Kiloelectronvolt Centimeter Profile Ion Beam Formation from Hollow Cathode Discharge in Conditions without Grid Stabilization of Emitting Plasma Surface

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Abstract – The qualitative concepts of general properties of ion emission from gas discharge plasma in plasma penetrating into the accelerating gap conditions are examined. Considerable influence of wall layer on stability of penetrating plasma is noted. It is shown that from experimentally observable two condition of plasma described by a various position of plasma border, one, corresponding to a condition $r_p/R > 0.54$, is steady, where r_p and R – radius of plasma in the accelerating electrode and radius of the accelerating electrode aperture, respectively. The existence of system a plasma-layer in the aperture of the accelerating electrode is possible only in case the voltage on a layer does not exceed some limiting magnitude dependent on parameters of plasma.

1. Introduction

The ion emission current, as it follows from Bom ratio, is defined as

$$I_i = 0{,}4en_i(2kT_eM_i^{-1})^{1/2}S, \qquad (1)$$

where n_i – plasma concentration, T_e – electron temperature, k – Boltzmann constant, M_i – ion mass, e – electron charge, S – emitting surface area depends on plasma density and its electron temperature. The ion emission current depends on distribution of electrical and magnetic fields in the discharge gap and the emission channel and on the size of the channel [1]. Generally the outlet ion current at the defined discharge current can be raised if to conduct selection of ions from the greater area of plasma. Expansion of the emission surface achievable in conditions plasma density constancy by increase of the emission channel sizes, when the condition $r_k >> l_k$ is satisfied (r_k – radius of the channel, l_k – cathode drop extent), results to break of ion case before the emission channel and to free plasma “issue” from discharge gap and its expansion in equipotential space [2]. In a result the discharge is realized [3], at which the penetrating plasma fills in the acceleration gap. The extraction of ions in this situation is possible due to the plasma “sausage”, i.e. creation of conditions, at which the steady existence in the wide aperture of the accelerating electrode of system a plasma – layer of a spatial charge is impossible [4]. The instability of penetrating plasma allows to extract ions through the wide aperture in the cathode, in absence of grid stabilization of the emitting plasma surface and to create wide-aperture ion sources, in which grids with small cells as a emitting electrode are not used. In these conditions the extraction of the charged particles from discharge plasma supposes use of an accelerating electrode with an aperture, which diameter, at least, is not less the cross sizes of the emission channel. The length of the accelerating gap appears much less than the diameter of the aperture in the accelerating electrode. The extraction of the charged particles (ions) in the mode of plasma penetration in the accelerating gap due to creation of conditions at which the steady existence in the aperture of the accelerating electrode of system a plasma-layer of a spatial charge is impossible is below considered.

2. Experimental Technique

In Fig. 1 the electrode circuit is shown, in which it is possible to receive penetrating into an accelerating gap plasma. The low pressure glow discharge with hollow cathode is initiated between hollow *1*, ring *2* cathodes and anode *3*. The induction of a magnetic field on an axis of the anod cylinder is of ~ 0.1 T. Discharge current 50–100 mÀ, voltage of burning ~ 350 V. Working gas argon. The gas pressure the accelerating gap between the cathode *2* and accelerating electrode *4* is of ~ $7.3 \cdot 10^{-2}$ Pa. Plasma concentration $n_i = 5.2 \cdot 10^{16}\,\text{m}^{-3}$ and electron temperature $T_e = 3.5 \cdot 10^4$ K are estimated on electron and ion currents of saturation of the single cylindrical probe placed in the aperture of the accelerating electrode. The emission channel represents a cavity, which diameter is equal to a diameter of the anode 20 mm, and height – 4 mm. The chosen sizes and form of the channel allowed to realize situations, at which in the accelerating electrode aperture by a diameter 26 mm plasma and layer of a spatial charge between border of plasma and walls of the aperture exist. The acceleration gap extent is of 3 mm. On distance of 100 mm from the cathode *2* the collector of ions *5* is placed. At measurement of ion current on the collector the current of secondary electron is taken into account. Except the direct measurements of ion current, observations of the penetrating plasma

