INFLUENCE OF A WEAK MAGNETIC FIELD ON THE INTENSITY OF THE PLASMA JET OF AN ARC PROTON SOURCE

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UDC 621.384.6

An arc source of a plasma jet, used as an element of a system of plasma diagnostics or as the injection system for a proton accelerator, experiences the influence of the stray magnetic fields of these systems. As was shown in [1], the influence of a longitudinal magnetic field with an induction $10 < B < 70$ G on the arc source of [2] leads to an increase in the density of the plasma jet generated by it and of the current extracted from the fixed plasma boundary in proportion to B. A similar result was obtained in [3] in the range of strong magnetic fields $300 < B < 800$ G. The influence of longitudinal magnetic fields with $B < 13$ G on these parameters is analyzed in the present paper in connection with problems of stabilization and control of the current of a source. The experiments of [1-3] differ in the scale of the magnetic fields applied and, evidently, in the character of their action on the process. In [3] the plasma electrons are magnetized, i.e., the condition $\rho/r \ll 1$ is satisfied (ρ is the Larmor radius and r is the radius of the anode opening of the arc chamber), so that electrons are concentrated in the region of the anode opening, thereby increasing the plasma density. In [1], where $\rho/r \gtrsim 1$, and especially in the present work, where $\rho/r \gg 1$, such a mechanism is of secondary importance and does not mask the appearance of other effects increasing the plasma flux density in the jet.

The measurements were made on the installation shown in Fig. 1. The system is placed inside a composite magnetic shield 12 with an inside diameter of 100 mm, a wall thickness of 10 mm, and a length of 420 mm and is evacuated by two Nord-100 pumps to a pressure of $2 \cdot 10^{-4}$ Pa. The arc source 1 ejects a hydrogen plasma 4 through the anode opening 2 onto a grid diode 5, 6, forming the initial proton beam. The anode of the source is made of D16 alloy, the diameter of the anode opening is 2 mm, and that of the grid aperture is 40 mm. The proton beam that forms enters a transport tube 7 with a diameter of 42 mm and a length of 125 mm, in which its space charge is compensated for by electrons. At the exit from the pipe, the characteristics of the beam are measured with a multiwire, two-coordinate profilometer 8, 9, supplemented by antidynatron rings 10 [4], as well as with a miniature, movable Faraday cylinder 11. The current in the beam is additionally measured from the currents I_h and I_g flowing in the circuits of the high-voltage supply of the diode and of its anode grid 6. The arc discharge is produced by pulses with a length of up to 100 μsec and a frequency of 0.2 Hz. A constant voltage of up to 15 kV is maintained on the diode. The distributions of the axial component of the constant magnetic field, produced by an internal coil 15 fastened to the chamber of the arc discharge and an external coil 13, 14, measured at the maximum currents in their windings, are designated as B_0, B_1, and B_2, where B_1 and B_2 correspond to two variants of the construction of the magnetic shield. A grid diode in two configurations – the Pierce configuration, analogous to that of [5], and a plane configuration – is used to form the beam. The filaments of the cathode and anode grids of the diode are oriented parallel to each other and made of tungsten wire 50 μm in diameter. The distances between the grid planes are 14.2 and 21 mm and the spacings of the windings in the plane and Pierce diodes are 226 and 625 μm, respectively.

Influence of a Weak Magnetic Field on the Beam Current and Profile

In this experiment the distribution of the magnetic field produced by the external coil corresponded to variant B_1. The peak value B_p of the distribution of the field B_0 of the internal coil was varied from −6.4 to 6.4 G. The placement of the elements of the system in these fields is indicated in Fig. 1; the distance between the anode opening and the cathode grid was $l = 76$ mm; the plane diode was used. In Fig. 2 we give the results of measurements of the current in the beam in different variants of connection of the external and internal coils. The current in the beam in the absence of a magnetic field is $I_{00} = 44$ mA, while after the outer coil was turned on it increased to $I_{0+} = 65$ mA. After the internal coil was turned on, producing a field in the same direction as the

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 9-15, May-June, 1987. Original article submitted July 28, 1986.

