Experience of forming combined low-energy electron-ion beams in plasma sources of charged particles

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Abstract. The paper shows the possibility of forming combined electron-ion beams in a single multi-discharge structure that does not contain incandescent elements. A design of the electrode structure of an electron-ion source is proposed, which consists of two «Penning type» discharge cells connected in series (along the axis). It is shown that the interconnection of separately controlled discharges in the structure increases the degree of gas ionization at reduced pressure, as well as the formation of double electric layers in the plasma, which ensure the formation of combined ion-electron flows in a single structure. This is ensured by creating conditions for the drift of the electron beam through the entire part of the electrode structure, which ensures the formation of the ion current of the source, and helps to increase the degree of ionization of the gas in this region. In addition, the deceleration of the electron beam in the ion acceleration gap ensures the return of electrons, which have lost part of their energy to gas ionization, into the region of the formation of the plasma emitting ions. This contributes to an increase in the density of the ion emission current. Some experimental parameters of the beams formed by the developed structure are presented.

1. Introduction
One of the mechanisms for increasing the efficiency of ion-plasma technologies is partial or full compensation of the positive ion charge in the stream or on the treated surface. For this purpose, as a rule, additional emitting systems are used that create compensating electron flows into the discharge space, the accelerating gap, or onto the surface to be treated. The most widespread in high-power technological magnetron systems are high-current solid-state incandescent emitters of electrons, which provide stable burning of the discharge or compensation of the space charge in the beam. Under conditions of intense ion fluxes, the resource of such emitters is limited due to intensive ion bombardment, and the glow emitters themselves are characterized by high energy consumption and low efficiency. Therefore, the search non-incandescent compensatory electron emitters remain relevant.

It is known to use hollow cathode discharge systems as compensating sources [1]. However, in these systems it is necessary to coordinate control systems for the parameters formed in the independent sources of ion and electron fluxes; it is necessary to take into account the mutual influence of the magnetic fields of these sources to ensure high efficiency of the process.

At the same time, low-energy electron beams can be used for thermal exposure of the substrate to intensify plasma-chemical processes and increase the speed of diffusion processes in the substrate during coating formation. Therefore, for a number of technologies, it may be of interest not only the

effect of partially or fully compensated ion beams, but also the alternating (thermophysical electronic and modifying ion) exposure to beams of charged particles of both charge signs.

To realize this effect, plasma sources of charged particles [1–4] that do not have incandescent elements are a promising tool. However, despite the fact that plasma is the emitter of charged particles in such systems, and when the polarity of the accelerating voltage is changed, beams of both signs can be formed, it is difficult to simultaneously achieve high emission efficiency in such systems, since the conditions for the emission of ions and electrons from plasma differ significantly.

It was shown [5–8] that since the conditions for the formation of ion beams in known magnetron-type systems are close, primarily in pressure, to the conditions for the formation of electron beams in systems with a plasma emitter, it is possible to create combined sources that ensure the formation of both electronic and ion beams [9].

In this paper, the possibility of the formation of combined electron-ion beams in a single multi-discharge structure that does not contain incandescent elements is shown. A design of the electrode structure of an electron-ion source is proposed, consisting of two «Penning-type» [10] gas-discharge cells connected in series (along the axis). It is shown that the interconnection of separately controlled discharges in the structure increases the degree of gas ionization at reduced pressure, as well as the formation of double electric layers in the plasma, which ensure the formation of combined ion-electron flows in a single structure. This is ensured by creating conditions for the drift of the electron beam through the entire part of the electrode structure, which ensures the formation of the ion current of the source, and helps to increase the degree of gas ionization in this region. In addition, the deceleration of the electron beam in the ion acceleration gap ensures the return of electrons, which have lost part of their energy to gas ionization, into the region of the formation of the plasma emitting ions. This contributes to an increase in the density of the ion emission current. The possibility of separate regulation of the accelerating voltages of electrons and ions in the developed structure provides regulation in a wide range of ratios of the energies of electrons and ions, as well as their current densities in the electron-ion beam. This broadens the range of possible technological applications of the electron-ion beam source. The results of the studies indicate the promise of using the developed structure for the design of technological sources of combined electron-ion beams.

