Application of a forevacuum plasma source of a focused electron beam for cutting quartz glass

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Abstract. The paper presents the results of studies of the effect of electron beam parameters on the geometric dimensions of the hole created in quartz glass by an electron beam with the power density of up to \(10^6\) W cm\(^{-2}\) generated by a forevacuum plasma source. It is shown that the electron beam with such specific power is capable of creating holes up to several centimeters deep. At the same time with the passage of time the hole acquires an established form. The dependences of the geometrical dimensions of the steady-state form of the hole depending on the parameters of the electron beam are presented.

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 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 [3]. The beam plasma generated at such pressure practically completely neutralizes the charging of the dielectric surface by the accelerated electron beam [4]. 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 [5–8].

A complex of investigations [9–12] aimed at studying the conditions of magnetic focusing of the electron beam in the region of elevated pressures in the forevacuum range allowed us to significantly improve the design of the forevacuum source for generating a narrowly focused beam with the power density of about \(10^6\) W cm\(^{-2}\) and the diameter of up to 0.15 mm. In [12], it was demonstrated that the electron beam with such specific parameters can be used to effectively cut quartz glass to a depth of up to several centimeters. Glass cutting in this case is carried out due to local melting and evaporation of the material during the effect of the accelerated electron stream. So that, mechanical stresses leading to the formation of cracks or microcracks and reducing strength characteristics don’t occur in the glass volume. Due to this, electron beam cutting compares favorably with the mechanical methods of processing glass using an abrasive tool [13]. At the same time, more sophisticated cutting methods consist in breaking glass sheets along applied risk, which serves as a stress concentrator and created by
either a mechanical cutter or laser radiation [14], and they are applicable only to glasses not more than 5 mm thick. Thus, the forevacuum source of the focused electron beam is an alternative tool for glass cutting with high accuracy, which has several advantages over existing analogues.

Earlier results of studies on the interaction of the accelerated electron beam with quartz glass in the forevacuum pressure range are presented in [15]. The purpose of this work was to study in more detail the influence of the parameters of the focused electron beam with the power density of up to $10^6 \text{ W}\cdot\text{cm}^{-2}$ on the geometric dimensions of the hole in quartz glass, including the maximum depth to which electron beam cutting can be carried out, as well as the development physical model, explaining the processes occurring when quartz glass is cutting by the electron beam.

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](image1.png)

Figure 1. Experimental setup and technique: 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 – quartz glass sample.

The working principle behind the electron source is the electron emission from the plasma 4 produced by the hollow-cathode 5 through the single emission channel 6 in the anode 7. The electrons were accelerated by the electric field in the gap formed by the anode 7 and the extractor 8. The beam was focused by the single magnetic lens 9. The focused electron beam was deflected by the magnetic deflecting system 10. The design of the forevacuum source and specifics of its work are given in details in [12].

An experimental study of the interaction of the electron beam was carried out on samples of quartz glass 11, having the shape of a parallelepiped with the height of 11.5 cm and square base with the side size of 2 cm.

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 beam current $I_b$ was controlled within $I_b = 5–55 \text{ mA}$ by changing the discharge current $I_d$. The beam current $I_b$ was measured when the electron beam was deflected to a separate Faraday cup (not shown in the figure). Accelerating voltage in the experiment was set in the range of $U_a = 20–30 \text{ kV}$.

3. Results and their discussion
When quartz glass is irradiated by the electron beam with the power sufficient to melt and evaporate the material, a dagger-shaped hole forms (figure 2). The dagger-shape form is characterized by the
presence of a wide mouth on the irradiated end of quartz glass, after which the cross-section of the hole decreases with increasing depth.

![Figure 2](image)

**Figure 2.** Photograph of a sample of quartz glass with a hole produced by the electron beam (a) and the shape of the hole produced in the calculation based on model (b): 1 – quartz glass; 2 – hole; \(L\) is the depth of the hole; \(D_0\) – diameter of the hole in the mouth; \(D_1\) – diameter of the hole at half depth.

