UDC 533.922

THE PLASMA SOURCE FOR THE FORMATION OF HIGH-ENERGY FOCUSED BEAMS OF CHARGED PARTICLES

EVGENY MALYUSCHENKO, DMITRY ANTONOVICH
Polotsk State University, Belarus

The results of the research on the formation of high-energy charged particle beams for the implementation of beam technologies on various materials are presented in the article.

Currently, there are quite a number of ways to process and modify the surfaces of materials in vacuum using streams of charged particles. Electron-beam, ionic, and combined methods of influence on the surfaces of materials have received the greatest development. This stimulates the development of sources of charged particles with a wide range of technological parameters that differ in power, current density, modes, and gas-dynamic working conditions. For solving specific technological problems, electronically focused beams of high brightness, electron beams of a large cross section of circular or other shape, ion beams can be used. The diversity of requirements imposed on technological beams cannot be realized in sources of the same type, although a number of fairly universal systems have been developed [1]. One of the rather promising tools for the implementation of such technologies are plasma sources of charged particles, operating at elevated pressures and having a high resource [1, 2].

In such systems, the formation of a beam of charged particles is carried out using plasma formations and presented in the fact that plasma is usually formed using a low-voltage anomalous glow discharge in an electronic structure with a small volume [3, 4]. The exit of plasma particles (electrons or ions) to the region of acceleration and beam formation, as well as the gas-dynamic coupling of the plasma formation and beam acceleration regions, is carried out through an orifice of small diameter (on the order of a millimeter). This provides a significant pressure drop between the areas of plasma formation (1 … 10 Pa) and beam acceleration and allows maintaining sufficiently low pressure in the areas of acceleration (10^{-2} … 10^{-1} Pa) and the technological use of a beam of charged particles (10^{-2} … 1 Pa). Under these conditions, the effect of gas separation and pressure increases in the technological area, accompanying the process of radiation exposure, on the parameters of the formed plasma and the beam of charged particles turns out to be insignificant. The pressure difference between the areas of formation of the discharge and the beam is determined by the geometrical dimensions of the emission channel, the rate of pumping of gas from the vacuum chamber and the inlet of the plasma-forming gas, which is carried out into the gas-discharge structure. The uniqueness of such structures lies in the possibility of the formation of both electron and ion, as well as combined beams of charged particles depending on the polarity of the accelerating voltage [5].

The geometric dimensions (diameter, length) of the orifice connecting the regions of plasma formation and electron acceleration are usually chosen so that the plasma penetrates into this orifice, called the emission channel. On the other hand, an accelerating field penetrates the emission channel. The depth of penetration of the plasma into the emission channel depends on its concentration and the potential difference between the plasma and the walls of the emission channel. The depth of penetration of the accelerating field into the channel depends on the intensity of the accelerating field at the entrance to the emission channel on the side of the accelerating field and on the diameter of the channel.

As a rule, the potential of the walls of the emission channel is lower than the potential of the plasma penetrating it. This leads to the possibility of the emergence in the emission channel of two different situations, which are common for the formation of a plasma surface (plasma boundary) in the channel separating the plasma and space charge regions in an electric field, to which the concept of plasma is not applicable. The difference in situations is due to the distribution of the electric field at the plasma boundary [4, 6]. Through plasma surface formed in the emission channel (plasma boundary) plasma particles due to thermal velocities go into the space charge region and the interval of their acceleration. In this, a certain analogy with the known emission-optical structures based on thermal emitters [7].

Therefore, it seems possible to consider a plasma surface forming in the emission channel (and in some cases outside it) as a plasma emitter of charged particles (electrons and ions) with physical properties and characteristics inherent only in it. However, despite the presence of specific properties of the plasma emitter, the method for analyzing the construction of electron-optical systems based on it turns out to be in many ways similar to that used for electron-optical systems with thermal cathodes [8].

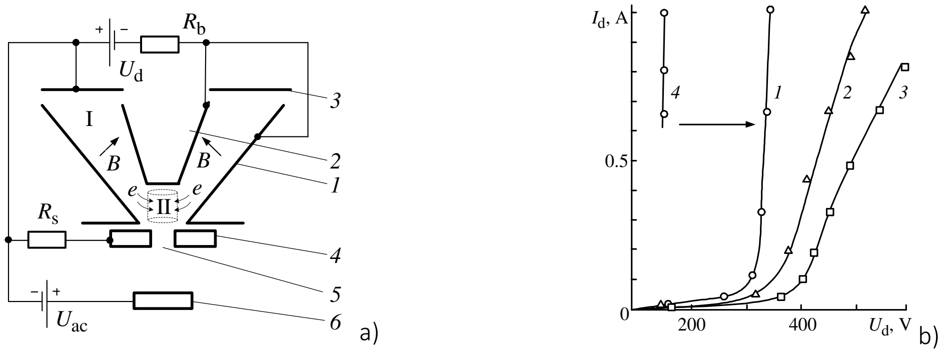
The source for the formation of high-energy focused beams of charged particles. To produce beams with current density and brightness required for technological applications, plasma must be formed in the discharge, providing a high emission current density (~100 A/cm^2) [9], which is possible either due to a high electron concentration of about 10^{18} m^{-3} in the region emission channel, or due to processes in the discharge, ensuring the effective switching of electrons from the entire plasma volume into the emission channel [4, 10]. When forming focused electron beams, it is impractical to provide high plasma concentrations in the entire volume of the discharge chamber, since the efficiency of the source of charged particles decreases and the thermal loads on the electrodes increase. In this case, it is preferable to use discharges with a high degree of inhomogeneity of the plasma concentration distribution in the discharge with a maximum concentration on the axis of the emission channel. The most common are gas-discharge structures with a hollow cathode [11].

