TIME-OF-FLIGHT PROBING OF A PLASMA JET IN A MAGNETIC FIELD

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An arc proton source [1-3], used as a unit in a plasma diagnostics system [4] or as a unit in high-voltage injectors of precision proton beams [5, 6], is affected by external magnetic fields. Moreover, a magnetic field can be used to control the plasma flow [5, 7, 8]. In view of this, the effect of a longitudinal magnetic field was studied in [8, 9] in the range from 1 to 100 G on a plasma jet. In [8] we determined that the fourfold increase in current under the effect of a 40-G magnetic field is due mainly to the focusing of the plasma jet; the reported data indicate that the focusing action is localized in a region 1 cm from the plasma generator anode. We also found that the focusing is associated with the existence of an electron current in the jet. In our study we generated a pulsed electron current, whose duration was much shorter than the time of flight of protons in the action region of the magnetic field; this enabled us to use the time-of-flight method to determine the distinctive features of the effect of the magnetic field on different parts of the jet.

Figure 1 shows the setup on which the measurements were made. The arc plasma generator 1 ejects a plasma jet onto a grid diode 8, 9 which forms a proton beam. The proton current in the jet was about 0.5 A and the beam current was 0.1 A. The magnetic field acting on the plasma jet was generated by solenoid 2, with a cross section of 10×4 mm^2 mounted directly on the anode or solenoid 4, with a diameter of 30 mm, at a distance of 70 mm from the grid electrode 8. A negative voltage of −100 V relative to the anode was maintained on electrodes 3, 5, 7. The magnetic field did not focus the plasma jet, since the electron currents in the plasma jet were low [8]. A pulsed electron current on screen 5 or on anode attachment 3 was produced in the jet by applying a pulse of positive voltage that generated an electron current of 0.5 A in the jet for 60 nsec. The effect of the magnetic field on the plasma jet was determined from the response of the beam current to the pulsed electron current. Since ions do not manage to move an appreciable distance during the time that the electron current interacts with the magnetic field, producing an ion-focusing field, the transverse momentum acquired by the ions will be proportional to the local value of this focusing field. As the ions fly apart further in the expander the spatial distribution of the transverse momenta is transformed into a time dependence of the flux density in the region of the diode and, therefore, a time dependence of the beam current.

Figure 2a depicts the time variation of the proton-beam current in relative units after the application of a pulse of positive voltage to the screen 5 (see Fig. 1) in cases when the anode was at a distance of 1, 2, 3, 4, and 6 cm (curve 1-5, respectively) from solenoid 4. The time τ was measured from the center of the pulse. The slight perturbation caused by the current pulse at zero magnetic field was subtracted from the values of the increase in the current. From Fig. 2a we see that the beam current begins to change appreciably 0.5-0.8 μsec after the pulsed current is generated. This delay is due to the time of flight of ions from the neighborhood of the solenoid to the diode. Curves approximating the experimental

