Three-electrodes open discharge in low-pressure deuterium: transition from the overvoltage regime into low-voltage one

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Abstract. Strongly overvoltage open discharges in a narrow gap (2-3 mm) between the solid cathode and the grid anode are used for generation of the pulsed high-current electron beams with the energy up to several tens of keV. Strongly overvoltage (SO) regime is unstable and the discharge tends to transit into low-voltage (LV) regime with a high-current. We studied this transition by example of the three-electrodes open discharge in D\textsubscript{2} at low pressure (about 0.5-2 Torr) being powered by stepwise voltage with amplitude up to 25 kV. The existence of the auxiliary third electrode allows one to get more stable operation of the open discharge. The physical properties of the SO and LV regimes and transition between them have been explored in detail with the usage of the fast multi-frame camera synchronized with the current and voltage of the open discharge.

1. Introduction

Electron beams with energy up to several tens of keV can be obtained not only with the vacuum systems but with the usage of gas discharges as well. In the latter case it is necessary to create very high electric fields in the discharge gap. The magnitude of the electric field strength has to exceed appreciably the critical value after which so-called run-away electrons appear in the discharge [1-4]. In the most cases, strongly overvoltage open discharges in a narrow gap (2-3 mm) between the solid cathode and the grid anode are used for generation of the pulsed high-current electron beams with the energy pointed above [5-10]. The low pressure discharge in a narrow gap exposed to high voltage is characterized as a discharge existing under overvoltage regime. In our case [6] we have created strongly overvoltage regime with the magnitude of the reduced electric field $E/N > 10^5$ Td. The breakdown process of the strongly overvoltage open discharge (SOOD) cannot be described by the concept of Townsend electron avalanches. A reason is that any electron being appeared in the gap immediately becomes as run-away electron and quickly leaves the gap without the ionizing collision vitally needed for the development of the avalanche. Respectively, the breakdown voltage of SOOD at the given product $Pd$ ($P$ is a gas pressure, $d$ is the length of the inter-electrode gap) does not coincide with Paschen curves described on the base of the Townsend electron avalanches concept: $\alpha_i d \approx \ln(1/\gamma)$, where $\alpha_i$ is the first Townsend coefficient characterizing the dependence of ionization rate on the $E/N$; $\gamma$ is the second Townsend coefficient characterizing the electron emissive processes on the cathode. The above statement is illustrated with figure 1 by the example of H\textsubscript{2}. Figure 1 shows the dependence of the ionization rate for electrons with increase in the $E/N$ magnitude. The dashed curve is calculated in the approximation neglecting the non-local effects. The solid curve in figure 1 takes...
into account the transition of more and more electrons into run-away regime under strong electric fields. The appearance of run-away electrons leads to the diminishing of the ionization rate under huge $E/N$. However, strongly overvoltage (SO) regime is unstable and the discharge tends to transit quickly into low-voltage (LV) regime with a high electric current but without high-energy electron beam. We studied this transition by example of the three-electrodes open discharge in $D_2$ at low pressure (about 0.5-2 Torr) being powered by stepwise voltage with amplitude up to 25 kV. The existence of the auxiliary third electrode allows one to get more stable operation of the open discharge in the SO regime. The low-current auxiliary discharge between the cathode and the distant anode played important role, namely, it provided preionization of the gas gap for the primary discharge and its fast ignition when the high-voltage pulse was applied.

The physical properties of the SO and LV regimes and transition between them have been explored in detail with the usage of the fast multi-frame camera synchronized with the current and voltage of the discharge. The obtained results give more insight into physics of the overvoltage open discharge generating the high-current pulsed e-beams with energy up to 25 keV.

![Figure 1](image1.png)

**Figure 1** The ionization rate for electrons in $H_2$ with increase in the $E/N$. The dashed and solid curves were calculated without and with taking into account the diminishing of the ionization rate with huge $E/N$.

2. Experimental setup

General scheme of the setup used for generation and investigation of the overvoltage open discharge in $D_2$ at low pressure with three-electrode system is shown in figure 2.

![Figure 2](image2.png)

**Figure 2**

a) The electrical scheme of the three-electrode system generating a high-current e-beam with energy up to 25 keV. 1 is the solid cathode; 2 is the grid anode of the main discharge; 3 is the grid anode of the auxiliary discharge; $T$ is the thyratron switching the capacitor $C_1$ to the electrode gap; $R_1 = 44 \text{ Ohm}$, $R_2 = 1 \text{ MOhm}$, $R_s = 0.024 \text{ Ohm}$; $C_1 = 12.5 \text{ nF}$, $C_2 = 100 \mu\text{F}$.

b) The sketch of quartz tube with the electrode system generating HV e-beam (the scale is not kept): 1 - the cathode, 2 - the main anode, 3 - the auxiliary anode, 4 -the transparent quartz tube of 24 cm in length, 5 –the flange with a quartz window.
The inter-electrode gap between the solid cathode and meshed anode is 3 mm. The discharge system has been mounted inside the quartz tube which can be pumped down to pressure $P = 10^{-2}$Torr and after that is filled with deuterium up to the needed pressure. 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 50 Ohm. All electrical signals were recorded by the digital oscilloscopes such as Tektronix TDS 520, Tektronix DPO2024 and Tektronix TDS 2012 with bandwidth of 500, 200 and 100 MHz. The discharge images were taken by multi-frame fast camera (equipped with the intensifier) with the exposure time down to 50 ns.