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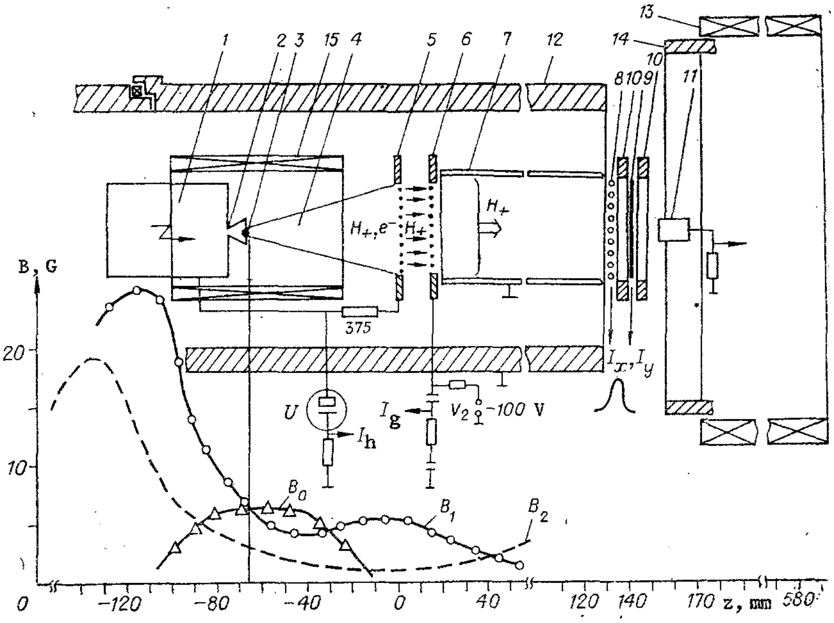

Fig. 1

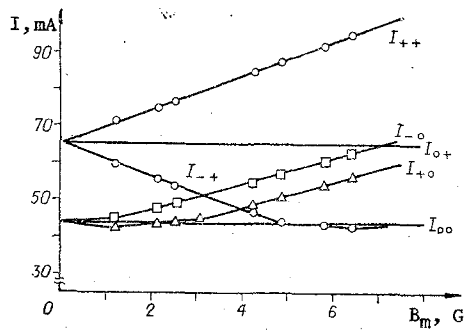

Fig. 2

external coil, a further increase in the current in the beam was observed, proportional to B_p and reflected in the straight line I_{++}. When the fields are subtracted, an increase in B_p leads to a decrease in the current in the beam, which is reflected in the curve I_{-+}. The curves I_{-0} and I_{+0} correspond to the variants when the external coil is turned off while the current in the winding of the internal coil is varied from zero to the maximum value in both directions. The minimum current I_m = 43 mA is observed for B_p = 1.2 G on the curve I_{+0} and means that in this case the total field, with allowance for the residual magnetization of the shield, influencing the plasma jet equals zero. A similar minimum of the current is observed on the curve I_{-+} for B_p = (6.5 ∓ 0.2) G, when mutual compensation of the magnetic fields of the two coils occurs in the vicinity of point 3 (see Fig. 1), at a distance of l_0 = 10 mm from the anode opening.

The magnetic field induction acting on the plasma jet when only the internal coil is turned on is $B_t = B_p -$ 1.2 G. The increments in proton current in the beam, $i(B_t) = I(B_p) - I_m$, caused by this action are obtained from the functions $I_{-0}(B_p)$ and $I_{+0}(B_p)$ and are represented by curves 1 and 1' in Fig. 3. The characteristic curve obtained contains two regions: a relatively slow nonlinear increase in i with an increase in $|B_t|$ from 0 to 2 G and a linear increase in i, proportional to $|B_t| - B_x$, where B_x = (1.6 ∓ 0.1) G, with a further increase in $|B_t|$ at the rate v = 3.8 mA/G. With an increase in I_0 (the beam current formed in the absence of a magnetic field), the value of i increases as $\sim I_0^{1/2}$ in the range of $40 < I_0 < 110$ mA, so that

$$i = K(|B_t| - B_x) I_0^{1/2}. \tag{1}$$

Here $K = v/I_m^{1/2}$ = (0.58 ∓ 0.01) $mA^{1/2}/G$.

