ACCELERATION OF IONS IN PLASMA BEAMS

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Experiments are reported on the acceleration of ions in a plasma column situated in a strong longitudinal magnetic field and through which passes an intense beam of fast electrons. It is found that ion acceleration is due to the instability of the intense electron beam in the plasma with respect to virtual-cathode formation. It is shown that the phenomenon can be employed to fill magnetic-mirror traps with a hydrogen plasma in which the ions have an energy of the order of 1—2 keV.

IN 1957, M. S. Ioffe told us of an interesting phenomenon he observed in the acceleration of ions in a plasma beam. It consists in the fact that the plasma beam, propagating in a vacuum along the axis of a trap with magnetic mirrors [1], becomes under certain conditions a source of fast ions (protons), with energies reaching several keV. The ions are accelerated perpendicular to the magnetic field. An analogous phenomenon was observed under somewhat different conditions by Neidigh [2].

The purpose of our work was a detailed study of this phenomenon, and, primarily, clarification of whether it can be used to inject plasma with fast ions into a trap with magnetic mirrors.

To produce the plasma beam we used a gas discharge with an incandescent cathode in hydrogen. Some preliminary experiments were made with a discharge in lithium vapor [3].

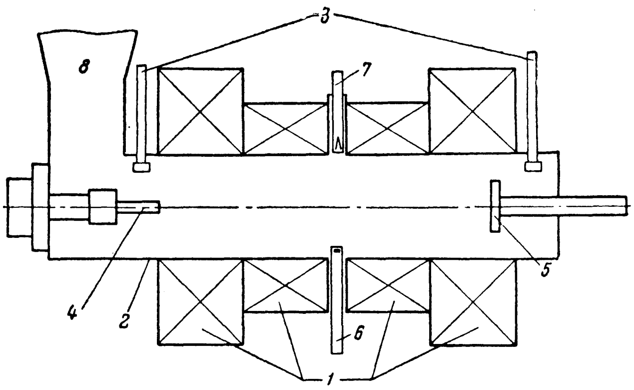

FIG. 1. Experimental setup: 1—Coils producing the magnetic field, 2—vacuum chamber, 3—titanium sorption pumps, 4—plasma source, 5—anode (plasma beam receiver), 6—analyzer probe, 7—fast neutral-atom receiver, 8—pump transition pipe.

1. EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

Experiments with a hydrogen plasma beam were carried out with an installation shown schematically in Fig. 1. A vacuum chamber of stainless steel 30 cm in diameter and 2 m long was pumped out by a 500 liter per second N-5T pump with a nitrogen trap, and by two titanium sorption pumps [1] with a total rating of about 40,000 liters of hydrogen per second.

The minimum pressure of the residual gases in the chamber following the sputtering of the titanium was $(2-3) \times 10^{-7}$ mm Hg.

The time-invariant magnetic field was produced by 12 sectionalized coils, which permitted the field distribution over the length of the installation to be varied over a wide range. The first experiments were carried out in a homogeneous field up to 7800 Oe. The greater part of the experiments was made in the field of the trap with the magnetic mirrors, the field reaching 7200 Oe at the center (H_0) and 9600 Oe in the mirrors (H_m), with a mirror ratio $H_m/H_0 = 1.33$ and a distance of 100 cm between mirrors.

The plasma beam is produced by the source described in [1]. The beam propagates along the axis of the vacuum chamber and is received by a water-cooled anode 15 cm in diameter, located 160 cm from the source. All the electrodes surrounding the plasma beam (the source discharge chamber, the anode, the walls of the vacuum chamber) are at ground potential. The diameter of the cathode at the source is 1 cm, the diameter of the opening in the discharge chamber is 2 cm. With 200 cc of hydrogen delivered to the source per hour, the hydrogen pressure in the discharge chamber is $\sim 10^{-3}$ mm Hg, and the concentration of the plasma in the beam is of the order of 10^{12}—

10^{13} cm^{-3}. In a discharge of this type, most hydrogen ions are protons.

In the experiments with the field of the magnetic trap, the plasma source is located outside the trap; the distance from the outlet opening of the discharge chamber to the magnetic mirror (that is, to the place with the maximum field) is 25 cm.

