Passage of a focused electron beam generated by a forevacuum plasma source through a narrow extended metal cavity

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Abstract. We report on our investigations of the distribution of diameter of a focused electron beam along the propagation direction at the forevacuum pressures as a function of beam parameters and working gas pressure. The influence of electron beam parameters on the fraction of current transported through a narrow, extended tube is considered. We find that the angles of convergence and divergence of the focused beam depend on the position of the beam crossover point, and that maximum beam transmission through the tube is ensured at lower gas pressure and higher beam accelerating voltage. Up to 90% beam transmission efficiency is obtained for beam transport through a metal tube with diameter 8 mm and length 30 cm.

1. Introduction
Electron beams are able to efficiently transfer energy to fairly small areas of the treated surface [1]. Ensuring a high power density of the electron beam at the same time allows for precision processing of various materials [2]. In this case, the electron-beam processing of dielectrics is complicated by the processes of beam deflection due to the charging of the treated surface [3]. Forevacuum plasma sources of electrons can generate electron beams in the range of relatively high pressures (3-100 Pa) [4]. The plasma formed by the electron beam in the background gas effectively neutralizes the incipient charging of the dielectric surface [5, 6].

Scattering of beam electrons by working gas molecules complicates effective focusing of the beam in the forevacuum. Despite this difficulty, it is possible to obtain the electron beams at the forevacuum pressures with a beam power density of up to $10^9$ W/cm$^2$ and a beam diameter of less than 1 mm [7].

In addition to the application of electron beams for material surface modification, the beam-produced plasma itself [8] has found use for plasma-chemical processing for various purposes [9–11]; the beam-plasma parameters can be effectively controlled by the electron beam energy and current density. In the plasma-chemical treatment of the inner surface of products with narrow extended cavity geometry, the formation of plasma in the interior region is a complication [12]. One way to facilitate the generation of plasma in narrow extended cavities is the injection of an energetic electron beam into the cavity [13].

Plasmas can be efficiently produced by energetic electrons at somewhat elevated gas pressures by forevacuum electron sources. Recent progress achieved in the focusing of beams from this kind of electron source [7] provides a means for injection of focused electron beams into extended cavities with diameter as low as just several millimeters. In this way, plasma can be formed in cavities with smaller
dimensions than can be formed by other existing methods of processing the internal surfaces of cavities [12, 13].

A fundamental question that arises when considering the propagation of an electron beam inside a narrow extended cavity is the effect of electron scattering by background gas at elevated forevacuum pressures. Thus, a relevant and important area of investigation is the profile and character of a focused electron beam as it propagates.

The aim of the work was to study the evolution of a focused electron beam generated by a forevacuum source as it propagates in gas, as well as the influence of the parameters of the electron beam and working gas on its propagation and passage through a narrow extended metal cavity.

2. Experimental setup

Figure 1 shows a schematic of the experimental setup. Forevacuum plasma electron source 1 is installed on a vacuum chamber equipped with a mechanical pump.

A description of the construction of the forevacuum plasma source designed to produce a focused electron beam 2 and its operating principles has been reported elsewhere [11-12]. Plasma 3 is produced by a glow discharge with a hollow cathode 4. Electrons are extracted from the plasma 3 through a single channel in a tantalum plate 5 in the anode 6. An accelerating electric field is formed in the space between the anode 6 and extractor 7.

The electron beam is focused by a magnetic lens 8. After the magnetic lens there is a deflecting magnetic system 9.

The electron beam diameter \( d_b \) was measured by the standard “deflection” method [14]. The beam moves across two long narrow slits in analyzer plate 10 and the diameter measured from the current signal of the collector plate 12. The analyzer can be moved along the vertical \( z \) axis (the \( z \) coordinate is measured from the extractor 7 of the e-beam source) by means of a displacement system installed in the vacuum chamber. This allows the beam diameter analyzer to be moved over a range of 30–60 centimeters from the extractor 7. The total electron beam current \( I_b \) is measured by a Faraday cup 13. The beam current and diameter were measured with beam propagation without tube.

Experiments on beam propagation inside the cavity were carried out using a metal tube 14 made of stainless steel with internal diameter 8 mm and length 30 cm. For these experiments, the metal tube was moved to the axis of the electron beam so as to replace the beam diameter analyzer (the possible directions of movement of the tube are indicated in Figure 1 by number 15). The current \( I_t \) flowing through the tube itself (“tube current”) and the current \( I_c \) which passes through the tube to Faraday cup 13 located directly under the tube) were measured. The tube current \( I_t \) arises from that part of the
electron beam that strikes the tube inner walls and also the upper (entry) end of the tube. The fraction of electron beam current that passes through the tube $I/I_b$ (hereinafter, the current transmission coefficient) is determined as $I/(I_c + I)$. The beam focusing conditions are adjusted by tuning the magnetic lens 8 to provide maximum current transmission coefficient.

The pressure in the vacuum chamber $p = 5–10$ Pa is controlled by nitrogen purge. The accelerating voltage was $U_a = 10–20$ kV; the beam current was up to $I_b = 22$ mA. The selected position of the crossover (focus) $z_c$ of the focused beam was set by adjusting the current in magnetic lens 8.

3. Experimental results

Figure 2 shows the distributions of beam diameter along the propagation direction for various crossover positions and accelerating voltages.

![Figure 2](image-url)  
**Figure 2.** Electron beam diameter $d_b$ as a function of distance along the $z$ axis, for different positions of the beam crossover $z_c$: 1 – $z_c = 35$ cm; 2 – $z_c = 40$ cm; 3 – $z_c = 45$ cm. Beam acceleration voltage $U_a = 10$ kV. Pressure $p = 5$ Pa.

