STUDY OF CHARGE EXCHANGE BETWEEN A DENSE PLASMA CURRENT AND A MAGNESIUM TARGET

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An experimental study has been carried out of charge exchange between a plasma bunch with ion density $n_i \approx 10^{12}$ cm^{-3} and an ultrasonic magnesium jet. It is shown that the charge-exchange process takes place in accordance with the classical model of two-body collisions, and no appreciable scattering of the particles is observed when the target thickness is increased to $n_m l \approx 2 \times 10^{16}$ cm^{-2}. The scattering which does take place for $n_m l \gtrsim 3 \times 10^{16}$ cm^{-2} cannot be classified as purely Coulomb scattering owing to the insufficient accuracy with which the thickness was measured. It is established that the ultrasonic magnesium jet can be used as a "shutter" for a plasma moving with velocity $v < 5 \times 10^7$ cm/sec.

ONE method of producing dense hot plasma in magnetic traps is to inject fast atoms at right-angles to the magnetic field. The advantage of this method is that it can be used to accumulate plasma in magnetic traps by the capture of fast ions from the short-lived plasma target with an efficiency of more than 0.1. The production of dense plasma with a lifetime of 10–20 μsec is a simpler problem than the production of long-lived plasma targets which are necessary for the efficient capture in the case of stationary injection of fast atoms.

On the other hand, bunches of fast atoms could be used for additional plasma heating in Tokamak installations in studies of the stability of plasma against local perturbations. They are also useful for diagnostic purposes. Unstable oscillations may develop in a plasma target under certain conditions during charge exchange between a fast plasma bunch and a gas target. In general, these oscillations may lead to undesirable additional scattering of the atoms at right-angles to the direction of motion. In this paper we report an experimental study of the charge-transfer process and of the scattering of the plasma current in an ultrasonic magnesium target.

APPARATUS

The experiments were carried out on the INES (neutral bunch injector) installation, which is illustrated in Fig. 1. The plasma bunches were generated by a coaxial plasma gun, which was supplied by a 30-μF capacitor bank charged to 20 kV. The half-period of the discharge current was 4.5 μsec and the discharge current amplitude was 200 kA. An electrodynamic valve for admitting gas into the interelectrode space was operated by a capacitor bank of 18 μF charged to 10 kV. The working pressure of the gas in the valve volume of 1 cm^3 was 4 atm.

After leaving the plasma gun the bunch entered the stainless-steel plasma guide, 150 mm in diameter, in which a guiding magnetic field up to 4 kOe could be produced. The frequency of the current in the solenoid producing the guiding field was 250 Hz. The fast and slow components of the bunch were separated in the plasma guide in accordance with the time of flight. The bunch then entered the ultrasonic magnesium jet produced by a magnesium nozzle.[2] The magnesium target could have a thickness of up to $n_m l \approx 5 \times 10^{16}$ cm^{-2}. The bunch of atoms leaving the charge-exchange chamber was recorded in the clearing chamber and the diagnostic volume.

An all-metal vacuum system was employed. The pumping arrangements were sufficient to produce an initial pressure of better than 10^{-7} mm Hg. The disposition of the diagnostic equipment is shown in Fig. 1. The velocity of the plasma bunches was determined in three ways:

1) by recording signals from diamagnetic coils distributed along the length of the plasma guide;

2) by determining the shift of the signal from the fast-atom detector relative to the ultraviolet signal from the gun;

3) by simultaneous determining, at a given point in the apparatus, the quantity $I_i = n_i \bar{v}_i$ with a double Langmuir probe with ion-current saturation, and the quantity $n_i \bar{v}_i \Delta t M \bar{v}_i^2/2$ with a three-layer bismuth bolometer.[3]

The last method also gave the ion density n_i in the plasma bunch. The electron density in the bunch in the middle part of the plasma waveguide was estimated from microwave absorption measurements at $\lambda = 8$ and 4 mm. The flux $I^0 = n_0 v_0$ of the atoms was recorded by the atom detector (25 in Fig. 1), which measured the ion current produced by fast-atom stripping in the gas. The thickness of the magnesium target was determined from the calorimeter signal and by weighing the amount of magnesium evaporated for a number of pulses. The double Langmuir probes and the bolometers which were distributed in the radial direction (24 in Fig. 1) provided information about the divergence of the beam of atoms after the magnesium target. The signals were recorded simultaneously with the Si-33 five-beam oscillograph and OK-17 oscillographs.

