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# About Influence of Runaway Electrons and X-Ray Emission on the Breakdown in the Non-Uniform Electric Field

**Victor .F. Tarasenko**

Institute of High Current Electronics,
Russian Academy of Sciences, Tomsk, Russia
*VFT@loi.hcei.tsc.ru*

**Dmitry V. Beloplotov**

National Research Tomsk State University, Tomsk, Russia
Institute of High Current Electronics, Russian Academy of Sciences,
Tomsk, Russia

**Mikhail I. Lomaev**

Institute of High Current Electronics,
Russian Academy of Sciences, Tomsk, Russia

**Dmitry A. Sorokin**

Institute of High Current Electronics,
Russian Academy of Sciences, Tomsk, Russia

**Abstract:** *The breakdown at high-pressure of nitrogen and SF6 in an inhomogeneous electric field was investigated. It was confirmed, that diffuse discharge at elevated pressure of gases is formed at the both positive and negative polarities of voltage pulses without using of additional ionization source. It was established, that diffuse discharge at negative polarity of voltage pulse is due to a runaway electrons, and at positive polarity of voltage pulse is due to a characteristic X-ray caused by interaction of fast electrons with an atoms and molecules of gases..*

**Keywords:** *Runaway Electrons (RAE); characteristic X-ray; Runaway Electrons Preonized Diffuse Discharge (REP DD); Diffuse corona; Supershort Avalanche Electron Beam (SAEB)*

## 1. INTRODUCTION

In recent years the interest to the nanosecond breakdown in high-pressure gases increased [1-7]. In [4, 7 – 13] supershort avalanche electron beam (SAEB) with FWHM of ~100 ps was registered behind anode made of thin foil in air and other gases of atmospheric pressure at negative polarity of nanosecond voltage pulses. As well, at the same conditions and in a wider range of ones X-ray was registered from discharge gap and anode [14 – 19]. Apperance of X-ray is due to influence of the ranaway electrons on the anode and gas.

At the end of the 60s of the last century, it was shown that diffuse discharge is formed in helium [20] and air [21] under conditions of X-ray generation. Formation of diffuse discharge is explained by preionization of gas by fast electrons generated due to amplification of electric field near cathode with small radius of curvature and on the ionization wave front. [7 – 9, 12, 13]. Interaction of fast electrons with gas leads to appearance initial electrons, from which electron avalanches develop [22]. However, diffuse discharge is formed at the both negative and positive polarity of voltage pulse [23 – 27]. First this fact, presumably, was described in [23] where the breakdown in air of atmospheric pressure was studied. In [23] it was found that diffuse discharge is formed at the both polarities of voltage pulse. Moreover, the potential electrode may have different radius of curvature. Also, it was found that the size of current flow region is changed with changing of polarity of voltage pulses. In [27] it was suggested, that at positive polarity of voltage pulses the diffuse discharge is formed due to a characteristic X-ray caused by interaction of RAE with gas particles. Fast electron knocks out electron from inner shell (K-shell) of atom. Then an electron from outer shell is transferred into inner shell, causing a characteristic X-ray. In [27, 28] it was shown, that efficiency of the characteristic X-ray generation is increased with decreasing of atomic number of the element. Moreover, energy of X-ray photons is enough for appearance of initial electrons at a distance of 4 mm. In [29] characteristic X-ray was registered experimentally in argon at low pressure.

The main objective of this work is to study the process of formation of diffuse discharge in nitrogen and SF6 and determine the reason of formation of diffuse discharges in high-pressure gases at positive polarity of an electrode with small radius of curvature.

## 2. Experimental Setup and Measurements

The study was performed on two setups consisted from discharge chambers and pulsers. On Setup #1 (Fig. 1) the voltage pulse formed with the RADAN-220 pulser applied through a short transmission line (1) to an electrode with small radius of curvature (2). Maximal amplitude of the voltage pulse was ~300 kV. In one case the potential electrode was made of razorblades of thickness of 100 μm and have a length 19 mm. In another case the potential electrode was made of 100-μm-thick stainless steel foil twisted into a tube (Ø ~6mm). Grounded electrode (3) was a flat, which was located at a distance of 13 mm from the edge of potential electrode. The voltage pulse was registered with a capacitive divider (4) located at the end of the transmission line. The voltage pulse duration at a matched load was ~2 ns, and the pulse rise time in the transmission line was ~0.5 ns. The current through the gap was measured with a shunt (5) made of thin-film chip-resistors. The chip-resistors were connected in series with the flat electrode (3) and were uniformly located at its circumference. SAEB current was measured with a collector (6) simultaneously with the discharge current and voltage pulse in the gap at the negative polarity of the voltage pulse. SAEB current registered behind the disk-like anode with diameter of 1cm (3) made of 50-μm-thick AlMg foil . It was reinforced by a metal grid with transparency 14 %. The collector (6) was located downstream of the anode foil. The discharge chamber was filled with nitrogen or SF6. The pressures of gases ranged from 0.1 to 0.3 MPa.

