Energetic Efficiency of Electron and Ion Emitters Based on Glow Discharges with Oscillating Electrons [1]

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Abstract – Electron and ion sources based on glow discharges with oscillating electrons have much higher service life in comparison with hot cathode systems. At the same time the operation voltage of the glow discharges is much higher, that is explained by small coefficient of ion–electron emission. It gives in large energy expenditures for maintaining of the discharge and leads to complication of a design of the sources due to necessity of intensive cooling of electrodes. Besides, there are difficulties in making of powerful discharge supply units, in which the transfer of necessary energy should be supplied to the electrodes of the discharge system being under high potential corresponding to required energy of the beam. So increase in energy efficiency of the sources of charged particles on the basis of these discharges is an actual problem. Its solution could ensure not only diminution of energy expenditures, that is very important in itself, but also would allow to simplify essentially designing both emitters and power supplies. The extremely possible parameters of the systems based on glow discharges with oscillating electrons and ways of their achievement are considered in the report.

1. Introduction

One of the main parameters of electron and ion emitters is the energetic efficiency α_e defined as the ratio of beam current I_b to power P expended on maintaining of the discharge and generation of emitting plasma in the discharge system of the source

$$\alpha_e = \frac{I_b}{P} \,. \tag{1}$$

The expended power in systems with cold cathode in which there is no power consumption on warming up of the cathode is equal to product of the discharge current I_d and voltage U_d. Then

$$\alpha_e = \frac{I_b}{I_d U_d} = \frac{\alpha}{U_d} \,, \tag{2}$$

where $\alpha = I_b / I_d$ is efficiency of extraction of electrons or ions from the discharge. From last formula it is obvious, that for increase in energetic efficiency it is necessary to rise the level of extraction of particles and at the same time to decrease the operation voltage of the discharge. However simultaneous realization of these requirements is problematic, as the emission of charged particles into accelerating gap for the beam formation can give in essential difficulties in operation of the discharge. The negative influence to maintaining of the glow discharges with oscillating electrons can be caused by extraction both of electrons and of ions. The basic physical processes ensuring maintaining of the discharge are ionization by electrons in volume of the discharge chamber and ion–electron emission on the surface of the cathode. It is clear, that the extraction of electrons will give in diminution of intensity of the first process, and the extraction of ions will impede course of the second process. So the problem of definition of some optimum level of extraction of charged particles, when rather high level of emission will be ensured without infringement of condition of self-maintaining of the discharge, is actual.

2. Energetic Efficiency of Electron Sources

The basic contribution to ionization of gas in the viewed discharges with oscillating electrons is brought with the so-called fast particles emitted from the cathode surface and accelerated in the cathode voltage drop. So it is desirable to create such conditions of extraction of electrons, that effective emission of plasma electrons was ensured but the leaving of the fast particles would be eliminated. However it is not possible in the hollow cathode discharge, in which both the fast and slow particles oscillate freely over all volume of the cavity and the distribution of electrons on energies is identical near to any part of the surface of the discharge chamber. Therefore, apparently, the optimum conditions for maintaining hollow cathode discharge in the mode of electron emission are achieved when the following requirement is realized:

$$(S_e + S_a)/S_c \sim \sqrt{m/M} \,, \tag{3}$$

where S_e, S_a and S_c are areas of emission hole, anode and cathode, m and M are masses of electron and ion, accordingly. If the total area of the emission hole and anode is more, than it is defined by relation (3), then it is necessary to expect difficulties with maintaining of the discharge owing to the prompt leaving of fast particles. If it is less, then the leaving of plasma electrons from the discharge is impeded, that can give in transition of the discharge in high-voltage regime.

The situation for discharge in magnetic field is other, as the magnetic field hinders free electron motion in the transverse direction. The spatial distributions of fast and slow particles in these conditions can differ essentially from each other not only quantitatively, but qualitatively too. The flow of fast particles gradually wanes in the direction from the cathode to the anode, while the flow of slow electrons is incremented in this direction. So it is possible to realize effective extraction of plasma electrons from anode region with rather small leaving of the fast particles and thus to avoid essential impairment of ionization processes. If the conditions for practically complete relaxation of the fast particles in the discharge chamber are ensured, then the operation voltage in this case is determined by the following relation [1]:

$$U_0 = \frac{W}{e\gamma}, \qquad (4)$$

where W is average energy expended on formation of a pair of charged particles, e is charge of electron, γ is coefficient an ion–electron emission. Then one can estimate the highest possible energetic efficiency using the following relation

$$\alpha_{em} = \frac{1}{U_0} \qquad (5)$$

Writing this relation it was accepted that the maximum value of energetic efficiency can be achieved, if all electron current is switched from the anode to the emission hole ($\alpha \sim 1$). As an example of the electron source, in which it is possible to implement requirements close to optimum, one can specify the emitter based on inverse magnetron system [2] shown schematically in Fig. 1. In this system the larger part of the fast electrons is generated on the cylindrical surface of the cathode. So these electrons get in central region, from which the extraction of particles is conducted, after realization of their ability to ionize. At the same time the suitable choice of number of the emission holes N and induction of the magnetic field B allows to achieve value of extraction efficiency up to 0.9.

