Difference in shape and width of Dα lines in the overvoltage and abnormal glow regimes of open discharge in narrow gap

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Abstract. Strong overvoltage discharges in a narrow gap between the solid cathode and grid anode (so called “open discharges”) are widely used for generation of the high-current electron beams. At low gas pressure (about 1 Torr) we revealed that discharge in the overvoltage gap stressed by stepwise voltage with amplitude up to 25 kV exhibits two regimes which follow one by one and generate the e-beams. The first of them produces the high-energy e-beam but the second generates the low-energy e-beam. The physical properties of these gas discharge regimes have been explored insufficiently. We have done the spectroscopic measurements of these regimes in D2 and found out that the overvoltage regime produces positive ions with high kinetic energy up to several keV but anomalous glow discharge forms the ions with energy of several tens of eV. The existence of high-energy ions in the overvoltage discharge provides a strong increase in the electron secondary emission from the cathode and possibly contributes to the ionization of the gas by fast ions. Our findings promote more insight into physics of the overvoltage discharge generating the high-current 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. The open discharges have a high efficiency in generation of the e-beams. As a rule, the e-beam current corresponds to 80-90% (or higher) of the total discharge current. At present the strong over-voltage pulsed discharges are widely used for generation of e-beams with energy up to 70 keV [1]. However, it necessary to note that the high-energy e-beams (about 100 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 high energy (about of 70 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 the voltage up to 25 kV and generating the high-current e-beams with energy up to 25 keV are of great interest to practical applications. Despite the importance of these discharges for practice, their physical properties have been explored insufficiently.

In this paper, the novel configuration of the pulsed open discharge is presented. We used 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. In this electrode system, gas discharge exhibits two regimes.
The applied –0.03 which formed in a narrow of discharge zone in the transverse
out
of 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 (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 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 DPO 2024.

Figure 1b shows the lay-out of the components of the experimental setup used for spectroscopic measurements. The optical system was focused in such a way in order to collect the light either from the discharge zone including the cathode area or from the exit of discharge zone in the transverse direction. To observe the review UV and visual spectrum of the discharge, the spectrometer Avantes AvaSpec-2048-USB2 was used. Its spectral resolution is as follows: 0.11–0.16 and 0.2–0.3 nm in region of 351–393 and 603–810 nm respectively. To investigate the shape of Dα spectral line in the overvoltage discharge and anomalous glow discharge, the double monochromator equipped with grids was used with a spectral resolution of 0.01 nm. The monochromator recorded the emission of Dα spectral line through each 0.05 nm throughout the width of this line. Based on this information, the spectral line shape was reconstructed. To determine the real shape of the spectral line, the slit function of monochromator was taken into account. The excitation electron temperature in discharge was determined from measurement of the ratio of intensities of the spectral lines of Balmer series.

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.

![Figure 1](image1.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) Scheme of spectral measurements: 1-the e-beam gun, 2-the quartz tube, 3-the output quartz window, 4-the quartz lens, 5-the monochromator or spectrometer, 6-PMT, 7-the oscilloscope.
3. Experimental results and discussion

The typical current-voltage waveform of the overvoltage discharge in short gap filled with D2 at pressure P=2 Torr and excited by the stepwise voltage with amplitude of 20 kV is shown in figure 2. Note that the high-voltage regime with the current growing up to 120 A is unstable and exists only up to 180 ns and then abruptly transits into abnormal glow regime with the discharge current about 300 Amps. Figure 3 presents the review UV-Visual spectra of the discharge light collected from the gap including the cathode area (a) and in transverse direction from zone close to the discharge exit (b), i.e. excluding the cathode area.

![Figure 2. The example of typical current-voltage waveform of the overvoltage discharge in D2. Gas pressure is P=2 Torr, the amplitudes of the applied stepwise and auxiliary DC voltages are 20 and 1 kV. The high-voltage regime exists up to 180 ns and then abruptly transits into abnormal glow regime.](image)

![Figure 3. The review UV-Visual spectra of the discharge light collected from the gap including the cathode area (a) and in transverse direction from zone close to the discharge exit (b), i.e. excluding the cathode area. D2, P=2 Torr, U=20 kV.](image)

One may see in figure 3 that gas discharge emits not only the atomic lines of Balmer series D\(_{\alpha}\), D\(_{\beta}\), D\(_{\gamma}\), D\(_{\delta}\) but molecular bands D\(_{2}\)(a-b), D\(_{2}\)(d-a), D\(_{2}\)(e-a) as well. Note the intensities of all lines emitted from the discharge zone including the cathode area (a) exceed by the factor about 4 the lines emitted from the zone excluding the cathode area (b). Besides, there are two features in spectrum (a): 1) there are no spectral lines of the cathode material (Fe) proving that there is no cathode local melting. It means that there are no high-current and hot arc spots on the cathode; 2) there are spectral lines of carbon in the cathode region - we suppose they appear due to the decarburization of steel that occurs without its melting but if local heating exceeds 700°C.

