Features of transition of the open pulse–periodical high-voltage discharge in D2 at low pressure into the low-voltage mode

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Abstract. The experimental results on properties of a strongly overvoltage open pulsing discharge being formed in a short gap (3 mm) filled with deuterium at low pressure (P=0.5 - 2 Torr) are presented. This discharge generates a high-current pulsed-periodical e-beam of 35 mm in diameter with a frequency up to 1.5 kHz and energy up to 25 keV. The repetition frequency influence on the reproducibility of e-beam generation was studied. It was found out that the high-current cathode spots being formed after the transition of the high-voltage regime into low-voltage regime restrict the maximum repetition frequency of a strongly overvoltage open pulsing discharge.

1. Introduction
Generation of the pulsed high-current electron beams with energy up to 25 keV by the overvoltage discharges in short gaps (d < 1 cm) at a low pressure of the plasma-forming gases (P < 10 Torr) is of great interest to many scientific and practical applications. The soft x-ray radiation that can accompany the work with e-beams of average energy doesn’t constitute a danger to service personnel as such radiation is easily shielded by the walls of a discharge device. One of the important applications of such e-beams is related to receiving ultrahigh charging of the dust particles containing deuterium or tritium. These particles are surrounded by the plasma created in the deuterium at low pressure. Creation of ultrahigh charged particles by electron beams gives the chance to realize a neutron generator [1] without the accompanying hazardous hard x-ray radiation which necessarily arises when e-beams with energy about 100 keV are used. This is a reason why generators of neutrons without the accompanying hard x-ray radiation are of great interest to biomedicine.

The properties of the overvoltage open discharge in the pulse-periodical mode formed with use of the three-electrode system developed by authors are investigated in this work. The three-electrode system provides a stable ignition of the overvoltage discharge in the pulse-periodical mode. The high-current cathode spots which are being formed after the transition of the discharge from the high-voltage mode into the low-voltage mode can influence the limit opportunities of the open discharge in pulse-periodical regime. The limit opportunities are found out.

2. Experiment
The electric and optical scheme of the experimental setup is presented in Fig. 1. The excitation of the diffusive overvoltage open discharge in a deuterium at a pressure of P=0.5 - 2 Torr was done in a
quartz tube in which the gas-discharge system consisting of three electrodes was placed: a solid cathode and two mesh anodes separated from each other. The detailed description of the gas-discharge setup and electrode system is given in [2]. This electrode system allows us to generate two discharges at the same time: the main discharge, i.e. the high-current overvoltage open discharge and the auxiliary discharge, i.e. the low-current discharge which creates the preionization of a gas inside the gap of the main discharge and provides its stable ignition. The pulse-periodical mode of the overvoltage open discharge was organized by using the thyatron operated in the pulse-periodical regime. The auxiliary discharge was working constantly. The existence of the auxiliary discharge increases the frequency and stability of the operation of the main discharge in the pulse-periodical regime. The invented three-electrode system allows us to form the diffusive discharge in a deuterium at the pressure P=0.5 - 2 Torr in the pulse-periodical mode with the voltage amplitude up to 25 kV and the repetition frequency up to 1.5 kHz.

The discharge current and voltage were registered with the low-inductive current shunt R = 0.024 Ohms and the compensated voltage divider PINTEK HVP-39 (1000:1, 40 kV, 200 MHz), respectively, signals from which were recorded by a digital oscilloscope Tektronix DPO 2024.

![Scheme of electrical measurements](image1.png)

**Figure 1.** The scheme of experimental setup for generation of the overvoltage open discharge in the pulse-periodical mode. a) 1 is the cathode; 2, 3 are the mesh anodes with geometrical transparency about 75%; R1 = 44 Ohm, R2 = 1 MOhm are the ballast resistors, Rs = 0.024 Ohm is the current shunt; D is the diode; C1 = 12.5 nF, C2 = 100 µF are the capacitors; K is the key for connection to the auxiliary discharge; T is the thyatron 1000A/25kV which is being switched on by the generator of impulses of the preset frequency. b) 1 is the block in which the three-electrode system of the overvoltage open discharge is mounted; 2 are the flanges which are densely pressed to a quartz tube 3; 4 is a window for observation of the discharge and recording his spectral emission; 5 is a camera or spectograph.