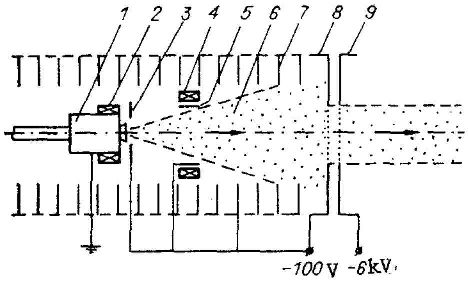

Fig. 1

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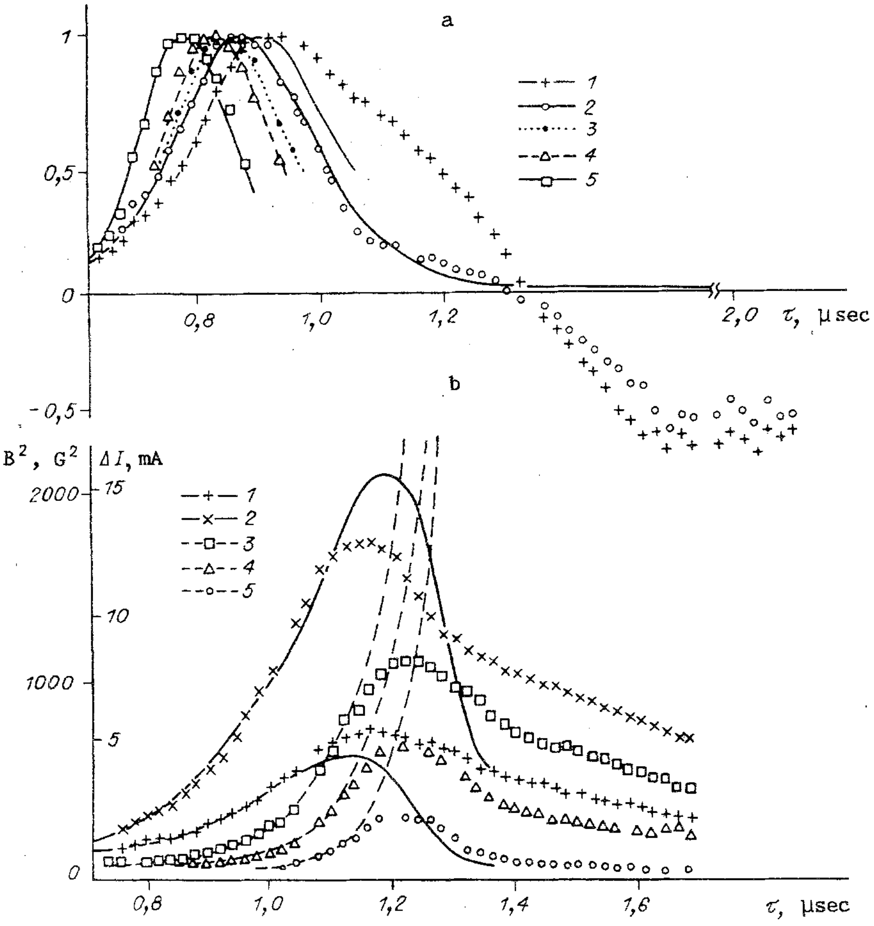

Fig. 2

data were plotted on the basis of the following assumptions. First, the time dependences are obtained by displacing the spatial distributions. Second, the effect of the focusing field on the beam current at each point is proportional to the squared magnetic induction at that point. Third, the average ion velocity in the 70-mm solenoid–diode gap is $7.9\cdot10^4$, $8.1\cdot10^4$, $8.4\cdot10^4$, and $8.8\cdot10^4$ m/sec in cases when the anode–solenoid distance is 2, 3, 4, and 6 cm and the ion velocity near the solenoid is $5.6\cdot10^4$, $6.4\cdot10^4$, $7.4\cdot10^4$, and $8.2\cdot10^4$ m/sec, respectively. The first quantity determines the position of the center of the curve and the second, the width of the distribution. The values obtained for the proton velocity lie in the same range as the results of measurements by a different method [10]. The good agreement between the calculated data (curves in Fig. 2) and the experimental data (point) shows that at distances greater than 1 cm from the anode the effect of the ion-focusing field is proportional to the squared induction of the axial magnetic field and the rise time of this field is substantially shorter than the characteristic ion time of flight.

At a solenoid–anode distance of less than 1 cm the beam response to the pulsed electron current changes: the beam-current pulse becomes asymmetric since the leading edge of the pulse remains the same as at a distance of 2 cm and the trailing edge of the pulse becomes flatter (Fig. 2a). The effect of the magnetic field manifests itself more graphically in the region near the anode if solenoid 2 is used instead of solenoid 4 (see Fig. 1). By using solenoid 2 to excite Foucault currents in the copper anode electrode, we can produce different magnetic-field configurations in the region next to the anode [8]. Figure 2b shows curves of the beam current versus time, similar to those in Fig. 2a, but observed under conditions when a positive voltage pulse was applied to the anode attachment 3 and a magnetic field of different configurations was produced by solenoid 2. Points 1-5 were obtained 0.5, 1.0, 2.0, 2.2, and 2.4 msec after the beginning of the solenoid-current pulse. The absolute values of the increment ΔI in the beam current are given. The curves reflect the values of the squared axial magnetic field B. The relation between the spatial coordinate and the time was chosen on the basis of the proton velocity of $5.6\cdot10^4$ m/sec in the jet. Coordinate ℓ is measured from the end surface of the anode. As we see from Fig. 2b, the experimental points lie near