It can be seen from these distributions that the e-beam angle of convergence (i.e., for distances before the crossover point, $z < z_c$) and the angle of divergence (i.e., for distances beyond the crossover point, $z > z_c$) differ significantly (the angles of convergence and divergence are determined from the slope of the relevant part of the curve). Thus for example, consider curve 3 in Figure 2, for which $z_c = 45$ cm, i.e., the beam focus lies in the middle of the investigated range $z = 30–60$ cm; for this case the beam diameter at $z = 60$ cm is about $d_b = 2$ mm, whereas at $z = 30$ cm the diameter reaches $d_b = 8$ mm. Hence the convergence angle (distances before the focus) exceeds the angle of divergence (distances beyond the focus) by more than a factor of 7.

Curves 1 and 2 in Figure 2 are illustrative of the beam diameter distribution for smaller crossover distances. One can see that with decrease in the crossover coordinate $z_c$ (i.e., focal length), the divergence angle (the slope of the $d_b(z)$ curve for $z > z_c$) increases. However, the convergence angle (the slope of the curve for $z < z_c$) decreases. The underlying cause for decreasing convergence angle with decreasing $z_c$ is probably related to the beam focusing by the magnetic lens. In order to decrease the crossover distance (the focal length), the lens magnetic field strength must be increased. This in turn reduces the electron Larmor radius. Thus for greater magnetic field strength, after passing through the magnetic lens the electron gyro-orbits are in general smaller and extend for a shorter distance from the beam axis, due to which the convergence angle decreases.

Based on the beam behavior exhibited in Figure 2, we can infer that, due to the difference in the angles of convergence and divergence, in the case of a beam passing through a tube of length 30 cm, the most suitable option is to locate the beam crossover not in the middle of the tube, but 5 cm closer to the electron source. Curve 2 of Figure 2 implies a maximum beam diameter of about 5 mm.

In further work we have found that the $d_b(z)$ distributions at a higher accelerating voltage $U_a = 20$ kV are identical to the results for $U_a = 10$ kV (Figure 2). With increasing accelerating voltage the beam diameter decreases and the angles of convergence and divergence. For $z_c = 40$ cm and $z_c = 45$ cm, the maximum beam diameter over the range investigated is less than about $d_b = 3.5$ mm.
The effect of gas pressure on the beam diameter distribution is presented in Figure 3.

![Figure 3](image_url)

Figure 3. Dependence of electron beam diameter $d_b$ along the propagation direction (along the $z$ axis) for different working gas pressures: $1 - p = 5 \text{ Pa;}$ $2 - p = 7 \text{ Pa;}$ $3 - p = 10 \text{ Pa.}$ $U_a = 20 \text{ kV, } z_c = 45 \text{ cm}$

Increase in pressure leads primarily to increase in beam diameter. Thus, an increase in pressure from $p = 5 \text{ Pa (curve 1)}$ to $p = 10 \text{ Pa (curve 3)}$ leads to an increase in diameter by about 40%. In addition, a significant increase in beam divergence is seen at higher pressure (curves 2 and 3) compared to lower pressure (curve 1).

These results indicate that one can achieve conditions such that the FWHM beam diameter is no greater than 5 mm over a beam propagation distance of 30 cm. For practical application, plasma formation in a tube or cavity by means of an electron beam should be accompanied by negligible loss of beam electrons to the tube wall. Our studies have shown that at a pressure $p = 5 \text{ Pa}$, the minimum diameter for which the coefficient of current transmission of the beam through the tube is greater than 90% is 8 mm. The results of the passage of the beam through a tube 8 mm in diameter and 30 cm in length are shown in Figure 4.

![Figure 4](image_url)

Figure 4. Dependencies of the coefficient of current transmission of the beam through the cavity, $I_c/I_b$, on total beam current $I_b$ for various accelerating voltages: $1 - U_a = 20 \text{ kV;}$ $2 - U_a = 10 \text{ kV.}$ Pressure $p = 5 \text{ Pa.}$

The data shown in Figure 4 are in complete agreement with conclusions drawn from the analysis of beam diameter distributions (Figures 2 and 3). Thus, the maximum value of current transmission coefficient, about 90%, is achieved at the higher accelerating voltage (curve 1). Note that the $I/I_b$ coefficient is quite significantly dependent on beam current. With increase in beam current $I_b$, the $I/I_b$ coefficient decreases – the decrease in $I/I_b$ at an accelerating voltage $U_a = 20 \text{ kV}$ is less than 5%, while at a lower $U_a = 10 \text{ kV}$ the decrease in $I/I_b$ is more than 20%. This is explained by changes in the electron beam focusing conditions with change in the emission plasma density (in the e-beam source), which provides the emission current. Thus, at lower accelerating voltage, increase in plasma density leads to a large change in the plasma boundary (the plasma meniscus) shape in the region of beam formation [15], which in turn leads to increase in convergence angle and deposition of electrons on the tube wall.
4. Conclusion

The axial distributions of focused electron beam diameter generated by a forevacuum source, with variation of beam focal length (beam crossover distance) are presented. When the focal point is moved toward the source, the angle of divergence (post-focus) of the focused electron beam increases and the convergence angle (pre-focus) decreases. With increase in beam accelerating voltage, the beam diameter and the angles of convergence and divergence decrease. Increase in working gas pressure affects the growth of beam diameter and leads to increase in the beam divergence angle after passing through the crossover. Using a metal tube of diameter 8 mm and length 30 cm as an example, we find that the fraction of current of the focused electron beam that is transported through the tube can reach 90%.

Acknowledgements

This work was supported by the Russian Science Foundation in the framework of Project No. 21-79-10217, https://rscf.ru/project/21-79-10217/. Special thanks to Dr. Ian Brown (Berkeley Lab) for English correction and helpful discussion.

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