Spatial-temporal dynamics of both the discharge emission and luminescence of the gas excited by the electron beam in a pipe was registered by Canon EOS 550 and CASIO-EX-F1 digital cameras (the maximum frequency of frames is 1200 a shot/s). The emissive spectrum (λ = 200-1100 nm) of gas excited by an electron beam was registered by a fiber-optical spectrometer of AvaSpec-2048L. To maintain high purity of the working gas (99.99% of D2), all experiments were performed at weak pumping the gas through the gas-discharge camera.

### 3. Experimental results and their discussion.

Images of the stationary low-current auxiliary discharge and high-current open discharge in the pulse-periodical regime (a look in the direction of a normal to the cathode at a small angle) are given in Fig. 2a and 2b, respectively. It is well visible that the auxiliary discharge is rather uniform. In the case of the periodical open discharge, one can see on the cathode the high-current spots which arise after the transition of the discharge from the high-voltage (HV) mode into low-voltage (LV) one. As a rule, in each impulse, there is no more than one current spot on the cathode (sometimes there is nothing). The existence of a large number of the cathode spots in the photo is explained by a long exposure time in
comparison with the period of the pulsing discharge, therefore, the image in Fig. 2b corresponds to the superposition of images of many individual discharge impulses. The blurred large spot in the left bottom corner of Fig. 2b corresponds to a luminescence of the gas excited by an e-beam.

Figure 2. Images of the stationary low-current auxiliary category (a) and the pulse-periodical high-current open discharge with a repetition frequency of 150 Hz (b). Deuterium, P = 2 Torr. The pictures are taken in the direction of a normal to the cathode at a small angle. The blurred large spot in the left bottom corner of Fig. 2b corresponds to a luminescence of the gas excited by the e-beam. The exposure time is 0.1 s (a) and 0.5 s (b).

The current and voltage oscillograms of the open discharge in a single pulse mode and in the mode of periodically repeating pulses are presented in Fig. 3a and 3b, respectively. After the transition of the HV mode into the LV mode, the voltage drop on the open discharge decreases almost by one order of the magnitude.

Figure 3. The current and voltage oscillograms of the open discharge in a single pulse mode (a) and in the mode of periodically repeating pulses with a frequency of 150 Hz (b). Deuterium, P = 2 Torr.

A single pulse mode. Exposure time is 0.6 s.

Periodically repeating pulses with a frequency of 10 Hz. Exposure time is 1 s.

Periodically repeating pulses with a frequency of 150 Hz. Exposure time is 0.5 s.
Periodically repeating pulses with a frequency of 1000 Hz Exposure time is 0.5 s.

**Figure 4.** The images (side view) showing the spatial structure of an e-beam in the direction of his propagation (from the right to the left, length of 23 cm) under different frequencies of the discharge repetition. Deuterium, P = 2 Torr. U = 20 kV, I = 100 A.

**Figure 5.** The emissive spectra of D2 excited by an e-beam at distance of 20 cm from the HV discharge. a) The spectrum collected from 47 single separated pulses; b) the spectrum collected from a pulse-periodical mode with a repetition frequency of 150 Hz, the time for accumulation of an optical signal is 30 s. One may see that the intensity of the spectral lines significantly increases in the case of discharge in the pulse-periodical regime.

The experiment has shown that in the pulse-periodical mode, the duration of the HV stage of the discharge fluctuates from one impulse to another much stronger compared to that in a single pulse mode. However, the average duration of HV stage increases with the growth of frequency but the average current of the e-beam changes insignificantly. It is possible that increase in duration is caused by the reduction of the gas density in a discharge zone due to his heating. Indeed, at the gas pressure reducing, the duration of the HV stage increases, but the average current of the e-beam decreases. With the growth of frequency, the scattering in the duration of the HV stage is expressed stronger that, perhaps, is connected with the influence of residual plasma from the cathode spots of the previous discharge pulse on development of the discharge in the subsequent pulse. It is obvious that this influence becomes more notable at the reduction of the time between two neighbor discharge pulses. This effect, apparently, limits the maximum frequency about of 1-1.5 kHz for the repetition of pulses of the overvoltage open discharge.

4. **References**

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4. **Acknowledgments**

This work has been carried out thanks to full financial support by the Russian Science Foundation (Grant № 16-12-10458).