Experiments on plasma confinement in a magnetic multimirror trap

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The results of experiments carried out with the aim of verifying the efficiency of plasma confinement in a magnetic multimirror trap are presented. The experiments were performed with a low-temperature alkali plasma. The density distribution along the trap axis was investigated under stationary conditions. The results are in satisfactory agreement with the theory previously proposed. Decay of the plasma after switching off of its source was also investigated. It is found that in a multimirror trap the plasma half-life is much higher than in a homogeneous field.

1. INTRODUCTION

As shown in[1,2], longitudinal containment of a dense plasma (dense in the sense that the mean free path λ is small compared with the length L of the apparatus) can be greatly improved by replacing the homogeneous field by a corrugated (multimirror) field. We report here the results of experiments posed for the purpose of verifying the efficiency of plasma containment in a magnetic field[1)] of such configuration.

The object of the investigation was a low-temperature alkali plasma, since the large Coulomb cross section makes it eady to satisfy the condition $\lambda \lesssim L$ in such a plasma, and the possibility of obtaining such a plasma by surface ionization permits its density to be regulated in a wide range. The plasma was produced on one end of the apparatus, and could flow freely along the magnetic field to the other end, where it was annihilated on a cold dielectric or metallic surface. The influence of the corrugation under these conditions can be investigated by comparing the flow properties in a homogeneous and in a corrugated field, as was done in the present study.

The plan of the paper is the following. In Sec. 2 we consider briefly, on the basis of theoretical papers[1,4,5], the flow features of an alkali plasma in a multimirror magnetic field, insofar as they pertain to our experiments. Section 3 contains a description of the experimental setup and of the measurement procedure. In Secs. 4 and 5 we present the results of investigations of stationary and nonstationary plasma flow, respectively. Section 6 contains a summary of the results.

2. PLASMA FLOW IN A MULTIMIRROR MAGNETIC FIELD

According to results of an earlier study[4], the plasma longitudinal flux density q can be expressed, under the condition $\lambda \lesssim L$ (this is precisely the case of interest in the plasma-containment problem), in the form

$$q = -\frac{H(z)}{H_{max}}\begin{cases} \alpha v_{Ti}\lambda\dfrac{\partial n}{\partial z}, & \lambda \geqslant \gamma l \\ \beta\,\dfrac{v_{Ti}l^2}{\lambda}\dfrac{\partial n}{\partial z}, & \lambda \leqslant \gamma l \end{cases}, \tag{1}$$

where H is the magnetic field intensity, H_{max} is the value of the field in the mirror, l is the length of each individual mirror trap (probkotron), $v_{Ti} = (2T_i/M)^{1/2}$ is the thermal velocity of the ions, n is the plasma concentration, λ is the ion mean free path defined by the formula

$$\lambda[\mathrm{cm}] = \frac{3\cdot 10^{12}T_i^2[\mathrm{eV}]}{n[\mathrm{cm}^{-3}]},$$

while α, β, and γ are numerical factors that depend on the profile of the magnetic field and on the ratio of the electron and ion temperatures. Exact expressions for the coefficients α, β, and γ were obtained in[4,5] under conditions of extremely strong corrugations ($H_{max}/H_{min} \gg 1$) and extremely weak ones ($H_{max} - H_{min} \ll H_{max}$). In our experiments $H_{max}/H_{min} = 1.83$; it is impossible to obtain exact values of these coefficients analytically, but one can use the fact that both approximations give approximately the same results, namely $\alpha, \beta, \gamma \sim 1$.

Strictly speaking, relations (1) are valid only if the electron and ion temperatures are homogeneous along the apparatus. For electrons this condition is satisfied automatically (in view of the large electronic thermal conductivity). As to the ions, their temperature is in general dependent on z. A more detailed analysis of the equations of[4] shows, however, that this variation is insignificant in our experiments.