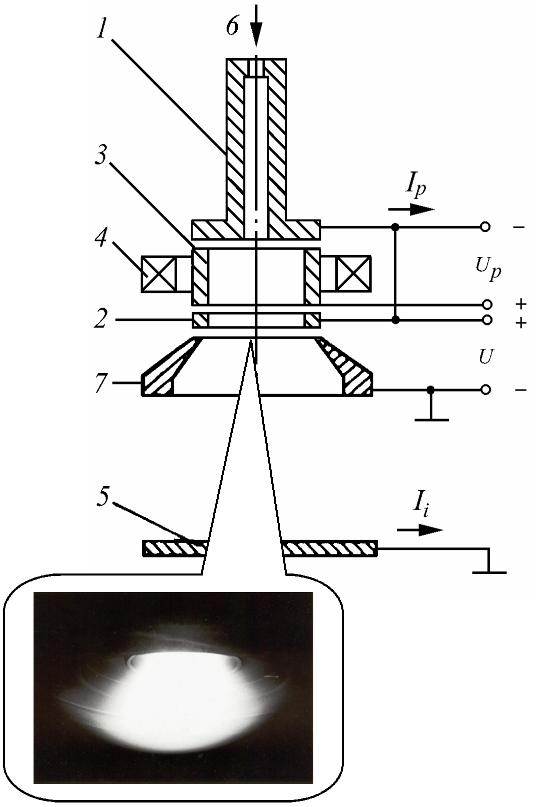

Fig. 1. The circuit of the experimental device and photo of epy luminescence of plasma penetrating into vacuum through epy accelerating electrode: *1* – hollow cathode, *2* – ring cathode, *3* – cylindrical anode, *4* – constant ring magnet, *5* – collector, *6* – channel of gas feeding, *7* – accelerating electrode

luminescence are realized visually through a special window and photographed by *Digital Stil Camera*. The rectifiers with an adjustable outlet voltage of 0–1.5 kV and 0–10 kV are served as the power supplies.

3. Experimental Results

In Fig. 2 the voltage-current characteristic indicating the existence of two types of the discharges: high-voltage low-current (reflective discharge) and low-voltage high-current (discharge with hollow cathode) in electrode structure of Fig. 1 is given. Experiments have shown that the direct transition from the high-voltage form of the discharge to low-voltage (from a luminescence in the anode cylinder to a luminescence in the hollow cathode) occurs at low pressure by step, at high pressure > 2.6 Pa – without step. In the latter case, it is difficult to divide these two forms of the discharge, as the slow rise of the voltage at once results in initiation of the discharge with hollow cathode. The display of the hollow cathode effect depends on a ratio between emitting internal surface of a cavity and the aperture area determining electron and ion loss [5]. At low pressures and voltage reduction before breakage of a current in the cathode cavity the discharge luminescence disappeared not only in the cathode cavity, but also in the anode cylinder, i.e. with discharge extinction in the cathode cavity the discharge extinction in the anode cylinder was observed. To pass on a way of development from the low-voltage discharge to high-voltage, by means of a voltage reduction it fails. It is obvious, that at low pressure the transition from high-voltage to the low-voltage discharge is possible only.

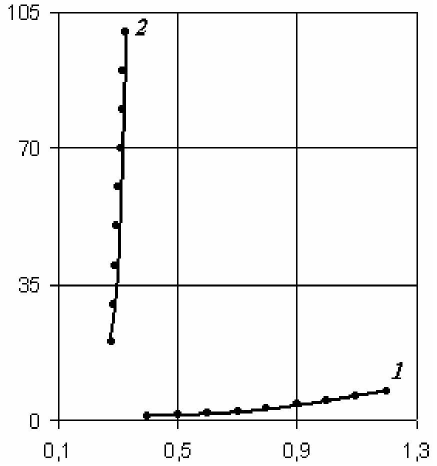

Fig. 2. Voltage-current characteristic of the discharge: *1* – reflective discharge, *2* – discharge with hollow cathode, $p = 3.6 \cdot 10^{-1} – 8$ Pa

The high-voltage and low-voltage form of the discharge differ with distribution of a current between cathodes. The distribution of a current between ring and end face of hollow cathodes in equal shares is characteristic for the high-voltage discharge. At initiation of the low-voltage discharge the character of distribution of discharge current essentially varies, Fig. 3. As follows from experiments, in the circuit the anode – hollow cathode proceeds ~ 0.9 discharge current I_p. Besides the relation of cathode currents is constant in all the investigated range of burning currents of the low-voltage discharge and equal ~ 8.5.

