LOSS OF PLASMA FROM A MAGNETIC-MIRROR SYSTEM. II

M. S. IOFFE, R. I. SOBOLEV, V. G. TEL'KOVSKIĬ, and E. E. YUSHMANOV

Submitted to JETP editor July 20, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) 40, 40-48 (January, 1961)

The anomalously rapid loss of plasma from a magnetic-mirror system described earlier[1] has been investigated. Measurements of the ionic component of the current to the walls of the system show that the loss is due to the motion of plasma across the magnetic field lines and that most of the charged particles are lost at the side walls of the system.

INTRODUCTION

IN experiments described by us in an earlier communication[1] we have studied the containment of a hydrogen plasma with a density of the order of 10^9 cm^{-3} consisting of fast ions ($E_i = 1 - 2$ kev) and slow electrons ($E_e \sim 10$ ev). The containment time of the plasma in the system was determined by measuring the time rate of decay of the fast-ion density after the plasma-production process was terminated. In addition to charge exchange, which should be the principal mechanism by which fast ions are lost under the present experimental conditions, it has been found that there is another mechanism which causes loss of ions from the system.

To determine the direction in which ions escape by virtue of this other mechanism (i.e., along the magnetic field, through the mirrors, across the field, to the side walls), we have carried out direct measurements of the number of fast ions which leave the plasma at the ends (mirrors) and at the side walls of the system.

MEASUREMENT OF THE NUMBER OF FAST IONS ESCAPING AT THE ENDS (ALONG THE MAGNETIC FIELD)

The number of ions escaping along the magnetic field of the system is measured by means of a metal electrode in the form of a sector of a disc, which is fastened to one of the diaphragms. The area of the sector is $1/6$ of the total end surface (cf. Fig. 1); a bias of -20 v is applied to the electrode and is sufficient to suppress plasma electrons. The signal from the sector is integrated in an RC circuit which has a time constant of 5 millisec. Thus, the total ion charge carried to the sector is measured. A correction is made for secondary electron emission; the secondary electron coefficient is approximately unity (cf. reference 2). To measure the charge after the accelerating-voltage pulse we use a blanking system in which the amplifier is switched on at the end of the pulse.

It is apparent that this method of measuring charge does not allow us to separate the fast ions from the slow ions. The slow ions are formed in this system by charge exchange of fast ions on the neutral gas. The decay of the plasma is characterized by two simultaneous processes: charge exchange, in a time* $\tau_{ce} = 1/n_0 v_i \sigma_{ce}$, and the other escape mechanism, characterized by a time τ_s; thus, the number of ions which experience charge exchange during the plasma decay time is

$$\int_0^\infty \frac{N_0}{\tau_{ce}} \exp\left[-\left(\frac{1}{\tau_{ce}}+\frac{1}{\tau_s}\right)t\right]dt = N_0\frac{\tau_s}{\tau_s+\tau_{ce}},$$

where N_0 is the initial number of fast ions in the system. Then the number of ions which escape the system because of the supplementary loss mechanism is $N_0\tau_{ce}/(\tau_s+\tau_{ce})$. It is apparent that if plasma decay is due primarily to the supplementary loss mechanism, then the fraction of the ions which experience charge exchange (forming slow ions) will be small. According to reference 1, if $H_0 = 5000$ oe, $p = 1 \times 10^{-6}$ mm Hg and $U_0 = 30$ kv, $\tau_s = 200\,\mu$sec and $\tau_{ce} = 700\,\mu$sec so that the total number of slow ions which is formed is 20% of N_0. On the basis of these results, it is reasonable to expect that the ion current which reaches the measurement electrode consists primarily of fast ions. In the results of the measurements given below it is assumed that all of the measured current is due to fast ions. (The experimental basis for the validity of this assumption will be given at the end of this section.)

The charge carried by the fast ions which escape at the ends is measured with $H_0 = 5000$ oe, $p = 1 \times 10^{-6}$ mm Hg, $U_0 = 30$ kv and $\alpha \equiv H_{max}/H_0$

*The notation is the same as in reference 1.