In all the plasma flows realized in the experiment, the condition $\lambda > l$ was satisfied in the last probkotron, i.e., the plasma flow was collisionless at the exit end of the apparatus. This circumstance enables us to determine readily the plasma flux q from the experimentally measured (with the aid of a Langmuir probe) value of the concentration in the last probkotron. Indeed, assuming that at the entrance to the last probkotron the ion distribution is the "half value" of the Maxwellian distribution ($v_z > 0$), and taking into account the adiabatic invariance of the magnetic moment of the ions we can easily show that

$$q_L = \frac{H_L}{H_{max}}\frac{n_L v_{Ti}}{\sqrt{\pi}}\left[1-\left(1-\frac{H_L}{H_{max}}\right)^{1/2}\right]^{-1},$$

where the subscript L denotes the values of the corresponding quantities at the point where the flux is monitored[2)]. Recognizing that the equality q/H = const holds in the absence of transverse losses, we can use the last relation to connect n_L with the plasma flux q from the ionizer:

$$n_L = \pi^{1/2}\frac{q_0}{v_{Ti}}\frac{H_{max}}{H_0}\left[1-\left(1-\frac{H_L}{H_{max}}\right)^{1/2}\right], \tag{2}$$

where H_0 is the magnetic field intensity at the ionizer.

We consider now the change in the plasma concentration along the system axis in a corrugated field in the absence of transverse losses ($q/H = \text{const}$). We start the case of not too high concentrations, when the condition $\lambda > l$ is satisfied along the entire installation, so that the upper equation of (1) is effective. We can then easily verify with the aid of (2) that

$$\frac{1}{n}\frac{\partial n}{\partial z} = -\frac{A}{\lambda_L}, \tag{3}$$

where λ_L is the ion mean free path corresponding to the density n_L, and

$$A = \left\{\alpha\sqrt{\pi}\left[1-\left(1-\frac{H_L}{H_{max}}\right)^{1/2}\right]\right\}^{-1}$$

is a numerical factor of the order of unity. Integrating (3), we obtain

$$n(z) = n_L \exp\left(A\frac{L-z}{\lambda_L}\right) \tag{4}$$

(the origin is located on the ionizer and L is the distance from the ionizer to the point where the flux is monitored). We see therefore that the plasma concentration increases exponentially when the ionizer is approached[3)] (i.e., when z is decreased). The concentration at the ionizer is given by

$$n_0 = n_L \exp(AL/\lambda_L), \tag{4$'$}$$

i.e., the ratio n_0/N_L, which is a measure of the efficiency of plasma containment in the corrugated field, increases exponentially with increasing plasma density at the output of the installation or, equivalent, with increasing plasma flux from the ionizer ($\lambda_L^{-1} \propto n_L \propto q_L$).

In the case of a sufficiently large plasma flux, the mean free path at the ionizer becomes much smaller than the length of each individual probkotron, and the lower of formulas (2) becomes effective in this region. In other words, the plasma concentration begins to satisfy here the equation

$$\frac{\partial n^2}{\partial z} = -2B\frac{n_L^2\lambda_L}{l^2}, \tag{5}$$

where

$$B = \left\{\beta\sqrt{\pi}\left[1-\left(1-\frac{H_L}{H_{max}}\right)^{1/2}\right]\right\}^{-1}$$

is a numerical factor of the order of unity.

The equality (4$'$) is obviously violated at the ionizer when $n_0 = n_L\lambda_L/l$, i.e., when

$$\lambda_L/l = \exp(AL/\lambda_L). \tag{6}$$

Recognizing that the ratio L/l (which is equal to the number N of the probkotrons) is large in comparison with unity, we can write the following approximate equation for the quantity $\lambda_L^{(c)}$ determined from (6):