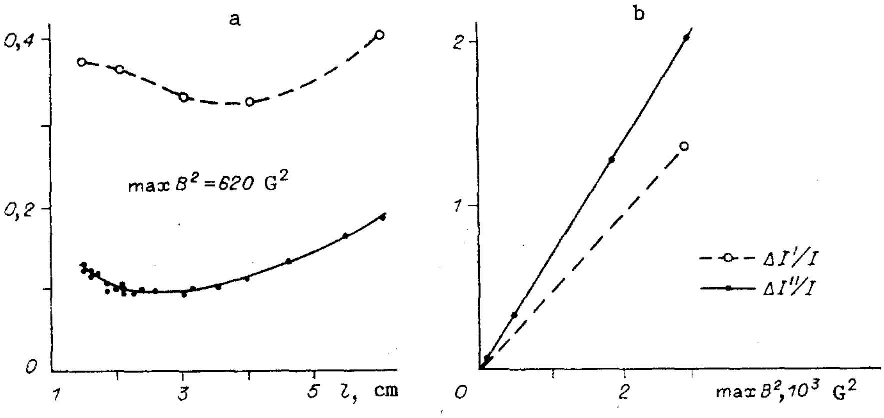

Fig. 3

the corresponding dependence of the squared magnetic induction at distances ℓ greater than 1 cm. At shorter distances from the anode ΔI does not correlate with the spatial distribution of the magnetic field and is determined mainly by the value of the field at a distance of 1 cm. The processes generating the focusing field in the anode region probably have a long transient period so that the temporal evolution of the beam current at time delays of more than 1.2 μsec is due to relaxation. The contribution of this region to the total focusing action can be estimated by comparing the results of pulsed actions with the beam-current increment caused by the magnetic field in the presence of a constant electron current in the plasma jet.

The relative change ΔI/I caused in the proton current by the effect of the magnetic field on the part of the plasma jet, at a distance of more than 1 cm from the anode, can be evaluated as

$$\Delta I/I = \alpha B^2 \tau, \tag{1}$$

if the electron current flows in the jet flows for a much shorter time (τ = 0.06 μsec) than the proton time of flight through the region where the magnetic field acts. At a distance ℓ = 1-3 cm from the anode the coefficient $\alpha = (2.1 \pm 0.1)\cdot 10^3$ $\mathrm{sec}^{-1}\cdot\mathrm{G}^{-2}$, if the electron current is extracted by the screen and $\alpha = (5.8 \pm 0.1)\cdot 10^3$ $\mathrm{sec}^{-1}\cdot\mathrm{G}^{-2}$ if the electron current is extracted by the anode attachment. With these values of α and the average proton velocity v in the region where the magnetic field B acts, using the formula

$$\Delta I'/I = \alpha \int (B^2/v)dl \tag{2}$$

we can find the relative change in the proton current under the effect of the magnetic field at a constant electron current. Figure 3 shows the experimental values of ΔI"/I when a constant electron current exists in the plasma jet and flows to the screen (Fig. 3a) and to the anode attachment (Fig. 3b). Here we give the corresponding values of ΔI'/I, calculated from formula (2). We see that in the first case the calculated values of ΔI'/I are substantially higher than the experimental values while in the second case they are much smaller. This is evidence that a considerable contribution to the change in the proton current is made by the region shown in Fig. 2 to the right of the dashed vertical line. This region reduces the proton current in the first case (see Fig. 2a) and increases it in the second case. When the electron current flows to the anode attachment, the additional increment in the ion current is proportional to the squared induction of the axial magnetic field at a distance of 1 cm from the anode and does not depend on the value of the magnetic field inside that region.