Table I. Number of fast ions escaping at the ends for various values of the mirror ratio

α	1.33	1.55	2.0	2.35
10^7 Q_s, Coul.	3.3	8.7	12.8	10.8
10^7 Q, Coul.	46	125	200	200
q_{end}, percent	7.0	7.0	6.4	5.4

= 1.33, 1.55, 2.0, and 2.35. The quantity which is obtained is compared with the charge due to the total number of fast ions which escape the system because of the supplementary loss mechanism. The quantity N_0 is determined from the mean density of fast ions at the central cross section under the assumption that the fast-ion concentration is uniform over the entire volume of the system.

The magnitude of the charge-exchange current, which must be known to find the density, is measured together with the fast-ion charge. The values of the measured charges, converted for the entire surface of both ends Q_e are given in Table I. The table also gives the charge of the fast ions which escape the system because of the supplementary loss mechanism, Q, as well as the ratio of these charges q_e for each value of the mirror ratio $\alpha = H_{max}/H_0$. It is apparent from the table that only a small portion of the fast ions which escape the system leave via the ends.

Since there is a measurement electrode at only one mirror, it is necessary to check that the results which have been obtained are not caused by some small asymmetry in the mirrors. If the mirror ratio is somewhat larger in the mirror in which the electrode is located (as compared with the opposite mirror), the particle loss can be stronger at the end with the smaller value of α. For this reason control experiments were performed with asymmetric mirrors; the mirror-ratio at the mirror containing the electrode was several percent smaller than the mirror ratio at the opposite end. Under these conditions the charge measured by the sector was approximately doubled. This result would seem to indicate that the results which have been obtained are not due to a mirror asymmetry.

It has been noted earlier, that during the plasma decay time slow ions amounting to 20% of the total number of fast ions in the system are formed. According to the results given in Table I, not more than 10% of the ions which escape from the system by virtue of the additional loss mechanism escape through the ends (the fraction of this charge compared with the total number of fast ions in the system is still smaller). A comparison of these data shows that the charge measured at the ends is undoubtedly not due to the fast ions, which have velocities which are predominantly in the transverse direction, but rather to the slow ions, which are not well contained by the mirrors. To investigate this problem we have compared the ion currents at the ends as measured with the sector electrode and with a special electrode system in which only the fast ions are detected. This system consists of eight metal plates 0.8 mm thick which form a curved comb. The height of the plates is 20 mm and the distance between them is 18 mm. In Fig. 1 we show schematically the shape and arrangement of the plates in the comb and the location of the comb with respect to the sector electrode.

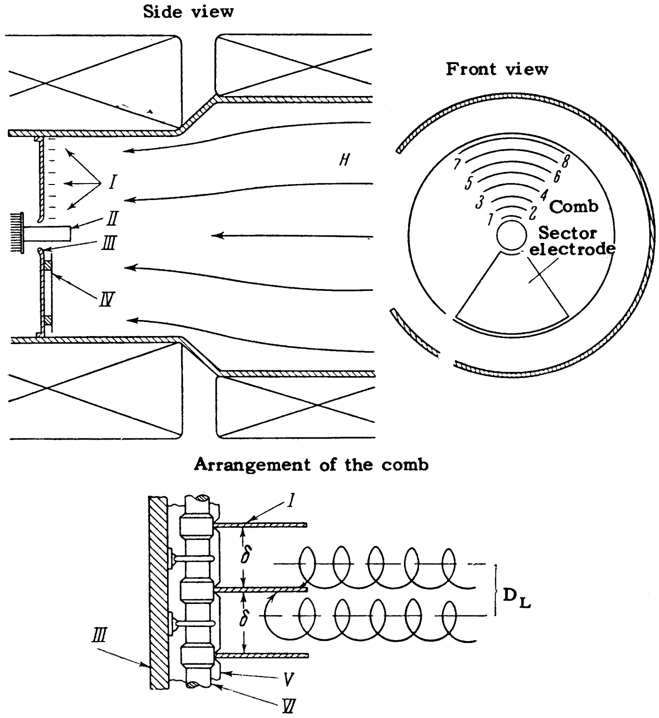

FIG. 1. Electrodes for measuring the ion current at the ends of the system. I) Measurement electrodes (comb), II) cap, III) diaphragm, IV) sector electrode, V) shield, VI) insulator.

