Investigation of Emission Increasing Effect at the Generation of Low-Energy Sub-Millisecond Electron Beam in the Diode with a Plasma Cathode[1]

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Abstract – The results of investigation of the effect of electron emission increasing in the diode based on a plasma cathode with a grid boundary stabilization of plasma are presented. As a result of investigations it was revealed, that with an increase of pressure at passage pulse (100 μs) electron beam with energy of 15–20 keV in the plasma formed as a result of gas ionization by an electron beam, the emission current increases at a constant discharge current of a plasma cathode and the emission current magnitude can exceed the discharge current in an absolute value.

1. Introduction

At present, the technological direction on the use of power pulsed electron beams for surface modification of metals, ceramic-metal materials and products actively develops [1]. Electron sources with a grid plasma cathode [2] have well-known advantages such as: long life time, high energy efficiency, high values of the uniform current density to > 10 A/cm^2 with a considerable emission surface (up to 100 cm^2), and an opportunity of the smooth and independent control of main parameters of the beam in a wide range, large current pulse duration of the beam at high frequencies (up to 1 kHz). In many cases, these benefits are preferable to implementation of technological process of pulsed thermal treatment of materials and products surface.

For performance improvement of the existing plasma cathode electron-beam sources, and for construction and manufacturing of the new one, investigations in the field of generation and transportation of beams in gas-filled gaps are necessary.

Traditionally, the efficiency of electron-beam sources with a plasma cathode [2, 3] is determined by the coefficient of electrons extraction from a discharge cell of the plasma cathode. The extraction coefficient α equaled to the relation of a beam current Ib to a discharge current Id for similar systems is $\alpha \leq 1$. In the presented work, the results of investigation of the effect of electron emission increasing in the diode based on a plasma cathode are given, at which $\alpha > 1$. The essence of the effect is that at increase of working pressure and at application of a longitudinal magnetic field, the current in an acceleration gap is considerably increased (in some cases in two and more times), exceeding in an absolute value a discharge current that generates plasma in electrode system of a grid plasma cathode.

2. Principles of the electron source operation

Figure 1 shows the diagram of the electron source. Plasma cathode consists of gas-discharge system with a two-step low-pressure arc discharge. Triggering discharge is ignited between hollow electrode *1* placed in the field of permanent magnets and cathode *2* when voltage pulse U_{trig} of 12–15 kV is applied. Triggering current amplitude is 10–15 A at pulse duration of 25 μs. The main arc discharge operates between cathode *2* and hollow anode *3*.

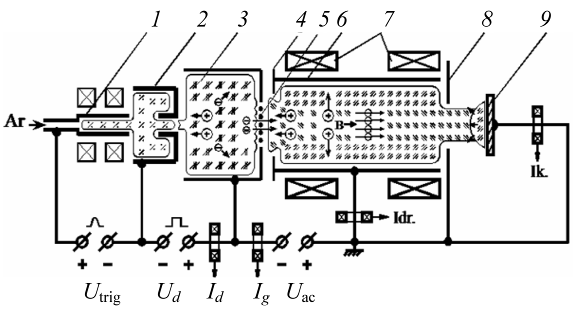


Fig. 1. Gas-filled diode diagram

Constant accelerating voltage is applied between planar emission electrode *3* and extractor *5* made as aperture of ∅82 mm. Extractor, drift tube *6*, aperture *8*, and collector *9* are grounded. Electron extraction under accelerating potential occur from the central part of the emission electrode, that has an aperture of ∅40 mm, covered with small-structured grid *4*. Cathode plasma boundary is stabilized by small-structured, while the boundary of anode plasma, generated by electron beam in the drift tube, remains movable. Beam electrons are transported to collector in the field of two Helmholtz magnetic coils *7*; the field magnitude is changed in a ranges of 0–30 mT. Current pulse duration of a beam of 50–200 μs is determined by the current pulse duration of the main discharge. Argon is used as a working-gas. Its pressure in the vacuum

[1] The work was supported by RFBR (Projects Nos. 08-02-12012-OFI, 08-08-99076-R-OFI, and 08-02-98063-R-OFI).

chamber is varied from 0.5 to $3.5 \cdot 10^{-2}$ Pa. As a gas inlet is realized into the electron source, the real pressure in the drift space of the electron beam is higher, and in the area of emission grid it exceeds the measured one in 4–5 times. Rogowski coils are used as current sensors, and accelerating voltage is measured by active potential divider.

