The probe measurements of the electron density in deuterium plasma created by the electron beam of moderate energy

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Abstract. The results of the probe measurements of the electron density in deuterium plasma at gas pressure \(P=1\) Torr are presented. Plasma was created in a quartz tube by stationary beam of electrons with moderate energy up to 10 keV. The electron beam of 35 mm in diameter was generated by the steady-state obstructed glow discharge in a narrow inter-electrode gap. The electrical probe comprises two large metallic plates oriented in parallel to each other with a space gap between them of 15 mm. The electron beam passes through this gap in parallel to the plates and creates plasma in the gap. The plasma density was determined from comparison between the calculated volt-ampere characteristics (VACs) and VACs measured in the experiment. The dependence of plasma density generated by e-beam on energy of electrons in the beam is found out.

1. Introduction

The great advantage of the e-beams of moderate energy (up to 25 keV) is that they do not generate a hard X-radiation which is very dangerous to health. The e-beams of moderate energy (EBME) are environmentally friendly object and therefore they are widely used for generation of non-thermal reactive plasma which is of great interest for different applications such as surface modification of various materials, biomedicine, pharmaceutics, laser techniques, etc [1-2]. One of the promising applications of EBME is the super-high charging of the dust particles in plasma by e-beam. This approach opens the opportunity to create a small-scale neutron source for biomedical applications [3]. In this source the EBME provides two functions: it makes the super-high charging of the dust particles and creates a non-thermal plasma around these particles. Positive ions of plasma accelerate in a strong electric field of highly charged particle and gather energy; after that they strike the target and initiate the reactions of nuclear fusion accompanied by release of neutrons. We have done the numerical calculations of both the super-high charging of the dust particles by e-beam and the appropriate reactions of nuclear fusion [3]. It was shown that the plasma-forming gas, the most suitable for this task, is a hydrogen isotope – a deuterium. In this paper the experimental results on the probe measurements of the electron density in plasma created by EBME are presented. To do that we used not the classical probe method but developed new approach.
2. Experimental setup

The e-beam with energy of electrons up to 25 keV was generated by the obstructed glow discharge in the narrow inter-electrode gap filled with deuterium at low pressure (P = 0.5 - 2 Torr). The electrode system of the e-beam generator (figure 1) comprises the solid metallic cathode (stainless steel) of 24 mm in diameter and two meshy anodes with geometrical transparency of 60% and 70% located at a distance of 1.5 and 6 mm from the cathode. This electrode system forms two gas discharges - basic and auxiliary. Every gas discharge has own power supply electrically isolated from each other. Low-current auxiliary discharge between cathode and distant meshy anode serves for preionization of gas in the gap of the high-current basic discharge between cathode and close-in meshy anode. Basic gas discharge is powered by high voltage and operates in the obstructed glow regime. The electrode system is placed inside quartz tube of 110 mm in diameter and 300 mm in length. This triple electrode system enables to generate a pulsed e-beam and steady-state EBME as well. In the case of a pulsed regime it is possible to get the e-beam with energy of electrons up to 25 keV and electron current up to 150 A. In steady-state regime the e-beam with energy up to 10 keV can be generated.

To measure the density of plasma created by e-beam we used a moveable probe which comprises two large plane electrodes oriented in parallel to each other with a space gap between them of 15 mm. Each electrode is a thin copper foil pasted on a dielectric plate. Sizes of the foil are 15x15 mm^2 with 50 µm in thickness. The VAC of a double electrode probe was measured by the electric scheme which has no electrostatic connection with the "ground" of both the basic and auxiliary discharges. This circumstance ensure the absence of the electric current leakage from the pointed discharges into the probe electric circuit.

Propagation of the e-beam through deuterium in the reactor is accompanied by optical emission of the plasma forming gas. The visible longitudinal structure of self-consistent system "plasma + e-beam" was registered by Canon EOS 550 digital camera. The transverse structure visualization of the e-beam was done with use of the moveable plate of phosphor (oxysulfide of the yttrium activated by terbium). All experiments were done under slow gas blowing through the reactor to keep the initial purity of deuterium (99.99% D_2).