The current measured by a given electrode in the comb is due essentially to the flow of fast ions from a portion of a cylindrical layer with a mean radius equal to the radius of the electrode. The thickness of this layer is equal to the Larmor diameter of the fast ions. The slow ions can be neglected because their Larmor orbits are small compared with those of the fast ions. This situation holds even more strongly for the electrons in the plasma. The secondary electron emission from the plates in the comb is small because the plates are parallel to the magnetic field.

Table II. Number of slow ions in the ion flux which escapes at the ends

α	1.33	1.55
10^8 Q_s, Coul.	5.5	19.0
10^8 Q_c, Coul.	2.4	7.6
Q_{slow}/Q_{fast}, percent	~5	~15

In measuring the charge collected by the comb, we must take account of the fact that the comb measures only a fraction of the total flux of fast ions at the region of the diaphragm occupied by the comb electrodes if the Larmor diameter of the ions D_L in the mirrors is smaller than the separation between the plates of the comb δ. To take account of the "transparency" of the comb we multiply the charge Q_c by the quantity δ/D_L.

The charge measured by the sector Q_s is equal to the sum of the charges carried by the fast ions Q_{fast}, the slow ions Q_{slow}, and the secondary electrons produced by the fast ions. By comparing the charges measured by the sector and by the comb under the same conditions we can determine the ratio of the number of slow ions to fast ions at the ends

$$Q_{slow}/Q_{fast} = (Q_s/Q_c)(D_L/\delta) - (1+k)$$

(k is the secondary emission coefficient).

The results of the measurements are shown in Table II (for $k = 1$). In calculating D_L we assume an ion energy of 1.5 kv.[1]

From the expression given for Q_{slow}/Q_{fast} it is apparent that the final result is sensitive to the magnitude of the secondary emission coefficient. However, even if we take $k = 0$, which is not very probable, the particle flux at the ends contains at least 50% slow ions. These relative measurements show that the charge measured by the sector is due primarily to fast ions. We may note that because the slow ions have been neglected the true charge carried to the ends by the fast ions is actually smaller than the measured charge.

Thus, the end-current measurements show that fast ions do escape through the mirrors, but that this loss is only an insignificant part of the total supplementary loss.

MEASUREMENT OF THE NUMBER OF FAST IONS LOST AT THE SIDE WALLS

In order to measure the number of fast ions lost at the side walls we use a system which consists of six insulated electrodes arranged along the length of the system at one side of the central cross section, as shown in Fig. 2. The electrodes are 2×8 cm^2 in size and are at a distance of 10 mm from the walls of the chamber. In order to keep the electrodes from protruding beyond the walls of the chamber, they are inserted in windows in a wide guard plate (150 mm) which is bent to follow the shape of the chamber and which is 10 mm from the walls. A bias of − 20 v is applied to the electrodes; this bias is sufficient to prevent plasma electrons from reaching the electrodes.

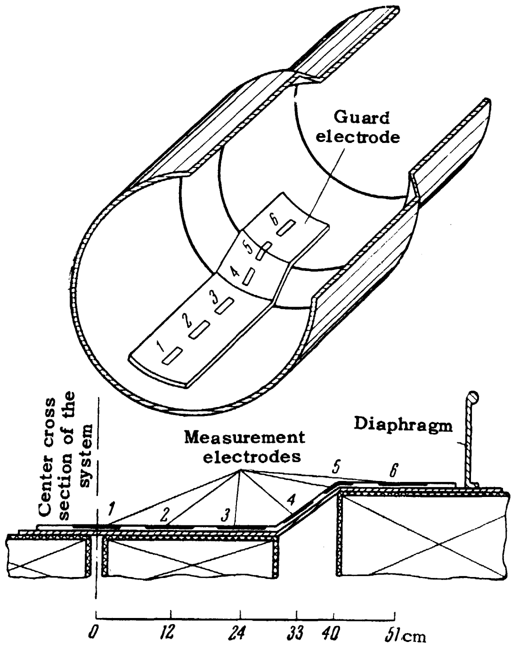

FIG. 2. Electrodes for measuring the ion current at the side walls of the system.