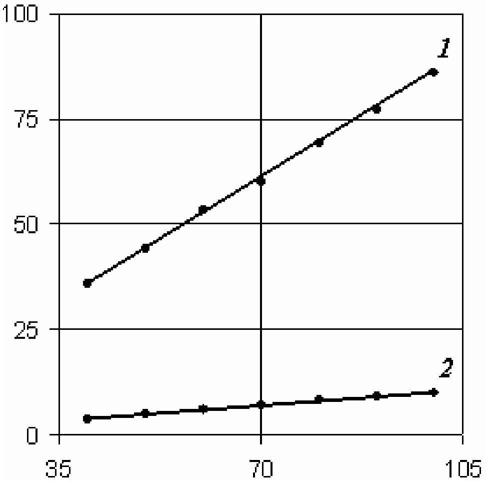

Fig. 3. Dependences of a current on hollow (*1*) and on ring (*2*) cathodes from the discharge current with hollow cathode at $p = 7.3 \cdot 10^{-2}$ Pa

In Fig. 4 the dependence of the initiation discharge voltage from pressure is submitted. With the pressure growth the initiation voltage is quickly reduced. At pressure of $\sim 6 \cdot 10^{-1}$ Pa the voltage reduction is slowed down and at $p > 6 \cdot 10^{-1}$ Pa the initiation voltage is lowered slowly. The range of the top and bottom pressures takes place, in which differently, weak or strong, the dependence is shown. In the bottom range of pressures $p < 6 \cdot 10^{-1}$ Pa the initiation of discharge with hollow cathode occurs at rather high voltage, and the discharge initiation at $p < 3.6 \cdot 10^{-1}$ Pa is reached due to high voltage > 1 kV. In the top range of pressure $p \geq 6 \cdot 10^{-1}$ Pa the initiation voltage < 0.5 kV.

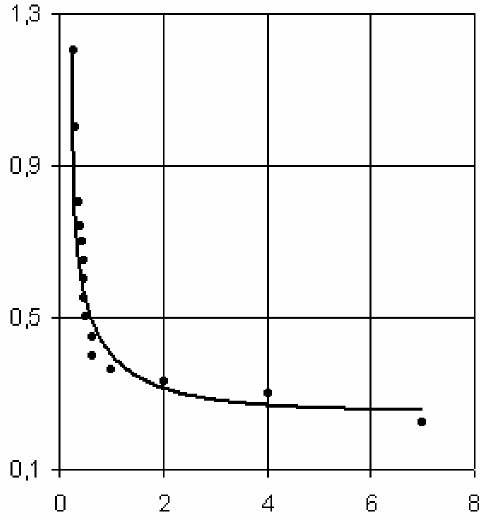

Fig. 4. Dependence of initiate discharge voltage with hollow cathode on pressure

On dependence of discharge current from pressure (Fig. 5) smooth insignificant reduction of the current with reduction of p in a range of the bottom pressures is marked.

