On transition from diffuse mode to the constricted one with high-current cathode spot in overvoltage open discharge in D2

To cite this article: Yu S Akishev et al 2017 J. Phys.: Conf. Ser. 927 012070

View the article online for updates and enhancements.
On transition from diffuse mode to the constricted one with high-current cathode spot in overvoltage open discharge in D2

Yu S Akishev1,2, V B Karalnik1, M A Medvedev1, A V Petryakov1, N I Trushkin1, A G Shafikov1

1 SRC RF TRINITI, 108840, Moscow, Troitsk, Pushkovykh street, 12, Russia
2 NRNU MEPhI, 115409, Moscow, Kashirskoe shosse, 31, Russia

Abstract. So called “open discharges” in a narrow gap between the solid cathode and grid anode are widely used for generation of the pulsed high-current electron beams with energy up to 100 keV. The need to get high-energy e-beams leads to the necessity in using of strong overvoltage of the short gas gap with the reduced electric field of the order of 10^5 Td or higher. The discharge under strong overvoltage is unstable and tends to transit into high-current regime with low voltage. In the case of the open discharge in D2 at low pressure (about 0.5-2 Torr) and powered by stepwise voltage with amplitude up to 25 kV we revealed that this discharge exhibits two diffuse regimes which follow one by one and finally transits into the constricted mode with formation of high-current spots on the cathode. The physical properties of these gas discharge regimes have been explored in detail with the usage of the fast multi-frame camera synchronized with the current and voltage of discharge. Our findings promote more insight into physics of the overvoltage open discharge generating the e-beams with energy up to 25 keV.

1. Introduction

Strong overvoltage pulsed discharges operating at low pressures (P < 10 Torr) in a narrow gap (d < 1 cm) between the solid cathode and grid anode are often called as “open discharges”. The reduced electric field E/N in these discharges reaches of huge magnitude of 10^5 Td and even more. Such electric fields correspond to an appearance of run-away electrons which are able to form the high-current electron beams with a high efficiency. This is a reason why the strong over-voltage pulsed discharges are widely used for generation of e-beams with energy up to 70 keV. A lot of useful information about properties of the open discharges powered with the voltage up to 100 kV can be obtained from [1]. Unfortunately, the discharge under strong overvoltage is unstable and tends to transit quickly into high-current regime with low voltage which does not generate the e-beam. Note that up to now, the physical mechanisms providing the existence of the overvoltage open discharges and their transition into low-voltage regimes are the subjects for discussions. We have studied these mechanisms by example of the strongly overvoltage open discharge in short gap (3 mm) in D2 at low pressure (2 Torr) powered with the voltage of amplitude up to 25 kV. Why we used the voltage of such amplitude? A reason is that the high-energy e-beams (about 70 keV) generate the hard bremsstrahlung X-radiation which has a high penetrability and brings a serious bio-danger. Due to that the installations using the e-beams of such high energy 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. Because of that the open discharges powered with the voltage up to 25 kV and generating the high-current e-beams with energy up to 25...
keV are environmentally friendly and of great interest to practical applications. Despite the importance of these discharges for practice, their physical properties have been explored insufficiently. Our findings promote more insight into mechanisms of the instability of the overvoltage open discharge powered with the voltage up to 25 keV.

2. Experimental setup
We have designed the three-electrode system which provides a higher reproducibility of the parameters of the open discharge compared to traditional two-electrode system. The electrical scheme of the three-electrode system used for generation of the open overvoltage discharge 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 thyratron T from the capacitor C1 through the ballast resistor R1 with a resistance of 44 Ohm. There was a complimentary discharge between the cathode (1) and additional grid anode (3). The distance between cathode and the auxiliary grid 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 the preionization of gas 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 PINEK 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.

Figure 1b shows total lay-out of the components of the experimental setup used for investigation of the transitions of unstable regimes of the overvoltage open discharge by the fast multi-frame camera equipped with the intensifier. The optical system was focused in such a way to take the image of the discharge zone including its cathode area. The three-electrode system was mounted inside the quartz tube. 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 from ambient air, the deuterium was constantly pumped over through a tube with a low gas flow rate.

![Image 1a](image1a.png)

**Figure 1.** a) The electrical scheme of the three-electrode system generating a high-current e-beam with energy up to 25 keV. 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 electrode system; 2 – flanges; 3 - quartz tube; 4- quartz window; 5- fast multi-frame camera.