The ion energy outside the plasma beam was measured, by the retaining field method, with the aid of two-electrode probe No. 1 (Fig. 2), which could move radially in the central plane of the setup (Fig. 1). Probe No. 2, with smaller dimensions, was used (Fig. 2) to estimate the ion concentration. Two such probes, moving longitudinally and radially respectively, served to measure the distribution of the fast-ion concentration along the radius and length of the trap.

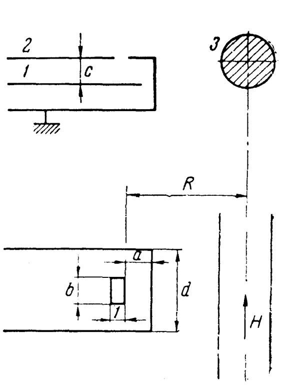

FIG. 2. Arrangement of probes 1 and 2 in two projections: 1—collector, 2—screen, 3—plasma beam. Probe No. 1: a = 5, b = 5, c = 4, d = 15 mm; probe No. 2: a = 2.5, b = 3, c = 1.5, d = 8 mm.

The principal method for measuring the concentrations of the fast ions was by determining the current of the fast neutral atoms (formed by charge exchange of the protons in the hydrogen) on the wall of the vacuum chamber. This was done with a receiver for fast neutral atoms, which registered the current of the secondary electrons knocked out by the neutral atoms from the receiver plate (stainless steel). It was constructed in the same way as in [1], had a working area of 0.5 cm^2, and was placed in a special tube in the central plane of the apparatus, near the wall of the vacuum chamber (Fig. 1). As in [1], the coefficient of secondary electron emission was assumed equal to unity and the photoelectron emission was neglected.

Two discharge modes were used. One was continuous, with a voltage V_d up to 1 kV and with a current I_d up to 4 A. The second mode was pulsed with a voltage up to 2 kV, a current up to 40 A, and a charging pulse duration P_d = 0.5—10 millisecond.

Experiments with the lithium plasma beam were carried out in the installation described in [3].

2. MECHANISM OF ION ACCELERATION IN A PLASMA BEAM

The plasma beam which we have investigated, like the one in [1,2], consists of three components: 1) fast primary electrons emitted from the incandescent cathode and accelerated in the cathode-potential-drop layer to an energy on the order of 0.5—1.5 keV; 2) plasma electrons with energies of several electron volts, produced in the gas by the primary electrons; 3) plasma ions.

Such a plasma ion, as shown earlier [3,4], is under certain conditions unstable with respect to the formation of a virtual cathode in the primary-electron stream. In order to investigate the possibility of a connection between this form of instability of the plasma beam and the ion acceleration, we measured in the experimental setup described in [3] the energies of the Li^+ ions emitted from the plasma beam transversely to the magnetic field. The measurements were carried out by the retaining field method using a three-electrode cylindrical analyzer encircling the plasma beam. They have shown that the fast Li^+ ions (with energies of the order of several hundred eV) are emitted from the plasma beam only in the mode wherein the beam is unstable with respect to the formation of a virtual cathode [1)]. When the beam is in the stable mode, the energy of the Li^+ ions does not exceed 20—30 eV.

Figure 3 shows oscillograms of the electron

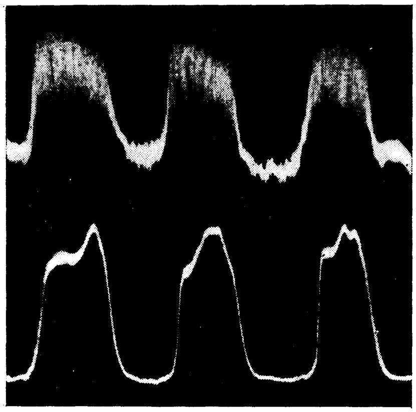

FIG. 3. Oscillograms of electron current in the anode (upper) and ion current in the collector of the analyzer (lower). Upward deflection—decrease in electron current and increase in ion current. Oscillation periods: major—300 μsec, minor —0.15 μsec. Taken with DÉSO-1 high-frequency oscilloscope.

[1)]By "unstable beam" we shall mean throughout precisely this type of instability, and a beam in which this instability does not occur will be called stable.

current to the anode (upper) and of the ion current I_c in the collector of the analyzer with $V_c = +250$ V (lower). The portions of the upper oscillogram with the large-amplitude oscillations correspond to the unstable mode, and the relatively "smooth" portions correspond to the stable mode[3]. We see that the fast Li^+ ions are emitted from the plasma beam only in the unstable mode.

