Supplemental material to the article

About parameters of runaway electron beams and electrons having "abnormal" energy at the subnanosecond breakdown of atmospheric pressure gases

Introduction. There are data on radiation from discharge gap during its subnanosecond breakdown in the additional material. Analysis of pulses of voltage, discharge current, runaway electron beam (REB) current and data on plasma radiation are allowed to establish general details of REB generation mechanism in atmospheric pressure gases. Generation mechanism of the REB generated near the cathode with an energy, corresponding to the distribution maximum greater than eU_m on the value of 100 keV (because of selfaccelerating at the front of polarizable streamer [2, 6, 7]) is not confirmed in our experiments. At maximal values of REB current share of electrons with an energy more than eU_m is relatively small (Fig. 3 in the main paper). REB current is significantly less at the formation of streamer and spark discharge. As well, decreasing of REB current and electrons energy was occurred when cathode-needle used.

Experimental setup. Setup consisted of discharge chamber and pulser RADAN-220 (voltage pulse amplitude of $\sim$250 kV, pulse FWHM at the matched load of $\sim$2 ns and rise time in the transmission line of $\sim$0.5 ns) was used for investigation of subnanosecond breakdown dynamics in the air and nitrogen. Discharge chamber, where potential cathode with small radius of curvature was mounted, and scheme of the experiment are shown on the Fig. 1. Voltage pulse from pulser through the short transmission line (*5*) was applied to the cathode with small radius of curvature (*7*). Voltage was registered with the capacitive voltage divider (*6*) which situated before discharge gap. Discharge current was registered with the shunt (*8*) made of thin-film resistors having small inductance. Cathode was a tube with diameter 6 mm made of 100-μm-thick stainless steel foil. Grounded flat electrode (*9*) made of grid or foil was placed at a distance of 13–16 mm from the cathode edge. Behind the grid electrode Al–Mg foil (*10*) with thickness of 50 μm was placed. REB current was registered with the collector (*11*) placed behind the foil (*10*). Using a lens (*3*) two-fold magnified image of discharge plasma was formed in the plane of

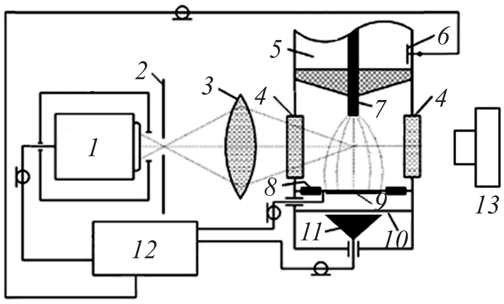

Figure 1: Schematic of the experimental setup: *1* – photodiode PD025 surrounded by metal case, *2* – screen with slit (1 mm), *3* – lens, *4* – side windows, *5* – transmitting line of the RADAN-220 pulser, *6* – capacitive voltage divider, *7* – potential electrode, *8* – currenty shunt, *9* – grounded grid electrode, *10* – foil, *11* – collector, *12* – digital scope, *13* – digital camera Sony A100 or spectrometer

the screen with slit (slit width is 1 mm) (*2*) situated before the photodiode PD025 (*1*) (cathode LNS20, Photek Inc., rise time $\cong 80$ ps). Photodiode PD025 (*1*) and screen with slit (*2*) were mounted on a moveable table. It provides registration of a radiation from different zones situated along the discharge gap axis with a spatial resolution of ~ 1 mm. For each zone 100 radiation pulses, 100 voltage pulses, and 100 discharge current pulses were registered. Then averaging was performed. Averaging for the voltage and discharge current was performed for 1400 pulses since ones do not depend on location where radiation is registered. Integral images of discharge plasma glow were taken with digital camera Sony A100. The emission spectra of the discharge plasma was registered with spectrometer HR-4000 (Ocean Optics Inc., spectral range $\Delta\lambda = 200-305$ nm).

