Diagnostics of beam plasma produced in dielectric cavity at fore-vacuum pressures

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Abstract. The results of the probe and optical measurements of plasma parameters produced during the injection of the electron beam with the energy of 3-8 keV and current of 30-60 mA into a dielectric cavity at the argon pressure of 2-12 Pa are presented. The possibility of continuous injection of the electron beam into the cavity without current-collecting electrodes inside is demonstrated. The axial distribution of the values of the plasma parameters (density, electron temperature and floating potential) in the cavity is discussed. The plasma concentration in the cavity is shown to be approximately 20% higher, and the electron temperature 1.5-2 times higher, than in the case of generating the plasma in the free space of the vacuum chamber.

1. Introduction
Creating plasma in the cavity bounded by the dielectric walls is important for ion-plasma modification of the internal surfaces of glass or plastic vessels [1]. Electrodeless HF or microwave discharge in a magnetic field is typically used to do this [2]. The disadvantage of this approach is the low efficiency of energy transmission from the source to the HF plasma and the limited range of operating pressures. Electron beam plasma generation is largely free of these shortcomings. However, injection of the beam into the cavity with pressure parameters traditional for the electron sources (10⁻² Pa) is difficult because of the negative charge accumulation inside the cavity, and the use of a differential pumping system greatly complicates the device. Application of the fore-vacuum plasma electron sources [3] operating at pressures of 1-100 Pa solves the problem of charge accumulation in the cavity owing to formation of a dense plasma in the electron beam transport area. The ions of this plasma neutralize the charge of the accelerated electrons accumulated on the dielectric surface [4]. The purpose of this study was to measure the parameters of the plasma generated in the fore-vacuum pressure range in a dielectric cavity during injection of the electron beam into the cavity.

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2. Experimental setup

Experiment scheme is shown in figure 1.

The electron beam (4) was created by a fore-vacuum plasma electron source based on a glow discharge with a hollow cathode [3] in the CW mode. The discharge in the source was maintained by the voltage $U_d = 300 - 500$ V between the hollow cathode (1) and the anode (2) with the discharge current $I_d$ in the range of 100 to 400 mA. The electron beam was extracted from the discharge plasma (5) through the holes in the anode (2), accelerated to energies of 3 - 8 keV by the voltage $U_a$ in the gap between the anode and the grounded extractor (2-3), and then focused by the magnetic field of the coil (6). The beam current was estimated from the current $I_e$ in the circuit of the accelerating voltage source (12) and was 30 - 60 mA. The beam diameter was 4-6 mm. Vacuum in the chamber (7) was sustained by the mechanical fore-vacuum pump ISP-1000C, pressure of the working gas – argon or air - was set to 2-12 Pa and regulated by the inlet valve. Accelerated electron beam was injected into the cylindrical quartz cavity (8) with the inner diameter of 40 mm, length of 200 mm and wall thickness of 2 mm, and created the plasma (9) inside the cavity. To study the distribution of the beam plasma parameters along the z-axis, five identical single, plane Langmuir probes (10) were inserted into the cavity through the 6 mm perforations made in the side wall. The diameter of the receiving surface of each probe was 3 mm. The distance from the axis of the beam to the receiving surface of the probe was 15 mm. In order to prevent the contact of the fast electrons of the beam with the probes, each probe was surrounded with a protective metal cylindrical screen having the diameter and length of 5 mm and being under the floating potential. Set of probes was firmly fixed with respect to the axis of the beam and the walls of the chamber, and the cavity could be extracted to identify differences in the behavior of the plasma inside the cavity and in conditions of free beam transport inside the chamber. Plasma emission was studied using the optical spectrometer USB-2000 from Ocean Optics. The light guide (14) of the spectrometer was located approximately in the middle of the cavity at a distance of 1.5 cm from its open end. Spectrometer signal was processed by a specialised software on the computer (15).
Beam plasma parameters were determined from the probe characteristic. The electron temperature $T_e$ was determined on the exponentially growing e-branch in the area between the floating potential of the probe and the plasma potential. The value of the probe voltage corresponding to the zero second derivative of the probe current with respect to the voltage was taken as the plasma potential. The plasma concentration $n_i$ was determined by the saturation current on the ion branch of the probe characteristic.

3. Results and discussion

The results of the measurements of the floating potential of the probe are shown in figure 2.

![Figure 2](image-url)

**Figure 2.** a) Floating potential of the probe $U_f(z = 52 \text{ mm})$ in the cavity (1) and in free space (2) vs. pressure.; b) axial distribution of the floating potential in the cavity for the pressure values of 12 Pa (1), 6 Pa (2) and 2.5 Pa (3). Experimental conditions: $I_e = 60 \text{ mA}$, $U_a = 3 \text{ kV}$; working gas: argon. Zero of the z-axis corresponds to the open end of the cavity.