It was shown earlier[3,4] that rapidly varying electric fields with amplitude ~ 200 V/cm and with period on the order of tenths of a microsecond occur in a plasma beam which is unstable against the formation of the virtual cathode. In connection with the experimental data presented here, it is natural to assume that it is in these fields that the observed effective ion acceleration takes place.[2)]

Experiments with a hydrogen plasma beam, carried out in a homogeneous magnetic field, yielded results which were completely analogous to those obtained with the lithium beam. They have shown also that the acceleration process encompasses almost all the ions which enter the plasma beam from the source, and that the overwhelming part of the energy of the accelerated ions (W) is connected with their rotation perpendicular to the magnetic field. This character of ion acceleration favors the possibility of their accumulation in a trap with magnetic mirrors. The purpose of all the subsequent experiments was the investigation of this possibility.

3. ACCUMULATION OF A PLASMA WITH FAST IONS IN A TRAP WITH MAGNETIC MIRRORS

Before we describe the results obtained in the measurements with the magnetic trap, we note the following. Ioffe's experiment have already shown that the energy of the hydrogen ions emitted from the plasma beam can reach 3 keV and more. However, the number of such high-energy ions was relatively small. In the present investigation the choice of the plasma beam modes was dictated primarily by considerations aimed at obtaining the maximal streams of accelerated ions. To this end we used a plasma source with an increased discharge chamber, operating in a high-power pulsed discharge mode. The duration of the discharge pulse (T_d) could be regulated between 0.5 and 10 milliseconds. The data presented below were obtained at $T_d = 0.5$ millisecond.

Figure 4 shows typical oscillograms of the discharge voltage (V_d), the discharge current (I_d), the current of accelerated ions in probe No. 2 (I_p), and the current of fast neutral atoms (I_{neut}), taken with a low-frequency ENO-1 oscilloscope.

In Fig. 4 the discharge pulse duration was $T_d = 500$ microseconds. Exactly similar oscillograms are obtained at 500 μsec $< T_d \lesssim 10$ millisec, that is, when T_d increases the durations of the pulses I_{neut} and I_p increase in proportion, while the amplitudes and average values of the currents I_{neut} and I_p remain approximately constant. We give throughout the maximum values of I_{neut} and the concentration N_+ of the fast ions in the trap.

Figure 5 shows a typical volt-ampere characteristic of analyzer probe No. 1, situated near the wall of the vacuum chamber. The abscissas denote

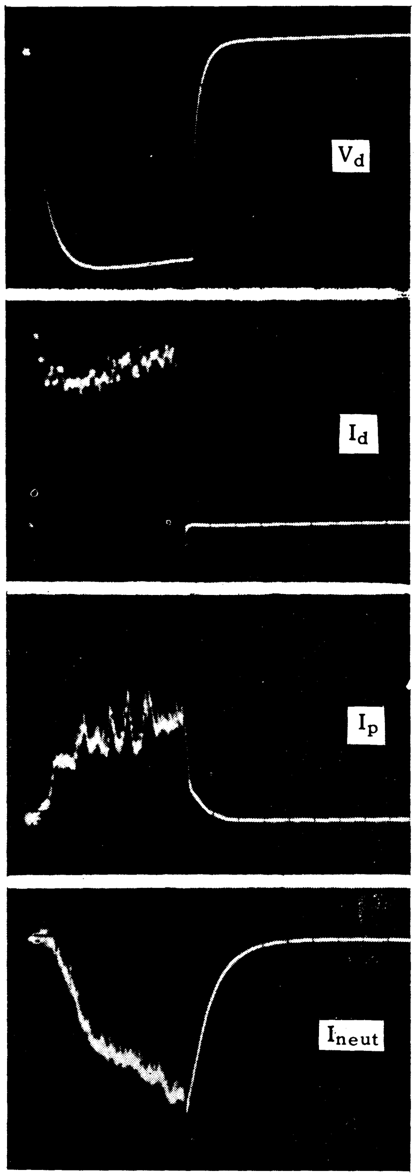

FIG. 4. Oscillograms of V_d, I_d, I_p, and I_{neut}. $H_0 = 2000$ Oe, $V_d = 1$ kV, $I_d = 10$ A. $Q = 100$ cc/hr, $p = 4 \times 10^{-6}$ mm Hg, $I_{neut} = 35$ μA, $T_d = 500$ μsec, $I_p = 3.6$ mA, $W_m = 2$ keV.