3. Experimental results and discussion

The typical current and voltage waveforms of the pulsed open discharge in deuterium at pressure $P = 2$ Torr is shown in figure 3a. We have performed the experiments with the three-electrode system in the wide range of the applied voltage $U$ from 7 kV to 25 kV. Based on the obtained results, the Current-Voltage characteristic of this discharge in the SO regime at $P = 2$ Torr is presented in figure 3b. Here the magnitudes of $I$ and $U$ were taken at the moments preceding the transition of the discharge from the strong overvoltage regime into the low-voltage regime. This characteristic can be approximated by expression $I(A) \approx (U - U_0)^{3/40}$, where $U_0 = 5$ kV. Note that the higher applied voltage and gas pressure, the shorter duration of the SO regime (figure 3c, 3d).

![Figure 3a](image1)
![Figure 3b](image2)
![Figure 3c](image3)
![Figure 3d](image4)

**Figure 3** a) The typical current and voltage waveforms of the three-electrodes pulsed open discharge in deuterium. $P = 2$ Torr; b) The Current-Voltage characteristic of the open discharge in the diffuse overvoltage regime at the moments preceding the transition into low-voltage regime. The solid curve is the approximation $I(A) \approx (U - U_0)^{3/40}$, where $U_0 = 5$ kV. $P = 2$ Torr; c) The dependence of maximum current $I_{max}$ of SOOD in $D_2$ before its transition into the low-voltage mode (dashed curves 1 and 2) and duration $\tau$ of the high-voltage mode (solid curves 3 and 4) on gas pressure $P$, $U = 20$ kV (curves 1 and 3), $U = 24$ kV (curves 2 and 4). $P = 2$ Torr. d) The dependence of duration $\tau$ of the high-voltage mode on applied voltage. $P = 2$ Torr. The auxiliary low-current discharge between the cathode and meshed anode 3 is powered with the voltage $U^* = 1$ kV.
Figure 4. The current-voltage waveforms of the SOOD in deuterium (a) and set of the discharge images (b). The white circle in each shot depicts the boundary of the cathode. $P = 2$ Torr, $U = 20$ kV, $U^* = 1$ kV; the enumerated time windows marked in the current-voltage waveform correspond to the same moments at which the enumerated images (1-9) were taken; the exposure time of each shot is 50 ns.

As it is mentioned above, the higher applied voltage, the shorter duration of the overvoltage regime which generates the high-energy e-beam. In fact, namely this SO regime is the most of interest from the practical point of view. Therefore there is an insistent need in studying of the mechanism of instability of this regime. The experimental data showing in detail the spatial-temporal evolution of the open discharge up to its transition into the low-voltage regime with the high-current cathode spot(s) are presented in figure 4. In this figure, the set of the open discharge images taken by a fast multi-frame camera was correlated with the current-voltage waveform of the discharge. This set of the
obtained data can be very useful for the development of the physical mechanisms responsible for the transition of the strongly overvoltage open discharge into the low-voltage regime.

Close examination of all shots in figure 4 leads to the conclusion that, first, the $SO$ discharge does not constrict but contrariwise increases his cross-section and brightness up to the transition into the $LV$ regime and, second, the bright cathode current spot(s) happen after the $SO \rightarrow LV$ transition and therefore they cannot be a reason initiating this transition. A reason is that the cathode spots in itself do not shunt the gap - they can only initiate the streamers (thin current filaments) which can propagate from the cathode towards the anode.

In principle, after the arrival of streamers to the anode, the gap can be shunted because the streamer quickly transforms itself into the high-conductive spark and the overvoltage regime transits into the low-voltage regime. However, the propagation of streamers towards the anode requires the existence in the gap of the intensive direct ionization of neutrals by the electron impact. Unfortunately, the extremely high electric field at the cathode in the overvoltage regime ($E/N$ reaches of huge magnitude of $10^5$ Td and even more) leads to that the electrons have become the run-away electrons which have the extremely low efficiency of the impact ionization. This is a reason why the propagation of streamers towards the anode is impossible in the overvoltage regime.

Based on the mentioned above, we can state that, in our opinion, the mechanism responsible for transition of the overvoltage regime into low-voltage mode is not connected with the cathode spots and anode directed streamers. One of the reasons of the observed instability of the $SO$ discharge can be a strong gas heating by ions at the cathode leading to switching on the thermal ionization at this place. This ionization provides the dramatic increase in the discharge current and transition of the open discharge into low-voltage regime. Our numerical calculations verified this hypothesis (figure 5). Besides, numerical calculations revealed an essential role of the plasma created by e-beam behind the grid anode in the sustaining the strongly overvoltage open discharge.

**Figure 5.** a) The calculated ($I$ and $U$) and experimental ($I_{exp}$ and $U_{exp}$) current and voltage waveforms of the $SOOD$. b) The calculated rates of ionization due to impact by e-beam (curve $I$), fast ions (curve $II$), slow electrons (curve $IV$) and the rate of thermal ionization (curve $III$) for the time moment (4). $U_0 = 25$ kV, $D2, P = 2$ Torr.

One may see in this figure that fast increase in the discharge current is associated with instant "switching-on" the thermal ionization. At this moment, the local gas temperature near the cathode is equal to 6560 K.

4. **Conclusion**

Our experimental investigation of the pulsed open discharge has led to the conclusion that the strong gas heating by ions at the cathode can be a reason promoting the transition of the open discharge into low-voltage regime. The numerical calculations taking into account the thermal ionization verified this
hypothesis. Besides, numerical calculations revealed also a crucial role of the plasma created by e-beam behind the grid anode in the sustaining the strongly overvoltage open discharge.

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