Generation of an electron beam by the forevacuum plasma source with a single emission channel

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Abstract. We present the results of our investigation on the influence of the geometry of a discharge-emission system on the parameters of the electron beam generated by the forevacuum plasma electron source based on the hollow-cathode glow discharge. The extraction of electrons was implemented through a single emission channel. We have determined the optimal geometric dimensions of the hollow cathode, yielding a maximum efficiency of the electron extraction at the beam power density level of $6 \cdot 10^5$ W/cm².

1. Introduction

The reason for interest in applying the electron beam technologies to modification of materials is due to the ability of the electron beam to effectively deliver energy to a localized surface area being processed [1]. In such processing, the achievable high power density of the electron beam enables an effective precision working of the material, including hole drilling, complex geometry groove and slit milling, etc. [2]. The direct electron-beam treatment of high-temperature dielectric materials (various brands of glass and ceramics) is hampered by the necessity to take special measures to neutralize the charging of the nonconductive surface of the dielectric during electron beam processing [3]. The currently being developed forevacuum plasma electron sources based on the hollow-cathode glow discharge are capable of generating continuous electron beams at increased pressure values, ranging from several to hundreds of pascals [4]. The beam plasma generated at such pressure practically completely neutralizes the charging of the dielectric surface by the accelerated electron beam [5]. Thus, the electron beam in the forevacuum range of pressure is capable to process dielectric materials as efficiently as the parts made of metals and their alloys [6-9].

During the electron beam generation in the forevacuum pressure range, the electron scattering on the working gas molecules makes it difficult to achieve an effective beam focusing. Despite that, earlier we managed to obtain, at the given pressures, an electron beam of the radius of 0.6 mm with the power density level of $10^8$ W/cm² [10]. Achieving these parameters became possible due to extracting the plasma electrons through a single emission channel with optimal diameter and length of, respectively, 0.75 and 1 mm [10]. However, for such dimensions of the emission channel, the efficiency of the electron extraction from plasma, $\eta$ (the emission current to the discharge current ratio), did not exceed several percent.
For the electron sources with a plasma cathode, the electron beam parameters and the extraction efficiency are directly determinable from the plasma concentration in the area of the electron emission [11]. There are a number of known methods to increase the emission plasma concentration by optimizing the geometry and dimensions of the hollow cathode [12-14]. The aim of the present work was to investigate the influence that the geometry of a discharge emission system of the forevacuum plasma electron source based on the glow discharge with the hollow-cathode may have on the electron emission efficiency.

2. Experimental Setup
The forevacuum electron source was installed on the vacuum chamber equipped with a sole stage of mechanical pumping. Figure 1 shows a layout of the functional elements of the electron source, focusing and deflection systems, as well as the equipment used to diagnose the electron beam parameters.

![Figure 1. Experimental setup and technique (a) discharge-emission system (b): 1 – electron beam; 2 – forevacuum electron source; 3 – vacuum chamber; 4 – plasma; 5 – hollow-cathode; 6 – emission channel; 7 – anode; 8 – extractor; 9 – magnetic lens; 10 – deflecting magnetic system; 11 – Faraday cup; 12 – measuring slits; 13 – collector; 14 – beam trace during the diameter measurements; 15 – hollow cathode inserts.](image)

The working principle behind the electron source is the electron emission from the plasma produced by the hollow-cathode through the single emission channel in the anode. The electrons were accelerated by the electric field in the gap formed by the anode and the extractor. The beam was focused by the single magnetic lens. The focused electron beam was deflected by the magnetic deflecting system. The design of the forevacuum source and specifics of its work are given in details in [15, 16].

