Discharge Localization in Split Aperture of Extended Hollow Cathode[1]

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Abstract – Results on ribbon electron beam generation by plasma source on the base of discharge with extended hollow cathode are presented. As it was shown, attempts to rise beam current density by narrowing hollow split aperture leads to appearance of local maximum in beam current density distribution. These maximum or maximums are the consequences of non-uniformity in plasma density distribution in extended hollow cathode. According to results of experiments and estimations the most probable reason of this non-uniformity is ion sheath crossing in split aperture of hollow cathode. In this case small casual local raise of plasma density causes sheath thinning and local anode current density growth. In its turn it leads to intensification of ionization processes and finishes by formation of stationary local high-density region (HDR).

1. Introduction

As we reported earlier ribbon electron beam may be used in pressure range 1–10 Pa for different applications such as surface modification, plasma generation, which in its turn may be applied for plasma chemical etching and films deposition [1]. Key parameters to be reached in all these applications are current density and linear beam uniformity. Attained electron beam current densities of j_e=5–10 mA/cm^2 [2] are still not enough for most applications. For this reason it is necessary to increase the value of j_e at least on one order of magnitude. Due to nonlinear dependence electron emission current on plasma emission area the value of j_e could be enhanced by optimization of emission electrode geometry. At the same time changing of electrode system has to influence both on electron source efficiency and on electron beam parameters. The purpose of present work is investigation influence of electrode system configuration on plasma and beam parameters.

2. Plasma density distribution in extended hollow cathode

The scheme of experimental instrument is presented at Fig. 1. It consists of hollow cathode 1 with inner dimen-sions 310×60×30 mm^3, flat anode 2 with a window 310×10 mm^2, insulators 3, 4, which serve also for displacement of electrodes. Hollow depth h may be regulated by insertion 5. The width of cathode aperture 6 was varied in interval 2–10 mm. Discharge voltage U_d and accelerating voltage U_a were applied to according electrodes as can be seen at Fig. 1. Plasma parameters were measured by single probe 7, introduced to hollow and moved along it. During probe measurements the metal mesh in anode window was removed, and accelerating voltage between anode 2 and accelerating electrode 8 was not applied. On the contrary, measurements of current density distribution in electron beam were carried out by movable collector (not shown at Fig. 2) and in presence of accelerating voltage. As had been showed in experiments, narrowing of emission window in anode causes beam current density growth (Fig. 2). At the same time total beam current decreases as a result of plasma electron losses to the anode. For cylindrical beams it was shown earlier, that electron losses might be avoided by decreasing of cathode aperture [3]. Taking this in mind, we tried to investigate dependence of beam current density on split width in cathode. The first result was, cathode split narrowing challenged plasma and current density growth, but if split width became equal or less 9 mm, one or several local maximums appeared in plasma density distribution along hollow. These maximums can be observed both visually by intensive lighting and by local increase of probe current. Since positions of maximums were able to change by jump in time of observation, fixation of position in this work was reached by minor (~0,5 mm) local broadening of cathode split in its middle part. This allowed investigation of observed dependencies in details. Local maximum is presented legibly at small discharge currents. Increasing of discharge current leads to maximum broadening and its subsequent disappearance (Fig. 3). Analogical result is observed at gas pressure growth (Fig. 4). Discharge current, named further as threshold, at which local maximum disappears, decreases with diminution of hollow volume. Threshold current reduces also with pressure growth (Fig. 5). Explanation of observed dependencies may be executed on the base of simple model, which takes into account ions generation and their disappearance processes in hollow cathode. One-dimensional continuity equations for ion and electron flows I_i and I_e look as:

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$$\frac{dI_i}{dx} = Wp + W\gamma - Zi, \tag{1}$$

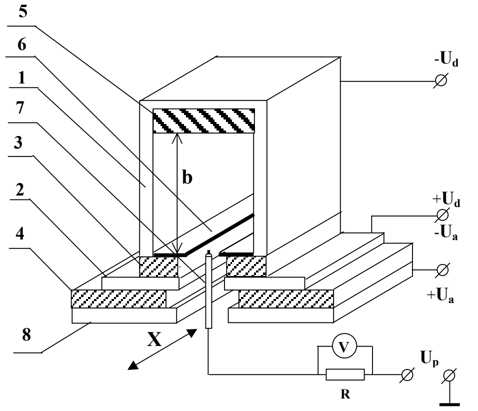

Fig. 1. Scheme of experiment

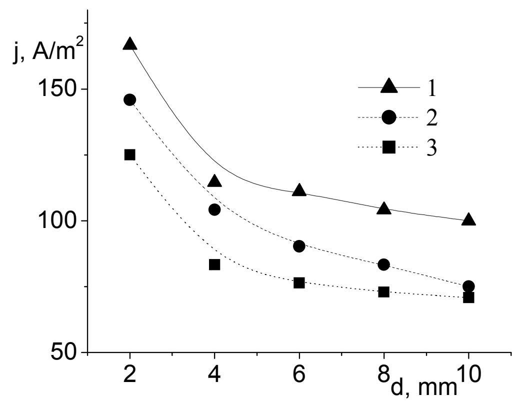

Fig. 2. Beam current density j as function of emission window width d in anode

$$\frac{dI_e}{dx} = Wp + W\gamma - Ze + Wa, \tag{2}$$

where W_p и W_γ – rates of ionization by plasma and γ-electrons; Z_i и Z_e – rates of ion and electron attendance to cathode and anode correspondingly; W_a – contribution of γ-electrons to plasma electron component. In diffusiondrift approach ion and electron flows have looks:

$$I_i = -D_i \cdot \frac{dn}{dx} \cdot S - \mu_i \cdot \frac{d\varphi}{dx} \cdot n \cdot S, \tag{3}$$

$$I_e = -D_e \cdot \frac{dn}{dx} \cdot S + \mu_e \cdot \frac{d\varphi}{dx} \cdot n \cdot S, \tag{4}$$

where μ_i, μ_e – ion and electron mobility; D_i, D_e – diffusion coefficients; S – plasma cross section; n – plasma density, φ – plasma potential.

Values W_p, W_γ, Z_i, Z_e, W_a may be expressed as

$$W_p = \beta \cdot n \cdot (a - 2 \cdot l_s) \cdot (b - 2 \cdot l_s), \tag{5}$$

$$W_\gamma = \frac{\varphi}{U_i} \gamma \cdot 0{,}4 \cdot n \cdot \sqrt{\frac{kT_e}{M}} (2a + b - 4l_s), \tag{6}$$

$$W_a = \gamma \cdot 0{,}4 \cdot n \cdot \sqrt{\frac{kT_e}{M}} \cdot (2a + b - 4l_s), \tag{7}$$

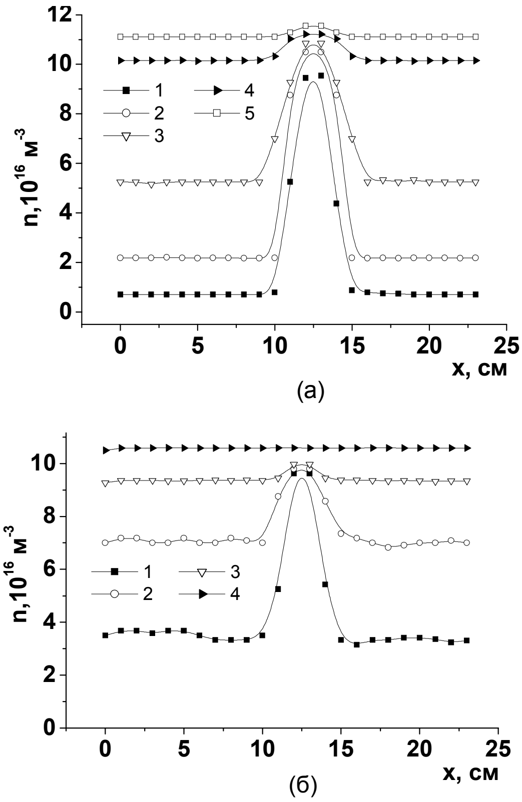

Fig. 3. Plasma density in hollow cathode as function of coordinate x for different discharge currents: 1 – 0,2 A, 2 – 0,4 A, 3 – 0,6 A, 4 – 1 A, 5 – 1,3 A. Hollow depth h is: 60 mm (a), 44 mm (b). Split width 8 mm, gas pressure 6 Pa

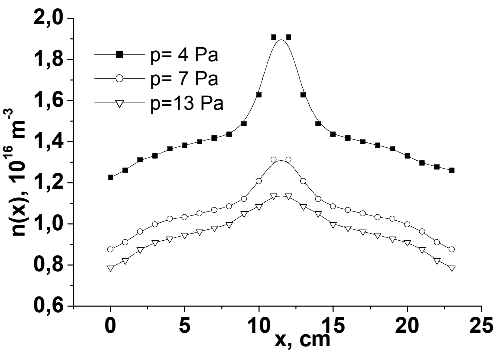

Fig. 4. Plasma density as function of x-coordinate for different gas pressures

$$Z_i = 0{,}4 \cdot n \cdot \sqrt{\frac{kT_e}{M}} (2a + b - 4l_s), \tag{8}$$

$$Z_e = \frac{1}{4} n \sqrt{\frac{8kT_e}{\pi m}} \exp\left(-\frac{\Delta\varphi}{kT_e}\right) \cdot (f - 2l_s), \tag{9}$$

$$W_a = \gamma \cdot 0{,}4 n \sqrt{\frac{kT_e}{M}} \cdot (2a + b - 4l_s), \tag{10}$$

where a, b – depth and width of cathode hollow; f – width of hollow split, l_s – thickness of ion sheath; U_i – average potential for ion-electron pair formation; M and m – ion and electron masses; γ – coefficient of ion-electron emission from cathode; $\Delta\varphi$ — potential difference between plasma and anode; β — rate of ion generation by one plasma electron, T_e — electron temperature.