The particle flux at the side walls consists of fast ions and fast neutral particles (the slow ions can be neglected for reasons which have been indicated earlier). Secondary electrons can be emitted at any or all of the electrodes, depending on the orientation of a given electrode with respect to the magnetic field. Thus, in determining the number of fast ions which escape from the system at the side walls, we must subtract off the part due to secondary electrons from the total charge measured by the electrodes.

To estimate the number of secondary electrons roughly we assume that secondary emission due to fast ions and fast neutral particles occurs only at electrodes 4 and 5 (Fig. 2) since these are at large angles with respect to the lines of force of the magnetic field (for $\alpha \leq 1.55$); we assume that the charge at electrodes 1, 2 and 3 is due to fast ions only, while the charge at electrodes 4 and 5 is due to fast ions and secondary electrons. (In all cases no charge is measured at electrode 6.)

Table III. Number of fast ions escaping at the side walls for different values of the mirror ratio

α	1.33	1.55	2.0	2.35
$10^6\,Q^+_{fast}$, Coul.	0.83	1.8	4.4	5.8
$10^6\,Q$, Coul.	1.9	5.3	16.3	23.2
q_{side}, percent	43	34	27	25

Thus, by measuring the charges $q_{1,2,3}$ at electrodes 1, 2, and 3, and $q_{4,5}$ at electrodes 4 and 5, and finding the total number of fast neutral particles formed during the plasma decay time Q^0_{ce} (from the amount of charge exchange), we determine the number of fast ions q^+_{fast} at the electrodes:

$$q^+_{fast} = q_{1,2,3} + (q_{4,5} - Q^0_L \cdot 1{,}6 \cdot 10^{-3} k)/(1+k), \quad (1)$$

where k is the secondary emission coefficient and the factor 1.6×10^{-3} is introduced to take account of the fast neutral particles which strike electrodes 4 and 5. (It is assumed that the fast neutral particle flux at the side walls is distributed uniformly over the length of the system.)

The charge at the side-wall electrodes is measured in the same way as the charge at the end electrodes. The quantity q^+_{fast} is found from Eq. (1) under the assumption, as before, that the secondary emission coefficient is unity. The number of fast ions striking the side wall of the system Q^+_{fast} is obtained by multiplying q^+_{fast} by the ratio of lateral surface of the system to the total area of the measurement electrodes.

In Table III we show the values of Q^+_{fast} obtained for the same values of magnetic field, accelerating voltage, pressure, and mirror ratio as for the measurements of ion loss at the ends. We also show the charge due to fast ions Q which escape from the system by virtue of the supplementary loss mechanism, as well as the ratio of these quantities q_{side}. It is apparent from the table that up to 40% (depending on α) of the fast ions which escape from the system (because of the supplementary loss mechanism) do so at the side walls.

A comparison of the charges measured separately at each of the five electrodes shows that the ion losses at the side walls are not uniform over the length and that the loss distribution depends on the mirror ratio. As expected, the majority of ions escape at those portions of the loss surface which intersect the lines of force which are close to the axis of the system. For mirror ratios of 1.33 and 1.55 these regions are the points at which the chamber is constricted, where electrodes 4 and 5 are located. At higher mirror ratios (α = 2.0 and 2.35) the lines of force touch the walls at the central cross section of the system and accordingly the largest part of the loss occurs in the region in which electrodes 1 and 2 are located.

