Generation of Focused Electron Beam by Plasma Electron Gun in Pressure Range 1 – 10 Pa[1]

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Abstract – Plasma electron gun based on hollow cathode discharge was used for narrow focused beam generation in pressure range 1 – 10 Pa. Intention to raise beam current by increasing discharge current led to appearance of discharge between hollow cathode and accelerating electrode. This is accompanied by voltage drop in accelerating gap and electron beam disappearance. Axial magnetic field allows rising as limiting discharge current and so increase of electron beams current. Explanation of it is plasma confinement at the system axis and restriction of plasma boundary area, which in its turn prevents discharge switching from anode to accelerating electrode. Another possibility to produce higher electron beam current is electron extraction from plasma through not single but multiple emission holes. In this case only problem is beam focusing. Our experiments showed that special form of emission electrode allows obtaining satisfactory results.

1. Introduction

Two problems occur in a process of design and maintain plasma electron gun for focused beam generation in so called fore vacuum range (1 – 10 Pa). First of them is electrical breakdown of accelerating gap and the other one is low beam current density [1]. According to results of our investigations, problem of electrical breakdown may be overcome by two different ways in dependence on which breakdown type takes place [2]. In case of inter-electrode breakdown main way is emission electrode cleaning and its roughness lowering for protecting of explosion emission centers appearance. Application of metals with high level of arc current as a material of emission electrode also gives positive results. Of course probability of electrical breakdown grows significantly if gas pressure rises. Another type of electrical strength loss is so called "plasma breakdown", which takes place due to plasma penetration from discharge region into acceleration gap. The way for its averting is decreasing of emission hole diameter so that ion sheath thickness was comparable with this diameter. However in this case it is not possible to produce high enough electron beam current. Additional possibilities appear if axial magnetic field exists in accelerating gap. Another way to rise as total beam current so beam current density is electron emission through several emission holes. Main problem in this case is beam focusing. The goal of this work is investigation of methods both for electron beam current rising and increasing of limiting working gas pressure.

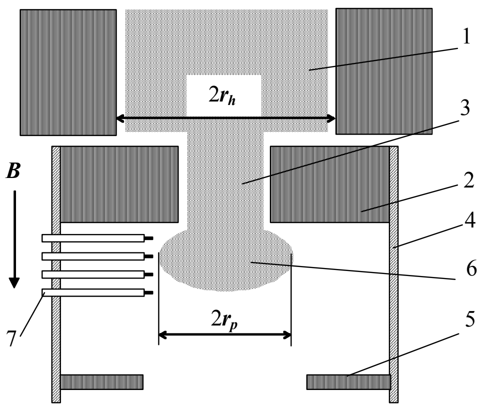

Fig. 1. Scheme of accelerating gap in electron source

2. Plasma boundary in presence of magnetic field

Scheme of experimental instrument is shown at Fig.1. It consists of hollow cathode 1 with inner diameter $2r_h$, anode 2 with emission channel 3 by diameter d in the center, insulator 4 and accelerating electrode 5. Penetrating plasma 6 forms its boundary in accelerating gap. Axial magnetic field B is maintained by solenoid, displaced out of electrode system. Sixteen single Langmuir probes 7 were inserted into accelerating gap through insulator 4 at different distances from emission electrode and different radiuses. The insulator 4 was made from transparent glass. Due to it visual observations of processes in accelerating gap were possible. Ion probe current measurements allowed investigating of plasma propagation in accelerating gap in