2.   Experimental models of sources of charged particles

Designed layout of electron-ion source, the appearance and outline of the electrode structure of which is shown in Figure 1, is a generator emitting plasma formed in the volume limited by the inner surfaces of the cathodes 2 and 4, the anode 3 and the emitter electrode 5 (discharge chamber I). Electrodes 6 and 7 form an electron acceleration gap where a plasma surface is formed that emits electrons. Electrodes 8-12 form a gas-discharge structure forming plasma, which is a source of atomizing ions. This structure consists of two «Penning type» discharge cells (II and III) connected in series (along the axis). Elements of this structure 9 and 11 are the anodes of the discharge cells; elements 8, 10 and 12 - cathodes, which are simultaneously pole tips of permanent magnets, providing electron oscillation between the cathodes of this (second) gas-discharge structure.
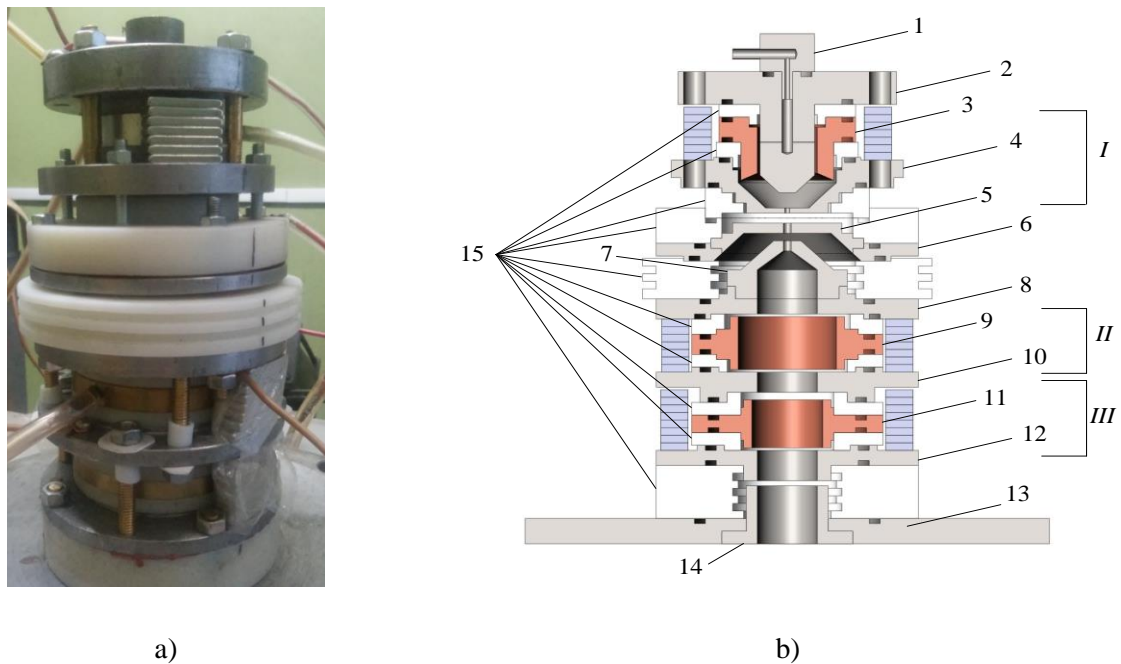
Fig. 1 - Appearance and internal structure of the developed layout electron-ion source with crossed E × H fields: (1) fitting for plasma gas inlet, (2) internal cathode, (3) the main anode, (4) external cathode, (5) emitter electrode, (6) auxiliary anode, (7) accelerating electrode, (8, 10, 12) cathodes, (9, 11) anodes, (13) flange for mounting the structure on the working chamber, (14) matching electrode, and (15) insulators; I, II, III – Areas of discharge chambers