Dependences of the depth of the hole cut by the electron beam in quartz glass on the irradiation time are shown in figure 3. From these dependences it is can be seen that with an increase in the accelerating voltage \(U_a\) from 20 kV (curve 1) to 30 kV (curve 2), the growth rate of the hole depth increases with the time less than 50 seconds. With the accelerating voltage of \(U_a = 20\) kV (curve 1), as time increases over 50 seconds, saturation is observed on the \(L(t)\) dependence, and in addition to stopping the growth of the hole depth, its shape also ceases to change. At the higher accelerating voltage \(U_a = 30\) kV (curve 2), the shape and size of the hole is also established over time, but this occurs after the longer time as compared with a smaller accelerating voltage (curve 1).

To explain the reasons for the steady-state size of the hole over time, a computational model was developed that describes the process of evaporation of silica glass under the action of the electron beam.

The calculation of the temperature field of quartz glass under electron beam irradiation was carried out using the finite definition method [16]. For this, the volume of quartz glass was split by a uniform grid along three coordinates \(x, y, z\). The size of the cells formed during the splitting (splitting step) was 0.05 mm for each coordinate. In each such cell, the temperature was assumed to be the same throughout the volume at a particular point in time. The values of thermal conductivity, density, heat capacity, coefficient of grayness for all cells of the volume of quartz glass were set the same.

![Figure 3](image)

**Figure 3.** Dependence of the depth of proplav \(L\) on time \(t\) (\(I_b = 55\) mA): 1 – \(U_a = 20\) kV; 2 – \(U_a = 30\) kV.
The process of heat transfer in quartz glass was carried out on the basis of the heat equation:

$$\frac{\partial T}{\partial t} - \lambda \frac{\Delta T}{c_p \rho} = f(x, y, z, t),$$

where $\lambda$ – coefficient of thermal conductivity; $c_p$ – heat capacity coefficient; $\rho$ – quartz glass density; $m$ – unit cell mass; $f(x, y, z, t)$ – function of the source of heat and thermal radiation from the surface of the cells. Boundary conditions: at the bottom of the quartz sample located on the water-cooled collector – $T(x, y, z, t) = 300$ K; no heat exchange on other surfaces – $\partial T/\partial n = 0$, where $n$ – surface normal direction.

When replacing the derivatives by their difference approximation, the expression for calculating the temperature of the cell with indices $i, j, k$ along the $x, y, z$ axes, respectively, after the time step $\Delta t$ has expired, has the form:

$$T_{ijk}^{t+\Delta t} = T_{ijk}^t + \Delta t \cdot \left[ \begin{array}{c} \frac{\lambda}{c_p \rho} \left( \frac{T_{i-1,jk}^t + T_{i+1,jk}^t - 2T_{ijk}^t}{\Delta x} + \frac{T_{ijk}^t + T_{ijk+1}^t - 2T_{ijk}^t}{\Delta y} + \frac{T_{ijk}^t + T_{ijk+1}^t - 2T_{ijk}^t}{\Delta z} \right) \\
+ \frac{1}{c_p \rho \cdot \Delta x \cdot \Delta y \cdot \Delta z} (P_b(x, y, z, t) + P_{th}(x, y, z, t)) \end{array} \right],$$

where superscript $t$ – previous temperature indication; subscript $t+\Delta t$ – temperature value after the time step $\Delta t$; $P_b(x, y, z, t)$ – power transmitted by the electron beam to the unit cell; $P_{th}(x, y, z, t)$ – power lost due to thermal radiation $P_{th}(x, y, z, t) = \varepsilon \cdot \sigma \cdot T(x, y, z, t)^4$, where $\varepsilon$ – grayness coefficient, $\sigma$ – Stefan-Boltzmann constant. In the case of heating the cell above the set melting point $T_{mp}$ ($T_{ijk}^{t+\Delta t} > T_{mp}$) it was removed from further calculation.

The electron beam in the model was assumed to be axially symmetric, propagating along the $z$ direction (figure 4a).

![Diagram of the computational model](image)

**Figure 4.** Diagram of the computational model (a) and the distribution of the power density of the electron beam at the level of the focusing lens $P_{bs}(m)$ (b): 1 – focusing lens; 2 – trajectory of electrons; 3 – quartz glass sample; 4 – $U_a = 0$ kV, $I_a = 55$ mA; 5 – $U_a = 25$ kV, $I_a = 55$ mA; 6 – $U_a = 30$ kV, $I_a = 55$ mA; F – focal length; $d_s$ – longitudinal spherical aberration.