Feature of the used electrical scheme was the connection of the accelerating voltage supply (AVS) to the cathode of the discharge system. In this case it is possible to use lesser powerful discharge power supply (DPS) which should supply not all discharge power $I_d U_d$, but only little part of it $I_a U_d \sim 0.1 I_d U_d$,

where I_a is the electron current to the anode. Larger part of the discharge power $I_b U_d \sim 0.9 I_d U_d$ was supplied by AVS which was used in the source not only for accelerating of particles, but for maintaining of the discharge too.
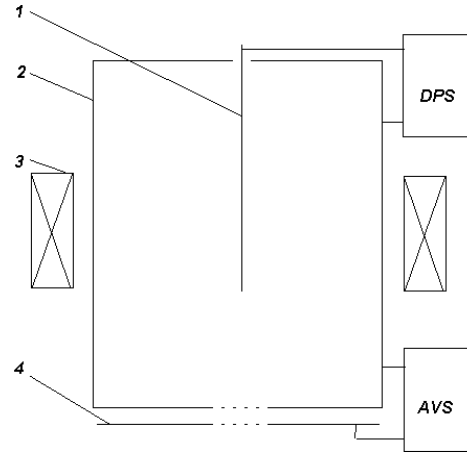

Fig. 1. Electron emitter based on inverse magnetron system. 1 – anode, 2 – hollow cathode, 3 – solenoid, 4 – accelerating electrode, DPS – discharge power supply, AVS – accelerating electrode

3. Energetic Efficiency of Ion Sources

Possible value of energetic efficiency in case of extraction of ions can be estimated by the following way: the extraction of a part of ions into accelerating gap will give in diminution of effective coefficient of ion–electron emission

$$\gamma_{ef} = \gamma(1-\alpha). \qquad (4)$$

Then for realization of self-maintaining condition the operation voltage of the discharge increases accordingly even in case of complete relaxation of the fast electrons

$$U_d = \frac{U_0}{1-\alpha}. \qquad (5)$$

So one obtain the following formula for energetic efficiency

$$\alpha_e = \frac{\alpha}{U_d} = \frac{\alpha(1-\alpha)}{U_0}. \qquad (6)$$

The function $F(\alpha) = \alpha(1-\alpha)$ is nonmonotonic one. Its maximum is achieved when $\alpha = 0.5$ and is equal to 0.25. Thus, the highest possible energetic efficiency is determined by the following relation:

$$\alpha_{em} = \frac{0.25}{U_0} = \frac{0.25 e\gamma}{W}. \qquad (7)$$

If working gas is argon, for which the average energy expended on formation of pair of charged particles is about 26 eV, and material of the cathode is stainless

steel (coefficient an ion–electron emission for the combination argon–stainless steel is about 0.05), then the value of the peak possible energetic efficiency is equal to 0.48 A/kW. The results of more precise (than the above estimation) calculations [3] performed for the hollow cathode discharge show, that the reaching of the peak energetic efficiency is possible if the pressure in the discharge chamber exceeds significantly the critical pressure below which the discharge operation is impossible. However in ion sources the discharge should be supported at pressures which are close to critical one, because it is necessary to prevent breakdown in the accelerating gap. In this case the optimum level of extraction is displaced from 0.5 to the smaller values, and there is some diminution of the highest possible energetic efficiency too.

The experimental definition of the optimum level of ion extraction was carried out with the use of the ion source based on Penning discharge with nonequipotential cathode [4], which construction allows to achieve values of α up to 0.3. In this system not only pressure of gas, but also magnetic field influence essentially processes in the discharge. Therefore searching of the optimum mode was performed by varying not only pressure, as in the hollow cathode discharge, but induction of the magnetic field too.
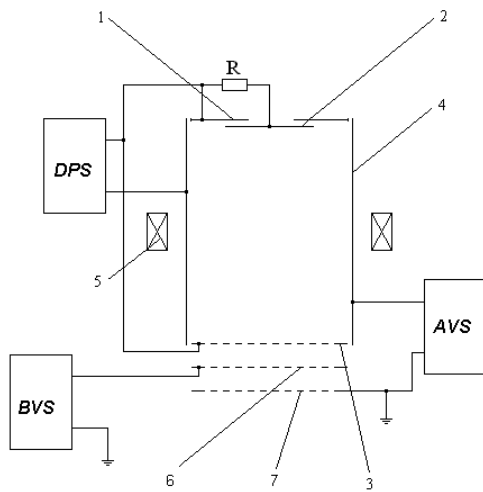