3. Experiment

Figure 2, *a* shows the main discharge current and acceleration gap current oscillograms at working pressure of $2 \cdot 10^{-2}$ Pa. One can see, that discharge current amplitude is 100 A, but the mean accelerating gap current is ~ 80 A. When increasing the working pressure up to $4 \cdot 10^{-2}$ Pa (Fig. 2, *b*), accelerating gap current value increases up to ~ 200A and becomes 2 times higher in the absolute value than discharge current amplitude. In the circuit if drift tube ion current achieving 80 A become registered, and in the collector circuit due to the production of plasma electrons the current amplitude reaches 250 A. The rise of ion current to the drift tube and considerable increase of current to collector is explained by significant increase of plasma concentration in the electron beam drift space.

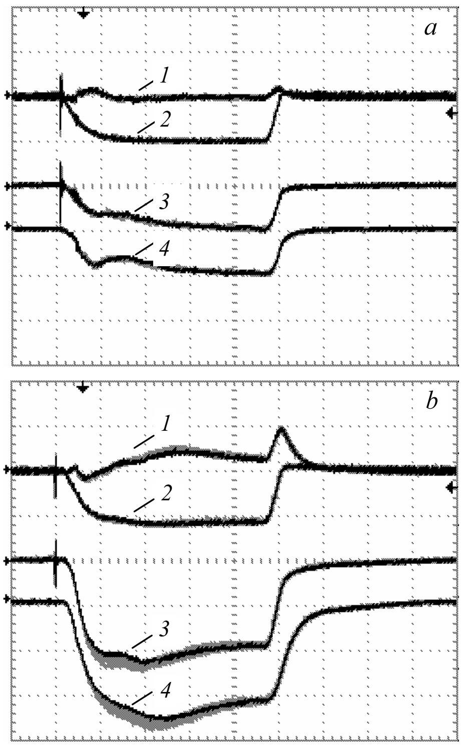


Fig. 2. Oscillograms of 10 imposed pulses of drift tube current I_t (*1*); discharge current I_d (*2*); current of accelerating gap I_g (*3*) and a current of collector $I_к$ (*4*); Pressure $P = 2 \cdot 10^{-2}$ Pa (*a*) and $4 \cdot 10^{-2}$ Pa (*b*); U_{ac} = 15 kV, magnetic field B = 30 mT. Scale: 100 A/div, 25 μs/div

If a current in the circuit of the acceleration gap is assumed to be transported by electrons extracted from the plasma cathode (vacuum case), the extraction coefficient equaled to the relation of a beam current I_b to a discharge current I_d, $\alpha \leq 100\%$, and acceleration gap current has not to exceed the current of main discharge of plasma cathode. Thereby, in the experiments “additional” current was registered. Its value was comparable and in some cases exceeded discharge current.

Calorimetric measurements of an integral energy of the beam at the collector showed that an increase of current in the acceleration gap is accompanied by proportional increase of energy, which proves the fact that current increasing is connected with the increase of amount of accelerated electrons.

The assumption was made that emission enhancement mechanism can be associated with secondary ion-electron emission from the emission electrode under the influence of ions, originated in the drift space and accelerated in the space-charge region between the boundary of beam plasma (anode plasma) and emission electrode up to the energy corresponding to applied accelerating voltage. For verification of given assumption the experiments were made which allowed to estimate qualitatively the contribution of secondary emission to the electron beam current. It should be mentioned, that emission electrode was a ∅82 mm planar plate with an ∅40 mm emission aperture in the center. The small-structured grid made of stainless steel with transparency of 50% covered the emission aperture. Thus, the area of planar metallic part of the emission electrode was 46.5 cm^2, and the grid meshes area was 6.3 cm^2 (the ratio is ~ 0.14).

Planar metallic part of the emission electrode was made of three materials with different secondary emission coefficients: copper, stainless steel, and aluminum.

The current in acceleration gap at the same specified values of the discharge current, working pressure, magnetic field and acceleration voltage was compared. The results of the experiments are presented in the Fig. 3.

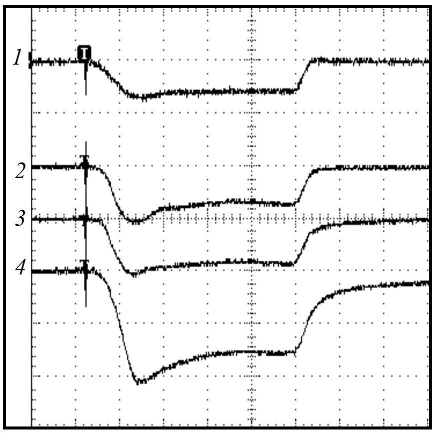


Fig. 3. Oscillograms of current pulses, discharge current I_d = 50 A (*1*), and current of accelerating gap I_g (*2–4*) for various materials of a flat part of emission electrode: (*2*) copper; (*3*) stainless steel; (*4*) aluminium. Pressure $P = 3 \cdot 10^{-2}$ Pa, U_{ac} = 15 kV, magnetic field B = 30 mT. Scale: 100 A/div, 25 μs/div

It is obvious that current amplitude in the acceleration gap has the lowest value for copper, increases for stainless steel and has a more rise for aluminum. These results are in a good accordance with literature [4].