$$\lambda_L^{(c)}/l \approx AN/\ln(AN) \approx N/\ln N. \tag{7}$$

For the plasma flux q_0 at which the condition $\lambda_L < \lambda_L^{(c)}$ is satisfied at the exit from the installation, Eq. (5) is valid near the ionizer, and (3) is valid in the remainder of the installation. By matching the solutions of these equations we can find the dependence of n_0 on n_L in the region of large n_L. Calculations show that a certain growth of the ratio n_0/n_L occurs initially, and with further increase of n_L the ratio begins to decrease like $n_0/n_L \approx 2(BL\lambda)^{1/2}/l \propto n_L^{-1/2}$. The maximum value of n_0/n_L is equal to $(AB)^{1/2}N/(2\ln N)^{1/2} \approx N(2\ln N)^{1/2}$. The general character of the dependence of n_0/n_L on n_L is illustrated in Fig. 1. At very large values of n_L (such that $\lambda_L < l^2/L$), the "friction" of the plasma against the magnetic field becomes negligibly small (see[4]), and the ratio n_0/n_L tends to unity.

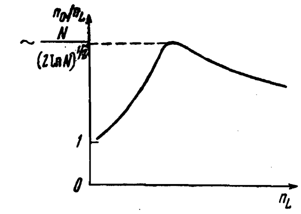

FIG. 1. Dependence of the longitudinal density drop in the plasma concentration at the exit from the system.

An interesting feature of an alkali plasma is the possibility of accelerating the ions in a Debye layer at the ionizer. This effect takes place when the electron emission current from the ionizer greatly exceeds the flux of the neutral atoms (see[7]). The energy E acquired by the ions in the layer depends on the temperature of the tungsten and on the density of the obtained plasma:

$$E \approx T_0(46 - \ln n_0) - W, \tag{8}$$

where W is the work function of the tungsten, T_0 is the temperature of the tungsten, and n_0 is the density of the obtained plasma (in cm^{-3}).

An examination of the ion energy balance shows that the following approximate equality holds in the presence of a pronounced corrugation effect ($n_0/n_L \gg 1$):

$$T_i = E/2 + T_0. \tag{9}$$

Naturally, at $E \gtrsim T_0$ the influence of corrugation becomes appreciable when the condition $\lambda < L$ is satisfied for the mean free path determined from the temperature (9) (and not from the ionizer temperature T_0).

The presence of the connection (8) between E and n_0 causes, generally speaking, the dependence of n_0 on n_L to cease to be purely exponential at small n_L (up to the maximum on Fig. 1), since it follows from (8) and (9) that the temperature of the ions, which enters in (4) as a parameter, decreases when n_0 increases. When n_0 is changed tenfold T_i changes approximately by an amount equal to T_0 (see (8) and (9)). But since most of the experiments described below were performed under conditions $T_i > 2T_0$, this circumstance can be neglected in the first rough approximation.

It is interesting to note that the plasma density can experience a certain change along the z axis even in a homogeneous magnetic field (we are speaking here not of the jump of the density in the Debye layer at the ionizer, but of a smooth variation of the density over a scale L). The reason for this phenomenon is that the ion distribution function in the plasma that enters the installation from the ionizer is not in equilibrium. Thus, in the case of a strong negative layer, when the ions are accelerated in the layer to a velocity v_0 $(2T_0/M)^{1/2}$, the longitudinal scatter of the ions emerging from the layer becomes much smaller than $(2T_0/M)^{1/2}$, and can be simply neglected in first approximation. In other words, we can neglect the longitudinal pressure of the ions that enter the installation. As to the transverse pressure, it is equal to nT_0. With increasing distance from the ionizer, the collisions lead to an equalization of the longitudinal and transverse pressures of the ions, and the longitudinal pressure reaches a value $2nT_0/3$. This leads to a certain deceleration of the flux and to an increase in the plasma density. Calculations show that the increase of the density is determined by the formula

$$\frac{\Delta n}{n_0} = \frac{2}{3}\frac{T_0}{Mv_0^2 + T_0} \tag{10}$$

(the last term in the denominator takes into account the role of the electron pressure). The scale over which the relaxation of the ion distribution takes place (and consequently the concentration reaches $n_0 + \Delta n$) can be estimated at $\lambda(Mv_0^2/T_0)^{1/2}$, where λ is calculated from the ionizer temperature T_0. Under conditions when a noticeable influence of the corrugation is observed, this value is small in comparison with L.