3. Experimental results and discussion
Figure 2 shows the Current-Voltage characteristic of the open discharge in the diffuse overvoltage regime which generates high-energy e-beam. This characteristic can be approximated by cubic dependence $I\sim U^3$. However, the higher applied voltage and current, the shorter duration of the overvoltage regime which is the most interesting for practice. 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 constricted low-voltage regime with the high-current cathode spots are presented in figures 3-5. This set of data obtained for different gas pressures can be very useful for development of the physical mechanisms responsible for transition of the open discharge from one regime into another.

Figure 2. The Current-Voltage characteristic of the open discharge in the diffuse overvoltage regime. The solid curve is the approximation $I \sim U^3$. Deuterium, $P = 2$ Torr, $U = 20$ kV, $U^* = 2.5$ kV.

Figure 3. The set of the discharge images taken by a fast multi-frame camera and correlated with the current-voltage waveform. The white circle in each shot depicts the boundary of the discharge area on the cathode. The exposure time of each shot is 50 ns. The enumerated time moments marked in the current-voltage waveform correspond to those at which the enumerated images were taken. Deuterium, $P = 0.5$ Torr, $U = 20$ kV, $U^* = 2.5$ kV.
Figure 4. The set of the discharge images taken by a fast multi-frame camera and correlated with the current-voltage waveform. The white circle in each shot depicts the boundary of the discharge area on the cathode. The exposure time of each shot is 50 ns. The enumerated time moments marked in the current-voltage waveform correspond to those at which the enumerated images were taken.

Deuterium, P = 1 Torr, U = 20 kV, U* = 2 kV.

Figure 5. The set of the discharge images taken by a fast multi-frame camera and correlated with the current-voltage waveform. The white circle in each shot depicts the boundary of the discharge area on the cathode. The exposure time of each shot is 50 ns. The enumerated time moments marked in the current-voltage waveform correspond to those at which the enumerated images were taken.

Deuterium, P = 2 Torr, U = 20 kV, U* = 1 kV.
Close examination of all figures 3-5 leads to the conclusion that the cathode current spots have a non-stationary in time and chaotically in space behavior — small spots can appear and disappear many times in different places of the cathode area before the formation of a single high-current spot at the constricted low-voltage regime. Besides, the existence of non-stationary cathode spots in itself does not influence the diffuse overvoltage regime and its duration. A reason is that the cathode spots in itself do not shunt the gap - they can only initiate the streamers (high-conductive current filaments) which can propagate from cathode towards the anode. In general, after the arrival of streamers to the anode the gap shunting happens and high-voltage regime transits into the low-voltage mode [2]. Note, the propagation of streamers towards the anode requires the existence in the gap of the intensive direct ionization of neutrals by electron impact. However, the extremely high electric field at the cathode in the overvoltage regime 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.

So, the non-stationary and chaotic cathode current spots can change a bit the transverse structure of the open discharge in the overvoltage regime but not eliminate this regime at all. Of course, the cathode current spots can influence the homogeneity of transverse structure of the e-beam generated by the open discharge as well. Based on the mentioned above, we can state that, in our opinion, the mechanism responsible for transition of the overvoltage regime into abnormal glow mode is not connected with the cathode spots but is related with the propagation of the plane ionization wave from the anode towards the cathode. After the wave approaches the cathode, the voltage drop across the gap will sharply decrease and the discharge will pass into the transverse uniform abnormal glow mode. However, just the cathode spots are responsible for shunting the discharge gap in the abnormal glow mode and its transition into the very low-voltage constricted mode with, as a rule, single high-current cathode spot.

4. Conclusion
The open discharge in D2 at low pressure (P = 0.5-2 Torr) and powered by stepwise voltage with amplitude up to 25 kV exhibits two diffuse regimes which follow one by one and finally transits into the constricted mode with the formation of high-current spots on the cathode. The physical properties of these gas discharge regimes have been explored in detail with the usage of the fast multi-frame camera synchronized with the current and voltage of discharge. Based on the results presented above, we can conclude that the mechanism responsible for transition of the overvoltage regime into the transverse uniform abnormal glow mode is not connected with the cathode current spots observed in the overvoltage regime but is related with the propagation of the ionization wave from the anode towards the cathode. Nevertheless, the cathode spots play essential role in the destabilization of abnormal glow mode - namely they are responsible for shunting the discharge gap in this mode and its transition into the very low-voltage constricted mode with, as a rule, single high-current cathode spot. In total, our findings promote more insight into mechanisms of the instability of the overvoltage open discharge powered with the voltage up to 25 keV.

Acknowledgments

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

References
[1] Sorokin A and Bokhan P 1994 Technical Physics Letters 20 86
[2] Akishev Yu, Grushin M, Kochetov I, Karal’nik V, Napartovich A and N Trushkin 2005 Plasma Sources Sci. Technol. 14 518