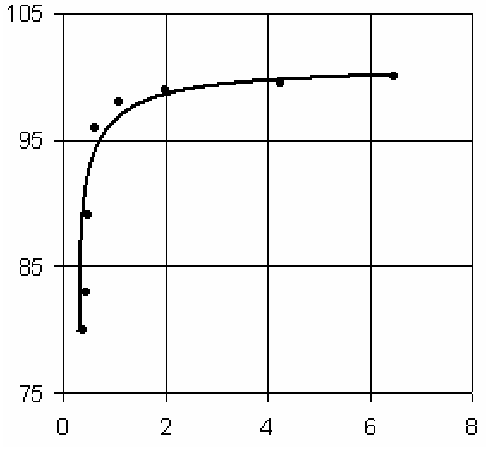

Fig. 5. Dependence of discharge with hollow cathode current on pressure

The breakage of discharge current is observed at pressure of $\sim 3.6 \cdot 10^{-1}$ Pa, thus the luminescence of the discharge not only in cathode cavity, but also in the anode cylinder disappears. With reduction of pressure at a constant current the voltage of discharge burning practically does not vary and grows only at p close to boundary pressure, at which the discharge breaks. In Fig. 6 the dependences of ion current on a collector from an accelerating voltage (voltage of burning ~ 350 V, discharge current 0.1 A) are submitted. Three characteristic areas appropriate to the high-voltage glow discharge (part *АБ*), extracting ion beam (part *ВГ*) and fast transition from ion current of penetrating plasma to emission ion current and back, respectively (parts *БВ* and *ДА*) are allocated. Let us consider dependence of collector current $I_к(U)$ (Fig. 6).

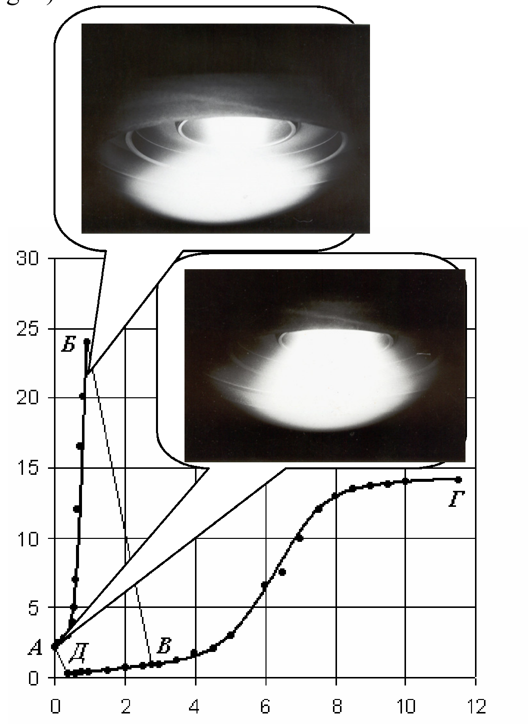

Fig. 6. Dependence of ion current on the collector on the accelerating voltage and photo of plasma luminescence: $I_p = 0.1$ A, $U_p = 350$ V, $p = 1.2 \cdot 10^{-1}$ Pa

At $U = 0$ ion current on a collector is of 2 mA. The occurrence of a current testifies to break of ion case before emission aperture and penetration of a wide plasma flow, Fig. 6 (photo of plasma luminescence appropriate to a point *А* on dependence of ion current on accelerating voltage) in space between extracting electrode and collector. With occurrence and insignificant increase of accelerating voltage there is a sharp growth of ion current. At the further slow voltage increase the plasma on output of the aperture of accelerating electrode is radial compressed, neck is formed, Fig. 6 (photo of plasma luminescence appropriate to point *Б* on dependence of ion current on accelerating voltage). At $U \sim 880$ V the plasma in narrowing place breaks up, the current is reduced by step from 24 up to 0.8 mA (part *БВ*), the voltage is increased up to 2.7 kV. The collector registers ion beam current. The increase of voltage up to value $U > 2.7$ kV results to plasma release into the emission channel (that testifies to reduction of losses of extracted ion current an accelerating electrode Fig. 9 (curve *2*)), reduction of losses of ions and growth extracted ion current of Fig. 6. The current growth is especially noted at $U > 5$ kV. With the further increase U ion current is sated [16]. If to reduce accelerating voltage up values < 2.7 kV, the ion beam current is slowly reduced. However receiving of ion current values close to zero is not success because of existence of critical accelerating voltage value (~ 450 V), which field does not keep plasma in emission channel. The plasma is pulled out, the current is sharply increased from 0.2 up to 2 mA, voltage falls up to ~ 80 V (part *ДА*).

4. Discussion of Results

Let us consider plasma in accelerating electrode aperture, which negative potential is less than potential of the ring cathode. Extent cathode drop is possible to present as

$$l_k = R - r_p, \tag{2}$$

where R – accelerating electrode aperture radius, r_p – plasma border radius. Let us transform (2) to a form

$$l_k R^{-1} = 1 - \xi, \tag{3}$$

where $\xi = r_p R^{-1}$.

