FOCUSING OF A PLASMA JET FROM AN ARC PLASMA GENERATOR BY A LONGITUDINAL MAGNETIC FIELD

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Ion emitters formed from a diverging plasma jet make it possible to obtain high-precision beams [1-3]. A feature of ion sources with such emitters is their high sensitivity to a weak magnetic field. In [4] a longitudinal magnetic field of 6 Oe increased ion current by 50%. In [5] a field of 1-100 Oe was used in order to control the beam current. It was shown by experiment in [6] that an increase in beam current by a factor of 3.7 under the action of a longitudinal magnetic field of 40 Oe arose for two reasons: by a relatively weak (7%) increase in the escape of plasma caused by an anodic opening connected with magnetic isolation of the anode [7], and focusing of the ion flux by a magnetic field outside the anode opening. In contrast to typical plasma optic devices [8-10] which focus ion beams with energy $\gtrsim 1$ keV in a strongly magnetized plasma, in the devices in question the natural plasma lens operates on a highly balanced ion flux with energy ≈ 30 eV [2, 11] with a weak magnetic field. The considerable effect of action of a weak magnetic field on the posibility to retain the small phase volume of the beam makes it desirable to use this phenomenon for controlling ion sources and to study it further. The present work is an account of this study.

The ion source shown in Fig. 1 was used in experiments. An arc plasma generator 1 discharges a plasma jet on to a grid diode 2, 3 which forms a beam of protons. A description of the plasma generator has been given in [12]. The plasma generator may be set up at different distances from inlet grid 2 by means of a movable rod. A solenoid 4 with a cross section of 10 × 4 mm is placed directly at the node of the plasma generator. In one of the experiments there was an additional solenoid 5. The surface of the anode outside the conical anode opening, the holder for the inlet grid, and solenoid 5 are closed by screens 6, 7, and 9. A radial expander is bounded by thin-walled metal rings 8. This construction makes it possible to control currents taken from the expanded plasma.

It was detected that with a negative potential blocking electrons at electrodes 6, 8, and 9 the effect of focusing is not observed. A study was made of the dependence of plasma jet focusing on the magnitude of the electron current for the plasma taken from the expander. The electron current was generated by electrode 6 with a negative potential at electrodes 8 and 9. This excitation method makes it possible to control directly the current of electrons since ions do not fall on electrode 6. Figure 2 shows that as electron current I_e increases there is an increase in beam current I at the source outlet. The dependences were recorded with three values of proton current I_Σ in a plasma jet (points 1-3 are 71, 260, and 430 mA) and expressed in relative units; I_0 is beam current with $I_e = 0$. Data were obtained with an axial magnetic field at a distance of 1 cm from the anode H = 46 Oe. All of the points in Fig. 2 comprise a single curve. This means the effect of focusing is governed by the ratio of electron current to ion current and it does not depend on plasma density. If under these conditions the field focusing ions is connected with plasma conductivity, then plasma conductivity is proportional to its density. This occurs if electron—atom collisions prevail over electron—ion collisions. A rough estimate of the frequency of electron ν_{ei} and electron—atom ν_{ea} collisions may be made by proceeding from the assumption that an expanding plasma is a balanced beam of ions with energy 30 eV diverging from the anode opening in a solid angle 2π, and in a similar way the neutral gas is a diverging jet. The hydrogen flow rate is $3\cdot 10^{20}$ sec^{-1}, the velocity of molecules is 1.8 cm/sec, and the relative collision frequency is 4.5×10^7 Pa·sec^{-1} [13]. With a temperature $T_e = 3$ eV and current $I_\Sigma = 0.5$ A the frequency $\nu_{ei} = 4\cdot 10^5/Z^2$ sec^{-1}, $\nu_{ea} = 4\cdot 10^7/Z^2$ sec^{-1} (Z is distance from the anode opening, cm). These estimates illustrate the conclusion made previously about the predominant role of electron—atom collisions in processes responsible for focusing a plasma jet.

