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25 keV electron beam formation based on a three-electrode system of the obstructed glow discharge in H2 and D2

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Abstract. The results of experimental study on the formation of high-current electron beams using three-electrode system are presented. This system enables to create a diffusive obstructed glow discharge in a pulsed regime with an amplitude of applied voltage up to 25 kV. The influence of such experimental parameters as the pressure of plasma forming gas and the amplitude of applied voltage on the obstructed glow discharge duration was investigated. Both the transverse and the longitudinal structure of formed electron beam was determined.

1. Introduction

The electron beams (e-beams) of moderate energy (ε ≤ 25 keV) and the non-thermal plasma created by these beams are widely used in various fields of science and practice: gas lasers excitation [1], surface modification of various materials [2,3], creation of new materials including nano-powders [4], etc. Some information about the formation of such electron beams can be found in [5,6]. The e-beams of moderate energy are perspective for the creation of small-sized neutron source based on the super-strong charging of dust particles [7]. In this source, the e-beam provides both the plasma around dust particles and their super-strong charging up to the potential energy equal to e-beam energy. Positive ions accelerate in the strong electric field of charged particle and increase their energy to high magnitude. The impact of high-energy ions with a particle leads to nuclear fusion reactions accompanied by neutron release. The numerical modeling of dust particles charging and nuclear fusion reactions [7] enabled us to formulate the requirements to the discharge and e-beam parameters providing the optimum experimental conditions for generation of neutrons. It was shown also that the most suitable plasma forming gas was deuterium. In this paper, the experimental results on the generation of pulsed high-current e-beam with the energy up to 25 keV are presented. The experiments were performed in H2 and D2 at pressure P = 0.5 - 2 Torr. The e-beam was generated by the obstructed glow discharge using a triple electrode system of an original construction. This e-beam source will be used for generation of neutrons due to super-high charging of dust particles by the e-beam.

2. Experimental setup

The e-beam with the energy up to 25 keV was generated by the obstructed glow discharge using a three-electrode system of an original construction (see figure 1a). The solid cathode of 24 mm
diameter made of stainless steel and two anodes made of metallic grids with geometrical transparency of 60% and 70% were used. The first and second grids were placed at 2 mm and 9 mm distance from the cathode. The electrode system was placed into a quartz tube of 110 mm inner diameter and 300 mm length. The main discharge was excited in a narrow gap between the cathode and the first anode. This pulsed discharge was powered by the applied voltage up to 25 kV and characterized as a high-current obstructed glow discharge with the amplitude of total current up to 150 A. Namely this main discharge formed the e-beam. The low-current discharge between the cathode and the second anode worked in the regime of normal glow discharge. The low-current discharge played complimentary but very important role - this discharge created the pre-ionization of gas gap and increased the stability of main discharge. Each discharge has been fed by its own electrical power. A three-electrode system enabled us to generate the pulsed and steady-state e-beams with the energy up to 25 and 10 keV, respectively.

The e-beams were formed in H2 and D2 of high purity (99.99%) at pressure P = 0.5 - 2 Torr. The experiments were performed using weak gas blowing through the reactor in order to keep the initial high purity of plasma forming gas. The applied voltage was measured by HV divider PIINTEK HVP-39 (1000:1, 40 kV, 200 MHz). The total discharge current was measured by low-inductive shunt with the resistance of 0.024 Ohm. The Faraday cylinder was used to measure the current of e-beam. The scheme of optical measurements of the dynamics of optical emission, which was excited in gas by the e-beam, is shown in figure 1b. The emission of different parts of reactor was collected by quartz lens and transferred to the line of quartz light guides, which were connected with appropriate photomultiplier tubes (PMT) FEU-100. All electrical signals were recorded by oscilloscopes such as Tektronix TDS 520, Tektronix TDS 2012 и Tektronix DPO2024. Spatial distribution of optical emission from the quartz reactor was registered by digital camera Canon EOS 550, which formed the image integrated in time. The transverse structure of e-beam was studied using flat phosphor, which was placed at various distances from the outlet of electron gun (e-gun). The plane of phosphor was oriented perpendicularly to the e-beam.

Figure 1. Total scheme of the experimental setup. a) Electrical scheme: 1 - cathode, 2,3 – grid anodes of main and auxiliary discharges, R1=56 Ohm, R2=1 MOhm – ballast resistors, Rs =0.024 Ohm - current shunt, D – high-voltage diode KC 201Е, C1=12.5 nF, C2 =100 μF – pulsed capacitors, К – switch for charging the capacitor of the auxiliary low-current discharge, T – thyratron TGI-1000/25. b) Optical scheme: 1 – the integrated in time image of optical emission of gas excited by the e-beam (the outlet of e-gun is at bottom), 2 - quartz lens with focus length F=11.2 см, 3 – the line of quartz light guides connected with PMT I, II, III.

3. Experimental data
The typical waveforms of the current and voltage of main discharge in a narrow gap as well as the synchronized with them signals of PMT I and PMT III are presented in figure 2a. In this figure, one can see that the high-voltage regime in D2 lasts approximately 200 ns, during which the current falls down from 150 A to 5 A. After that, the discharge abruptly transfers from a high-voltage regime to a high-current regime with a low voltage. In fact, depending on experimental parameters (gas pressure,
the voltage applied to an auxiliary and main discharge), duration of high-voltage regime can vary from 0.15 μs to 5 μs. The e-beam is generated by the discharge under high-voltage obstructed regime. As a rule, the current of e-beam is equal to 95% of the total discharge current. An optical gas emission initiated by e-beam appears with some delay regarding to the appearance of e-beam at this place. The image of pulsed discharge is presented in figure 2b. The photo was taken from the side of anode grid. This photo gives the discharge image integrated over a long time period. It means that the images of diffusive discharge under high-voltage regime and the constricted discharge under low-voltage regime with high-current cathode spots are imposed.

