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VELOCITY OF IONS OF A PLASMA JET FROM AN ARC SOURCE AT VARIOUS POTENTIALS ON THE PLASMA BOUNDARY

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The effect of the potential of a conical electrode near the anode of an ion source on the speed of ions of the plasma jet ejected from the anode orifice is studied. An original method for measuring the velocity is used. Qualitative differences in the effect of the electrode on ions in the anode region and on the periphery of the plasma flow are discussed.

It has been established [1, 2] that gas-discharge sources of ions produce a directional plasma jet. This is due to the presence of an ambipolar electric field, which accelerates the ions when the plasma flow is expanded. The high directivity of plasma jets from a pulse arc source [3, 4] (kinetic energy of ions 30–50 eV and cross-section temperature 30–70 meV) make it a promising device for research and technological applications [5]. In this connection, the question arises of what mechanism is involved in the acceleration of ions and whether it is possible to control the energy of the ions.

The main condition for existence of a plasma flow is its neutrality. The decrease in charge density of the plasma ions ρ_i during plasma divergence is given by the relation $\rho_i \sim \sqrt{qU}/s$, where q is the ion charge, U is the potential difference accelerating the ions, and s is the cross-sectional area of the flow. The ambipolar mechanism of ion acceleration assumes a Boltzmann distribution of the electron $\rho_e \sim \exp(eU/kT_e)$, where ρ_e does not depend on s and, for different dependences of ρ_i and ρ_e on the potential, neutrality of the plasma is ensured by its divergence. In order that the electrons have the Boltzmann distribution, they should occupy an energetically accessible phase volume instead of performing directional motion like the ions. The first is possible if, during divergence of the plasma flow, the electrons are reflected at the walls, which are at negative potential relative to the plasma. This condition is satisfied in the ion sources described in [1, 2] but not in the source used in [3], where plasma divergence proceeds inside a conical orifice in the anode, which is at positive potential relative to the plasma. It is assumed that the plasma jet has a distinct boundary and is not in contact with the anode. In the case of one-dimensional motion [6], the originally distinct transverse boundary of the diverging plasma acquires an exponential density profile with an exponent $-1/c_s t$ or $-1/(\sqrt{eT_e/2qU}z)$, where c_s is the velocity of ion sound and t and z are the time and longitudinal coordinate. When T_e is close to 5 eV and the ion energy is 10–20 eV, the angle of divergence of the ions is $2c_s t/z \simeq 0.8$ rad, i.e., it is of the same order as the cone angle of an anode orifice having height 7 mm, entrance radius 3 mm, and exit radius 11 mm. The transverse decrease in the ambipolar field potential turns out to be less than the longitudinal decrease and cannot obviously explain the containment of fast electrons in the plasma jet. The absence of a clear explanation for ion acceleration has forced us to study experimentally the effect of the electrode potentials around the plasma jet on the ion velocity. Results of these experiments are given in the present paper.

The experimental setup (Fig. 1) consists of two parts: the first includes ion source 1 supplemented by conical electrode 2, and an expander bounded by metallic shield 3, and the second incorporates a device for separating ions by longitudinal velocity, which contains an ion extractor 4 in the form of a grid diode, slit

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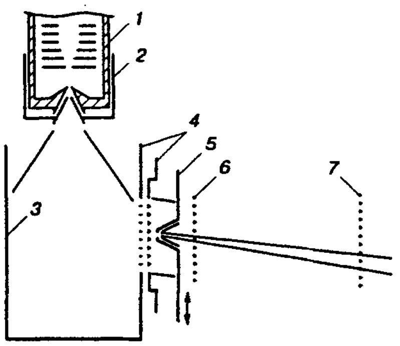

Fig. 1

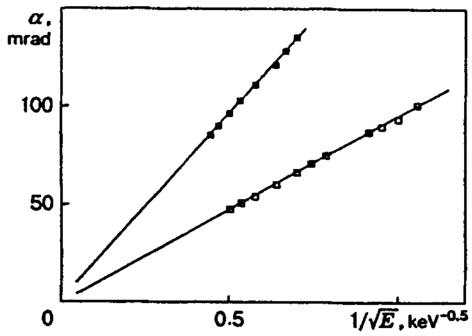

Fig. 2

Fig. 1. Diagram of the experimental setup: 1) ion source; 2) electrode; 3) shield; 4) ion extractor; 5) slit collimator; 6 and 7) wire profilometers.