[2)]Some annoying errors have crept into [3]. To read Fig. 6 correctly it should be turned upside down, while the captions of Figs. 8 and 9 must be interchanged.

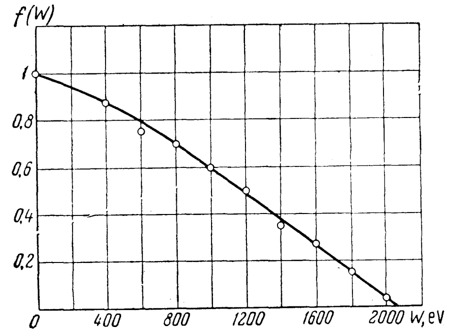

FIG. 5. Integral energy spectrum of the ions in the magnetic trap. $H_0 = 2000$ Oe, $p = 4 \times 10^{-6}$ mm Hg, Q = 100 cc/hr, $V_d = 1.1$ kV, $I_d = 12$ A, $I_a = 2.6$ A, $I_{neut} = 36.5$ μA, $n_{+max} = 7.5 \times 10^{10}$ cm^{-3}.

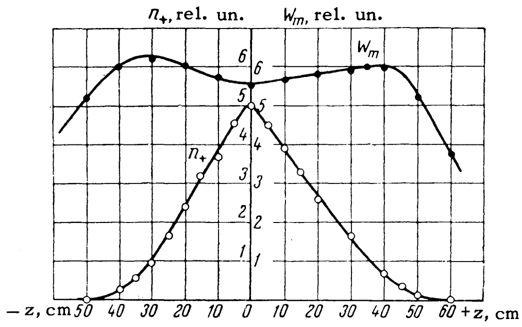

FIG. 6. Distribution of the maximum energy and concentration of the ions along the trap, z—distance from the central plane of the trap, mirrors located at ±50 cm, source located at z = +75 cm.

the positive collector potential, and the ordinates a quantity proportional to the total charge passing through the probe collector during the time of the discharge pulse. We see that half of the ions registered with the probe have energies in the range (1—1.2) keV ≤ W ≤ (2—2.1) keV.

We see also that the average ion energy (W_{av}) is equal to approximately half the maximum ion energy W_m, so that consequently the value of W_m (which is easily measured by experiment) describes rather unambiguously the energy distribution of the ions. In the following estimates of the fast-ion density it is assumed that

$$W_{av} \approx W_m/2 \approx 1 \text{ keV}.$$

The use of a pulsed discharge makes it possible to estimate directly the value of the average lifetime of the fast ions in the trap (τ), by taking oscillograms of the current in the analyzer probe after the end of the discharge pulse. At a hydrogen pressure of $p \approx 2 \times 10^{-6}$ mm Hg, the time necessary for the ion current to drop by a factor e was ~ 50 sec. This quantity will be assumed in the following estimates as the average lifetime of the fast ions in the trap. It is easy to see that it is approximately one order of magnitude smaller than the charge exchange time of the protons in the hydrogen[3)].

Measurements with moving probes made it possible to study the spatial distribution of the ions in the trap (we are referring throughout to the accelerated ions). Figure 6 shows the distribution of the maximum energy (W_m) and the ion concentration (n_+) along the trap. We see that the density of the ions is maximal at the center of the trap and decreases linearly towards the mirrors. Such a character of the longitudinal distribution of the ion density indicates that the ions are accelerated perpendicular to the magnetic field uniformly along the entire plasma beam (within the confines of the trap). We can determine from Fig. 6 the average length L_0 of the volume occupied by the plasma with the fast ions:

$$L_0 = \frac{1}{n_+(r,0)} \int_{-z_n}^{+z_n} n_+(r, z)\, dz \approx |z_n| \approx 50 \text{ cm}, \quad (1)$$

where $2|z_n| \approx 100$ cm —distance between the mirrors.

