied. Experiments showed that the probability of several peaks of RAE being registered depends on the cathode and anode geometry. That is, it was obtained that a cylindrical cathode most often leads to RAE with a many-peak structure being registered, and that an increase in the diameter of the hole in the anode leads to RAE with only one peak being registered.

Numerical simulations of RAE generation in N_2 gas at $P = 10^5$ Pa and RAE propagation in a vacuum diode with a geometry similar to that used in the experiments and supplied by the experimentally obtained HV pulse showed an RAE current duration of several tens of picoseconds, which agrees with the experimental results. However, this current consists of only one peak, which indicates the presence of several emission centers on the cathode edge, which appear with a time delay with respect to each other. Two-dimensional simulations of RAE propagation in the vacuum diode showed that the anode hole diameter and its thickness influence the RAE current behind the anode significantly. Namely, if the diameter of the hole in the anode is small or the anode is very thick, complete cut off of the RAE beam can result. An increase in the hole diameter or decrease in the anode thickness leads to an increase in the RAE current behind the anode because of the RAE divergence that electrons acquire in the vicinity of the cathode. If two or more RAE beams are generated in the vicinity of the cathode with a time delay, two or more peaks, depending on the diameter of the anode hole, can be registered behind the anode.

The work in Institute of High Current Electronics was supported by RFBR Grant No. 12-08-00105-a.

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