EXPERIMENTAL RESULTS

The interaction between a plasma bunch and the target was investigated by first determining the radial distribution of ions leaving the plasma guide for free

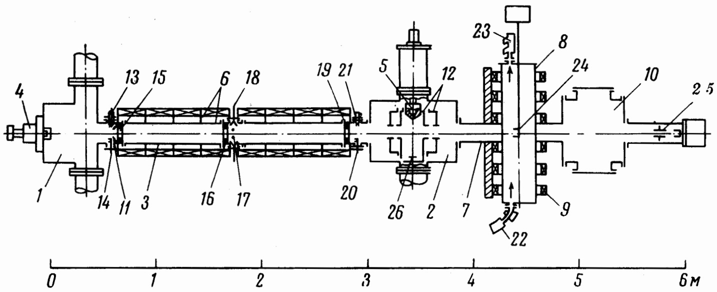

FIG. 1. Diagram of the apparatus: 1, 2—vacuum chambers, 3—plasma guide, 4—plasma gun, 5—magnesium nozzle, 6—guiding-field solenoid, 7—expansion pipe, 8—clearing chamber, 9—clearing-field solenoid, 10—diagnostic volume, 11—conical aperture, 12—copper envelope, 13, 17, 21—double Langmuir probes, 14, 20—bolometers, 15, 16, 19—diamagnetic coils, 18—microwave antennas, 22, 23—source and receiver of cross beam, 24—comb carrying double probes and bolometers, 25—fast-atom detector, 26—calorimeter for measuring the flux of magnesium vapor.

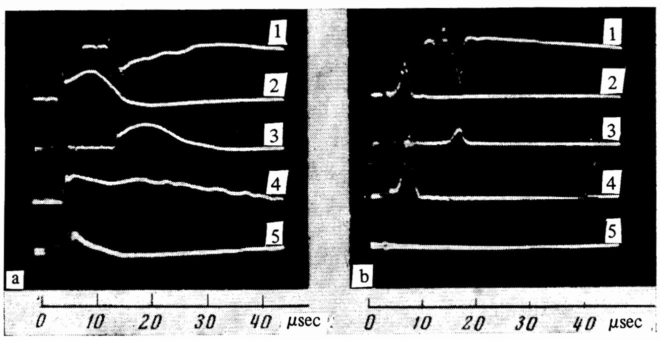

FIG. 2. Ion-current oscillograms obtained with double Langmuir probes. a) Magnesium target absent; traces 1-4 correspond to probes 24 (Fig. 1): 1—probe at axial distance r = 12.1 cm, trace shifted by 10 μsec; 2—r = 8.8 cm; 3—r = 5.5 cm, signal delayed by 9 μsec; 4—r = 2.0 cm, trace 5—probe 17. b) Oscillograms obtained with magnesium target present; traces 1-4-signals from probes as in case a; trace 5—no signal.

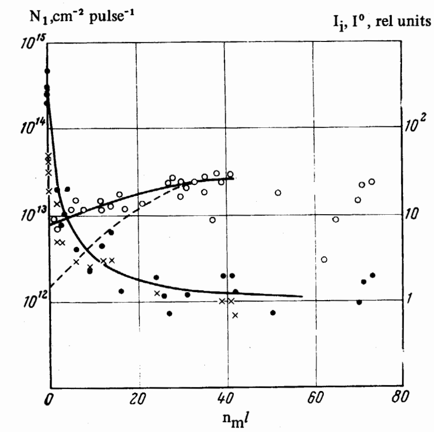

FIG. 3. Number of ions N_1 received by probe at a distance of 2 cm from the axis for velocities $v_i \geqslant 5 \times 10^7$ cm/sec, number of ions I_i with $v_i = 10^8$ cm/sec and the intensity I^0 of fast atoms with $v = 10^8$ cm/sec as functions of the thickness of the magnesium target (in scale divisions; 20 divisions correspond to $n_m l \approx 10^{16}$ cm^{-2}): ●—N_1, ×—I_i, ○—I^0; broken curve—intensity I^0 without the flux of atoms obtained during charge exchange on the residual gas.

space. The measured values of the ion density before and after the magnesium target yielded the density of the plasma bunch at the target. This was found to be $n_i \approx 10^{12}$ cm^{-3}. Most of the experiments were carried out without the guiding magnetic field in the plasma guide. A field of 400 Oe was switched-on to establish the velocity of the plasma bunches from the shift of the diamagnetic signals.