In Fig. 3 we also give the results of measurements of the flux profile with the multiwire sensor in the presence of a magnetic field with B_t = 5.5 G (points 1) and in its absence (points 2), where N are the numbers of the sensor wires, mounted with a spacing of 3 mm, while i_0 are the currents to these wires, in relative units,

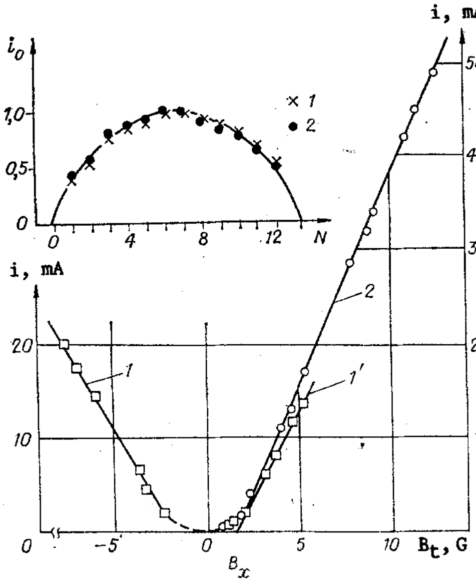

Fig. 3

produced by the beam. We used the plane diode, in which the shape of the beam profile practically repeats the shape of the density distribution of the plasma jet at the cathode grid of the diode [1]. The current of the arc discharge was fixed, while the currents in the beam and the forming voltage on the diode were matched by a "3/2" law and equalled 55 mA and 10.6 kV for $B_t = 0$ G and 87 mA and 14 kV for $B_t = 5.5$ G. As can be seen from Fig. 3, magnetic enhancement of the current does not alter the shape of the density distribution in that part of the plasma jet falling in the diode aperture. This is also confirmed by the fact that when the distance of the plasma source from the diode is increased from 76 to 114 mm, the coefficient of magnetic enhancement $b = i/I_0$ of the current in the beam did not change if the currents of the arc discharge and in the winding of the internal coil remained unchanged. Constancy of the shape of the beam at $l > 76$ mm was also observed when the nonuniform magnetic field B_1 and B_2 acted on the jet and in the absence of a magnetic field with variation of the current of the arc discharge corresponding to beam currents of from 15 to 100 mA.

Localization of Action

The region of the jet sensitive to the action of weak magnetic fields can be found by comparing the increments of current in the beam and the distributions of the axial magnetic field B_t acting on the jet, using the data given in Figs. 1 and 2. In Fig. 4a we give four variants of the distributions $B_t(l_0)$, for which the increments of current in the beam are i = 0, 0.8, 0, and 1.4 mA. The average values of $|B_t|$ for curves 1 and 2 differ significantly only at $l_0 > 45$ mm, where the difference in currents is (0.8 ∓ 0.3) mA and is almost an order of magnitude less than can be expected from Eq. (1), obtained for $l_0 < 40$ mm. Consequently, the region of the jet remote from the anode of the arc chamber is insensitive to weak magnetic fields. In agreement with (1), a difference in currents of (1.4 ∓ 0.3) mA is observed only for curves 1 and 4, when the difference in the $B_t(l_0)$ distributions at $l_0 < 40$ mm is localized in the vicinity of the point $l_0 = 10$ mm, while for curves 1 and 3, when a similar difference is observed at $l_0 = 30$ mm and at $l_0 = 10$ mm, there are no differences in B_t and the currents are equal. Hence, the region of the jet sensitive to the action of a weak magnetic field is localized in the vicinity of the point $l_0 = 10$ mm, while its length is limited to $\Delta l = 20$ mm. Therefore, when both coils are turned on and the field is nonuniform in space, the increment of current in the beam must be compared with the value of the magnetic field induction taken at $l_0 = 10$ mm. The function $i(B_t)$ found in this way is represented by line 2 in Fig. 3 and is similar to curves 1 and 1' obtained for a spatially uniform field B_0, although there is a higher rate of increase in current in the linear region, equal to 4.5 mA/G, which corresponds to $K = (0.69 \mp 0.01)$ $mA^{1/2}/G$. This means that the magnetic action on the jet also depends on the gradient of B_t, equal to 2 G/cm for curve 2 and 0 for curves 1 and 1', and hence it is not a point action.

