Evolution of the shape of a high-current and moderate energy electron beam at its propagation through D2 at low pressure

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Abstract. The paper presents the experimental data on the time-spatial evolution of electron beam that is formed and propagates in a dielectric tube of large volume filled with D2 at low pressure of 1-2 Torr. The e-beam is generated by gas discharge in a short gap powered by the stepwise high voltage with amplitude up to 25 kV. Initially, this discharge appears in a strongly over-voltage regime which is unstable and eventually (in several hundreds of ns) transits into abnormal glow discharge at the voltage about of 1.5 - 2.5 kV and the current amplitude of several hundreds of Amps. The every of the mentioned discharge regimes generates the e-beam with energy up to 25 and 2.5 keV respectively. The ability of the over-voltage gap to generate the high- and low-energy e-beams happening one by one can be of great interest for many applications. The features in spatial structures of high-energy and low-energy e-beams in the course of their propagation over long distance through deuterium at low pressure are revealed and discussed.

1. Introduction

Strong over-voltage pulsed discharges at low pressures ($P < 10$ Torr) in a narrow gap ($d < 1$ cm) between the solid cathode and grid anode (so called “open discharges”) operate under conditions which correspond to an appearance of run-away electrons which are able to form the electron beam. It means that it is possible to generate the electron beams not only in a vacuum with the use of the e-emissive cathodes but in gaseous atmosphere as well. The open discharges have a high efficiency in generation of the e-beams. Typically, the e-beam current corresponds to 80-90% of the total discharge current. At present the strong over-voltage pulsed discharges are widely used for generation of e-beams with an energy $e$ ranging from 1 to 70 keV [1]. As a rule, the increase in magnitude of parameters $P$, $d$, $e$ leads to strong diminishing in duration of both the over-voltage discharge and the e-beam generated by gas discharge.

If to speak about practical applications, it necessary to note that the high-energy e-beams (about 70 keV) generate the hard bremsstrahlung X-radiation which is bio-hazard and has a high penetrability. Due to that the installations using the e-beams of high energy (about of 100 keV) represent bio-danger at their service and demand the application of special measures of bio-protection. In contrast, the e-beam of 25 keV in energy does not generate the hard bremsstrahlung X-radiation. This is a reason why the gas discharges powered with voltage up to 25 kV and generating the high-current e-beams with energy up to 25 keV are of great interest.

In this paper the three-electrode system operating in D2 at lower pressure (1-2 Torr) and powered by the stepwise applied voltage with amplitude up to 25 kV is presented. This pulse discharge system...
exhibits two regimes (strong over-voltage discharge and anomalous glow discharge) and generates the sequence of two e-beams with energy up to 25 and 2.5 keV respectively which happen one by one. The features in spatial structures of high-energy and low-energy e-beams in the course of their propagation over long distance through deuterium at low pressure are revealed and discussed.

2. Experimental setup

Sketch of the used experimental setup is shown in figure 1. The electrical scheme is depicted schematically in Figure 1a. The pulsed over-voltage discharge has been formed in a narrow gap between the solid cathode (1) and the grid anode (2). The distance between these electrodes is equal to 3 mm. This discharge is ignited with a high voltage transferred by high-current thyatron T from the capacitor C1 through the ballast resistor R1 with a resistance of 44 Ohm. There was a complimentary discharge between the cathode and additional grid anode (3). The distance between cathode and the auxiliary anode is equal to 16 mm. The geometrical transparency of each grid was about 70%. The auxiliary low-current and low-voltage discharge was fed by the capacitor C2 through the ballast resistor R2 with a resistance of 1 MOhm and used to form preionization in the gap of the main discharge. High-voltage diode D prevents the transfer of a negative high voltage from capacitor C1 to the low-voltage capacitor C2. The applied high voltage was measured by HV divider PINTEK HVP-39 (1000:1, 40 kV, 200 MHz). The discharge current was measured by a low-inductive shunt with resistance of 0.024 Ohm. All electrical signals were recorded by the digital oscilloscopes such as Tektronix TDS 520, Tektronix TDS 2012 and Tektronix DPO2024.

Side view of a transparent long quartz tube with three-electrode system generating the sequence of two e-beams of high and low energy is shown in figure 1b. This tube was 11 cm in the inner diameter and 30 cm in length. The right-hand flange of a tube had also a quartz window to observe the image of the discharge and record its UV-Visible spectrum. The discharge and e-beam images were taken by digital camera Canon EOS 550 with the exposure time down to $10^{-4}$ s and multi-frame fast camera equipped with the intensifier with the exposure time down to 50 ns.