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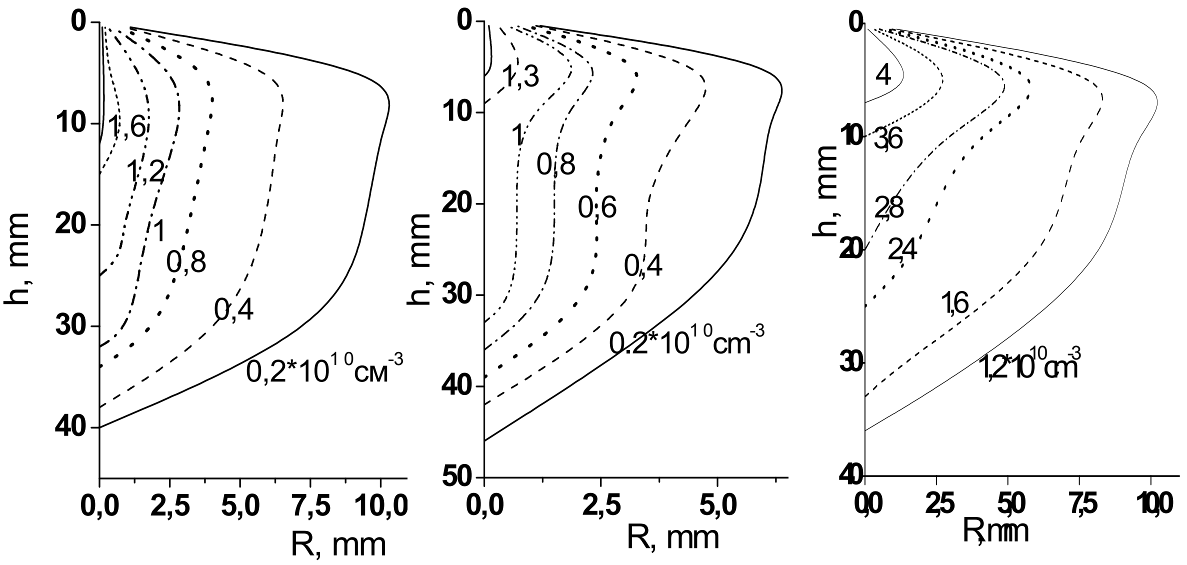

Fig. 2 – Equal concentration lines for plasma, penetrating through emission hole into accelerating gap in axial ***h*** and radial ***r*** coordinates for different magnetic fields (*a* – 4 mT, *b* - 15 mT, *c* – 0) and accelerating voltages: a, b -0, c – 250 V. Gas pressure ***p*** = 6 Pa, discharge current I_D = 300 mA

both cases of absence and presence of accelerating voltage. There was no special gas flowing into cathode hollow. If necessary, the gas was added into working chamber. Fig. 2 shows plasma boundary transformation as result of magnetic field and accelerating voltage applications. Magnetic field confines plasma along axis of system.

3. Influence of magnetic field at limiting parameters of electron gun

Experiments were carried out to investigate dependencies maximum values of beam current, gas pressure and accelerating voltage on axial magnetic field strength. It was shown, magnetic field allows producing more beam current and generating electron beam at higher pressures (Fig. 3). Fig. 4 shows minimal magnetic field ***B*** for preventing of breakdown as function of gas pressure ***p*** for different discharge current. We interpret these facts as averting of accelerating gap breakdown, which takes place as a result of plasma penetration through emission channel into accelerating gap and subsequence switching of discharge current from anode to accelerating electrode [3]. Conditions for this switching are given by expression

$$fG \geq 1 \tag{1}$$

In our case $f = \frac{\pi r_p^2}{\pi r_h^2}$ is the ratio of plasma boundary area to the hollow cross section (Fig. 1). *G* is the ratio of chaotic electron current density j_c to anode current density ***j***.

$$G = \frac{j_c}{j} = \exp\left(\frac{e(\varphi_p - \varphi_a)}{kT}\right) \tag{2}$$

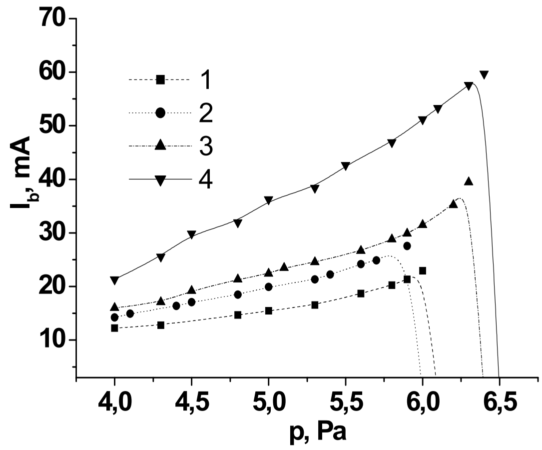

Fig. 3 – Beam current I_b as function of gas pressure ***p*** for different magnetic fields: 1 – 1 mT, 2 – 5,3 mT, 3 - 7 mT, 4 - 10 mT. Emission hole diameter ***d*** = 1,2 mm; accelerating voltage U_a = 1 kV