In the case when the plasma is confined in the cavity (Figure 2a, curve 1), the $U_f$ is lower and decreases along with the reduction of the pressure. This might be explained by accumulation of the electrons inside the cavity because the conditions of losing the charge deteriorate progressively as the plasma density decreases. The $U_f$ increase with the pressure reduction in the absence of the cavity (figure 2a, curve 2) can be associated with a more efficient removal of the electrons from the plasma region due to the reduction of the electron-atom collisions. Character of the axial distribution of the floating potential in the cavity, as shown in figure 2b, depends on the pressure. For example, at 12 Pa, $U_f$ value weakly grows inward the cavity, and at 6 and 2.5 Pa this value decreases. Such a behavior indicates a change of the axial electric field distribution in the plasma by the pressure change and requires further study. Comparison of the axial distributions of concentration and temperature of the plasma electrons created in the cavity with those in the plasma produced in the absence of the cavity is shown in figure 3. At the beam energy of 3 keV, the plasma density in both cases decreases along the beam direction, but is approximately 20% higher in the cavity (figure 3a, curve 1). This could be attributed to additional ionization of the gas inside the cavity by the secondary electrons which are dislodged from the surface by the beam electrons and the plasma ions and accelerated in the Debye sheath.
Figure 3. Axial distributions of the electron density (a) and temperature (b) for the plasma created inside the cavity (1) and in the free space of the chamber (2). Pressure is 6 Pa, $I_e = 40$ mA, $U_a = 3$ kV.

The electron temperature in both cases is nearly independent of $z$, but the electron temperature is 1.5 - 2 times higher in the cavity. This can be explained by a reduction of the outflow of the plasma energy from the volume of plasma in the cavity compared to the case of the absence of the cavity, since the energy leaves the volume with the plasma particles only through the open end of the cavity. The higher temperature of the plasma electrons in the cavity can be indirectly confirmed by the emission spectra, which are shown in figure 4.

As follows from figure 4a, in the case of beam plasma creation in the chamber without cavity, the 391 and 428 nm lines appear in the plasma emission spectrum. These lines are specific of the First Negative Band (FNB) of molecular nitrogen ions $N_2^+$, the excitation potential of which is rather high,

Figure 4. Optical spectra of the beam plasma created in the free space (a) and inside the quartz cavity (b). Pressure is 3.5 Pa, beam current $I_e = 30$ mA, $U_a = 8$ kV; working gas: air.
about 20 eV [5]. Excitation of this system can be attributed to the energetic electrons of the beam. At the same parameters of the experiment, in the case of plasma generation in the dielectric cavity, as shown in figure 4b, the 315, 336 and 357 nm lines appear in the emission spectrum in addition. These lines belong to the Second Positive Band (SPB) of the excited nitrogen molecules \( \text{N}_2 \) with a lower excitation potential of about 13 eV [6]. By increasing the gas pressure to 12.5 Pa, the SPB lines appear also in the emission spectrum of the "open" beam plasma. The observed features of the optical spectra can be explained as follows. The generation rate for the nitrogen molecules can be described by the following formula:

\[
\frac{dn^*}{dt} = n_e n_g K(T_e)
\]

where \( n_e, n_g \) are the densities of the plasma electrons and gas molecules, respectively, and \( K(T_e) \) the reaction rate constant that is directly proportional to the electron temperature in the beam plasma.

Since \( T_e \) is lower in the "open" beam plasma than in the quartz cavity (figure 3b), even with \( n_e \) and \( n_g \) held approximately equal, the rate of generation of molecular nitrogen ions with the excited SPB will be much lower than in the quartz cavity due to the lower \( K(T_e) \). It is known that the electron temperature generally decreases along with the pressure increase and the plasma concentration increases, so the number of the molecular ions with excited SPB increases due to the increase of the plasma density with pressure.

4. Conclusion
The results of the probe and optical measurements illustrate the difference in the characteristics of the behavior of the beam-generated plasma (in terms of the floating potential, density and temperature) in the cavity compared and that in the free space. The parameters of the plasma are suitable for using it in technological applications.

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References
[1] Sakudo N, Ikenaga N, Ikeda F, Nakayama Y, Kishi Y, Yajima Z, Jiro Matsuo, Masataka Kase, Takaaki Aoki and Toshio Seki 2011 *AIP Conference Proceedings* 1321 266
[2] Conrads H and Schmidt M 2000 *Plasma Sources Sci. Technol.* 9 441
[3] Burdovitsin V A and Oks E M 2008 *Laser and particle beams* 26 419
[4] Burdovitsin V A, Klimov A S and Oks E M 2009, *Technical Physics Letters* 35 511
[5] Stewart D.T. 1956 *Proc. Phys. Soc. A* 69 437
[6] Thompson N and Williams S E 1934 *Proc. Roy. Soc. A* 147 583