Spatial discharge forms at the REB generation and their dynamics. Integral photos of plasma glow during the discharge in the air and nitrogen at atmospheric pressure are presented on the Fig. 2. When applying nanosecond voltage pulses across the gap with a cathode having small radius of curvature diffuse discharge formation in the air, nitrogen and other gases of atmospheric pressure is occurred. The highest emission intensity of discharge plasma of the nitrogen and air belongs to UV radiation of 2^+-system of the nitrogen molecule formed by transition $C^3\Pi_u$–$B^3\Pi_g$. Waveforms of voltage, discharge current, REB current and radiation from near-cathode area during initial 3 ns are presented on the Fig. 3. Maximal value of the REB current is registered after 600 ps with respect to applying of a

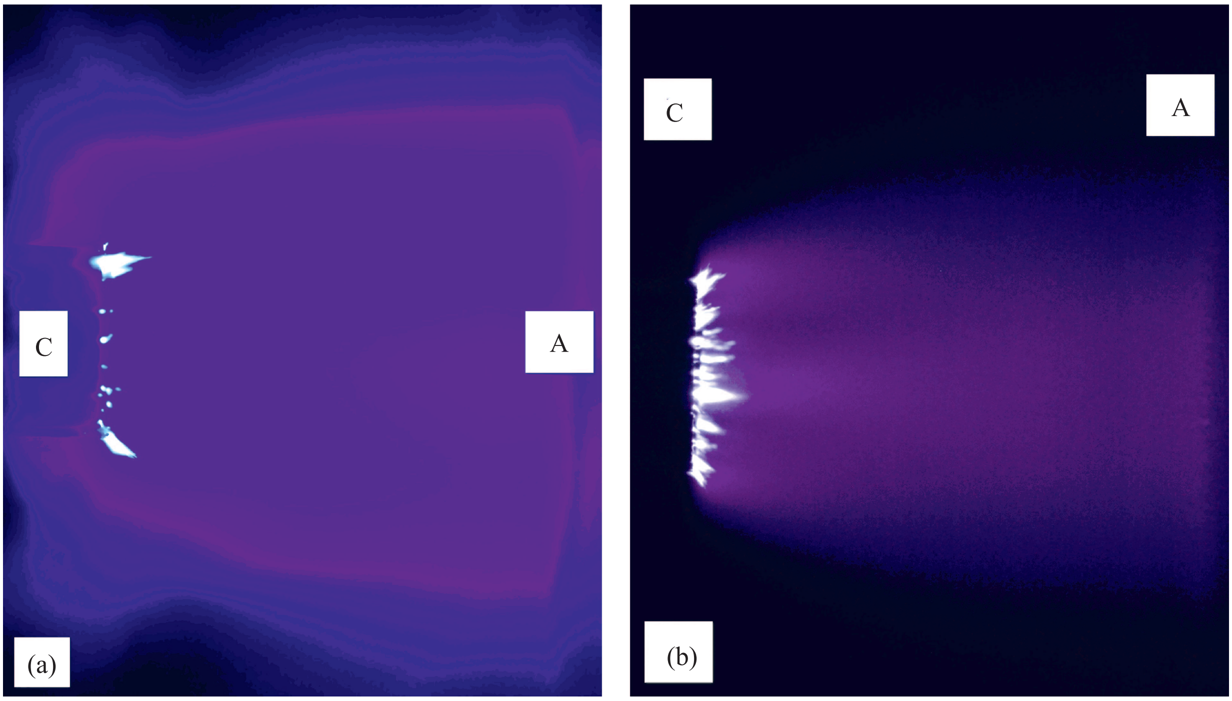

Figure 2: Integral photos of plasma glow during the discharge in the nitrogen (a) and air (b) of atmospheric pressure. Interelectrode distance of 14 mm

voltage pulse to the gap. Radiation in the zone near the potential cathode arises after 250 ps and achieves its intensity maximum when ionization wave has crossed the gap. At elevated pressures of the nitrogen and air (4 atm. and higher) maximal value of radiation intensity P of 2^{+}-system is reached simultaneously with maximum of the current through the gap. This is due to reduction of effective lifetime of the state $C^3\Pi_u$ with a pressure increase.