The values of q_{end} and q_{side} obtained by comparison of the fast-ion charge measured at the ends and at the side walls, and the fast ions lost to the system because of the supplementary loss mechanism, are not very accurate. The principal error is the uncertainty in the number of fast ions in the system at the end of the acceleration-voltage pulse. This quantity is determined from the mean density of the fast ions at the central cross section (the cross section at which the neutral particle detector is located) and it is tacitly assumed that the density is the same over the entire length of the system. The total number of ions in the system is actually smaller than the number obtained in this way because of the lower density of charged particles in the high-field regions (mirrors). The fact that the exact value of the secondary emission coefficient is not known introduces an additional error. Because of these errors, the measurements carried out at the ends and at the side walls under identical conditions give values of q_{end} and q_{side} whose sum is less than 100%.*

It should be kept in mind, however, that the uncertainties in q_{end} and q_{side} due to these errors are the same for both quantities. Hence, we can compare the ratios $q_{end}/(q_{end} + q_{side})$ and $q_{side}/(q_{end} + q_{side})$, which characterize the relative ion losses at the ends and at the side walls. A comparison of this kind, made on the basis of the data in Tables I and III, shows that for H_0 = 5000 oe, p = 1×10^{-6} mm Hg and U_0 = 30 kv, not less than 80% of the ions lost at the walls of the system escape across the magnetic field and are lost at the side walls; correspondingly, no more than 20% of the ions escape along the magnetic field to the ends. This ratio between the ion losses transverse to the field and along the field is found at all mirror ratios.

Similar measurements of the ion losses at the ends and at the side walls have been carried out for H_0 = 8000 oe, U_0 = 30 kv, p = 1×10^{-6} mm Hg, and α = 1.33 and 1.55. The analysis of the results of these measurements is more complicated; when H_0 = 8000 oe the measured charge may contain a

*The sum $q_{end} + q_{side}$ decreases with increasing mirror ratio α (cf. Tables I and III), because in finding the total number of ions in the system we do not take account of the contraction of the region occupied by the plasma when the mirror ratio is increased.

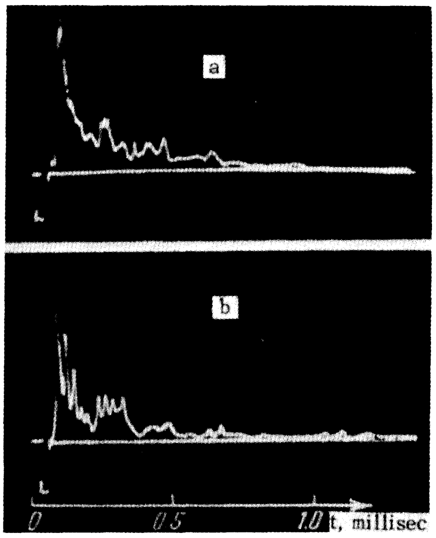

FIG. 3. Oscillograms of the current. a) at the comb electrode in the mirror and b) at the side walls.

considerable slow-ion component because charge-exchange becomes the predominant source of loss. Nonetheless, at this field we also find qualitatively that most of the fast ions move across the magnetic field in escaping from the system.

TIME VARIATION OF THE ION CURRENT AT THE WALLS

Oscillograms of the ion current at the wall electrodes show that this current is highly modulated by irregular fluctuations; the phase and amplitude of the fluctuations are both irregular. Typical oscillograms of the current at individual electrodes in the mirrors and in the side walls are shown in Fig. 3. These oscillograms would seem to indicate that the mechanism responsible for the escape of ions from the system is nonstationary. In this connection it is important to note that the depth of modulation depends on the area of the electrode at which the ion current is measured.