Figure 2 shows current oscillograms obtained with the Langmuir probes with and without the magnesium target. It is clear that the signals are very different in length. When the target is present there is a considerable reduction in the current of ions with low velocities, so that in the analysis of the oscillograms we calculated two quantities, namely, $I_i = n_i v_i$ for $v_i = 10^8$ cm/sec and $N_k = n_i v_i \Delta t$, where Δt is the length of the signal at the 0.5 level, which corresponds to the time interval during which the probe receives ions with velocity $v_i \geq 5 \times 10^7$ cm/sec (k is the number of the probe on comb 24).

Figure 3 shows the quantity I_i, N_1, and $I^0 = n_0 v_0$ as functions of the thickness of the magnesium target. The ion signal is given for the probe lying at a distance of 2 cm from the axis of the installation, and I^0 was measured on the axis by the atom detector. It is clear that as the target thickness is increased the signal N_i initially rapidly decreases and this reduction is largely due to the reduced length, i.e., the target prevents the transit of the slower ions. It follows from the oscillograms that for a target thickness $n_m l \approx 10^{15}$ cm^{-2} the current of ions with velocities $v_i < 5 \times 10^7$ cm/sec is reduced by a factor of more than 20. The magnesium target thus acts as a "shutter" for the slow ions.

From the slope of the initial straight-line region of the curves in Fig. 3 we can, in general, estimate the cross section for the process responsible for the reduction in N_1. Unfortunately, measurements of the target thickness performed with the aid of the calorimeter are subject to considerable errors. Our estimates yield $\sigma_e \approx 3 \times 10^{-15}$ cm^2. The Coulomb cross section for protons on singly-charged magnesium ions for scattering through angles $\theta > 0.1$ is $\sigma_{theor} = 2 \times 10^{-15}$ cm^2 for proton energies of about 100 eV. On the other hand, the maximum value of the charge exchange cross section for protons in magnesium at 10 keV is 2×10^{-15} cm^2 [4] and may decrease rapidly with decreasing energy. Consequently, the scattering of ions with velocities $v_i \approx 5 \times 10^7$ cm/sec is a more likely explanation of the strong reduction in the number of ions per pulse at small target thicknesses. However, uncertainties in the measured target thickness and proton velocity prevent us at present from concluding definitely that the initial rapid fall is connected exclusively with the scattering of ions or charge exchange.

The curves shown in Fig. 3, which give I_i and I^0 as functions of the target thickness, show that up to $n_m l \approx 2 \times 10^{16}$ cm^{-2} the charge-exchange process proceeds in accordance with the classical model of two-body collisions. The charge equilibrium which is achieved in the thick target corresponds to the tabulated value of

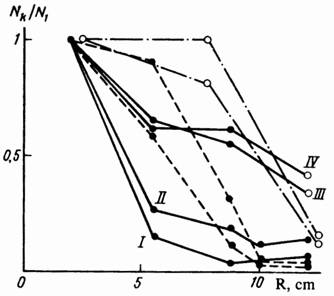

FIG. 4. Radial distribution of the number of ions with $v_i \geqslant 5 \times 10^7$ cm/sec and the energy carried by the ions after the magnesium target (curve I corresponds to $n_m l \approx 10^{15}$ cm^{-2}, II–$n_m l \approx 10^{16}$ cm^{-2}, III–IV–$n_m l \gtrsim 3 \times 10^{16}$ cm^{-2}; broken curve–no magnesium target; dot-dash curve–energy distribution measured by bolometers in the absence of magnesium target.

the equilibrium fraction $\Phi_\infty^0 = 0.95$.[4] The increase in the current of atoms by a factor of only three, when the ion current is reduced by a factor of 20–30, is explained by the relative high gas pressure in the apparatus ($P \approx 10^{-5}$ mm Hg) when the magnesium nozzle is hot. This is demonstrated by measurements of the fast-atom current as a function of hydrogen pressure in the apparatus. It was found that, if we normalize the atom current to the value which is obtained with the thick-equilibrium magnesium target, the atom current in the absence of the magnesium target (see Fig. 3 for $n_m l = 0$) is determined by charge exchange between the plasma bunch and the residual gas at a pressure of 10^{-5} mm Hg. If we subtract the current produced during charge exchange between the bunch ions and the residual gas from the experimental values of the neutral-atom current, assuming that molecular hydrogen is present in the installation, we obtain the broken curve in Fig. 3. If we compare this relation between the neutral-atom current and the target thickness with the quantity I_i, we obtain an adequate agreement with the charge-exchange model for two-body collisions in magnesium vapor. For $n_m l > 2 \times 10^{16}$ cm^{-2} there is a considerable spread in the values of I^0.