Neglecting electron charge and considering movement of ions in layer collisionless (at pressure of $7.3 \cdot 10^{-2}$ Pa free path of argon ions $\lambda \sim 10^{-1}$ m), emitting plasma surface – cylinder shape, the longitudinal gradient of plasma in the aperture of accelerating electrode insignificant, and throughput of gap appropriate emission ability of plasma, is possible, using "the law 3/2", to write down expression for ion current density of the vacuum cylindrical diode as

$$j_i = 0{,}444\varepsilon_o(2eM_i^{-1})^{1/2}U^{3/2}R^{-2}(f(\xi))^{-1}, \tag{4}$$

where $f(\xi)=\xi\beta^2(1/\xi)$, $\beta^2(1/\xi)$ – transcendental function (Fig. 7). Present "law 3/2" as

$$\xi = 0{,}444\varepsilon_o(2eM_i^{-1})^{1/2}U^{3/2}j_i^{-1}R^{-2}(\beta^2(1/\xi))^{-1}, \tag{5}$$

where j_i is defined by Bom formula (1).

With the account (5) expressions (4) after transformations can be resulted in a form

$$\xi = 1{,}1\varepsilon_o U^{3/2}n_i^{-1}R^{-2}(ekT_e)^{-1/2}(\beta^2(1/\xi))^{-1}. \tag{6}$$

Let us calculate value $\xi\beta^2(1/\xi)$, at which the decomposition of plasma in the aperture of accelerating electrode is experimentally observed and emitting plasma surface is squashed into the emission channel. Substituting in (6) values $R = 1.3 \cdot 10^{-2}$ m; $\varepsilon_o = 8.85 \cdot 10^{-12}$ Ф/m; $n_i = 5.2 \cdot 10^{16}$ m^{-3}; $T_e = 3.5 \cdot 10^4$ K; $e = 1.6 \cdot 10^{-19}$ C; $k = 1.38 \cdot 10^{-23}$ J/K; $U = 880$ V, find out