Dynamics of the value G that is proportional to the time derivative of excitation rate of the $C^3\Pi_u$-state and local electric field strength in observation zone are presented on the Fig. 4. In experiments, time dependence of radiation intensity P from different parts of the discharge gap was registered and then analyzed. It can be concluded from the Fig. 4, that decreasing of the value G after ~ 0.4 ns with respect to the moment corresponding to applying of a voltage pulse in the zone at a distance of 1 mm from the cathode is due to reducing electric field strength $E(t)$ there. In subsequent zones, decreasing is observed later. The sharp jump of the

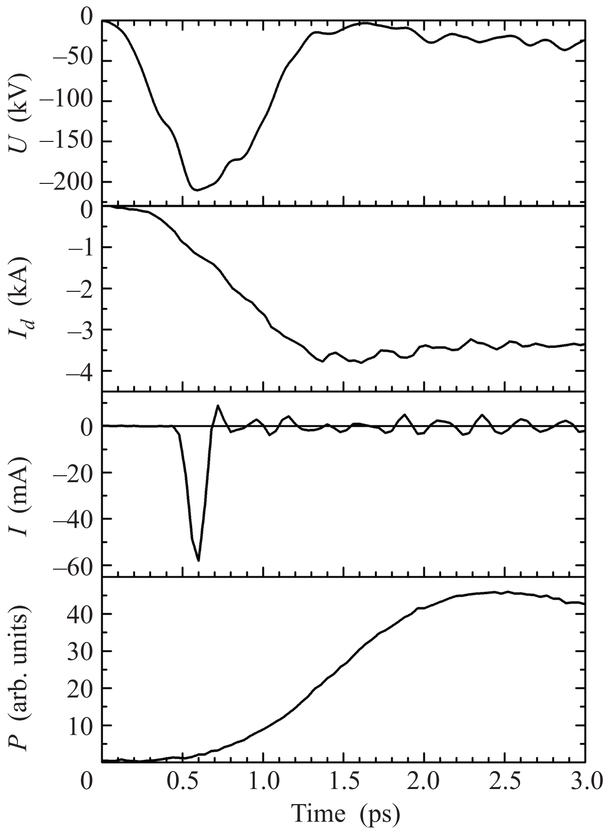

Figure 3: Waveforms of pulses of voltage U, discharge current I_d, REB current I, and radiation from the near-cathode area P. Atmospheric pressure nitrogen. Interelectrode distance of 13 mm

value G in zones remoted by 10–13 mm from electrode with a small radius of curvature indicates that electric field strength there increases almost simultaneously. The observed dynamics confirms that gap breakdown under these conditions is occurred in the form of an ionization wave. It is shown from figures that ionization wave starts from electrode with a small radius of curvature and crosses the gap. At the nitrogen pressure of 4 atm. firstly of approximately 2/3 of the gap length is broken down (Fig. 4). As concerning the remaining part, that both it breaks almost simultaneously or ionization wave speed there increases. After the first ionization wave reaches flat electrode a second ionization wave directed toward the electrode with a small radius of curvature is formed. At this time REB generation terminates. When second ionization wave arrives to the electrode with a small radius of curvature breakdown stage ends and commutation stage begins. The latter is

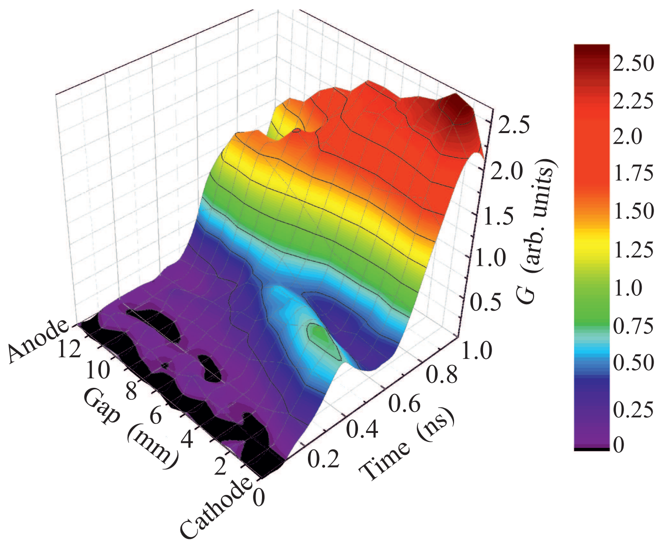

Figure 4: Dependence of the value G (proportional to the local electric field strength in the observation area), on time and distance from the potential cathode. Nitrogen at pressure of 4 atm

accompanied by voltage decrease (Fig. 3) and increasing of conduction current and plasma radiation intensity.