The emission of spectral lines of Balmer series in the anomalous glow regime is produced predominantly by plasma located in vicinity of the anode. Spectral information about intensities of the D\(_{\alpha}\), D\(_{\beta}\), D\(_{\gamma}\), D\(_{\delta}\) lines (see figure 4a) similar to that presented in figure 3a was used to determine so called the excitation temperature \(T_{exc}\) of electrons in plasma of anomalous glow discharge. This temperature is determined from Boltzmann plot for Balmer series in accordance with this formula:

\[
kT_{exc} = -\frac{E_i - E_j}{\ln\left(\frac{1}{\beta_{ij}}\frac{\theta_i A_i}{\theta_j A_j}\right)}
\]
where $E_i$, $E_j$ and $I_i$, $I_j$ are the energies of $i$ and $j$ levels and the intensities of the lines from these levels; $g_i$, $g_j$, $A_i$, $A_j$, $\lambda_i$ and $\lambda_j$ are the statistical sums, Einstein coefficients and the wave lengths corresponding to transitions from these levels. The obtained data for $T_{exc}$ vs gas pressure P are presented in figure 4b.

**Figure 4.** The scheme of Balmer series (a), $D_\alpha$: (n=3 $\rightarrow$ n=2); the obtained dependence of the excitation temperature $T_e$ of electrons in plasma near anode vs gas pressure (b). Gas D$_2$, $U$ = 20 kV.

The number density of electrons $n_e$ in D$_2$ plasma of abnormal glow open discharge at $P$=2 Torr was estimated with use of Saha equation for $T_e$ $\approx$ 0.7 eV. We have got that $n_e$ is equal approximately to $3 \times 10^{13}$ cm$^{-3}$. This magnitude in a reasonably concordance with the estimation obtained from the known current density and electron drift velocity in plasma of abnormal glow regime.

**Figure 5.** The current-voltage waveforms of the open pulsed discharge in the overvoltage (a) and abnormal glow (c) regimes and the shapes of $D_\alpha$ spectral lines (b) and (d) corresponding to (a) and (c) regimes. D$_2$, $P$=2 Torr, $U$=22 kV. Average current in regimes (a) and (c) is 120 and 320 Amps. Spectral lines 1 and 2 in (b) correspond to the emission of fast excited atoms formed due to: (1) the charge exchange of fast ions and (2) impact the cathode by fast ions (see figure 6a).

All experimental profiles were well approximated with Gauss formula. It means that Doppler effect makes the main contribution to the formation of the line broadening. Note that the shape of $D_\alpha$
emission in the overvoltage regime is very unusual for gas discharge plasma at moderate electric fields. In the case of super high the reduced electric field $E/N = 10^5$ Td, $D_2$ emission is characterized by the existence of a wing corresponding to emission of very fast excited D atoms (figure 5b). As a rule, such wing is observed in the emission produced by the impact of high-energy ion beams to solid surface (see figure 6a and paper [2]). Based on this, we can state that the wing in figure 5b is formed due to the impact of fast positive ions with the cathode. It leads to neutralization of some ions and their reflection in a form of fast and excited D atoms. However, the symmetrical profile of $D_2$ line is formed by emission of fast excited atoms happens mainly due to the charge exchange of fast ions and other reactions [3] listed in figure 6b.

In the overvoltage regime, fast run-away electrons quickly leave the gap. Therefore the space charge in the gap is formed predominantly by positive ions. In this case, the electric field strength increases towards the cathode. Because of that the ions in vicinity of the cathode will have maximum kinetic energy and produce the fast excited atoms practically with the same energy. Close examination of the spectroscopic data like those presented in figure 5 has led us to the conclusion that the overvoltage open discharge fed with the voltage of 20-25 kV produces the positive ions with kinetic energy up to 3 keV (or higher) at the cathode and fast excited atoms in the bulk of the gap due to the charge exchange with the energy of 0.3±0.1 keV. In the case of abnormal glow regime, the kinetic energy of fast excited atoms is estimated not higher of 100 eV.

4. Conclusion
Spectroscopic investigation of the open discharge powered with a high voltage up to 25 kV in D2 at gas pressure of 2 Torr revealed that the overvoltage regime of this discharge produces the positive ions with kinetic energy up to 3 keV (or higher) at the cathode and fast excited atoms in the bulk of the gap due to the ion charge exchange with the energy of 0.3±0.1 keV. In the case of abnormal glow regime, the kinetic energy of fast excited atoms is estimated not higher of 100 eV.

5. References
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