In other experiment, the aperture diameter of the electrode *5* (Fig. 1) was decreased from 82 mm to 44 mm so that ions from plasma created in the drift tube were screened and did not get to the planar part of the emission electrode. The results are shown in the Fig. 4. It is evident that with the use of the aperture, a current in the acceleration gap is decreased by the value of ~ 40 A.

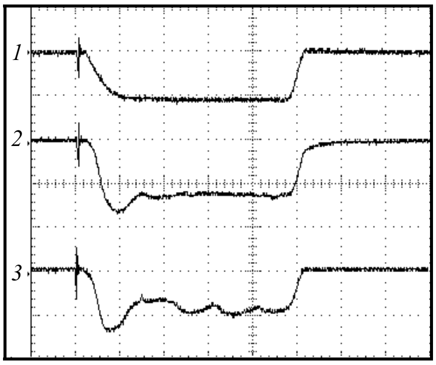


Fig. 4. Oscillograms of current pulses, discharge current I_d (*1*), and a current of accelerating gap I_g in experiment with the open emission electrode (*2*) and with a shielding diaphragm (*3*). Pressure $P = 3 \cdot 10^{-2}$ Pa, $U_{ac} = 15$ kV, magnetic field $B = 30$ mT. Scale: 100 A/div, 25 μs/div

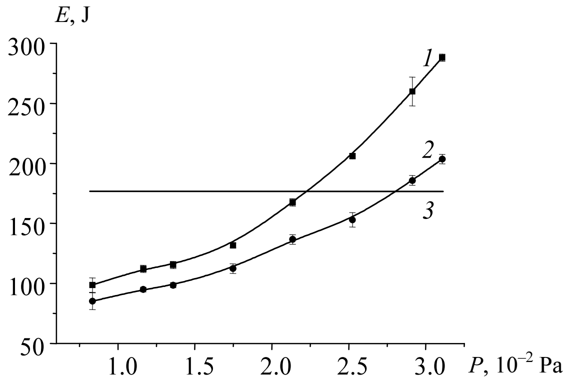
For quantitative estimation of an ion-electron emission contribution to the increase of current and, accordingly, of an electron beam energy, the calorimetric measurements of integral beam energy at the collector independence on gas pressure were made. The discharge current amplitude was fixed. Discharge current, acceleration gap current and voltage were recorded with a digital oscilloscope simultaneously with calorimetric measurements in each pulse.

In Figs. 5, *a* and *b* the dependences of measured and calculated from the oscillograms values of integral energy versus pressure (curves *1* and *2*) for two fixed values of discharge current (100 и 50 A) are presented. Line *3* shows the level of integral beam energy values on condition that 100% of electrons are extracted from the plasma cathode. One can see that energy is gradually increased with the increase of pressure and beginning from $P \sim 3 \cdot 10^{-2}$ Pa, the measured values of integral beam energy exceeds the calculated values under condition that 100% electrons are extracted from the plasma cathode.

Supposing the presence of ion-electron emission, the registered total current in the acceleration gap I_g can be represented as a sum of currents:

$$I_g = I_e + I_i + \gamma I_i, \quad (1)$$

where I_e is the current of electrons emitted from the plasma cathode; I_i is the back ion current from the drift tube space to the emission electrode; γ is the effective coefficient of ion-electron emission of an emission electrode material.



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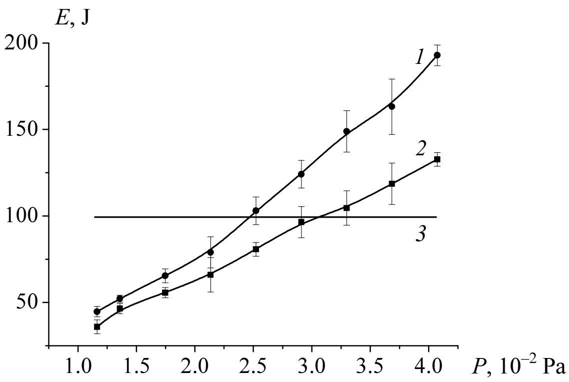

b

Fig. 5. The dependence of integral beam energy measured at the collector (*2*) and calculated from the oscillograms of total current in the circuit of the emission electrode (*1*), versus the pressure in the working chamber; (*3*) – level of integral energy under the condition of 100% extraction of electrons from plasma cathode. U_{ac}=15 kV, magnetic field B = 30 mT, I_d = 100 A (*a*); I_d = 50 A (*b*)

The current of electrons extracted from the plasma cathode can be suggested not to exceed the discharge current.