Formula (10) is valid, strictly speaking, only at $Mv_0^2 \gg T_0$, but for an approximate estimate it can be used also at $Mv_0^2 \sim T_0$. Thus, if the layer is neutral and the ions are not accelerated in it, then the ion distribution at the exit from the layer is the "half-value" of the Maxwellian distribution, so that $v_0 = (2T_0/\pi M)^{1/2}$, and from (10) we obtain

$$\Delta n / n_0 = 2\pi / 3(2+\pi) \approx 0.4.$$

Thus, in a homogeneous magnetic field the plasma density at the exit from the installation is given by

$$n_L = q_0 (M/2E)^{1/2} \tag{11}$$

at $E \gg T_0$ and by

$$n_L \approx \sqrt{\pi}\, \frac{6+5\pi}{3(2+\pi)}\, q_0 \left(\frac{M}{2T_0}\right)^{1/2} \tag{12}$$

at $E = 0$.

In the experiments described below, the flow of the plasma in the corrugated magnetic field was monitored by comparing the values of n_L measured in the homogeneous and corrugated fields (the details will be given later). It is therefore of interest to find the possible limits of variation of the quantity[4)] n_L/n_L^* as a function of the conditions at the ionizer after complete passage of the plasma. With the aid of (2) and (9)–(12) it is easy to show that at $E \gg T_0$ we have

$$\frac{n_L}{n_L^*} = \sqrt{2\pi}\, \frac{H_{max}}{H_0} \left[1 - \left(1 - \frac{H_L}{H_{max}}\right)^{1/2}\right] \approx 1.6,$$

and at $E = 0$

$$\frac{n_L}{n_L^*} = \frac{3(2+\pi)}{6+5\pi}\, \frac{H_{max}}{H_0} \left[1 - \left(1 - \frac{H_L}{H_{max}}\right)^{1/2}\right] \approx 0.4.$$

In concluding this section, let us agree to assume that the distribution functions of the ions moving from the plasma to the ionizer and to the cold end are not exactly Maxwellian, so that the formulas obtained in this section are semiquantitative in character.

3. DESCRIPTION OF INSTALLATION

Figure 2a shows a diagram of the experimental setup. Its principal elements are an ionizer (1), magnetic-field coils (2), vacuum chamber (3) with pumps (4), movable Langmuir probes (5), and a heated container (6) with the alkali metal. The vacuum chamber of the installation is a tube of stainless steel 240 cm long with inside diameter 6 cm. The evacuation is with two magnetic-discharge pumps. The limiting vacuum in the system is $\lesssim 10^{-7}$ Torr.

The magnetic system consists of two types of coils. The corrugated field is produced by large coils (inside diameter of the winding 8 cm, outside diameter 24 cm, width of winding 4 cm), with spacing l = 16 cm between them. When the windings are all turned on, the field intensity in the mirrors is H_{max} = 5400 Oe at a mirror ratio H_{max}/H_{min} = 1.83. The field distribution along the z axis is shown in Fig. 2b. The variation of the mirror ratio over the radius of the installation does not exceed 30%. The number of probkotrons in the

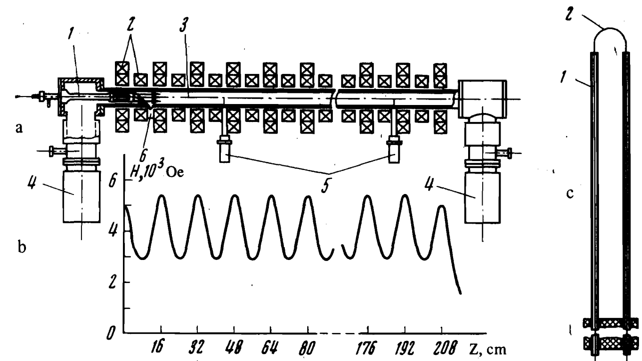

FIG. 2. a) Diagram of experimental setup: 1) ionizer; 2) magnetic-field coils; 3) vacuum volume; 4) magnetic-discharge pumps; 5) probes; 6) setup for the inlet of cesium vapor. b) Profile of magnetic field at the systems axis. c) Construction of incandescent probe: 1—quartz capillary; 2—tungsten filament.