At the same time, the magnetic field generated by the cathodes 8, 10 and 12 forms a magnetic focusing system for an accelerated electron beam propagating along the axis of this (second) gas-discharge structure until the ion-electron beam exits the source into the process chamber. A voltage is applied between the electrodes 12 and 14, accelerating the ions to the energy of the atomizing ions required by the technology. At the same time, in this gap (between the electrodes 12 and 14), the beam of electrons accelerated in the gap between the electrodes 6 and 7 is decelerated. The plasma surface emitting ions between the electrodes 12 and 14 determines the trajectories of both ions and electrons in the drift space of the electron-ion beam to the sputtering target, and hence determines the distribution of the ion and electron current densities over the target surface. Figure 2 shows a diagram of the connection of power supplies to the layout electrodes.
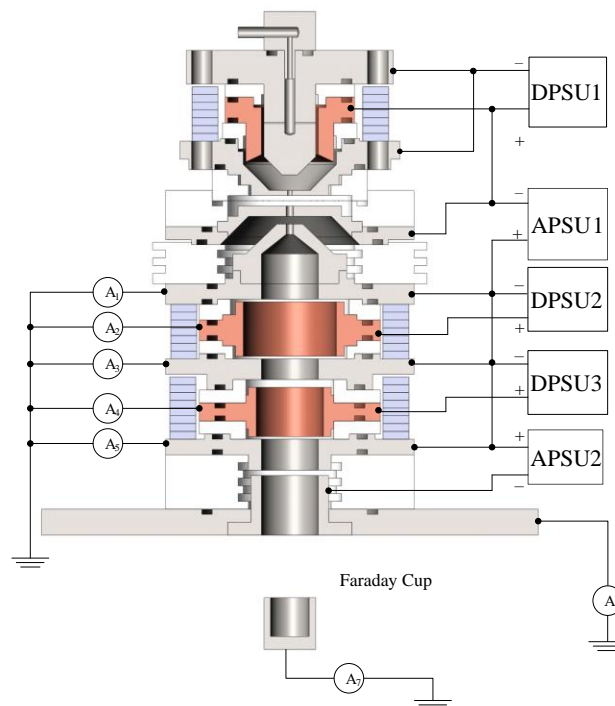
Fig. 2 - Diagram of the connection of the electrodes of the discharge chambers of the electron-ion source based on discharge in crossed E × H fields: DPSU1, DPSU2, DPSU3 – power supply unit of the corresponding discharge (I, II, or III camera) with discharge voltage U_d up to 1000 V and current I_d up to 1.2 A; APSU - accelerating power supply unit with voltage U_{ac} up to 5 kV and current up to 0.5 A; APSU 1, electron acceleration unit; APSU 2, ion acceleration unit

3. Results and Discussion

The initiation of a discharge in two discharge chambers (I and II - Fig. 1) in the electron extraction mode indicates the prospect of using similar structures as prototypes of high-plasma electron sources. The following mechanism of operation in this mode is assumed: the electron beam formed in the I chamber (Fig. 1), after acceleration, gets into the structure formed by the electrodes of the chamber II (Fig. 1), propagates along the axis in this structure and initiates a low-pressure discharge in which a plasma that emits ions is formed. Ions propagate into the upper structure, increasing the ionization of the gas in the region of electron extraction, increasing the density of the emission current and partially compensate for the space charge of the accelerating gap, which generally leads to an increase in the source perveance. This is evidenced by the current-voltage characteristics of extraction in the presence and absence of discharge initiation in the discharge chamber II (Fig. 1) of the source layout shown in Figure 3 and Figure 4. The presented characteristics indicate a weak influence on the perveance of the source of variation in the working range of the gas inlet (pressure in the discharge chamber) and the discharge current. From the presented characteristics it is seen that the determining effect on the source perveance is exerted by the presence of an additional discharge in chamber II (Fig. 1).
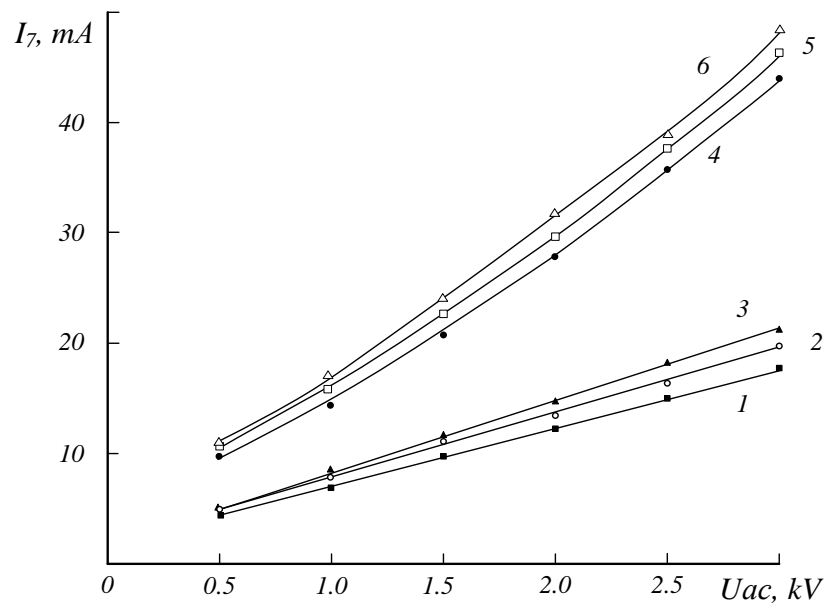
Fig. 3 - Current I_7 (into the Faraday cup) in the absence (1-3) and the presence of (2-4) initiation discharge in discharge chamber II: I_d in chamber I (Fig. 1) is 200 mA, the discharge voltage of the discharge is 420 V, I_d in chamber II (Fig. 1) is 180 mA, and the discharge voltage of the discharge is 410 V
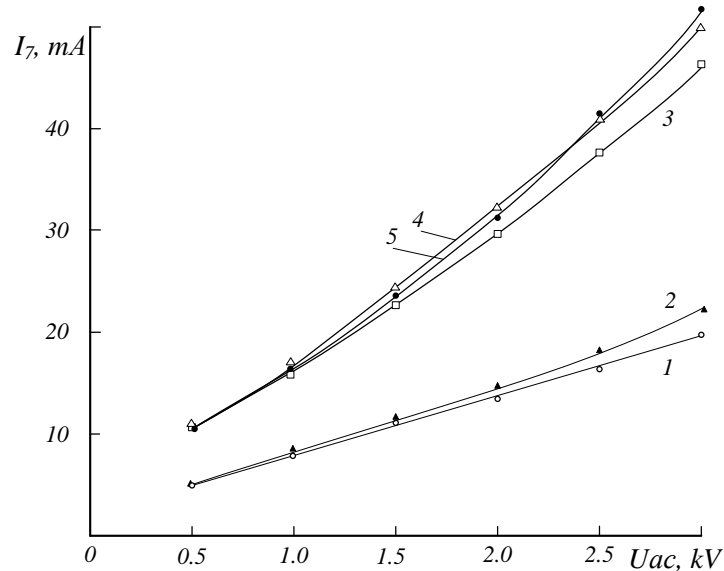Gas inlet Q: 1, 4 – 1,1 mPa·m³/s; 2, 5 – 2,2 mPa·m³/s; 3, 6 – 3,5 mPa·m³/s