LITERATURE CITED

1. G. I. Dimov, G. V. Roslyakov, and O. Ya. Savchenko, "Formation of a flux of ions and neutral atoms from the plasma of a pulsed arc sources," Preprint No. 145 [in Russian], Akad. Nauk SSSR, Sib. Otd., Inst. Yad. Fiz., Novosibirsk (1967).
2. G. I. Dimov, Yu. G. Kononenko, O. Ya. Savchenko, and V. G. Shamovskii, "Obtaining intense beams of hydrogen atoms," Zh. Tekh. Fiz., 38, No. 6 (1968).
3. V. I. Batkin, V. N. Getmanov, O. Ya. Savchenko, and R. A. Khusainov, "Diagnostics of a plasma jet by grid electrodes," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1982).

4. V. I. Davydenko, G. I. Dimov, and G. V. Roslyakov, "Obtaining precision high-intensity ion and atomic beams," Dokl. Akad. Nauk SSSR, 271, No. 6 (1983).
5. V. I. Batkin, V. N. Getmanov, I. M. Ikryanov, and O. Ya. Savchenko, "Proton source with a regulated current for an electrostatic accelerator," Vopr. At. Nauki Tekh. Ser. Tekh. Fiz. Eksp., No. 1/22, Kharkov (1985).
6. V. N. Getmanov and O. Ya. Savchenko, "Pulsed proton linear accelerator," Otkryt. Izobret., No. 26 (1989).
7. V. I. Davydenko, I. I. Morozov, and G. V. Roslyakov, "Proton source of the hydrogen-atom injector of the AMBAL device," Preprint No. 85-3 [in Russian], Akad. Nauk SSSR, Sib. Otd., Inst. Yad. Fiz., Novosibirsk (1980).
8. V. I. Batkin and O. Ya. Savchenko, "Effect of a weak magnetic field in the expander of an ion source for controlling the beam current and profile," Prib. Tekh. Éksp., No. 3 (1989).
9. V. N. Getmanov and O. Ya. Savchenko, "Effect of a weak magnetic field on the value of the current of an arc proton source," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1987).
10. V. I. Batkin, "Beam modulation by a grid electrode in the expander of an ion source," in: Author's Abstracts, 11-th All Union Seminar on Linear Accelerators of Charged Particles [in Russian], Kharkov (1989).

FARADAY DARK SPACE FOR A DISCHARGE IN HELIUM

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Discharges in monatomic gases have been researched for more than half a century, but our knowledge of the Faraday dark space is still inadequate [1]. Existing models give a satisfactory description only at pressures up to a few torr [2, 3]. In experiments [4] with helium at 1.3-9.3 kPa (10-70 torr), the length of the dark space was many times the tube radius. The result [4] is unexpected from the classical viewpoint [3] but agrees qualitatively and quantitatively with the model proposed here.

We consider the transition region from the weak-field area in the cathode layer to the positive column. If the plasma is quasineutral, the electron temperature is constant over the cross section of the tube, and the gas heating is slight [1, 3], so we get the solution for that region from the particle conservation equation

$$\nabla\left(D\nabla n - \frac{\mathbf{j}}{e}\frac{\mu_+}{\mu_e(E)}\right) = \nu(E)n - \beta n^2, \tag{1}$$

in which D, μ_+, μ_e, β, ν are the ambipolar diffusion coefficient, the ionic and electron mobilities, the bulk recombination constant, and the ionization frequency. On the left in (1), the ambipolar drift accompanies the diffusion one, which is due to the electron mobility being dependent on the field [5, 6]. We neglect the generation and loss terms for the bulk in the Faraday dark space. The particle balance in the positive column is governed not only by plasma diffusion to the wall but also by bulk processes, and therefore the proportion of ionization falls sharply as one passes from the positive column to the Faraday dark space because the ionization term is exponentially dependent on the field, and it cannot balance the plasma loss to the wall. For example, if the field in helium is reduced by 10% from that in the positive column, the ionization proportion becomes less than a third of the diffusion loss, and as the field falls further, it ceases to play a part in the balance. A detailed comparison can be made for the recombination losses and the diffusion ones from the [7, 8] results and the [9] temperature dependence; incorporating the bulk recombination term is necessary for electron temperatures less than 0.1-0.16 eV (for p = 1.3-9.3 kPa and j = 10^{-2} A/cm^2). The rates of the processes are similar in magnitude in each branch of the collisional-radiative recombination involving electrons. The dissociative recombination rate

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