$$\xi\beta^2(1/\xi) = 0.11. \tag{7}$$

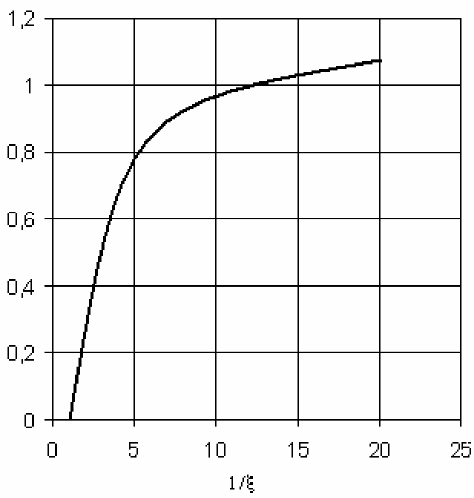

Fig. 7. Graph of function $\beta^2(1/\xi)$

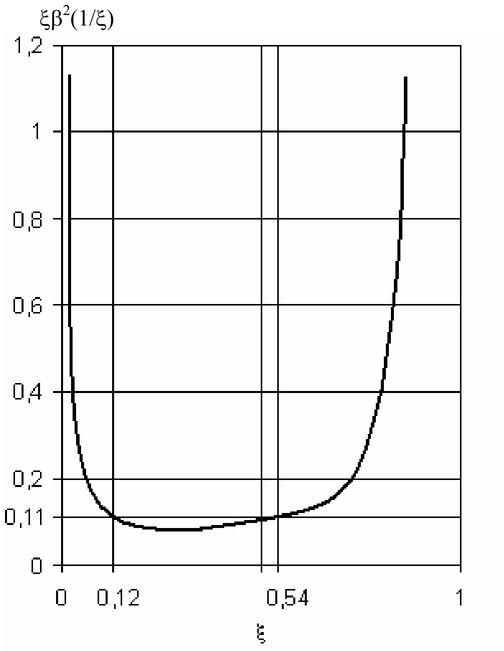

Fig. 8. Graph of function $f(\xi)$

Not monotonous character (Fig. 8) functions $f(\xi)$ give for $f(\xi) = 0.11$ two values $\xi = 0.54$ и $\xi = 0.12$, that corresponds to two condition of plasma with different radiuses $r_p \sim 7 \cdot 10^{-3}$ and $r_p \sim 1.5 \cdot 10^{-3}$ m. The value $\xi = 0.12 < \xi_m = 0.31$ corresponds to the left branch of dependence, i.e. to unstable condition plasma – layer (ξ_m – limiting bottom value of stability). The sizes of radius $\xi = 0.54$ are on the right branch of dependence $f(\xi)$, describing a steady condition of plasma. However, found $\xi = 0.54$ exceeds the minimal value $\xi = 0.31$, calculated in [6, 7]. The divergences in limiting bottom values of stability, apparently, are explained by flat rise of $f(\xi)$ in interval $0.31 \le \xi \le 0.54$. The photography of the least section, at which the extreme small disturbance causes its fast decomposition, has given value $r_p \sim 7.2 \cdot 10^{-3}$ mm

($\xi = 0.54$), coincident with calculated value. Obviously, the steady existence of system plasma – layer in the investigated structure of electrodes is possible not at any values ξ of the growing branch of function, but only at $\xi \geq 0.54$, thus the voltage on the layer does not exceed some limiting volume dependent on parameters of plasma [6]

$$U^* < 8.79 \cdot 10^{-8} n_i^{2/3} T_e^{1/3} R^{4/3}. \qquad (8)$$

The plasma concentration can not be lower than some critical value [7]. The wide channel in the emitting cathode not only gives to the cathode the form of a ring, changes appreciably structure of magnetic field and creates conditions of high vacuum not characteristic for discharge systems with a small aperture in emitting cathode, but also attracts necessity of realization of conditions complicating steady existence of penetrating plasma in the channel of the accelerating electrode. Due to which the plasma decomposes, than the fast transition from ion current of penetrating plasma to emission ion current is caused.

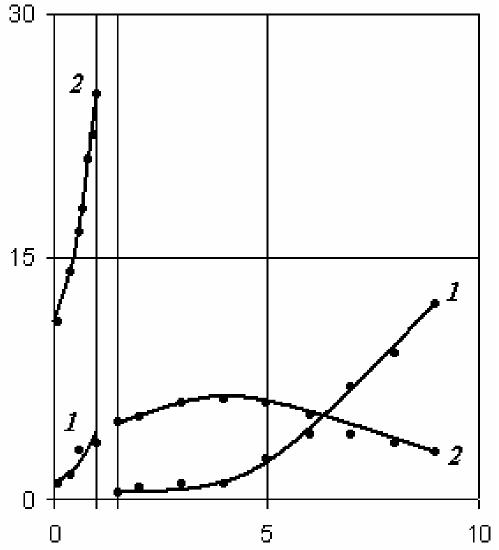

Fig. 9. Dependences of ion current on the collector (*1*) and on the accelerating electrode (*2*) from the accelerating voltage: $I_p = 70$ mA, $U = 350$ V, $p = 1.2 \cdot 10^{-1}$ Pa

The additional growth of ion current can be received by the expense of a choice of the rational design of the accelerating electrode causing an extreme small leaving of extracted ions on its walls. Such potential opportunity is evident and is obvious, as the ion current losses for the open discharge on the accelerating electrode can make the large part from complete extracted ion current. Let us consider dependences of ion current on the accelerating electrode and collector from U and analyze an additional opportunity of reduction of the extracted ion price expressed as $C_i \sim I_p U_p / I_i$, relation of emitter power to emission ion current. As data are visible from submitted in Fig. 9 extracted ion current is redistributed between the accelerating electrode and collector. For the current on the accelerating electrode (curve *2*) there are growing and falling parts, to which there corresponds slow and fast growth of ion current on the collector (curve *1*). At accelerating voltages up to 5 kV the plasma is poorly squashed and the emitting plasma surface on the output of the emission channel is convex. The ion current losses on the accelerating electrode are significant, collector current is less than the accelerating electrode current. With growth of a voltage the emitting plasma surface is flatten, the losses of ion current on the accelerating electrode are reduced (falling part of dependence on Fig. 9 (*2*)), collector current quickly grows, testifying about increase of accelerating electrode capacity.