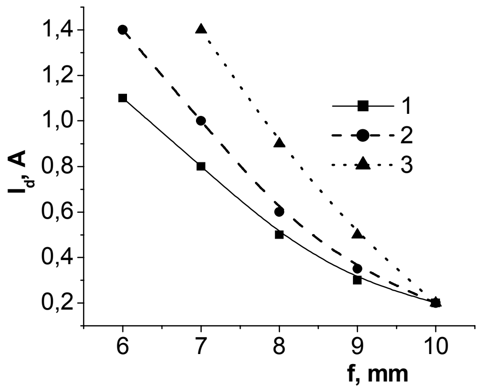

Fig. 5. Threshold discharge current I_d as function of cathode split width f for different gas pressures: 1 – 10 Pa, 2 – 6 Pa, 3 – 4 Pa

In case of linear approximation of ionization cross sec-tion vs energy expression for β is

$$\beta = en_a\left(\frac{8kTe}{\pi m}\right)^{1/2}\alpha_i \exp\left(-\frac{eU_i}{kTe}\right)\left(U_i + \frac{2kTe}{e}\right), \quad (11)$$

where n_a — neutral concentration; α_i — coefficient in linear approximation.

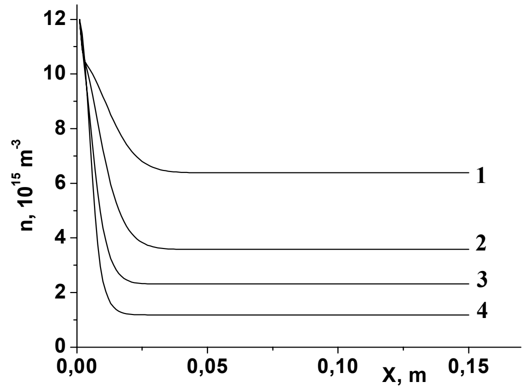

Fig. 6. Calculated plasma density n as function of longitudinal coordinate x in hollow cathode for different gas pressures: 1 – 9,2 Pa; 2 – 9 Pa; 3 – 8,6 Pa; 4 – 8 Pa

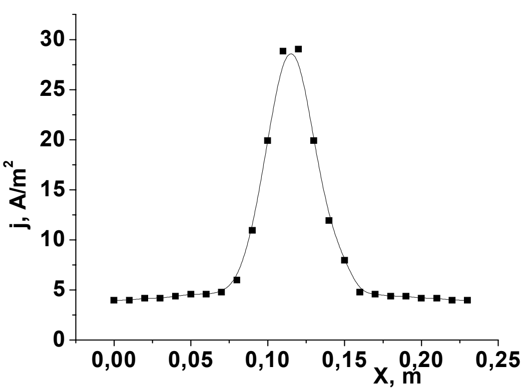

Fig. 7. Electron beam current density j as function of coordinate x across the beam. Split width 7 mm, I_b=600 mA

As result of calculations produced with equations 1–4 and taking into account expression 5–11 plasma density distributions were obtained. However, if n_a is supposed constant for all x, transformation of calculated curve $n(x)$ with pressure variation was not agreed with experimental one. Good agreement was obtained only if dependence of n_a on electron current density in split aperture of hollow cathode was taken into account [4]. In this case owing to correlation $T_e \sim E/n_e$, where E is electric field strength, sharp local plasma density maximum was obtained, and its width was broaden with gas pressure growth (Fig.6) as was observed in experiments.

3. Current distribution along beam cross section

Confirmation of strong correlation between plasma concentration and current density distributions is presented at Fig. 7. Earlier [5] we reported about ribbon beam nonuniformities, caused by back ion stream from accelerating gap to discharge region. This stream locally raises plasma density due to positive feedback between electron current density, ion stream and plasma density. As results of present work show, it is possible more one reason of beam nonuniformity, caused by peculiarities of plasma distribution in hollow cathode discharge.

4. Conclusion

Current density and beam uniformity are two main problems in generation of ribbon beam by plasma cathode electron gun based on discharge with extended hollow cathode. These parameters are in contradiction one to another. Increasing of current density by diminishing of plasma emission area caused appearance of local high current density streams. These beam nonuniformities reflect breaking off uniformity in plasma density distribution along hollow cathode. The reason of it is, in our opinion, closing of split in hollow cathode by ion sheath. In this case small casual local rise of plasma density or anode current cause total redistribution of plasma in hollow cathode. This process is finished by formation of one or several high-density regions.

Referencies

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[5] Burdovitsin V.A., Burachevsky, Oks E.M., Fedorov M.V., Technical Physics, 2004, V. 49, No.1, pp. 104–107.