Fig. 2. Electrode scheme. 1 – ring cathode, 2 – control electrode, 3 – end cathode (emitter electrode), 4 – anode, 5 – solenoid, 6 – accelerating electrode, 7 – decelerating electrode, DPS – discharge power supply, AVS – accelerating voltage supply, BVS – bias voltage supply

Experimental model of the ion source and electrical circuit of the experiment are shown in Fig. 2. The discharge system of the ion source includes the cylindrical anode, ring cathode, control electrode, and end cathode which plays simultaneously the role of the first emitter electrode of ion optics. Extraction of ions from the discharge chamber was realized by three-electrode accelerating – deccelerating ion optics. The used ion optics permit to change the extraction efficiency over a wide range. It was ensured by the use of

emitter electrodes with different number of emission holes N. 5 emitter electrodes had been made, in which there were 19, 37, 61, 91 and 137 holes of 8 mm diameter. The number of holes in the accelerating and decelerating electrodes was equal to 137.

Feature of the electrical circuit of the experiment was the absence of additional power supply destined for the adjustment of potential of the control electrode. We used the control electrode of 30 mm diameter, and for the disk of this size the optimum value of potential, at which the uniformity of the radial plasma distributions is achieved, is close to floating. Therefore the central disk was connected to the negative pole of the DPS through a high-ohmic resistor.

The induction of the magnetic field was varied by changing current through a solenoid. Pressure was varied by change of gas feed Q. The working gas was filled into the discharge chamber through an axial hole in the control electrode and was pumped out through holes in the electrodes of the ion optics. During the experiments the accelerating voltage was equal to 10 kV, bias voltage was equal to 2 kV, and the discharge current was 50 or 100 mA.

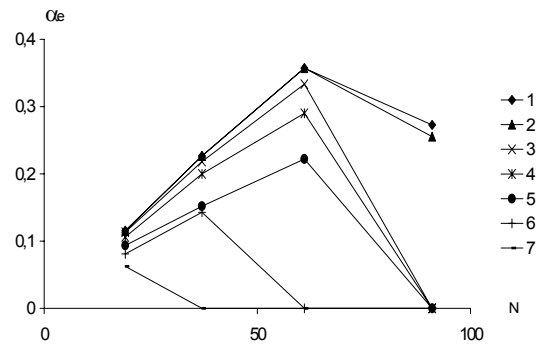The dependences $\alpha_e(N)$ are presented in Figs. 3, 4.

Fig. 3. Energetic efficiency vs. number of holes. $Q = 0.25$ cm³/c. B (mT): $1 - 10$, $2 - 8$, $3 - 7$, $4 - 6$, $5 - 5$, $6 - 4$, $7 - 3$
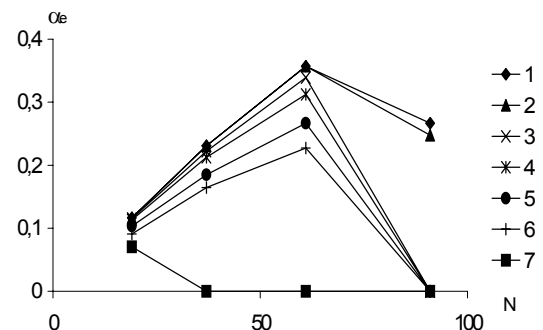
Fig. 4. Energetic efficiency vs. number of holes. $Q = 0.35$ cm³/c. B (mT): $1 - 10$, $2 - 8$, $3 - 7$, $4 - 6$, $5 - 5$, $6 - 4$, $7 - 3$

All obtained curves are nonmonotonic functions, and the point of the maximum is shifted to the higher values of N with increase in gas feed and induction of the magnetic field. Thus, as well as in the hollow

cathode discharge, the excessive magnification of the extracted ion current is inexpedient, as it gives in diminution of energetic efficiency of the source owing to difficulties with maintaining of the discharge.

The peak value of the energetic efficiency grows with magnification of gas feed and magnetic induction and achieves 0,36 A/kW when $Q = 0,35$ cm^3/s and $B = 10$ mT. The further magnification in Q is restricted due to diminution of the electric strength of the accelerating gap, and the further amplification of B can give in excitation of large-scale instability of plasma. However it is necessary to mark, that the reached value α_e is already close to extremely possible α_{em}. So the further progress in this direction can be due to searching of material of the cathode with higher coefficient γ or due to the use of other emission mechanisms alongside with the ion-electron emission.

References

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