Using the assumption for a linear dependence of the increment K on the magnetic field gradient, we can find the region of localization of the magnetic action on the jet in another way. For this, with the plasma source at the maximum distance from the diode, the coefficient b was measured at the point $l = 114$ mm for two values of the current j in the winding of the external coil, producing a magnetic field distribution $B_2(l)$ in the region of the jet given by curve 1 in Fig. 4b and corresponding to the maximum value of j. Writing (1) in the form b ≈

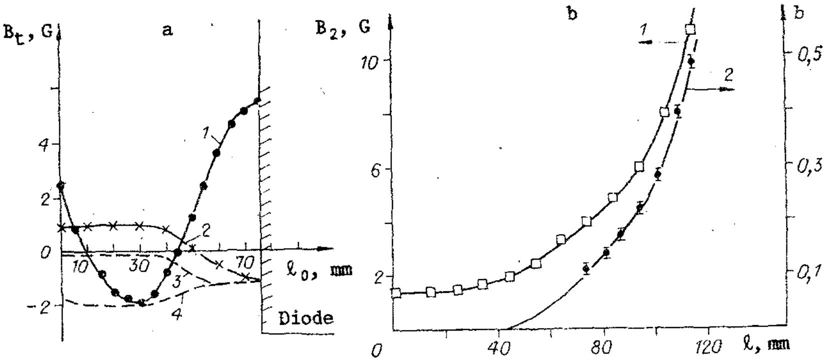

Fig. 4

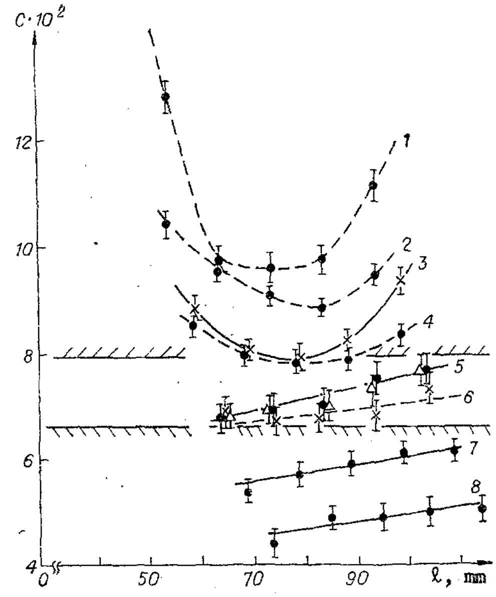

Fig. 5

$K(B' - B_x)$ (B' is the magnetic field induction in the region of the jet sensitive to its action), we obtain $B' = B_x(g - G)/(Ag - G)$, where $A = j_2/j_1$, $g = b_1/b_2$, and $G = K_1/K_2$. In the experiment with $A = 0.48 \mp 0.01$ and $G = 1.09$, we found $g = 3.3 \mp 0.08$, and hence $B' = (7.2 \mp 0.6)$ G and it is far larger than the value of $B_2(l)$ averaged along the trajectory of dispersal of the jet and equal to 4 G. This means that the main action on the jet is localized within the region of $79 < l < 114$ mm with an extent $\Delta l < 35$ mm, in which the average magnetic induction can equal B', and that such action takes place outside the region adjacent to the anode opening at $109 < l < 114$ mm, in which $B_2(l) > 7.8 \text{ G} \geq B'$. It is natural to assume that the center of this region is located at $l = 102^{-4}_{+2}$ mm, where the equality $B_2(l) = B'$ is possible, and hence is shifted relative to the anode opening by $l_0 = 12^{+4}_{-2}$ mm.