On Setup #2 For initiation of a discharge, we used a FPG-60 pulser which produced voltage pulses of negative polarity with a voltage rise time of 2 – 3 ns and FWHM of 4 – 5 ns. In the experiments, the amplitude of the incident voltage wave was normally 30 kV. The pulse repetition frequency was up to 1000 Hz. Transmission line consisted of 4 cables with a characteristic impedance of 75 ohms. Length of excited region was about 35 cm. The cathode was made of 50 steel sewing needles (Ø ~0.7 mm). Needles were mounted in line and attached to one conductor at the same distance from each other. The anode was made from a part of a stainless steel cylinder with radius of 7 cm and had rounded edges. Voltage pulses produced by the FPG-60 applied through 4 cables to the cathode. Nitrogen was pumped through the discharge gap with fans at speed up to 20 m/s. The pressure of nitrogen ranged from 0.04 to 0.1 MPa.

Signals from the voltage dividers, shunt, collector, and photodiode were recorded with Tektronix DPO70604 digital oscilloscope (6 GHz, 25 GS/s) (7). The detectors were connected to the oscilloscope via RadioLab 5D-FB PEEG coaxial pulse cables with standard N-type connectors and Barth Electronics 142-NM attenuators with a bandwidth up to 30 GHz. The integral emission spectra were recorded with the spectrometer EPP-2000C (Stellar-Net Inc.). The images of discharge plasma glowing were photographed with Sony - A100 (8). X-ray exposure dose was measured with Arrow–Tech, Inc (Model 138) dosimeter. Sensitivity of dosimeter was less maximal sensitivity on 20 % at 16 keV photon energy. In the range of photon energy from 30 to 1000 keV the dosimeter has maximum sensitivity. The dosimeter was located at a distance of 1 cm from the plane of foil perpendicularly to the axis of the gas diode. Electron beam and X-ray were detected with RF-3 photo film warped with 120-μm-thick black paper. For X-ray detection a shield which absorbs electron beam was used. To obtain autographs of X-ray it was necessary on two orders of magnitude more pulses, than for obtain autograph of the electrons beam.

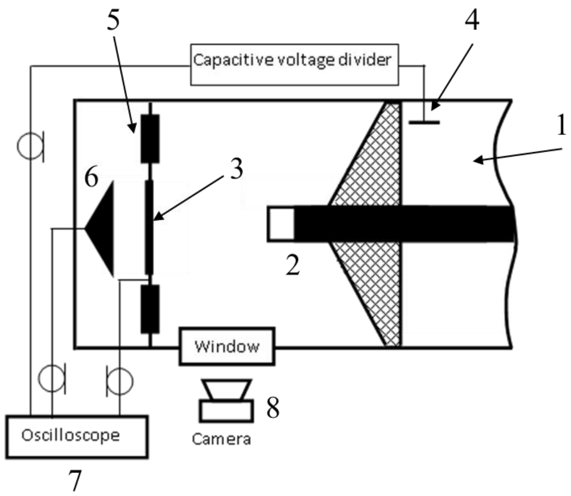


**Fig1.** *Block-diagram of experimental setup #1: 1 – transmission line of RADAN-220 pulser; 2 – high voltage electrode; 3 – grounded electrode made of thin foil; 4 – capacitive voltage divider; 5 – current shunt; 6 – collector; 7 – oscilloscope; 8 – camera Sony – A100.*