Figure 7 shows the distribution of the maximum energy and the ion density along the radius of the trap, from which we can determine the average radius of the plasma with the fast ions (R_0) in the central plane of the trap:

$$\pi R_0^2 n_{+max} = \int_0^{R_c} 2\pi r n_+ (r, 0)\, dr, \quad (2)$$

where $n_{+max} = n_+(0, 0)$ is the maximum ion concentration in the trap, and R_c is the radius of the vacuum chamber. From (2) and Fig. 5 it follows that

$$R_0 \approx 7 \text{ cm}. \quad (2a)$$

Thus, the volume of the plasma with the fast ions is

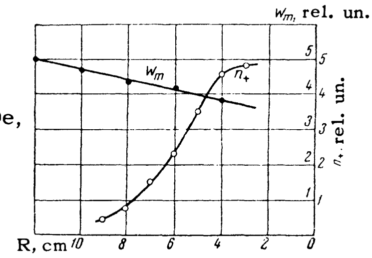

FIG. 7. Distribution of maximum energy and concentration of the ions along the radius of the trap. $A_0 = 2500$ Oe, $V_d = 1$ kV, $I_d = 10$ A, Q = 100 cc/hr, $p = 6 \times 10^{-6}$ mm Hg (at R = 12 cm, $W_m = 2.2$ keV).

3)The mechanism of fast escape of the plasma from the trap was investigated in detail in [1], where it was shown to be due to the "flute" instability of the plasma in a magnetic field with convex force lines.

$$V_0 \approx \pi R_0^2 L_0 \approx 7.5 \cdot 10^3 \text{ cm}^3. \quad (3)$$

From the point of view of using the investigated phenomenon of plasma acceleration to fill magnetic traps with plasma with fast ions, of greatest interest are two quantities, the current I_+ of accelerated ions injected per unit time from the unstable plasma beam into the trap, and the maximum ion concentration n_{+max} attained in a trap with known volume and ion lifetime. These quantities are related by

$$I_+ = n_{+max} V/\tau. \quad (4)$$

We determined n_{+max} by measuring the current I_n of the fast neutral atoms (produced by charge exchange of the protons in the hydrogen) using a special transducer located in the central plane of the trap near the wall of the vacuum chamber. The connection between I_{neut} and n_{+max} is given by

$$I_{\text{neut}} = n_0 n_{+max} \langle \sigma v \rangle_n \frac{\pi R_0^2}{2\pi R_c} S, \quad (5)$$

Where n_0 is the neutral gas molecule concentration, σ the effective cross section for the charge exchange of an ion with velocity v and a neutral gas, and S the working area of the transducer. The quantity $\langle \sigma v \rangle_n$ was determined from the known [5] dependence of the effective cross section for the charge exchange of protons and hydrogen on their energy (when $W_{av} \approx 1$ keV, we have $\langle \sigma v \rangle_n \approx 2.4 \times 10^{-8}$ cm^3 sec^{-1}).

Figures 8 and 9 show the dependence of the concentration n_{+max} and of the ion energy W_m on the current and voltage of the discharge. We see that the quantities n_{+max} and W_m reach their maximum values for $I_d \approx 18$–20 A and $V_d = 1.2$–1.5 kV (with a hydrogen flow $Q \approx 100$ cc-atm/hr). The dependence of the values of n_{+max} and W_m on the magnetic field at the center of the trap (H_0) was plotted in this mode. The result is shown in Fig. 10, from which it follows that the magnetic field in which the most effective ion acceleration occurs has a value $H_0 \approx 2000$ Oe. At this value of H_0 we have $n_{+max} \approx 10^{11}$ cm^{-3} and $I_+ \approx 2$ A.

What is striking is that $I_+/Q \approx 7.5$. This is attributed to the effect of ionic pumping out of the gas from the discharge chamber of the plasma source.

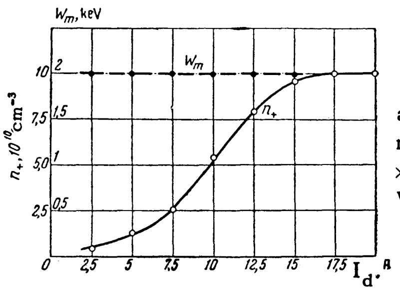

FIG. 8. Dependence of n_+ and W_m on the discharge current. $H_0 = 2000$ Oe, $p = 6 \times 10^{-6}$ mm Hg, $Q = 100$ cc/hr, $V_d = 1.05$ kV.