system is 13. In the gaps between the large coils are installed small coils that differ from the large ones only in the outside diameter of the winding (D = 16 cm). In principle, the magnetic system can produce a magnetic field with inhomogeneity less than 5%, but in the present study, to simplify the switching, we have used a connection variant with field inhomogeneity ~15%. As predicted by the theory[5] (and confirmed experimentally), no corrugation effects are noticeable in this case. The field could be changed from the homogeneous to the multimirror configuration within ~0.1 sec.

To produce the alkali plasma we used an ordinary ionizer (see, for example,[8]), in which a tungsten plate of 40 mm diameter was heated by electron bombardment. The main difficulty was in obtaining a uniform tungsten-surface temperature in a strong magnetic field. Satisfactory results were obtained at a tungsten thickness 1.5 mm. In this case, with the magnetic field turned on, the temperature drop from the center to the edge did not exceed 7%. To ensure constancy of the surface temperature in different series of measurements, an automatic power control system was connected in the ionizer supply circuit. The experiments were performed with the temperature of the tungsten surface at the system axis T = 2400°K (the measurements were made with an optical pyrometer).

The neutral-atom flux was directed to the ionizer through a hole in the metallic container (hole diameter 2 mm). The hole was located 3 cm from the vacuum-chamber axis and 7–8 cm from the ionizer. The flux was controlled by external heating of the container, and the required temperature could be maintained automatically.

The system was equipped with a pulsed shutter for the nonstationary measurements. By using shutter holes with different shapes it was possible to produce pulses with different waveforms, particularly pulsed turning-on of the flux followed by a stationary regime, pulsed turning-off of the flux from the stationary regime, etc. The time that the flux was turned on (or off) was ~0.25 msec.

The plasma concentration n was determined with the aid of six movable Langmuir probes located at geometrically equivalent points of different probkotrons. Each of the probes could move radially from the axis to the wall of the vacuum chamber. In the experiments described below, the probes were mounted on the system axis. The probes were made of tungsten wire of diameter $d = 4 \times 10^{-4}$ cm, drawn through two parallel quartz capillaries (length 6 cm, outside diameter 80–100 μ). The plane passing through the probe filament and through the capillaries was perpendicular to the axis of the installation. A schematic diagram of the probe is shown in Fig. 2c. The lengths a of the bare parts of the probes used in the experiments ranged from 0.35 to 0.55 cm. The probe construction made it possible to heat them to incandescence. The probe surface was conditioned by incandescence for 15–20 minutes regularly before each measurement. Control measurements have shown that the current to the probe does not depend on the presence of other probes, i.e., the probes do not influence the state of the plasma.

The measurements were performed in the regime of saturation of the ion current at a negative bias φ exceeding by one order of magnitude the ion temperature. Under these conditions, the current I to the probe did not depend on the plasma temperature, and the plasma concentration was determined by the formula

$$n = \frac{I}{ead}\left(\frac{M}{2e\varphi}\right)^{1/2}. \tag{13}$$

Since the plasma density was determined in different experiments simultaneously with the aid of several probes (up to 4 probes), it should be indicated that the last probe was always located one probkotron away from the end of the installation, as shown in Fig. 2a. The plasma concentration measured with this probe is designated n_L on all the graphs that follow. The position of any other probe relative to the last probe is labeled with the number of n. For example, the combination n_9 denotes that the concentration was measured with the probe located at a distance nine probkotrons from the last.