For each time instant $t$, the function $P_{bs}(x, y, z, t)$ was determined on the basis of a trajectory analysis of the beam electrons with allowance for the spherical aberration of the single magnetic lens. For this, the radial distribution of the power density of the beam $P_{bs}(m)$ at the level of the focusing lens was set as the initial condition. The longitudinal spherical aberration $d_s(m)$ for electrons separated from the axis of the focusing lens at the distance $m$ was defined as $d_s(m) = m^2 \cdot S_l / 2F$ [17], where $S_l$ – spherical aberration coefficient, $F$ – focal length. Thus, for each value of $m$, the beam power density $P_{bs}(m)$ was transmitted to the very first cell that falls on the trajectory of electrons, calculated as:
The value of the spherical aberration coefficient $S_I$ and the distribution of the beam power density at the level of the focusing system $P_{bs}(m)$ for each value of $U_a$ and $I_b$ were determined using the previously developed model described in [11]. Typical $P_{bs}(m)$ distributions for different values of $U_a$ are shown in figure 4b.

The model described above makes it possible to calculate the dynamics of the formation of the hole in quartz glass over time. In the course of calculations, the termination of the evaporation of quartz glass under the action of the electron beam over time was achieved primarily by specifying the converging electron beam. So, for example, the use of a paraxial electron beam in the model leads to the formation of the hole with parallel walls and a continuous increase in its depth. The maximum depth directly depends on the angle of convergence of the electron beam and is determined primarily by the brightness of the electron beam at its center. Also, the key factor causing the formation of the hole of exactly the dagger-shape form (the form of the hole obtained by calculation is shown in figure 2b) is the spherical aberration of the magnetic lens.

Experimental dependences of all key size of the hole in quartz glass (depth $L_{max}$, diameter at the mouth $D_0$ and diameter at half-height $D_1$) depending on beam current $I_b$ and accelerating voltage $U_a$ are presented in figures 5 and 6. Similar dependences obtained using model-based calculations are presented together with experimental data.

**Figure 5.** Dependences of the maximum penetration depth $L_{max}$ on the beam current $I_b$: 1 – $U_a = 20$ kV; 2 – $U_a = 25$ kV; 3 – $U_a = 30$ kV; points – experimental data; curves – calculated values in arbitrary units.

**Figure 6.** The dependencies of the diameter of the hole in the mouth $D_0$ (a) and at the half-height of the hole $D_1$ (b) in the steady state from the beam current $I_b$: 1 – $U_a = 20$ kV; 2 – $U_a = 25$ kV; 3 – $U_a = 30$ kV; points – experimental data; curves – calculated values in arbitrary units.
From the presented results, it can be seen that, as expected, the maximum penetration depth $L_{\text{max}}$ increases with increasing accelerating voltage $U_a$ and beam current $I_b$ (figure 5) due to a corresponding increase in the power density and brightness of the beam on its axis. For the same reason, an increase in beam current $I_b$ leads to an increase in the diameters $D_0$ and $D_1$ of the hole (figure 6). An increase in the accelerating voltage $U_a$, despite the narrowing of the radial distribution of the beam power density $P_{bs}(m)$ (figure 4b), also leads to an increase in the diameters of the hole.

4. Conclusion
The paper presents the results of studies of the effect of electron beam parameters on the geometric dimensions of the hole created in quartz glass by an electron beam with the power density of up to $10^6$ W·cm$^{-2}$ generated by a forevacuum plasma source. It is shown that the electron beam with such specific power is capable of creating holes up to several centimeters deep. At the same time with the passage of time the hole acquires an established form. The dependences of the geometrical dimensions of the steady-state form of the hole depending on the parameters of the electron beam are presented. It is shown that an increase in the accelerating voltage and beam current leads to an increase in both the maximum depth of the hole and its diameter. A model is presented that allows to calculate the shape of the melt in quartz glass depending on the electron beam irradiation regimes.

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