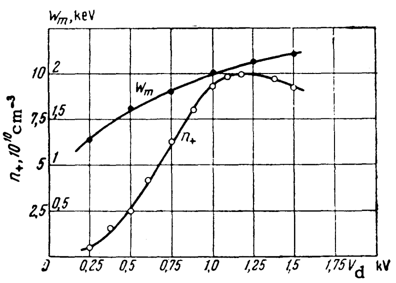

FIG. 9. Dependence of n_+ and W_m on the discharge voltage. $H_0 = 2000$ Oe, $p = 6 \times 10^{-6}$ mm Hg, $Q = 100$ cc/hr, $I_d = 17$ A.

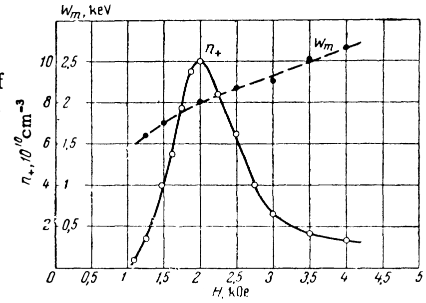

FIG. 10. Dependence of n_+ and W_m on the magnetic field. $p = 6 \times 10^{-6}$ mm Hg, $Q = 100$ cc/hr, $V_d = 1.1$ kV, $I_d = 17$ A.

The data of Figs. 8, 9, and 5 were obtained with hydrogen pressure in the trap $p \approx (5$–$6) \times 10^{-6}$ mm Hg. Of great interest is the question of how these data change when the vacuum becomes much higher, that is, under the operating conditions of a "good" magnetic trap.

In order to answer this question, we plotted n_{+max} and W_m against the hydrogen pressure (at near-optimal beam conditions: $I_d = 17$ A, $V_d = 1.1$ kV, $H_0 = 2000$ Oe, $Q = 100$ cc/hr). The results are shown in Fig. 11. We see that with decreasing gas pressure the concentration of the fast ions in the trap increases, and the ion energies at $p \lesssim (6$–$7) \times 10^{-6}$ mm Hg become approximately constant. As the pressure is increased to $(2$–$3) \times 10^{-5}$ mm Hg, the beam conditions approach stability, and W_m and n_{+max} decrease appreciably (in the stable state of the beam $n_{+max} \approx 0$ and $W_m \approx 0$).

Let us examine in somewhat greater detail the question of the influence of the neutral gas on the density of the fast ions in the trap. This influence is brought about by two circumstances. On the one hand, the ions involved in the acceleration process are not only those entering the plasma beam from the source but also those formed in the trap when the neutral gas is ionized by the beam, the number of the latter increasing in proportion to the gas pressure. The total ion current injected into the trap is

$$I_+ = I_{+0} + a n_0. \quad (6)$$

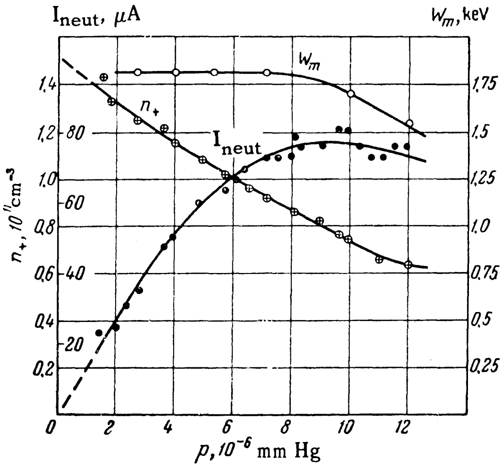

FIG. 11. Dependence of I_{neut}, n_+, and W_m on the hydrogen pressure in the trap. $H_0 = 2000$ Oe, $V_d = 1.1$ kV, $I_d = 17$ A, $Q = 100$ cm^3/hr.