![Figure 2](image1.png)

**Figure 2.** a) The current and voltage waveforms of the obstructed discharge and signals of PMT I and PMT III, which collect the light from the places located at x=0 and x=22 cm (x=0 corresponds to the e-gun outlet). b) The image of pulsed discharge taken from the side of anode grid. U_d = 24 kV. In both cases the plasma forming gas is D2 at pressure P=1 Torr; the voltage magnitude U_aux applied to the auxiliary discharge is equal to 2 kV.

The dependence of maximum current in the high-voltage obstructed discharge on gas pressure P at different amplitudes U_d of the applied voltage is presented in figure 3 (curves 1 and 2) and figure 4. In these figures, one can see that the higher P and U_d, the higher current in obstructed discharge. Contrariwise, the duration of high-voltage obstructed discharge decreases with increasing gas pressure (curves 3 and 4 in figure 3).

![Figure 3](image2.png)

**Figure 3.** The maximum current in high-voltage obstructed discharge vs deuterium pressure. U_d = 20 kV (curve 1); U_d = 24 kV (curve 2). The obstructed discharge duration vs pressure of D2. U_d = 20 kV (curve 3); U_d = 24 kV (curve 4).

![Figure 4](image3.png)

**Figure 4.** The maximum current in high-voltage obstructed discharge vs the applied voltage amplitude. Gas - deuterium at pressure P = 2 Torr.
The side view of reactor showing the distribution of optical emission of H2 excited by the pulsed e-beam with the energy $\varepsilon = 20$ keV is presented in figure 5. Each photo in figure 5 is taken with a long exposure time and therefore, gives the integrated image though in fact, the optical emission varies in space and time. The gas pressure is equal to $P=0.5$, 1.0 and 2.0 Torr in figures 5a, 5b, and 5c, respectively.

Figure 5. The integrated in space and time distribution of optical emission of H2 excited by the pulsed e-beam with the energy $\varepsilon = 20$ keV. The voltage magnitude $U_{aux}$ applied to the auxiliary discharge is equal to 2 kV. The gas pressure was $P=0.5$ Torr (a), $P=1$ Torr (b) и $P=2$ Torr (c).

The spatial distribution of optical emission in the reactor is determined by the distribution of current density in the e-beam. In such a case, the set of images in figure 5 reflects the evolution of spatial structure of the e-beam with increasing gas pressure. One can see that the e-beam enters the reactor as a broad diffusive beam. However, in the course of its propagation through the gas, the e-beam can constrict itself and be concentrated approximately around the tube axis. At gas pressure $P=1$ Torr, the e-beam has 36 mm diameter at the e-gun outlet, however, at the distance of 8 cm from the outlet it constricts itself to 8 mm diameter. Further, the increase of e-beam diameter up to 15 mm is observed. The intensity of optical emission from the constricted e-beam is higher, compared to that of diffusive e-beam.

The length of e-beam diffusive mode diminishes with increasing gas pressure but the length of its constricted mode grows. For instance, at gas pressure $P=2$ Torr, the e-beam constricts itself to the diameter 5 mm already at 4 cm away from the outlet, and further, the e-beam diameter is increasing insignificantly. The appearance of e-beam constriction with increasing gas pressure correlates with increasing e-beam current under growing gas pressure (figures 3 and 4). We assume that the constriction of e-beam happens due to the magnetic field, which is formed by its own current (pinch-effect [8]).

The e-beam transverse structure correlates with the spatial distribution of the emission of flat phosphor placed perpendicularly to e-beam. Figure 6 presents the set of images of the luminescent phosphor. These images show the evolution of transverse e-beam structure, depending on the distance from the e-gun outlet. The initial e-beam energy $\varepsilon$ is equal to 20 keV. The variable experimental parameters are: the gas pressure $P$ and the voltage $U_{aux}$ of auxiliary discharge.
Figure 6. The set of photos of the luminescent phosphor emitted by the e-beam with the initial energy $\varepsilon = 20$ keV. The distance of phosphor from the e-gun outlet is shown at the bottom of each column. The circle in each photo marks the boundary of e-gun outlet (36 mm diameter). a) $P=0.5$ Torr, $U_{aux} = 2$ kV; b) $P=1$ Torr, $U_{aux} = 2$ kV; c) $P=2$ Torr, $U_{aux} = 1$ kV; d) $P=1$ Torr, $U_{aux} = 0$ kV.
In figure 6, one can see that the distribution of current density in the e-beam is modulated by the grid at the e-gun outlet. In other words, the e-beam formed by the e-gun is split into a set of thin e-beams by the grid. At low pressure, the modulation is kept over a long distance despite of the beam scattering and its increasing transverse sizes. The modulation disappears in the constricted mode of e-beam.

The absence of auxiliary discharge \((U_{aux} = 0 \text{ kV})\) leads to the instability of main discharge ignition. For instance, at \(P = 0.5 \text{ Torr}\), applied voltage amplitudes \(U_d = 20 \text{ kV}\), and \(U_{aux} = 0 \text{ kV}\), the ignition start of obstructed high-voltage discharge in a narrow gap happens, on the average, one time of four attempts. The absence of the auxiliary discharge leads also to the strong inhomogeneity of e-beam. The transverse inhomogeneity of e-beam exhibits itself in the appearance of a star-like structure (see figure 6d). The drawbacks pointed above do not allow the practical usage of high-voltage obstructed discharge without auxiliary low-current discharge. So, the developed three-electrode system has a good perspective in practical using for stable generation of the high-current and transversely homogeneous pulsed e-beam with the energy up to 25 keV.

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