3. Results and discussion

The photos presented in figure 2 show the spatial distribution of optical emission from low pressure deuterium (P=1 Torr) excited by e-beam propagating through the reactor from right to left. The image in figure 2a corresponds to the case of high-current pulsed e-beam (energy of electrons is 20 keV, the
electric current of e-beam is 50 A). The image in figure 2b corresponds to the case of low-current steady-state e-beam (energy of electrons is 5 keV, the electric current of e-beam is 2.2 mA). These photos are taken at different exposures. The exposure time in figure 2b much more exceeds exposure time in figure 2a. Due to that the visible high intensity of emission at the exit of e-beam gun in steady-state regime is a trick - in fact the intensity of optical emission from reactor in the pulsed regime of e-beam gun is much higher than that in steady-state regime. One can see in figure 2 that the e-beam diameter at the exit of the gun is the same (∼35 mm) for both the pulsed and steady-state regimes. However, the spatial structure of the e-beam in a long distance from a gun exit depends on the current and energy of e-beam. High-current pulsed e-beam constricts itself after some distance from the e-gun. Contrariwise, the propagation of low-current steady-state e-beam is accompanied with its monotonic divergence with the angle of disclosure about 10°. Inside the reactor there is a block made of two dielectric rings which are located at a distance of 40 mm from exit of the e-gun (see figure 2b). This block supports the double electric probe in the region where the e-beam is transversely homogeneous.

![Figure 2](image)

**Figure 2.** Two photos showing the spatial distribution of optical emission from low pressure deuterium (P = 1 Torr) excited by e-beam propagating through the reactor from right to left. a) high-current pulsed e-beam, energy of electrons is 20 keV, the electric current of e-beam is 50 A, duration of the e-beam is 200 ns; b) low-current steady-state e-beam, energy of electrons is 5 keV, the electric current of e-beam is 2.2 mA, the exposure time is 200 ms.

The plasma density created by e-beam was determined from comparison between the calculated and measured VACs. Numerical calculations were performed with the use of 1-D non-stationary diffusive-drift model which takes into consideration the continuity equations for electrons and positive ions and Poisson equation for the electric field strength. Poisson equation took into account not only the space charge of electrons and ions of plasma but space charge of the e-beam. The processes of electron-ion recombination as well as ionization of deuterium by plasma electrons and e-beam were included in the model. This approach differs from the classical one used at the processing of VACs of Langmuir's electrical probes. In fact, our model simulates the non-self-sustained gas discharge supported in the gap by e-beam.

As an example, figure 3 presents the calculated distributions in the gap of the number densities for electrons and positive ions and for electric field strength as well. Plasma forming gas is D2, P=1 Torr. Important that the applied voltage across the gap is lower compared to the normal cathode drop for self-sustained glow discharge. One can see that practically all gap is filled with a quasi-neutral plasma except the narrow layer of a positive space charge in the vicinity of a negative electrode (something like cathode layer). Only in this layer there is an ionization by electrons of plasma. However, owing to a small size of this area it does not influence density of the plasma created by the e-beam electrons.
The experimental VACs of a double plane probe measured at different energies of the steady-state e-beam are given in figure 4. Herein, the results of calculations executed for the conditions of experiment are presented as well. One can see the calculated data well coincide with experimental parametrical dependence that proves the applicability of the developed model for processing of the probe VACs.

![Figure 3](https://example.com/fig3.png) **Figure 3.** Spatial distribution of electrons, ions and electric field strength in the probe gap. Anode at the left, cathode on the right. The applied voltage across the gap is 75 V. Energy of steady-state e-beam is 5 keV, D2.

![Figure 4](https://example.com/fig4.png) **Figure 4.** The probe VACs at different energies of the steady-state e-beam. D2, P=1 Torr. Solid marks are the experimental data; open marks are the calculated data. E-beam energies: 1 - 5 keV; 2 - 7.5 keV; 3 - 10 keV.

The dependences of the experimental e-beam current and calculated plasma density vs energy of the steady-state e-beam are presented in figure 5. One can see that density of plasma created by steady-state e-beam increases monotonically with energy and current of the beam.

![Figure 5](https://example.com/fig5.png) **Figure 5.** The dependences of the calculated plasma density (1) and the experimental e-beam current (2) vs energy of the steady-state e-beam. D2, P = 1 Topp.

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