To refine the position of the region of localization of the magnetic action on the jet, the plasma source was shifted in the nonuniform field $B_2(l)$ and the values of $b(l)$ were measured, represented by points ● in Fig. 4b. The variation of the angle of capture of the jet into the diode aperture as the source is shifted does not affect b, since the magnetic increment in the density of the jet is uniform over its cross section, so that we can use (1) in the form $b(l)/[B_2(l) - B_x] = K(l)/I_0^{1/2} = C(l)$ $(0.58 < K(l) < 0.69 \text{ mA}^{1/2}/\text{G})$. In this experiment $I_0 = 77$ mA at $l = 76$ mm, so that $0.067 < C(l) < 0.079$ 1/G, which is reflected by the two lines in Fig. 5. The values of $C(l)$ can be calculated by using $b(l)$ and averaging $B_2(l)$ in a freely chosen zone characterized by the position l_0 and the length Δl. As can be seen from Fig. 5, the condition for $C(l)$ is satisfied in equal measure by two sets of these parameters, 10 and 0 mm and 10 and 10 mm, corresponding to the points ● and Δ on curve 5. The other sets of values of l_0 and Δl are (mm) 0 and 0 and 0 and 20 for curves 1 and 8; 20 and 40, 15 and 30, 10 and 20, and 5 and 10 for curves 2, 4, 6, and 7; and 15 and 10 for curve 3, and they are unacceptable since they are at variance with (1). As a whole, the set of data obtained allows us to state that the region of the jet sensitive to the action of a weak magnetic field is localized in the vicinity of the point $l_0 = 11^{+3}_{-2}$ mm and has a length $\Delta l =$

10^{+5}_{-3} mm. Using these values, the distribution $B_2(l)$, and the hypothesis of a linear dependence of the increment K on the gradient of B_2, from (1) we obtain the function $b(l)$ represented by curve 2 in Fig. 4b, which agrees with the experimental points with a reliability of ~0.9 [6], and hence this hypothesis is correct and $K = 0.58(1 + s \text{ grad } B)$ $mA^{1/2}/G$, where $s = (0.095 \mp 0.013)$ cm/G.

Influence of Gaseous Conditions and the Return Flux of Electrons

With an increase in the delay T in igniting the arc relative to the pulse opening the electromagnetic gate [7] for the admission of hydrogen from 400 to 900 μsec, the hydrogen density n in the region of formation of the plasma jet increases practically linearly [5], while the values of n(400) and n(900) near the diode are $1.5 \cdot 10^{13}$ and $5 \cdot 10^{13}$ H_2 molecules/cm^3 at a pressure $p = 1.8 \cdot 10^5$ Pa in the gate. In the absence of magnetic fields, this leads to a linear decrease in the beam current $I_0(T)$ from 42 to 33 mA, while for $B_t = 6$ G it leads to a decrease in the magnetic increment in beam current $i_{exp}(T)$ from 20 to 9.2 mA, considerably larger than that calculated from (1) without allowance for gaseous effects, where $i_{cal}(T) \propto I_0^{1/2}(T)$, in particular, $i_{cal}(900) = 18.1$ mA. From the experiment it follows that $i_{exp}/i_{cal} \approx 1 - 2K_1$, where $K_1 = 1 - I_0(T)/I_0(400)$. From this we obtain $(i_{cal} - i_{exp})/i_{cal} \approx \beta[n(T) - n(400)]/I_0(400)$. Here, according to supplementary measurements [4], $\beta = (6 \mp 0.8) \cdot 10^{-13}$ mA · cm^3/H_2 molecule. Hence, a relative decrease in the magnetic increment of the proton current in proportion to the additional admission of gas and recombination of protons in the jet on hydrogen molecules is more likely than ionization of these molecules by electrons, in contrast to [3], where the magnetic field is large and ionization dominates.