Expression (1) shows that current switching takes place if plasma boundary area exceeds some limited value. This may happen if plasma flows out of emission channel. Magnetic field prevents plasma radial motion and thus plasma surface increasing. To analyze this dependence it is possible to use continuity equation

$$div j_r = W_i, \tag{3}$$

where j_r is radial ion flow and W_i – rate of ion generation by plasma electrons. In case of linear approximation expression for W_i is

$$W_i = n_n \left(\frac{8kT_e}{\pi m} \right)^{\frac{1}{2}} \alpha_i \exp\left(-\frac{e\varphi_i}{kT_e} \right) \left(\varphi_i + \frac{2kT_e}{e} \right) n, \qquad (4)$$

where $\boldsymbol{n_n}$ and $\boldsymbol{\varphi_i}$ – neutral concentration and ionization potential, $\boldsymbol{n}$ and $\boldsymbol{T_e}$ - electron concentration and temperature, $\boldsymbol{\alpha_i}$ - coefficient in linear approximation on energy dependence of ionization cross section. In cylindrical coordinates eq. 3 looks as:

$$D \frac{1}{r} \frac{d}{dr} \left(r \frac{dn}{dr} \right) = -W_i \,. \qquad (5)$$

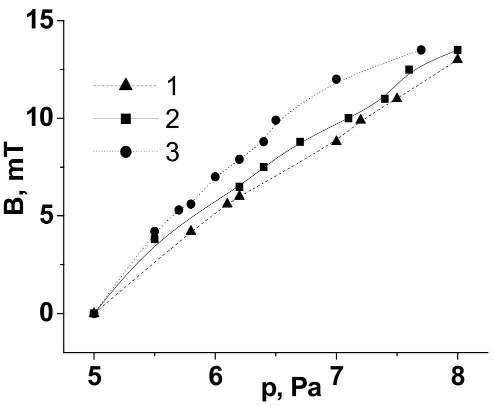

Fig. 4 – Magnetic field induction $\boldsymbol{B}$ for preventing of breakdown as function of gas pressure $\boldsymbol{p}$ for different discharge currents $\boldsymbol{I_D}$: 1 – 500 mA, 2 – 600 mA, 3 – 700 mA. Emission hole diameter $\boldsymbol{d}$ = 1,2 mm; $\boldsymbol{U_a}$=1 kV

$\boldsymbol{D}$ is transversal diffusion coefficient in magnetic field

$$D = \frac{D_0}{1 + \dfrac{\lambda_i \lambda_e}{r_i r_e}}, \qquad (6)$$

where $\boldsymbol{D_0}$ – ambipolar diffusion coefficient without magnetic field, $\boldsymbol{\lambda_i}$, $\boldsymbol{\lambda_e}$ – free path lengths for ions and electrons, $\boldsymbol{r_i}$ $\boldsymbol{r_e}$ – their cyclotron radiuses.

Equation (5) allows calculating $\boldsymbol{r_p}$. Substituting it in (1) we obtain possibility to connect limiting plasma density at the system axis (i.e. discharge current) and magnetic field strength. Results of such calculations, presented at Fig. 5, show good qualitative agreement with experimental measurements.

4. Electron extraction through perforated emission electrode

If perforated metal plate is applied as emission electrode, electron beam consists of great number of small beams. Total beam current is high enough, but there are difficulties in beam propagation through electrode system and beam focusing so that to reduce crossover and to rise beam current density. Calculations performed with Kobra program [4] allowed finding optimal form of emission electrode to produce beam current density about 10 A/cm^2 and beam diameter 3 – 4 mm. These results were obtained for multi channel tantalum emission electrode: total holes quantity 60, their diameter 0,6 mm, electrode thickness 0,2 mm. At electron energies 15-20 keV obtained power density is enough for melting and evaporation of row of metals. At the same time small exceeding of noted current density caused beam-plasma discharge appearance. This, in its turn, leaded to beam defocusing and current and power density drop [5].

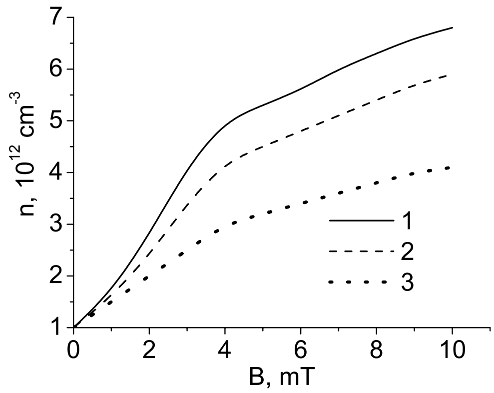

Fig. 5 – Calculated plasma density $\boldsymbol{n}$ as function of axial magnetic field $\boldsymbol{B}$

Conclusion

Axial magnetic field in accelerating gap of plasma electron gun ensured generation of electron beam with more current and more current density at higher gas pressures. This fact is result of plasma confining at the axis of accelerating gap. Magnetic field prevents radial propagation of plasma penetrating through emission channel into accelerating gap. This restricts plasma boundary and prevents discharge current switching from anode to emission electrode.

References

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