Another variant of the plasma generator is gas-discharge structures in which switching of the electron current from the entire plasma volume into the emission channel takes place — with a different hollow cathode shape and using E×H crossed fields [1], which have several advantages compared to hollow cathode structures.

In Figure 1a, an electrode structure and a current–voltage characteristic (CVC) of a modified gas-discharge structure with crossed E×H fields. The discharge is excited in the space between cathodes 1 and 2 (region I, Figure 1, a), where, as in the reflective discharge with a hollow cathode, the main ionization processes are realized. Plasma-forming gas is fed into the space between the cathodes, and the pressure drop is provided by the geometry of the emission channel. The plasma formed in the discharge between the cathodes diffuses into the region of the emission channel. This contributes to the additional electrode 4 (anode), which acts as an emitter electrode. The presence of a magnetic field in almost the entire volume of the discharge structure contributes to the effective ionization of the gas.

In such an electrode structure, the stage of discharge initiation is excluded, which is reflected in the shape of the CVC (Figure 1, b). In the region of the emission channel (region II, Figure 1, a), the magnetic field has the direction of the induction in the longitudinal axis of the channel and does not prevent the emission of electrons. Electrons are extracted through the emission channel in the emitter electrode with an anode (or close to it) potential. Diffusion of electrons to region II from region I of plasma generation (region I) occurs in a magnetic field with a significant transverse component of the induction vector, which to some extent restricts the movement of electrons to the emission channel region and makes it difficult to implement unwanted full switching of the electron current from the plasma to the emission channel.

When a discharge is excited, the emitter electrode plays the role of an auxiliary anode, and the value of its potential is not so critical for the formation of a gas-discharge plasma as the potential of the emitter electrode in a discharge with a hollow cathode. Therefore, to increase the resource, extraction efficiency and stability of the emission current in a plasma emitter of this type, the potential of the emitter electrode can vary in the range from anode to almost cathode, which is regulated by the choice of bias resistance (Figure 1, a), or have a floating potential. The emitter electrode can be manufactured single-piece or sectioned with different potentials of parts [12]. The possibility of a significant reduction in the potential drop in the near-wall layer at the emitter electrode in such a plasma generator allows a significant increase in the emission channel resource.