The energy, calculated from the current and voltage oscillograms in the acceleration gap is of the form

$$E_c = I_g U_{ac}\tau = [I_e + I_i + \gamma I_i]U_{ac}\tau, \quad (2)$$

where U_{ac} is the acceleration voltage; τ is the pulse duration of a beam.

The energy measured of integral calorimeter do not include the ion component

$$E_b = I_b U_{ac}\tau = [I_e + \gamma\, I_i]U_{ac}\tau. \quad (3)$$

An energy gained by plasma electrons we assume to be negligible.

Thus, from (2) and (3) the mean ion current in the acceleration gap during one pulse can be estimated:

$$I_i = (E_c - E_b)/U_{ac}\tau. \quad (4)$$

From Figs. 5, *a*, *b* it is seen, that with the increase of working pressure the disparity between measured and calculated energy (curves *1* and *2*) increase. It suggests the increase of ion current in acceleration gap with the increase of pressure.

For example, for the point corresponding the pressure $P = 3 \cdot 10^{-2}$ Pa (Fig. 5), the mean amplitude of ion current per pulse is $I_i = 42$ A. At the same time in the minimum pressures region one can find a point where the calculated and measured values are approximately the same (confidence intervals are intersected), that is ion current, roughly, can be assumed to be negligible and total current in the acceleration gap is determined by the current of electrons extracted from the plasma cathode. In the experiment condition this point corresponds the pressure $P \sim 0.8 \cdot 10^{-2}$ Pa. The electron current amplitude is equal to 55 A and coefficient of electrons extraction from plasma cathode can be estimated as 60%.

It is necessary to note, that, as the calorimeter measures integral energy, for all pulse, all values calculated by this method (current of electrons extracted from plasma cathode and ion current in an accelerating gap) are average for the pulse.

Knowing the current of electrons extracted from plasma cathode and back ion current it is possible to estimate the effective γ coefficient. For stainless steel bombarded by argon ions with energy 15 keV it has made 1.5–2.

Measurements of plasma parameters in drift space of beam shows that values of density of saturation ion current have made 0.17 A/cm^2 at a distance of 2 mm from the wall of drift tube, and 0.35 A/cm^2 at a distance of 10 mm. Values of plasma density $5 \cdot 10^{12}$ cm^{-3} and $9 \cdot 10^{12}$ cm^{-3} respectively at $T_e = 6.5$ eV. Measurements were carried out at pressure in the working chamber $3 \cdot 10^{-2}$ Pa. In view of difference of pressure, gas pressure in the area of probe measurements can be estimated as 0.1–0.15 Pa. From these results follows, that the plasma created by electron beam in space of drift has a high ionization degree (tens percent) and density of plasma increase in a direction from periphery to axis of beam.

Besides the intensive electron beam, getting on a collector, causes to desorption of gas from surface of collector, and in some cases causes also evaporation of the collector material, that also increases density of plasma during of pulse.

4. Conclusion

The experimental data and estimations allow offering the following mechanism for emission increasing effect explanation.

The intensive pulse electron beam generated in gas-filled diode and transported in the drift tube placed in axial magnetic field creates intensive plasma. The ions formed in space of drift and accelerated in a layer of a spatial charge between beam-created (anode) plasma boundary and emission electrode up to energy corresponding to accelerating voltage (15–20 keV) get on a metal surface of emission electrode and beat out secondary electrons which then also are accelerated.

Thus, the current of an electron beam consists of a current of electrons, emitted from the plasma cathode and secondary electrons current.

Plasma probe measurements and estimations have shown, that the density of plasma created by electron beam in a drift tube, allows providing the ion currents value resulted from experiment.

At the application of axial magnetic field to the drift tube plasma electrons movement to the tube wall is difficult. As a result of this between plasma and a tube wall the layer of positive anode potential drop is formed. This additional potential drop prevents the movement of ions to the tube wall and directs their most part to the emission electrode side. As a result of this redirection of ion flow take place increasing of ion current to emission electrode and, hence, secondary electron current from it.

References

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