Fig. 2. Angular displacement α of the center of the collimated beam versus the energy E for two different plasma jet regimes (different points).

collimator 5, provided with deflection plates, and two wire profilometers 6 and 7. The electrode is similar in shape to the orifice in the anode of the source, is separated from it by 2.5 mm, and is at controlled potential. This makes it possible to model conditions in the anode orifice. The shield together with the first grid of the diode is also at controlled potential relative to the anode of the source and isolates the plasma jet from the external electric field. The ion separator is a refinement of the setup used in [4]. The device operates as follows. The planar grid diode imparts transverse acceleration to the ions, maintaining their longitudinal speed, and produces an ion beam which moves at this velocity in the direction of acceleration. Unlike in [4], this shift of the beam of previously collimated ions can be both compensated by the electric field of the deflecting plates and directly recorded by the profilometers. The presence of two profilometers allows one to combine accurate measurements with the possibility of moving the collimator unit. The velocity measurement accuracy is confirmed by the dependences of the angular displacement of the center of the collimated beam on the energy E imparted to the ions in the diode in Fig. 2. The filled points refer to a plasma jet regime with higher ion velocity and open points refer to a regime with lower velocity. The data are approximated by straight lines. The angle of displacement of the beam α is proportional to $1/\sqrt{E}$ with an accuracy of 1%, indicating that accuracy of the measurements of the longitudinal velocity of the ions.

The effect of the potentials of the conical electrode U_2 and the shield U_3 on the kinetic energy E_k of the plasma-jet ions was studied. Figure 3 shows curves of $E_k(U_2)$ at $U_3 = -110$ V (curves 1 and 2) and a curve of $E_k(U_3)$ at $U_2 = 8$ V (curve 3). Curves 1 and 2 are similar, in spite of the fact that they are obtained for ion-current densities differing by an order of magnitude. In both cases, E_k considerably increases as the potential decreases U_2 from -5 V. This is explained by poorer selection of fast electrons by the electrode and leaning of the ionic components of the plasma. At $U_2 > -5$ V, the plasma jet is isolated from the electrode. An increase in the current I_2 from 1 to 50 A (curve 1), which accompanies the change in the potential U_2 from -5 to $+20$ V, does not markedly change the ion energy. The effect of isolation of the plasma jet is observed only in the anode region. At $U_2 = 8$ V, an increase in the shield potential U_3 leads to a decrease in the ion velocity to almost zero (curve 3). One can determine how the effect of the electrode changes with distance from the anode orifice by comparing the kinetic energy of the ions $E_k = 30$ eV [4], 17, and 5 eV in the absence of a cone at $U_2 = 0$, $U_3 < 0$, and $U_3 = 0$, respectively. When the charge is transferred from the anode to the cone, the energy E_k returns to the value of 30 eV.

An important characteristic of the spectrum of longitudinal velocities of the ions is its width. Figure 4 gives values of the spectrum width Δv at a level 0.5 of the maximum determined in the same measurements as data E_k (curve 1 in Fig. 3). These values are small enough to suggest that the ions were delivered into the plasma jet from one place — the anode orifice of the source — and the variation in the kinetic energy of the

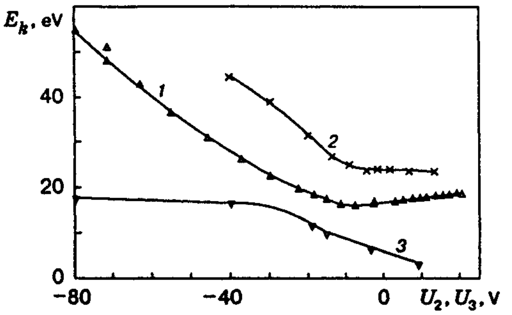

Fig. 3

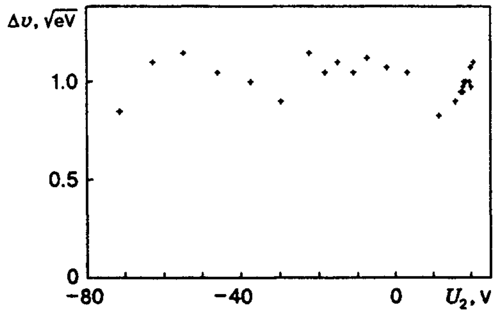

Fig. 4

Fig. 3. Effect of electrode potentials on the kinetic energy E_k of ions: curves 1 (arc-discharge current 82 A and ion current from the anode orifice about 400 mA) and 2 (24 A and 50 mA, respectively) are curves of E_k versus U_2 and curve 3 is a curve of E_k versus U_3 (discharge current 82 A).