## 3. Experimental Results

Integral images of runaway electron preonized diffuse discharge (REP DD) in nitrogen at pressure of 0.2 MPa for the both polarities of voltage pulse and “blade-plane” configuration of electrodes are presented in Fig. 2 (setup #1). It is seen, that discharge has a diffuse glowing at both polarities of voltage pulse. Diffuse discharge consists of individual jets, which start from bright spots on the electrode with small radius of curvature and end on grounded electrode. At negative polarity of voltage pulse there are bright spots only near electrode with small radius of curvature. However, at positive polarity there are bright spots near flat electrode. From spots on the electrode with a small radius of curvature spark leaders germinate, whose length at positive polarity several times more than at negative one. In Fig. 2b it is seen how the spark leader was transformed into spark channel. Glow of spark channel has less intensity because of the spark leader bridged the discharge gap in the end of voltage pulse. From these experiments, it follows, that diffuse discharge in an inhomogeneous electric field is formed at both polarities of nanosecond voltage pulses. At negative polarity the diffuse discharge is more homogeneous than at positive one. As well under the same conditions (gas, pressure, interelectrode distance) a constriction of discharge occurs later at negative polarity than at positive polarity.

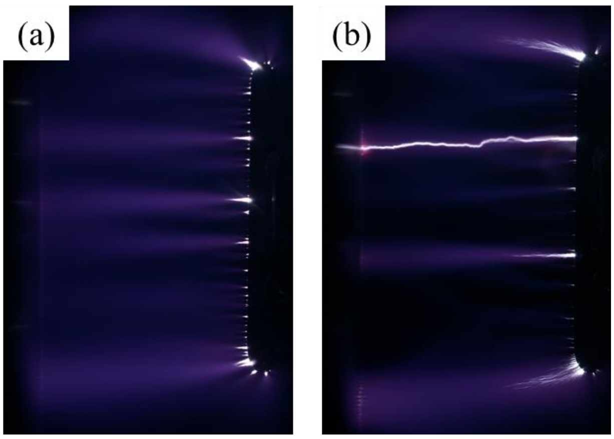


**Fig 2.** *Images of REP DD in nitrogen at pressure of 0.2 MPa for the negative (a) and positive (b) polarities of voltage pulse. “blade-plane” configuration. Interelectrode distance of 13 mm. Setup #1.*

In Fig. 3 images of REP DD in nitrogen in pulse-periodic mode and at negative polarity of voltage pulses are presented (setup #2). The camera was placed at a slight angle to the axis of the discharge gap. On top of Fig. 3 you can see cathode made of 50 steel sewing needles. The breakdown of discharge gap was occurred only at low pressure of nitrogen by reason of decreasing amplitude of voltage pulses and increasing interelectrode distance. Diffuse discharge was formed at nitrogen pressure of 70 Torr or less. At higher nitrogen pressure only a corona discharge was formed. Size of glowing region of corona discharge is decreased at increasing nitrogen pressure (Fig. 3b and Fig. 3c). Cathode spots were not observed because of small amplitude of voltage pulse and low pressure. Diffuse discharge was formed in pulse-periodic mode with frequency of 1kHz due to pumping of gas.

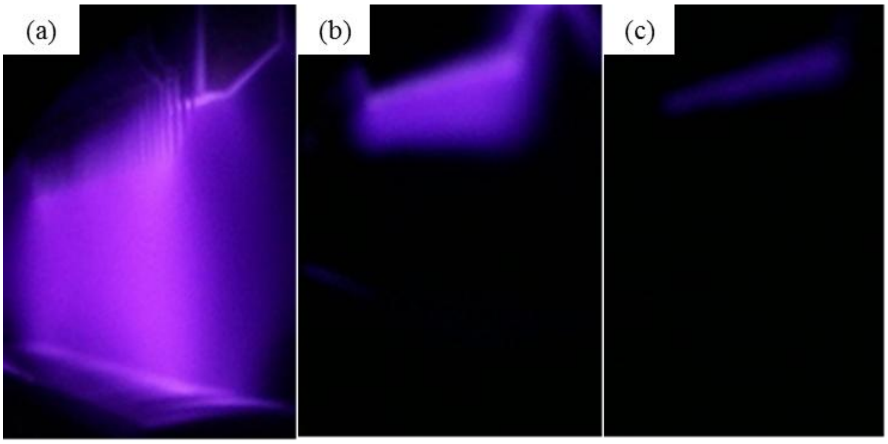


**Fig 3.** *Images of REP DD (a) and the corona discharge (b, c) in nitrogen at pressure of 70 Torr. Interelectrode distance of 20 mm. Setup #2*