The electron beam current $I_b$ was measured upon its deflection on a Faraday cup. The beam diameter $d_b$ was measured at the focal plane by a double-slit analyzer consisting of the grounded plane plate with two 01 mm wide measuring slits and the current collector. When measuring the beam diameter $d_b$, the beam was continuously moved along the line perpendicular to the measuring slits. Upon crossing one of the measuring slits, a portion of the electrons hit the current collector and was detected using an oscilloscope. The registered current signal was re-calculated in terms of the radial distribution of the beam current density, with the distribution width at half height taken for the diameter. The power density $q$ was calculated using the measured values of the current and diameter by the formula $q = \frac{4 \cdot U_a \cdot I_b}{\pi \cdot d_b^2}$, where $U_a$ is the accelerating voltage.

The modification of the emission channel diameter $D_{em}$ and length $H_{em}$ was carried out using replaceable plates in the anode. During the measurement, the anode-cathode distance was 1 mm, while that between anode and extractor was 13 mm. The shape of the cathode inner hollow was varied using...
1) the two inserts 15 of equal heights, thus enabling to independently change the diameters of the hollow’s upper ($D_1$) and lower ($D_2$) sections, figure 1.b; and 2) by changing the hollow cathode diameter $D_{hc}$ and length $L_{hc}$.

The experiments were conducted at the working gas (helium) pressure $p = 30 \text{ Pa}$, which was set by a direct gas flow into the vacuum chamber. The experimental discharge current was up to $I_d = 2.4 \text{ A}$ and the accelerating voltages were $U_a = 20$ and $30 \text{ kV}$. The emission channel length in the experiments was $H_{em} = 2 \text{ mm}$. The experiments aiming at the improvement of the electron extraction efficiency were conducted with the emission channel diameter of $D_{em} = 1 \text{ mm}$.

### 3. Experimental results

The conducted investigations reveal a linear dependence of the efficiency of the electron extraction from plasma $\eta$ on the upper cathode diameter $D_1$ (figure 2, curve 1). The value of $\eta$ grows linearly up to $D_1 = 0$, i.e., until a complete overlap of the hollow cathode’s upper half (figure 2, curve 1). As seen, with the change of the hollow’s lower diameter $D_2$, a decrease of $D_2$ results in a decrease of $\eta$.

From the results presented in figure 2, one can conclude that the emission from a single channel forevacuum source is the most effective when the hollow cathode has a cylindrical shape, and there is a definite ratio of the hollow’s diameter $D_{hc}$ to its length $L_{hc}$. For example, for the hollow’s diameter $D_{hc} = 45 \text{ mm}$, the maximum extraction efficiency $\eta$ occurs at the hollow’s length $L_{hc} = 30 \text{ mm}$ (figure 3). The change of $L_{hc}$, either towards the lesser or greater values than the optimum, results in a sharp fall of $\eta$ (figure 3).

![Figure 2](image2.png) **Figure 2.** Electron extraction efficiency $\eta$ vs. the hollow cathode’s upper ($D_1$) and lower ($D_2$) diameters: $1 - \eta = f (D_1), D_2 = 30 \text{ mm}; 2 - \eta = f (D_2), D_1 = 0$.

![Figure 3](image3.png) **Figure 3.** Electron extraction efficiency $\eta$ vs. the hollow cathode length $L_{hc}$ (the hollow cathode diameter $D_{hc} = 45 \text{ mm}$).

For each diameter of the hollow cathode, the form of the dependence shown in figure 3 remains the same. The length of the hollow cathode $L_{hc\, max}$, which corresponds to the maximum value of the efficiency, decreases with the increase of the hollow cathode diameter $D_{hc}$ (figure 4, curve 2); while the maximum efficiency $\eta_{max}$ has a non-monotone dependence on the hollow cathode diameter $D_{hc}$ (figure 4, curve 2). As seen from figure 4, curve 2, the maximum extraction efficiency $\eta_{max} = 24 \%$ takes place at $D_{hc} = 20 \text{ mm}$ and $L_{hc} = 40 \text{ mm}$.