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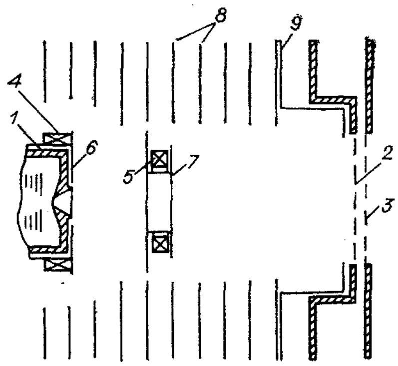

Fig. 1

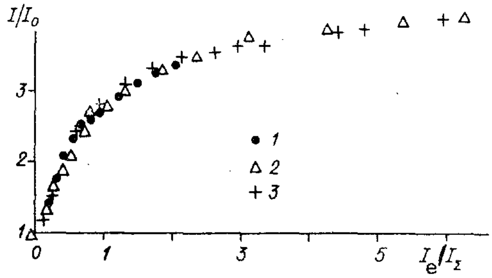

Fig. 2

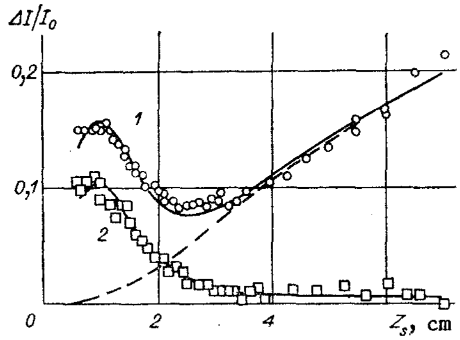

Fig. 3

In addition, it can be seen that the plasma is almost collisionless. Experiments in which the current I_e was excited by means of electrodes 8 and 9 (Fig. 1) gave similar results. The steep dependence $I(I_e)$ makes it possible by means of small electron currents to control the plasma emitter. A floating potential at the walls of the expander ($I_e/I_\Sigma = 1$) provides an increase in beam current by a factor of 2.7. In [4-6], where a focusing effect was observed, an uncontrolled electron current was created by the end surface of the anode and connecting the holder the inlet grid of the diode through a resistance to the anode.

With the aim of checking directly hypotheses [6] about spatial localization of the focusing effect for a plasma jet at a distance of 70 mm from the inlet grid of the diode a solenoid 5 was set up (Fig. 1) with an average diameter of 29 mm and a winding cross section of 4 × 6 mm. By moving the plasma generator by means of a moving rod it is possible to change within the limits 4-70 mm distance Z_s between the solenoid and the anode. The dependence of relative increase in beam current $\Delta I/I_0 = (I - I_0)/I_0$ caused by the magnetic field of solenoid 5 on Z_s (I_0 is beam current on connecting solenoid 5) was studied. Given in Fig. 3 are these dependences with a magnetic field at the center of the solenoid of 25 Oe. An electron current of 0.5 A was created by means of electrodes 7 or 6 (lines 1 and 2). With $Z_s < 20$ mm, $\Delta I/I_0$ behaves in the same way in the first and second cases: action of a magnetic field under these conditions depends weakly on the method for exciting the electron current and it is governed by the magnitude of the magnetic field at a distance of 9 mm from the anode. With large Z_s the behavior of $\Delta I/I_0$ differs markedly. When electrode 7 creates an electron current close to the solenoid plasma jet focusing is observed, which increases with an increase in Z_s. This is easily explained by the effect on a beam of ions diverging from the anode opening by a plasma lens forming around solenoid 5. When a current is created in the anode region by electrode 6 this lens does not form. The quantitative conformity of the model suggested with experimental data is illustrated by the curves. Curves 1 and 2 are described by the equations

$$\Delta I/I_0 = KB^2/(1 + B/B_0) + Z(2 - Z/F)/F(1 - Z/F); \quad (1)$$

$$\Delta I/I_0 = KB^2/(1 + B/B_0); \quad (2)$$

$$F = F_0(1 + (Z_0/Z)^2) \quad (3)$$

(B is magnetic field at a distance of 9.2 mm from the anode, B_0 = 16.3 G, $K = 3.89 \cdot 10^{-4}$ G^{-2}, $Z = Z_sL(Z_s + L)$, Z_0 = 2.64 cm, F_0 = 35.5 cm, L is distance from the lens to the ion collector). The value of B_0 is obtained from experiments in which the field of solenoid 5 was varied with