Discharge images at different pressure of $SF_6$ at negative and positive polarity for a “tube-plane” configuration of electrodes are presented in Fig. 4. Heavy $SF_6$ was chosen for formation of diffuse and corona discharges. To observe surface of flat electrode the camera was placed at a slight angle to side window. In the result, one can see on images the surface of the plane electrode and nearest edge of tube electrode. Due to using of $SF_6$ the diffuse (Fig. 4a, d, e) and the corona (Fig. 4b, c, f) discharges were formed. Diffuse discharge in $SF_6$ was formed at both polarity of the voltage pulse, as well as in air [23] and nitrogen. However, in nitrogen (see Fig. 2), diffuse discharge was more homogeneous at negative polarity. At negative polarity a bright spots were observed on the electrode with a small radius of curvature only. In the case of diffuse discharge, at positive polarity a bright spots were observed on a flat electrode (Fig 4d, e). At positive polarity a corona discharge was formed at more lower pressure than at negative polarity (Fig. 4a, f). Size of glowing region of corona discharge is decreased at increasing of $SF_6$ pressure. As one can see diffuse discharge is formed in an inhomogeneous electric field at both polarities of voltage pulse, and at increasing pressure of gas a diffuse corona discharge is formed.

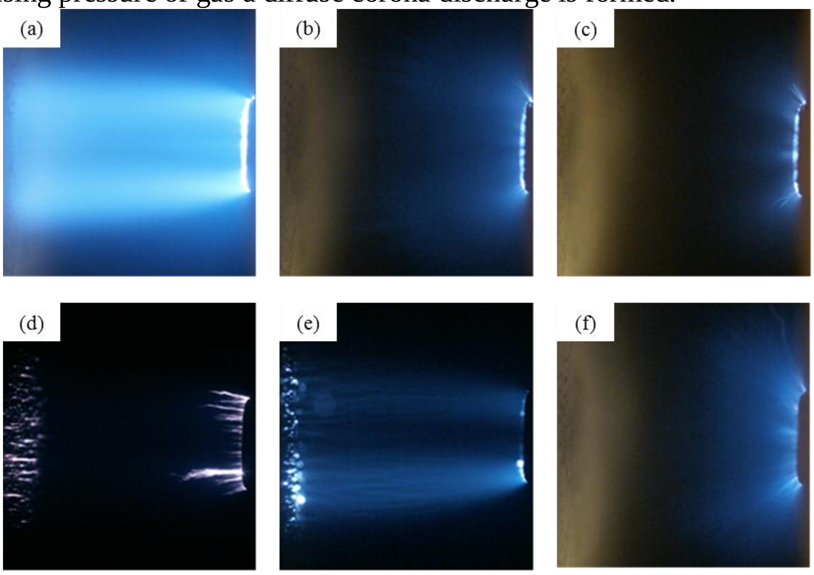


**Fig 4.** *Images of REP DD (a, d, e,) (per 1 pulse) and the corona discharge (b, c, f) (per 20 pulse) at different pressure of SF6 at negative and positive polarity. “tube-plane” configuration. Negative polarity of voltage pulse. Interelectrode distance of 13 mm. Setup #1.*

Waveforms of voltage pulses, SEAB current and current through the gap, which is consisted from a displacement current, dynamic displacement current and conduction current are presented in Fig. 5 for setup #1. At the front of the discharge current a SAEB was registered whose amplitude decreases with increasing pressure. In these conditions it is possible to obtain autograph of electron with photo film beam and exposure dose ~1 mR with dosimeter.

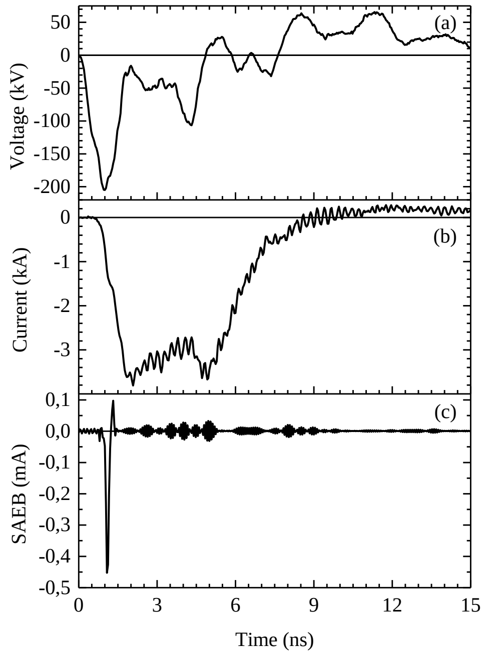


**Fig 5.** *Waveforms of voltage pulses (a), current through gap (b) and runaway electron beam behind foil (SAEB). Pressure of SF6 is 0.05 MPa. Setup #1.*