Fig. 4 - Current I_7 (into the Faraday cylinder) in the absence (1-2) and the presence of (3-5) initiation discharge in discharge chamber II for different discharge current into the chambers I and II: 1-5 – gas inlet Q – 2,2 mPa·m³/s;
3, 4 – I_d in chamber II (fig. 1) 180 mA, the discharge voltage 410 V;
5 – I_d in chamber II (fig. 1) 210 mA, the discharge voltage 430 V;
I_d in chamber II (fig. 1): 1, 3, 5 – 200 mA, the discharge voltage 420 V;
2, 4 – I_d in chamber II (fig. 1) 240 mA, the discharge voltage 450 V

Figure 5 shows the current-voltage characteristics of extraction during the simultaneous formation of an electron and ion beam for two modes: a fixed voltage of a block accelerating ions of 1.5 kV (APSU 2, Fig. 2) and variation of the voltage of the electron acceleration block (APSU 1, Fig. 2) - Fig. 5 (curve 1) and the second mode of operation, when the electron acceleration voltage was recorded, and the ion acceleration voltage varied.
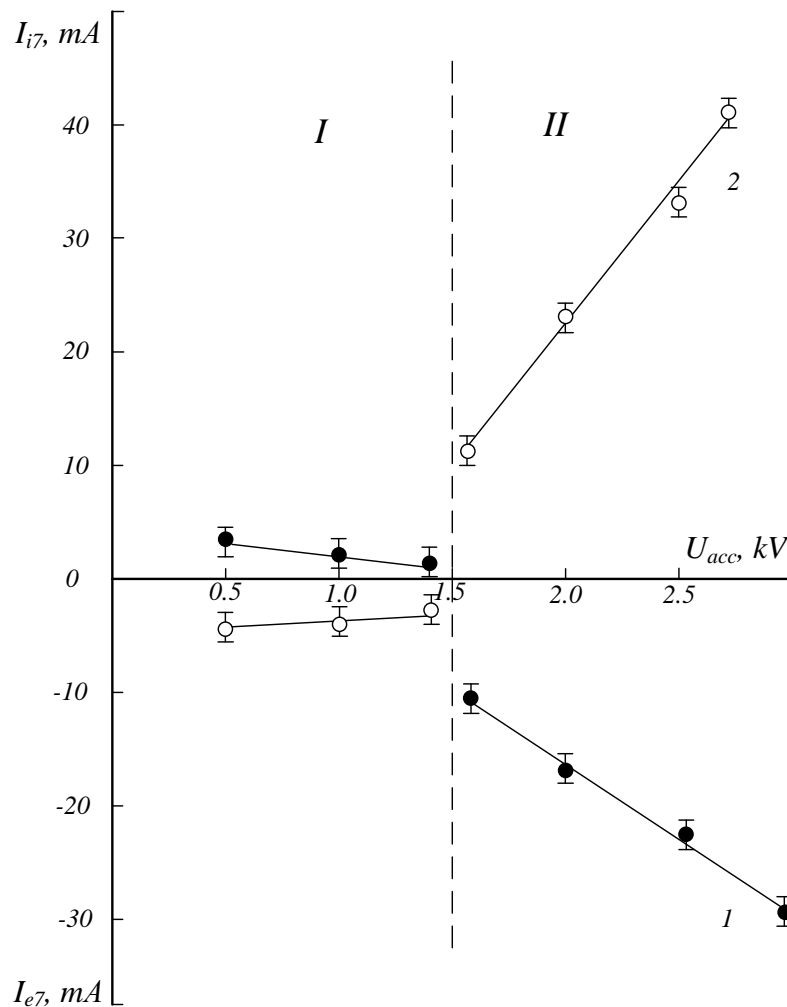