Fig. 4. Width of the spectrum of ion velocities Δv versus the potential U_2 at $U_3 = -110$ V (discharge current 82 A).

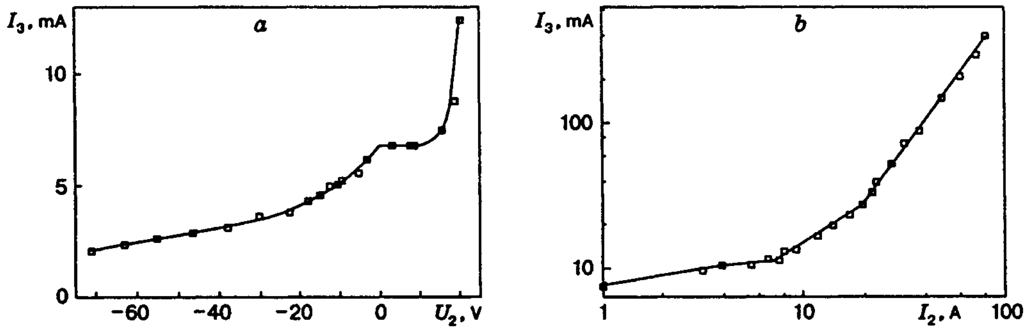

Fig. 5. Ion current versus the potential U_2 (a) and the current I_2 (b).

ions was caused by variation in the plasma jet potential. If the spectrum width Δv were determined by the initial energy spread of the ions, it would monotonically $\sim E_k^{-0.5}$ depend on their energy. This was observed only for $E_k < 7$ eV, for which the value of Δv varied from 1 to 1.8 $\mathrm{eV}^{0.5}$. In the plasma jet from a source with an additional conical electrode, the spread of ion velocities $\Delta v = 1$ $\mathrm{eV}^{0.5}$ is half that [4] for a source without an electrode. The value of Δv increases by a factor of two when the current I_2 becomes higher than the discharge current to the anode of the source.

For the particles flying out of the source, a solid angle of about 1.3π is covered by the shield. Therefore, at a negative potential U_3, the current I_3 is close to the total ion current in the plasma jet. Figure 5a shows a curve of I_3 versus U_2 at $U_3 = -110$ V and an anode current of 82 A. The bending of the curve of $I_3(U_2)$ corresponds to the transition from potentials attracting ions to repulsing potentials at $U_2 = 0$ and indicates that the ions formed near the anode potential. In the range of U_2 from 0 to 15 V, we observe saturation of the ion current and then fast growth, which indicates transfer of discharge to the electrode. The current I_2 in this case varies from 3 to 6 A. Figure 5b shows the curve of the current I_3 versus the current I_2, where the sum of the anode and electrode currents was maintained at about 85 A, and the contribution of the current I_2 varied from 1 to 99%. Attention is drawn to the anomalously low ion current at small values of I_2. At I_2 close to the total discharge current, the ion current I_3 is typical of the present source. With decrease in I_2, the ion current decreases by a power law with an exponent of about 1.8. This dependence is stronger than the dependence of the ion current on the anode current without an electrode [4], in spite of the fact that the anode current increases in this case. At $I_2 < 10$ A and $I_2 = 80$ A, the ion current I_3 differs by a factor of 40, and this cannot be explained by partial covering of the anode orifice by the electrode. The absence of electrodes having negative potentials and capable of taking ions suggests that a virtual anode forms before the electrode and the ions are reflected in the longitudinal direction.

The capability of the plasma jet for isolation with respect to the positively charged electrode near the anode is accompanied by its abnormal behavior in a magnetic field [7]. The focusing action of a longitudinal magnetic field on the ion flow is significant at distances from the anode exceeding 1 cm and suddenly decays near the anode. This can be explained by the action of an ambipolar electric field if one finds a mechanism whereby a barrier for both ions and electrons is produced on the electrode which confines the plasma flow radially. A barrier for the low-energy fraction of electrons can produce a space charge of the electron flow sliding along the surface of the conical electrode. A detailed description of the surface barrier mechanism requires invoking additional data.

The original nondisturbing technique for measuring ion velocity and the model experiments performed revealed distinguishing features of the formation of a plasma jet in the anode orifice of an arc ion source. The data obtained can be useful in both understanding of the physical processes occurring in gas-discharge devices and in applications of fine plasma technologies.

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