Using the setup #1, at positive polarity the RAE was not registered behind cathode made of foil As well known, main part of RAE directed to the anode. Only at special conditions it is possible to register RAE beam oppositely directed from the anode behind cathode made of grid. which directed in the opposite direction from the anode Registration of X-ray radiation is also very difficult task at positive polarity of voltage pulse. However, there are some works [16, 21, 26] where it was done in the literature. In [16] X-ray was registered with a scintillator and a PMT in the moment of streamers formation on an anode with a small radius of curvature. In [26] X-ray was registered with using the RF-3 photo film at interelectrode distance of 0.4 mm, and tungsten anode. On setup #1 X-ray was registered with using the RF-3 photo film at positive polarity during the significantly reducing of interelectrode distance and large exposure (~1000 pulses).

Thus, the results of experiments and analysis of the literature are shown, that at a negative polarity of the voltage pulses which are applied to the cathode with a small radius of curvature the RAE and X-ray are registered. Formation of diffuse discharges in these conditions it is easy to explain by preionization of gap by RAE which are generated and accelerated near the cathode and in the gap. X-ray and RAE are registered at positive polarity of voltage pulses. However, the recorded X-ray intensity and the photon energy of one are small, and the runaway electrons were recorded only behind cathode made of grid.

## 4. About Mechanism of Formation of Diffuse Discharges in Gases at Elevated Pressure at a Positive Polarity of Voltage Pulses Applied to the Electrode with a Small Radius of Curvature

Formation of diffuse discharge at elevated pressures of various gases in an inhomogeneous electric field at negative polarity of voltage pulses applied to the electrode with a small radius of curvature can be uniquely attributed with the generation of runaway electrons near the cathode and in the gap. First electrons are extracted from the cathode due to the field emission. Thus, the intensity of electric field for the field-emission of electrons is greater, than the critical strength of the electric field for the transition of electrons into runaway mode. Therefore, part of the electrons emitted from the cathode turn into runaway mode. They gain energy sufficient to create the initial electrons in the near-cathode region. Further, electron avalanches are developed from the initial electron and. their heads are overlapped before reaching the critical size. As the result, the diffuse discharge is formed [33].

At positive polarity, the first electrons appear near micro-inhomogeneities of anode due to the tunnel effect [34]. As we assume, some of these electrons also turn into runaway mode and causes the X-ray bremsstrahlung from the anode. Bremsstrahlung creates initial electrons near the anode. Then, electron avalanches are formed from the initial electrons. The heads of electron avalanches are overlapped. Dense plasma is produced near the anode and its front moves toward the cathode with high speed (a few centimeters per 1 ns). Thus, some of the electrons in a high electric field turn into runaway mode near anode, and then at an ionization wave front. However, the energy of the fast electrons is relatively small, as they move into the dense plasma, where intensity of electric field is small. We consider, that characteristic X-rays are the cause mainly appearance of initial electrons. The characteristic X-ray propagates in all directions and produces preionization of the gap. Since the photon energy of X-ray of K-line is relatively small (390 eV for nitrogen and 525 eV for oxygen), accordingly the lenght of their propagation is small (4 mm for nitrogen). Registration of characteristic X-rays in gases, which consist from atoms with small atomic number, it is very difficult. It failed to do in gases of elevated pressures. However, the photon energy of characteristic X-rays is enough for preionization of region ahead of the ionization wave front. We note, that in our opinion in [16, 26] the bremsstrahlung, which is caused by electrons with energy of ~10 keV, was registered at positive polarity of voltage pulses.

## 5. Conclusion

Carried out investigations are confirmed, that diffuse discharge is formed at elevated pressure of gases in an inhomogeneous electric field without additional sources of ionization at both polarities of voltage pulses. It was shown, that diffuse discharge at positive polarity of voltage pulses is formed due to generation of RAE and characteristic X-ray..

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