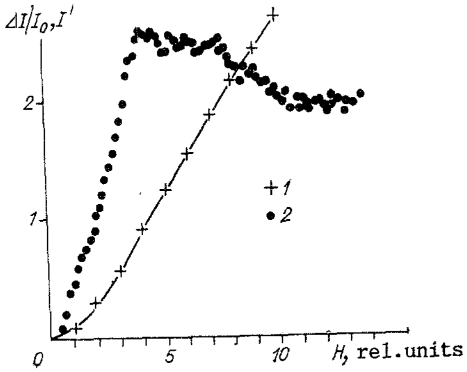

Fig. 4

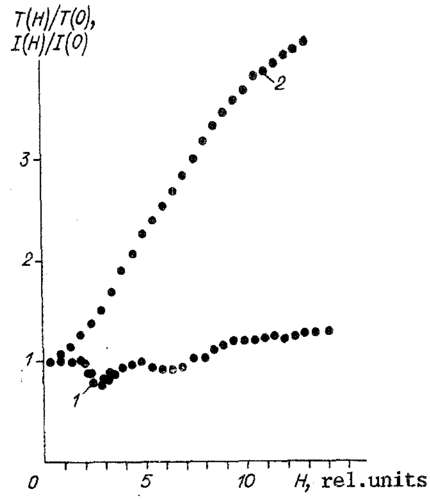

Fig. 5

fixed Z_s. The first term in Eq. (1) describes ion focusing in the anode region, and the second describes the effect of the lens with a focus distance F on a beam emerging from a point source at distance Z_s from the lens. A small dependence of F on Z_s is assumed (see (3)) which may be explained by a drop in neutral gas density with distance from the anode.

With magnetic fields of >10 Oe the focusing effect increases almost linearly with the field. This is illustrated by the dependence given in Fig. 4 for the relative increase in beam current $\Delta I/I_0$ on magnetic field H (point 1). At a distance of 10 mm from the anode the field had a value of 41 Oe with H = 10 rel. units. The field was created by solenoid 4 and solenoid 5 was absent. The values of the derivative $I' \sim dI/dt$ depicted in Fig. 4 (points 2) indicate that the apparently simple dependence I(H) conceals two different focusing regimes. With a weakly magnetized plasma the current increases quadratically with the magnetic field. With a field of 15 Oe there is a sharp change-over to a regime typical for a magnetized plasma. This nature of the change-over is probably connected with development of instability. The difference in two values of I obtained with imposition on the field of solenoid 4 of a uniform field 0.5 Oe of two different polarities was taken as an experimental estimate of the derivative.

The practical desirability of using a weak magnetic field in order to control a plasma emitter is confirmed by measurements of the transverse temperature of the beam of ions. The procedure and means of measurement are described in [2]. Given in Fig. 5 is a dependence of unity for relative values of temperature T(H)/T(0) of the ion beam and dependence 2 for the relative values of beam current I(H)/I(0) on H. It can be seen that with an increase in magnetic field the beam current increases more rapidly than temperature. The original temperature was T(0) = 80 meV, the current was $I_e = 6I_\Sigma$, the distance from the anode to the diode was 134 mm, and the arc discharge current was 90 A.

With the aim of qualitative interpretation of the results obtained we consider three focusing models. It is normal [8] in describing a plasma-optic device to assume that the plasma is magnetized so that equipotentials build up along the force lines of the magnetic field. This model does not correspond to experimental conditions when the Larmor radius of electrons is not very small compared with the dimensions of the system. Control of focusing is carried out by an electron current and not by a potential as in standard plasma lenses. There are published data [14] indicating that in the present case the radial electric field focusing ions changes in the longitudinal direction in proportion to the square of magnetic field intensity $E \sim H^2$ instead of $E \sim H$ in this model. Another possibility is to consider the plasma as a conducting medium ignoring the inertia of electrons. The ohmic model quantitatively truly reproduces the change-over from a quadratic dependence of focusing effect on magnetic field to a flatter dependence as the plasma is magnetized. However, in this model the electric field is rigidly connected with plasma conductivity or with the density of the neutral gas, which contradicts experimental results. In addition, an explanation is not obtained here for the saturation with respect to electron current which occurs. A third possibility is to assume an effective yield of electrons with rare collisions. Electrons fill the vicinity of the lens from a volume placed outside the magnetic field. The current of electrons is in a self-consistent electric field which provides balancing of the spatial charge. The effect of a magnetic field on electrons leads to development of an additional electric field. As its upper estimate it is possible to take a field which balances the Lorentz force. The potential of this field $\phi(r, z) = (e/2m)(\Psi/2\pi r)^2$, where e, m are electron charge and mass; r is radius; z is coordinate along the axis; Ψ is magnetic field current embracing a circle of radius r. This mechanism gives a plausible estimate of the effect if it is used in order to explain focusing of ions in the anode region. Applied to a plasma lens close to solenoid 5 this model predicts a focusing distance an order of magnitude less than the actual value of F_0 from Eq. (3).

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