Figure 5 shows the dependence of the electron beam power density $q$ on the discharge current $I_d$ for various emission channel diameters $D_{em}$ for the optimal hollow cathode geometry ($D_{hc} = 20 \text{ mm}$ and $L_{hc} = 40 \text{ mm}$) at the accelerating voltage $U_a = 30 \text{ kV}$. As seen, at small diameter values of the emission channel, the power density $q$ increases (curves 1-3). With an increase of the emission channel diameter $D_{em}$, the power density $q$ increases (curves 4-6) and there appear dependency maximums. At the maximum channel diameter $D_{em} = 1.5 \text{ mm}$, which still ensures a stable work of the plasma source, the power density reaches the value of $q = 6 \times 10^5 \text{ W/cm}^2$. The extraction efficiency values for this are
shown in figure 6 (curve 1). The maximum extraction efficiency reaches its maximum of $\eta = 45\%$ at the minimum discharge current; and with a further increase of the discharge current $I_d$, the efficiency sharply drops. At the discharge current $I_d = 0.6$ A and $q = 6 \times 10^5$ W/cm$^2$, the extraction efficiency equals $\eta = 15\%$. At smaller emission channel diameters, the dependence $\eta(I_d)$ behaves in a similar way (figure 6, curve 2), however, the absolute values decrease.

Figure 4. Maximum value of the electron extraction efficiency $\eta_{\text{max}}$ and the hollow cathode length $L_{hc\text{ max}}$, at which the maximum of $\eta_{\text{max}}$ occur, vs. the hollow cathode diameter $D_{hc}$: 1 - $\eta_{\text{max}} = f(D_{hc})$; 2 - $L_{hc\text{ max}} = f(D_{hc})$.

Figure 5. Electron beam power density $q$ vs. the discharge current $I_d$ for various emission channel diameters $D_{em}$: 1 - $D_{em} = 0.6$ mm; 2 - $D_{em} = 0.8$ mm; 3 - $D_{em} = 1.0$ mm; 4 - $D_{em} = 1.2$ mm; 5 - $D_{em} = 1.4$ mm; 6 - $D_{em} = 1.5$ mm.

Figure 6. Electron extraction efficiency $\eta$ vs. the discharge current $I_d$ for the emission channel diameters $D_{em} = 1.5$ mm (1) and $D_{em} = 1.4$ mm (2).

When the diameter of the emission channel $D_{em}$ changes, the optimum cathode cavity sizes ensuring maximum extraction efficiency also changes. So, for the diameter of the emission channel of $D_{em} = 1.5$ mm, with the increase in the cathode cavity length $L_{hc}$ from 40 to 50 mm, the extraction efficiency $\eta$ increases and at the minimum discharge current reaches 100% (figure 7 b curve 1).

But the beam power density in this case does not exceed the value $q = 10^5$ W/cm$^2$ (figure 7 a curve 1). In turn, the maximum power density of $q = 8 \times 10^5$ W/cm$^2$ is ensured at the geometry of the cathode cavity providing the small value of efficiency of $\eta = 2.5\%$ (figure 7 curves 3). Thus, these results indicate that with an increase in the extraction efficiency $\eta$ by changing the geometry of the cathode cavity, the maximum power density of the electron beam $q$ decreases. The geometry with $D_{hc} = 20$ mm and $L_{hc} = 40$ mm is the most optimal, since it leads to a small decrease in the power density to $q = 6 \times 10^5$ W/cm$^2$, but at the same time provides the sufficient extraction efficiency of $\eta = 15\%$. 
4. Conclusion
Thus, we have determined an optimal geometry of the hollow cathode which yields a maximum electron extraction efficiency through a single emission channel of a forevacuum source. Under the found configuration, the beam power density increases with an increase of the emission channel diameter. The dependence of the power density on the discharge current has a maximum at the level of 0.6 A; and for the diameter $D_{em} = 1.5$ mm, the maximum beam power density equals $q = 6 \times 10^5$ W/cm$^2$ with the extraction efficiency $\eta = 15\%$. However, the maximum extraction efficiency is provided at the minimal discharge current and for $D_{em} = 1.5$ mm it equals $\eta = 100\%$, but the beam power density is reduced to the value of $q = 10^5$ W/cm$^2$.

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