The divergence of the neutral-atom beam produced as a result of charge exchange between ions and the magnesium target is determined by measuring the radial distribution of the ion-current density and the energy of the beam after the target. This gives the upper limit for the divergence of the atoms during motion in a thick target.

The divergence of the ion current can be characterized by the ratio of the number N' of particles passing through an axial area $S' = 95$ cm^2 to the number of particles passing through the entire cross section $S = S' + S'' = 460$ cm^2, i.e., the quantity $\eta_N = N'/(N' + N'')$, where N'' is the number of ions passing through S''. The radial distribution of ions with velocities $v_i \geq 5 \times 10^7$ cm/sec is shown in Fig. 4, in which N_k/N_i is plotted as a function of the radial distance, where N_k is the number of ions collected by the k-th probe and N_1 is the number of ions collected by the probe at a distance of 2 cm from the axis. Each curve corresponds to a single pulse. The broken curves refer to distributions obtained for different pulses without magnesium.

Analysis of the curves taken without magnesium yields $\eta_n = 0.43$–0.60, whereas the ratio of areas is $\eta_S = S'/S = 0.21$. Consequently, roughly half of all the ions leaving the plasma guide pass through the area S' at a distance of 150 cm from it.

The figure also shows the energy distribution in the plasma current obtained with the aid of the bolometers. Unfortunately, there are only three points and, therefore, only a very rough estimate of the nature of the distribution can be obtained. Denoting $\eta_E = E'/(E' + E'')$, we find that $\eta_E = 0.3$–0.4, where E' is the energy of the current through the area S' and E'' is the energy through S''. It follows that the bolometer readings also show that the particle density near the axis is higher by a factor of about 10 than at a distance of 12 cm from it.

The nature of the ion distribution in the plasma current undergoes a qualitative change after passage through the ultrasonic magnesium target. When the target is thin, i.e., $n_m l \approx 10^{15}$ cm^{-2}, there is an increase in the relative number of ions passing through S' near the axis. In this case, $\eta_n = 0.8$, i.e., practically all the ions passing through the target also pass through S'. The absolute number of ions is reduced by a factor of about 10, but this reduction does not occur uniformly and depends on the ion velocity. The intensity of ions with velocity less than 8×10^7–7×10^7 cm/sec is reduced by a factor of more than 20, whereas that corresponding to velocities of the order of 10^8 cm/sec or more is reduced by a factor of about three. The greater reduction of the slower part of the bunch can, as shown above, be related to Coulomb scattering or protons by magnesium ions. On the other hand, the reduction in the current of ions with velocity $\overline{v}_i = 10^8$ cm/sec by a factor of three when the magnesium is present is in adequate agreement with the attenuation of the ion current due to charge exchange: $n_m l \sigma_{10} \sim 2$ for $n_m l \sim 10^{15}$ cm^{-2}, $\sigma_{10} \approx 2 \times 10^{-15}$ cm^2.

An increase in the target thickness is accompanied by the formation of "tails" in the radial distribution of the number of ions. For $n_m l \approx 10^{16}$ cm^{-2} we have $\eta_n = 0.54$, whereas for $n_m l \gtrsim 3 \times 10^{16}$ cm^{-2} we observe the maximum measured spread of ions, $\eta_n = 0.29$. This also exceeds the value $\eta_S = 0.21$. We note that, in this case, there is a considerable spread in I^0 (Fig. 3).

We may thus conclude that, even in the case of a thick target, about 30% of all the ions and at least a comparable number of neutral particles pass through the area $S' = 95$ cm^2 at a distance of 100 cm from the center of the magnesium target. The probability of a Coulomb scatter of a 5 keV proton by magnesium through an angle of $\theta > 0.1$ rad is close to unity for $n_m l = 8 \times 10^{16}$ cm^{-2}. Consequently, existing data do not enable us to confirm unambiguously that Coulomb interactions are exclusively responsible for the observed additional scattering of ions (and, consequently, of the atoms in the bunch which has undergone charge exchange) for large target thicknesses. The measured bunch energy before and after the magnesium target, obtained with the aid of the bolometers, shows that the energy carried by the current is independent of the presence of the target to within experimental error. This shows that the radial distribution of the ions is an adequate measure of the divergence of the stream of ions in our experiment.

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90