REB generation mechanism. Let us briefly describe main stages of the REB generation mechanism. Generation of runaway electrons can be divided on four main stages. First stage corresponds to appearance of initial electrons from the cathode due to field emission. Cathode must have sharp edges and large emitting surface to generate REB with a maximal current amplitude behind the anode foil. Field emission arises at the front of voltage pulse with an amplitudes of hundreds kV owing to macro- and microinhomogeneities of the cathode on which electric field strength achieves values of 10^7 V/cm. It exceeds critical value of field strength required for the runaway electron, which, according to the criteria proposed in the [3], is an order of magnitude smaller for small values of pd (p – gas pressure, d – interelectrode distance).

In the second stage share of an electrons passed into runaway mode (fast electrons) ionizes gas and creates initial electrons near cathode from which an electron avalanches develop. Concentration of initial electrons near cathode is sufficient for overlapping of avalanches heads until ones reach critical size and streamer formation. In a short time, dense cloud of diffuse plasma or some diffuse plasma jets near the cathode are formed. In this stage, at the subnanosecond front of voltage pulse, discharge current together with displacement current achieves hundreds amperes (Fig. 3, as well Fig. 2 in the main paper) and field emission turn into the explosive emission. By reducing of the voltage pulse duration to 0.1–0.2 ns or increasing gap length or when shooting discharge gap with a CCD-camera it can be observed diffuse corona near the cathode and bright spots on it. These spots and anode-directed leaders growing from spots are visible on the integral photos of the discharge as well (Fig. 2). REB generation at atmospheric pressure of the air and nitrogen are observed after bright spots arising. In the case of the nitrogen radiation of near-cathode plasma effect on electrons emission from the cathode. Abutment of diffuse discharge to the lateral surface of tubular cathode are seen on the Fig. 2a. It should be noted, that electric field near the cathode is additionally enhanced by positive charge of the ions. It could also lead to the generation of fast electrons including from area at the cathode sidewall. Positive potential of the ions cloud and electron beam with small energy (directed opposite to the potential anode) were detected with collector behind the grounded grid cathode.

Generation of general runaway electrons share is occurred during the third phase. It is due to the electrons acceleration between dense polarized plasma front (ionization wave front) and anode. In this case, electrons moving in the ionization wave front and in the gap are influenced by negative charge of the avalanches heads and anode voltage.

During the fourth stage, an ionization wave front reaches anode. In this case, electric field strength distribution become more uniform and REB generation terminates, as well voltage across the gap decreases (Fig. 3). The magnitude of voltage drop across the gap depends on the gas pressure and its kind. Voltage decrease in the gap is observed after 200–500 ps (Figs. 2 and 3 in the main paper). During this time interval ionization wave front reaches anode and ionization amplifies in the whole gap (Fig. 4). Ionization wave speed depends on kind and pressure of gas and achieves values of ~ 10 cm/ns. Increasing of voltage across the gap and REB current amplitude are synchronous in optimal modes.

Runaway electron beam current duration $\tau_{0.5}$ (FWHM) from whole surface of an anode foil at atmospheric pressure and voltage of hundreds kV is ~ 100 ps (Fig. 4 in the main paper). REB duration $\tau_{0.5}$ depends on some factors. Firstly, it depends on time difference between moment of achievement of critical electric field and arrival ionization wave to the anode. At decreasing of voltage amplitude and increasing of gas pressure (for heavy gases) $\tau_{0.5}$ increases. Secondly, reaching various anode parts by ionization wave front and runaway electrons is not simultaneously. It increases $\tau_{0.5}$ too.

According to mechanism above, in the present time the highest amplitudes of runaway electrons beam current are obtained behind the thin-foil anode during the discharge in the atmospheric pressure air [8].