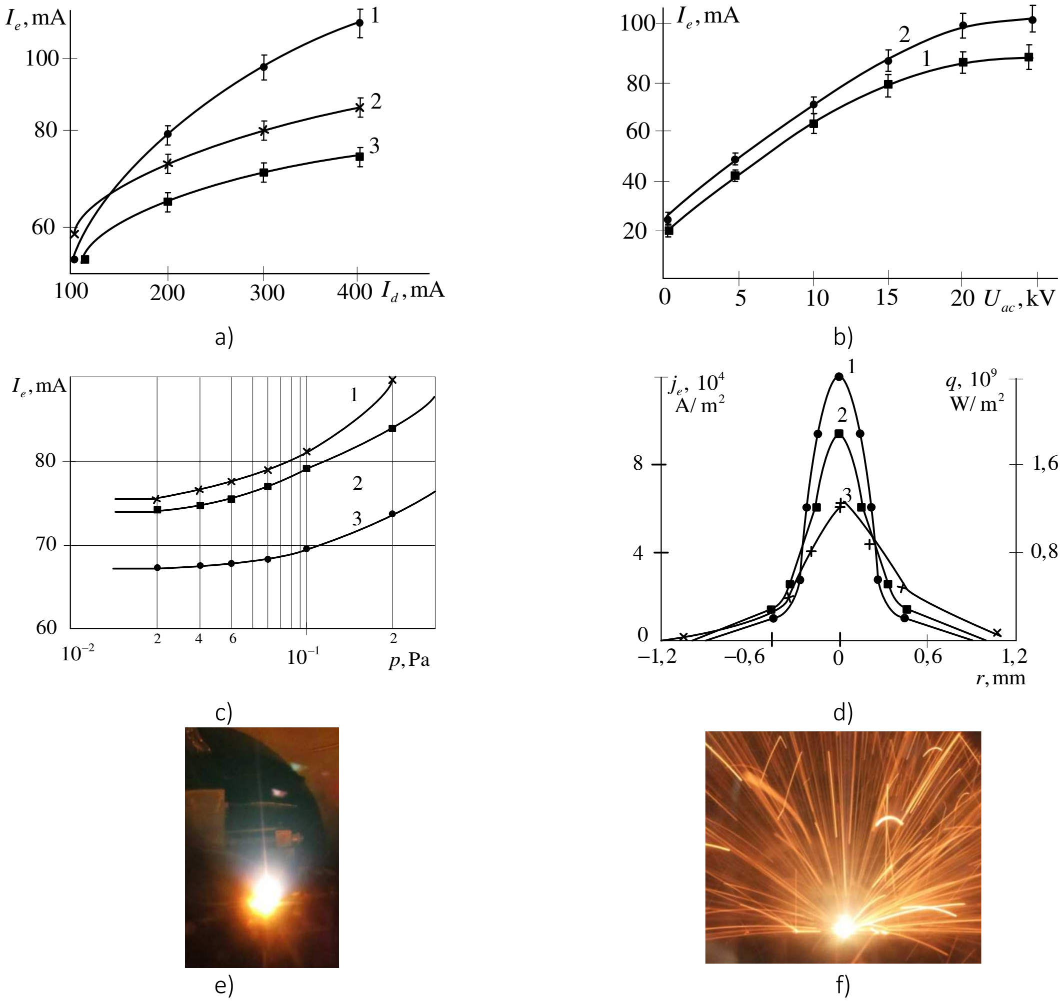


a - electrode system [1] (1 - external cathode; 2 - internal cathode;
3 - anode; 4 - emitter electrode; 5 - emission channel; 6 – accelerating (removing) electrode; U_d is the discharge burning voltage; U_{ac} – accelerating voltage;
R_s is the bias resistance; R_b - ballast resistance; B - magnetic field induction);
b - current-voltage characteristics (CVC) (gas (air)): 1 - 2.8 mPa·m^3/s (100 atm·cm^3/h);
2, 4 - 1.7 MPa·m^3/s (60 atm·cm^3/h); 3 - 1.25 mPa·m^3/s (45 atm·cm^3/h)
Figure 1. – The discharge in the modified structure with crossed E × H-fields

In the range of operating values of the discharge currents, the form of the current – voltage characteristics (Figure 1, b) is close to the form of the corresponding characteristics for a discharge with a hollow cathode. This allows the use of the same type of power source of the plasma generators considered.

In [13] there is a detailed description of the source of high-perverse beams of charged particles developed taking into account the principles presented. In a plasma emitter of this type, the following methods are possible to control the extraction efficiency and stability of the emission current, which are not realizable in plasma electron sources based on a hollow cathode. The first method is to create conditions for the redistribution of currents between the emitter electrode and the emission channel by changing the parameters of the space charge layer near the emitter electrode. This can be provided both by automatic displacement of the potential of the emitter electrode by the bias resistance in the circuit of the corresponding electrode, and through the use of inserts into the emitter electrode in the region of the emission channel under the floating potential [4, 12]. The second method is implemented by creating electric fields in the emitting plasma, which ensure the formation of electron fluxes to the emission channel region. The intensity of such flows is determined by the configuration of the magnetic and electric fields (the displacement of the potential of the anode relative to the emitter electrode) in the gas-discharge structure and the gas pressure (the amount of gas inlet into the discharge chamber) [2, 4].

In Figure 2 the typical characteristics of this source is shown. The main advantage of this source is the weak dependence of the emission current on pressure up to 0.3 Pa (Figure 2, c). This feature is realized both due to the configuration of the discharge chamber electrodes and due to the additional autostabilization of the electron beam parameters by including resistance R in the emitter electrode circuit relative to the anode. In Figure. 2, d, the distributions of the current density and the electron beam power density over the cross section are presented. The maximum value of the power density $q_{max} \approx 10^9$ W/m^2 and the effective diameter of the electron beam (which is determined at a level of 0.1 q_{max}) corresponds to typical values of the power density of the electron beams used for electron beam welding [2, 4]. This, as well as the type of gas characteristics, indicate the possibility of using this source for welding, including materials with increased gas separation in the heat treatment process.



a)

b)

c)

d)

e)

f)

a - emission characteristic: accelerating voltage 18 kV;
gas inlet 1.5 mPa·m^3/s; pressure, Pa: 1, 2 - 0.04; 3 - 0.1; R_{bi}, kΩ: 1 - 0; 2, 3 - 1;
b - current-voltage characteristic: gas inlet 1.5 mPa·m^3/s; discharge current 0.2 A;
gas pressure, Pa: 1 - 0.04; 2 - 0.1; c - gas characteristic: accelerating voltage of 16 kV; gas inlet 1.5 mPa·m^3/s; R_{bi}, kΩ: 1 - 0; 2 - 0.5; 3 - 1; d - current density and power density distribution over the beam section:
accelerating voltage 18 kV; gas inlet 1.5 mPa·m^3/s; discharge current 0.2 A;
emission current 0.08 A; R_{bi}, kΩ: 1 - 1; 2 - 0.5; 3 - 0

Figure 2. – The main characteristics of the plasma electron source (a, b, c, d) and the photo beam in the process of welding various materials (e, f):

The results obtained correspond to the typical characteristics of plasma sources of charged particles and show how these can be used to develop new technologies for radiation exposure of materials and the implementation of existing ones.

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