On the other hand, owing to charge exchange of the fast ions with the neutral gas, the lifetime of the ions decreases with increasing gas pressure. The effective lifetime τ is determined by the relation

$$\tau^{-1} = \tau_0^{-1} + \tau_n^{-1} = \tau_0^{-1} + n_0 \langle \sigma v \rangle_n, \tag{7}$$

where $\tau_n = 1/n_0 \langle \sigma v \rangle_n$ is the average ion charge exchange time, and τ_0 is the lifetime of the ions, limited by factors not connected with charge exchange.

Substitution of (6) and (7) in (4) yields

$$n_+ = (I_{+0} + an_0)/(\tau_0^{-1} + n_0 \langle \sigma v \rangle_n) V_0. \tag{8}$$

Hence

$$(dn_+/dn_0)_{n_0 \to 0} = (a/\tau_0 - I_{+0} \langle \sigma v \rangle_n) \tau_0^2/V_0. \tag{9}$$

From (9) we see that the sign of the derivative $(dn_+/dn_0)_{n_0 \to 0}$ is determined by the difference of the two terms

$$an_0 - I_{+0}\tau_0 n_0 \langle \sigma v \rangle_n, \tag{10}$$

of which the first (N_i) corresponds to the entrance into the trap of accelerated ions produced by ionization of a gas in the trap by the plasma beam, while the second (N_{ce}) is due to the loss of fast ions from the trap because of charge exchange with the neutral gas. If the charge exchange prevails over the ionization, then (10) is negative and the function $n_+(p)$ decreases with increasing p; in the opposite case this function increases. The flux ratio N_{ce}/N_i depends on the energy of the accelerated ions W_+ and the energies of the primary electrons of the beam W_e. With increasing W_+ and W_e, this ratio increases both because of the increase in the effective proton charge exchange section with increasing W_+ and as a result of the decrease in the effective cross section for the gas-ionization by the primary beam electrons with increasing W_e. The fact that in the experiment the ion density in the trap decreases with increasing gas pressure (Fig. 11) offers evidence that charge exchange prevails over the ionization under the experimental conditions.

According to the point of view developed here, at sufficiently small W_+ and W_e, the ionization should prevail over charge exchange, and with the increasing gas pressure in the trap, the density of the ions should increase. To check this assumption, an experiment was carried out, in which the energies of the ions and the electrons of the beam were artificially decreased to approximately one-half by suitable choice of the plasma beam mode ($W_{av} \approx 2W_e \approx 0.5$ keV). Under these conditions, the increased pressure of the hydrogen indeed led to an increased growth in the ion density in the trap.

Thus, the experimental data presented here leave apparently no doubt that in an "ideal" vacuum it is possible to obtain the same values of n_+ and I_+ as can be obtained for $p \sim 10^{-6}$ mm Hg, that is, $n_{+max} \approx 10^{11}$ cm^{-3} and $I_+ \approx 2$ A.

It must be noted that the value of n_{+max}, measured with probe No. 2 (Fig. 2), was only 2—3 times as small as in Figs. 8—11, and is patently underestimated because of the incomplete gathering of the ions by the probe.

As already noted, the values of n_{+max} and I_+ (averaged over the time T_d) do not decrease with increasing duration of the discharge pulse (T_d) from 0.5 to 10 milliseconds.

CONCLUSION

The experimental data obtained in the present investigation lead to the conclusion that in a plasma beam that is unstable with respect to the formation of a virtual cathode in a current of primary electrons, the ions become quite effectively accelerated so that such a beam can be used as a powerful injector of fast ions for magnetic traps. A beam of length ~ 1 m with primary electron energy ~ 1 keV and a current ~ 20 A gives a quasistationary proton current ~ 2 A with energy 1—2 keV. With a proton lifetime $\tau \sim 50$ μsec, this yields a plasma with a fast-proton concentration ~ 10^{11} cm^{-3} in a trap volume ~ 10^4 cm^3. It can be hoped that if the lifetime of the ions in the trap can be considerably increased (and such hope is connected with the experiments on traps with combined magnetic fields[6]) it will become apparently possible to increase appreciably the concentration of the plasma and the ion energy.

The results obtained also lead to the conclusion that it is important to investigate the mechanism of this interesting accelerating process. Such an investigation is now under way.

In conclusion, the authors are deeply grateful to M. S. Ioffe for numerous useful discussions, advice, and continuous cooperation. The authors thank V. M. Petrov, who constructed the experimental setup.

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