When, in the experiment in the absence of a magnetic field, the voltage U on the diode was increased from 6 to 14 kV, an increase in the proton current in the beam from 46 to 54 mA was observed, i.e., by $i_+ = (8 \mp 1.5)$ mA. Since the current of the arc discharge, equal to 190 A, and the gaseous conditions (T = 500 μsec and $p = 1.8 \cdot 10^5$ Pa) were fixed, it is natural to explain this effect by the fact that the current of secondary-emission electrons, knocked out of the anode grid of the diode and penetrating into the region of the plasma jet, increased by $i_- = (10.5 \mp 1.5)$ mA with an increase in U. Consequently, the coefficient of the increment in the proton current in the beam under the action of the return flux of electrons is $K_- = i_+/i_- = 0.76 \mp 0.18$. A similar effect was observed when electrons from the transport tube were drawn into the diode. For this the potential V_2 of of the anode grid of the diode was increased from its usual value of −100 V, when total blanking of electrons in the tube occurs, to $V_0 \geq 100$ V, assuring the saturation of their flux into the diode. We measured the currents I_h and I_g for these two values of V_2 and calculated i_+ and i_-. In the case when the current of the arc discharge was 280 A, U = 10 kV, and the current in the beam with $V_2 = -100$ V is 100 mA, it was established that $i_+ = (57 \mp 1.5)$ mA, while $i_- = (94 \mp 3)$ mA, so that $K_- = 0.61 \mp 0.03$. Consequently, return fluxes of electrons can considerably influence the operation of the source as a proton injector.

The sensitivity of the plasma jet to the action of a weak magnetic field with B > 1 G and its local character indicate that the subject of the action is precisely the process of formation of the jet, rather than the plasma stream already formed. The dependence of the effect on the gradient of B means that this is not a point action. The decrease in the magnetic increment of the current upon the additional admission of gas into the region of the jet shows that it is not connected with the process of ionization of the gas by electrons. The dependence of the effect on return electron currents, for which B ≪ 1 G, indicates the important role of the charge drawn into the region of formation of the jet, which evidently alters the potential distribution in it, acting on the oxide films formed on the surface of the anode of the arc chamber in the presence of a plasma, in particular. The results obtained can be used to develop systems of deep regulation of the current of a proton source, to estimate the influence of stray magnetic fields and return electron fluxes on the stability of the current of the beam formed from the plasma jet, and to develop a model of the formation of the plasma jet adequate to the experiment.

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SHOCK-WAVE METHOD OF GENERATING MEGAGAUSS MAGNETIC FIELDS

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UDC 537.639

Relatively recently, we and Japanese investigators proposed a new method of generating superstrong magnetic fields through the compression of magnetic flux by a system of shock waves (SW) converging in a substance capable of converting from a nonconducting to a conducting state during compression [1-4]. In the present paper we study the possibilities of generators using this principle.

1. Compression of Magnetic Flux in a Perfectly Packable Substance with an Unlimited Electrical Conductivity Behind the SW Front

A fundamental property of the method of magnetic cumulation under consideration consists in the unavoidable losses of a certain (most often considerable) fraction of the magnetic flux. These losses are connected with the compressibility of the substance and occur even when the electrical conductivity of the material in the conducting state is unlimited. The mechanism of this kind of loss is simplest to understand on the model of a porous substance with an initial density ρ_0, which acquires electrical conductivity upon compression to a density ρ. In this case the magnetic flux initially penetrating a nonconducting granule of the substance remains frozen into the granule material after the phase transition, and only that part of the flux which was initially in the pores between granules of the substance is displaced into the region filled with uncompressed and nonconducting substance. If we designate the change in the area occupied strictly by particles of the substance as dS_c and consider that in compression this quantity is negative, and we also assume that the sizes of individual particles ahead of the SW front are small enough to establish equilibrium between the fields in the pores and the particles, then the equation for the flux losses from the compression region can be written in the form

$$d\Phi = B dS_c. \tag{1.1}$$

Using the equation of conservation of the mass flux at the SW,

$$\rho_0 dS = \rho dS_c, \tag{1.2}$$

we rewrite (1.1) for a uniform field:

$$d\Phi = \frac{\rho_0}{\rho}\frac{\Phi}{S}dS. \tag{1.3}$$

There are many reasons to assume that in the compression of metal powders coated with a film of nonconducting oxides, electrical conduction develops when a certain density ρ_c is reached, which is lower than the density of the crystalline state of the substance, of course, but which can prove to be a constant quantity for the same material and for initial grains of about the same shape. Under such an assumption, Eq. (1.3) is easily integrated and yields relations for the flux

$$\varphi = \frac{\Phi}{\Phi_0} = \left(\frac{S}{S_0}\right)^{\rho_0/\rho_c}$$

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 15-24, May-June, 1987. Original article submitted July 25, 1986.