On the collector the large part of ions enters, than is grasped by the accelerating electrode. Though the ion current losses with the growth of accelerating voltage in the investigated geometry of acceleration gap are reduced, nevertheless they remain still significant and make 0.4–0.5 from the ion current on the collector. Therefore one of expedients of ion current increase on the output of the accelerating electrode with the wide aperture becomes optimization of accelerating electrode geometry. It is possible to expect, that the selection of the form and sizes of the accelerating electrode will reduce action of the external factor of unproductive ion current losses up to an extreme allowable minimum 0.9–0.95.

Submitted Fig. 10 dependences on the accelerating voltage of extracted ion current testify to most complete use of plasma with wide emission channel. The sevenfold increase of extracted ion current is reached without increase of discharge current, at the expense of expansion of emission channel diameter from 3 up to 18 mm. The limiting values of extracted ion current are received at the maximal sizes of the aperture in the ring cathode determined by the diameter of the cavity in an anode electrode.

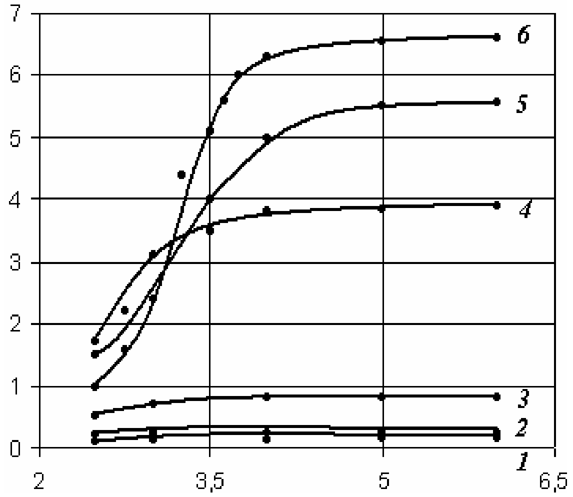

Fig. 10. The characteristics of ion extraction (d – diameter of the emission channel): *1*, *2*, *3* – $d = 3$; *4*, *5*, *6* – 18 mm; discharge current: *1*, *4* – $I_p = 50$; *2*, *5* – 80; *3*, *6* – 100 mA; pressure in the accelerating gap: *1*, *2*, *3* – $4 \cdot 10^{-2}$; *4*, *5*, *6* – $4 \cdot 10^{-1}$ Pa

5. Conclusion

The analysis of the discharge properties and conditions of ion extraction in the mode of plasma penetration into the accelerating gap has shown that:

– the discharge is initiated and stably burns with broken off ion case before the emission channel in a vacuum regime of cathode cavity at low gas pressure in the anode cylinder equal $4 \cdot 10^{-2}$ Pa;

– the steady existence of the plasma – layer system in the aperture of the accelerating electrode is possible only at $\xi \geq 0.54$;

– the expansion of the emission channel area in the cathode up to the sizes equal to cross section of the anode cylinder window, gives reduction of the extracted ion price from 10 up to 1–1.5 W/mA;

– the external factor of plasma decomposition in the aperture of the accelerating electrode is the quite certain difference of potentials between the ring cathode and the accelerating electrode, therefore to apply high accelerating voltage $U > U^*$ expediently only before formation of penetrating plasma, observing strict sequence of operations (at first to set the electrical field sagging to the emission channel then to initiate the discharge). The performance of conditions of obstructing plasma penetration to the aperture of the accelerating electrode allows to stably extract of ions through the wide aperture in the cathode, in absence of grid stabilization of the emitting plasma surface and to create wide aperture ion sources, without use of grids with small cells;

– at selection of ions from the discharge plasma the important value is got by optimization of the form and sizes of the accelerating electrode;

– the vacuum boundary conditions of initiation and stationary burning of the discharge with hollow cathode in structure with ring emitting cathode are determined and the opportunity of extraction of the charged particles (ions) in absence of pressure gradient of in accelerating gap is shown, the significant growth of the extracted ion current is received by expansion of the emitting plasma surface.

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