Fig. 5 - Current I_7 (into the Faraday cup). I_{e7} is the electron current in the Faraday cup. I_{i7} is the ionic current in the Faraday cup. (1) fixed ion acceleration voltage of 1.5 kV (APSU 2, Fig. 2). (2) fixed electron acceleration voltage of 1.5 kV (APSU 1, Fig. 3). The discharge current in chamber I (Fig. 1) is 200 mA, and the discharge voltage is 420 V. The discharge current in chamber II (Fig. 1) is 180 mA, and the discharge voltage is 410 V

In the case of a fixed ion acceleration voltage in section I (curve 1, Fig. 5), almost complete compensation of the electron beam is realized in the range from 0 to 1.5 kV and the current to the Faraday cup is close to zero. When the accelerating electrons voltage exceeds 1.5 kV (a fixed value of the ion acceleration voltage), the current to the Faraday cup rises, but it (region II on curve 1, Fig. 5) is lower than the emission current when the discharge is initiated in the discharge chambers I and II (Fig. 3, curve 2) and the supply of accelerating electrons to the voltage. When the electron acceleration voltage is fixed at 1.5 kV and the ion acceleration voltage is varied (region I, curve 2 in Fig. 5), the current into the Faraday cup undergoes a jump-like increase in the voltage region of 1.5 kV (Fig. 5,

curve 2), which indicates the mutual compensation of the electron and ion beams up to this value and emission from the ion source at voltages above 1.5 kV. The value of the emission current at a voltage of 3 kV is 45 mA, and the density of the emission current is about 10 mA/cm^2, which indicates the prospects of using this design to develop a technological electron-ion source for implementing various processing technologies and surface modification of materials.

In the region of graphs I (Fig. 5), there is some current uncertainty, which is apparently caused by the presence of double electric layers in the discharge structures II and III (Fig. 1). In the area of graphs II (Fig. 5), i.e. at accelerating voltages of more than 1.5 kV, the field of double electric layers already has a weak effect on the movement of charges in gas-discharge structures II and III (Fig. 1), and the currents of electrons I_{e7} and I_{i7} ions (Fig. 5) have more definite values. It should be noted that the experiments were carried out for various gas inlets - in the range (1,1-3,5) mPa·m^3/sec. and discharge currents (0.18-0.24) A, the characteristics were similar to those presented in the figure not given.

The above characteristics generally indicate the possibility of using such a model for the development of a technological source of charged particles for the implementation of technologies that require combined exposure to electron and ion beams, and also serve as a prototype of a multi-discharge source cell to form an effect on large areas.

4.   Conclusion

The presented designs of plasma sources of charged particles far from exhaust the entire spectrum of possible technological and structural solutions, but only show the potential capabilities of this type of sources for solving urgent problems of the formation of technological electron and ion beams. Such systems can form compensated ion beams, beams of neutral atoms or provide alternate or simultaneous exposure to beams of both types of charged particles, and, therefore, represent a unique universal tool for applying film coatings for various purposes [9, 11], which opens up new prospects for the implementation of more effective combined methods of exposure.

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