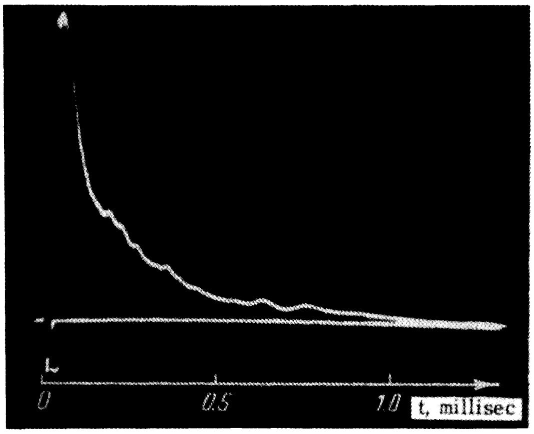

FIG. 4. Oscillogram of the current at the sector electrode.

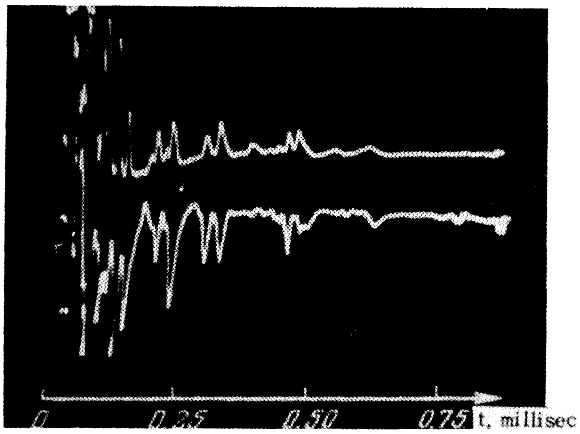

FIG. 5. Oscillograms of the current at electrodes 1 and 5, located at the side walls of the chamber.

In Fig. 4 we show an oscillogram of the current to the isolated sector located at the same diaphragm as the comb electrodes. It is apparent that the current modulation at the sector is much weaker than that at an individual comb electrode. This means that the plasma perturbations responsible for the observed fluctuations do not arise over the entire volume of the plasma simultaneously, but are localized in separate regions; moreover, the transverse dimensions of these regions (perpendicular to the magnetic field) are appreciably smaller than the transverse dimensions of the system.

The longitudinal dimensions of these regions can be investigated by making simultaneous oscillograms of the current at different electrodes located along one of the lines of force. In Fig. 5 we show an oscillogram of the current at electrodes 1 and 5 located at the side walls of the chamber; electrode 1 is located at the central cross section of the system while electrode 5 is at a distance of 400 mm; this distance represents $^2\!/_3$ of the distance from the central cross section to the region of maximum mirror field (cf. Fig. 2). At the cross section at which electrode 5 is located the mirror ratio is 1.33; the maximum mirror ratio is 1.55.

It is apparent from the oscillogram that the current fluctuations at these electrodes are synchronous; we may also note a distinct correlation in the amplitudes of the individual maxima. On the basis of these results we can conclude that the plasma perturbations extend along the magnetic field over the entire length of the system.

CONCLUSION

The anomalously rapid loss of plasma from a mirror system, which has been observed earlier[1] in measurements of the fast ion lifetime, has been verified in the present work through a study of ion losses at the walls of the system. Direct measurements of the ion current at the walls have shown that the greatest part of these losses (at least 80%) is due to the escape of ions at the side walls of the system (perpendicular to the magnetic field); no more than 20% of all the ions lost from the system escape through the mirrors (along the magnetic field). The process in which the charged particles escape from the system is a nonstationary one. Fluctuations in the current at electrodes located at the ends of the system and at the side walls show that the charged particles are "expelled" from separate regions which are not connected; these regions are small in the direction perpendicular to the magnetic field as compared with the transverse dimensions of the system, and extend over the entire length of the system in the direction of the field.

The way in which the charged particles escape would seem to indicate that in the experiments described here the plasma containment time is limited by a flute type instability, inherent to the convex magnetic-field configuration.

[1] Ioffe, Sobolev, Tel'kovskiĭ, and Yushmanov, JETP **39**, 1602 (1960), Soviet Phys. JETP **12**, 1117 (1961).

[2] V. G. Tel'kovskiĭ, Dissertation, Moscow State University, 1959.

Translated by H. Lashinsky
8