Before each experiment, the tube was pumped out up to the pressure of $P=10^{-3}$ Torr and then filled with deuterium of high purity (99.99%) up to the required pressure. To avoid the accumulation in the tube of the impurities happening due to plasma chemistry and inleakage of ambient air, the deuterium was constantly pumped over through a tube with a low gas flow rate.

![Figure 1](image1.png)

Figure 1. a) The electrical scheme of the used experimental setup. 1 - the solid cathode; 2 - the grid anode of the main discharge; 3- the grid anode of the auxiliary discharge; R1=44 Ohm, R2 =1 MOhm, Rs = 0.024 Ohm; C1 = 12.5 nF, C2 = 100 µF, b) The sketch of side view of a transparent long quartz tube with three-electrode system generating the sequence of two e-beams of high and low energy.

3. Experimental results and discussion

The integrated in time images of the e-beam propagating within the tube filled with D2 at pressure of 2 Torr for different applied voltage to the discharge are presented in figure 2. One may see that the e-beam is more or less diffuse at the discharge exit (left-hand side in each photo) but transists to the constricted mode after propagation of some distance from the exit. This effect is more pronounced if the applied voltage and discharge current grow. As the discharge exists in two modes (over-voltage
regime and abnormal glow regime) and each of these modes generates an electron beam (high-energy and low-energy e-beam), it is interesting to find out which of these two e-beams has been constricted. In order to do that it is necessary to take the sequence of e-beam images with a short exposure time (50 ns) and compare them with the images of discharge and its current-voltage waveforms at the same moments. The proper information has been collected and is presented in figures 3 and 4. To keep a high spatial resolution, we took the e-beam images separately for the first and second part of its length.

**Figure 2.** The integrated in time images (side view) of the e-beam propagating in D2 at pressure of 2 Torr for different applied voltage to the main discharge. The voltage of the auxiliary discharge is 1 kV. The e-gun exit is situated at left-hand side in each photo. Exposure time of the every picture is 0.5 s.
The series of images showing the evolution of both the discharge and e-beam (a) which are correlated with the current-voltage waveform of the discharge (b). The e-beam images correspond only to the first half of the distance travelled by e-beam in the tube. The location on time axis and width of the enumerated squares in figure (b) correlate with the moments and exposure time of the discharge images (upper series) and e-beam images (bottom series) enumerated with the same figures. The voltage amplitude applied to the main discharge is 20 kV. Gas pressure is 2 Torr. Auxiliary voltage is 1 kV.

Figure 3

Figure 4. The sequence of the e-beam images corresponding to the second half of the distance travelled by e-beam in the tube. Exposure time of the every shot is 50 ns. The enumeration of the shots correlates with that in figure 3. The discharge parameters are the same as those in figure 3.

Close examination of figures 2-4 reveals that the transverse inhomogeneity of the e-beam which looks like its partial constriction in vicinity of the axis, in fact, is associated at the beginning with a weak transverse inhomogeneity of the over-voltage discharge. However, after the transition of the over-voltage discharge into the transverse uniform abnormal glow regime with a high current but lower voltage, the e-beam partial constriction increases appreciably in spite of the fact that the glow discharge keeps its homogeneity in the cross direction. We suppose that this increase happens due to the pinch-effect produced by the very high amplitude of the e-beam current (about 400 Amps). Eventually, low-energy e-beam disappears after transition of abnormal glow cathode layer into low-voltage pre-arc cathode spot with high current density [2] (see shot #7 in figure 3).

4. Conclusion

In order to generate the pulsed e-beam, the three-electrode system operating in D2 at lower pressure (1-2 Torr) and powered by the stepwise applied voltage with amplitude up to 25 kV was used. It is shown that this pulse discharge system exhibits two regimes (strong over-voltage discharge and anomalous glow discharge with lower voltage) and generates the sequence of two e-beams with energy up to 25 and 2.5 keV respectively. The ability of the over-voltage gap to generate the high- and low-energy e-beams happening one by one opens new opportunities which can be of great interest for many applications. It is revealed that the high-energy e-beam is more homogeneous compared to the low-energy e-beam. Weak expressed partial constriction of the high-energy e-beam in vicinity of the axis is associated with a weak transverse inhomogeneity of the over-voltage discharge. After transition of the over-voltage discharge into abnormal glow regime with a high current, the partial constriction of low-energy e-beam increases appreciably in spite of the fact that the glow discharge becomes more uniform in the cross direction. We suppose that this increased constriction happens due to the pinch-effect produced by the very high current (about 400 Amps) of the low-energy e-beam. Our findings
promote more insight into physics of the high-current over-voltage discharge used for generation of the e-beams with energy up to 25 keV.

5. References
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