4. MEASUREMENTS UNDER STATIONARY CONDITIONS

In the stationary measurements we used the dependence of the longitudinal distribution of the plasma density on the plasma flux. The flux was varied smoothly by heating (cooling) the container with the alkali metal. At definite time intervals (1–2 min), the magnetic field was turned on for approximately 5–6 sec. Each switching produced in succession two field configurations, multimirror and homogeneous. This made it possible, for each value of the flux, to compare the plasma distributions in the homogeneous and multimirror fields and to monitor the absence of transverse plasma losses.

We used in the experiments up to four probes simultaneously. The signals from them were fed either to oscilloscopes or to a high-speed multichannel automatic recorder. Each series of measurements, corresponding to the change of the flux from zero to the maximum value, lasted 20–30 minutes. The plots of n_9/n_L and n_5/n_L against n_L, obtained in one such series of measurements, are shown in Fig. 3.

From the results of Sec. 2 it follows that the ratio n_k/n_L should increase exponentially with increasing n_L:

$$\frac{n_k}{n_L} = \exp\frac{Alk}{\lambda_L} = \exp(\gamma_k n_L),$$

where

$$\gamma_k[\mathrm{cm}^3] = \frac{5.3 \cdot 10^{-12} Ak}{T_i^2[\mathrm{eV}]} \tag{14}$$

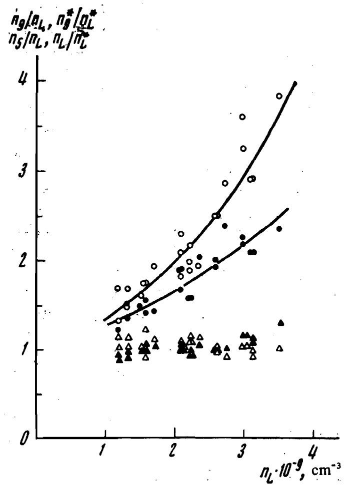

FIG. 3. Effect of corrugation of the magnetic field on the longitudinal density drop (n_L is the plasma concentration at the exit from the installation, n_5 and n_9 are the concentrations at distances of five and nine probkotrons from the end of the system, respectively): ○–n_9/n_L, ●–n_5/n_L, Δ–n_L/n_L^*, ▲–n_9^*/n_L^*. The asterisks mark quantities corresponding to the homogeneous magnetic field.

The solid lines in Fig. 3 are exponentials drawn through the experimental points by least squares. The coefficients γ_k obtained by these methods turned out to be $\gamma_5^{\exp} = 2.7 \times 10^{-10}$ cm^3 and $\gamma_9^{\exp} = 4.0 \times 10^{-10}$ cm^3. Their ratio is $(\gamma_5/\gamma_9)^{\exp} = 0.67$, whereas formula (14) predicts $\gamma_5/\gamma_9 = 5/9 \approx 0.55$. We see that theory and experiment are in reasonable agreement.

From the experimentally obtained values of γ_5 and γ_9 we can determine the ion temperature with the aid of (14). Calculations lead to the following results: $T_i = 0.32$ for a base of five probkotrons and $T_i = 0.35$ eV for a base of nine probkotrons (the constant A is set equal to unity).

The lower part of Fig. 3 shows experimental points pertaining to the monitoring of the plasma passage. The fact that n_9^*/n_L^* is close to unity is evidence of complete passage of the plasma in the homogeneous field, and the constancy of the ratio n_L/n_L^* shows that there are no plasma losses in the multimirror field. The value of the ratio n_L/n_L^* ($n_L/n_L^* \approx 1$) agrees reasonably with the value expected for a plasma with an ion temperature exceeding the ionizer temperature by a factor 1.5–2 (see the end of Sec. 2).

The experimentally attained value of n_9/n_L is close to the possible limit for a base of 9 probkotrons ($n_9/n_L \approx N/(2 \ln N)^{1/2} \approx 4.3$). We were unable to observe under "clean" conditions the decrease of n_n/n_L in the region past the maximum (see Fig. 1), for at $n_L \gtrsim (3–5) \times 10^9$ cm^{-3} the plasma passage through the corrugated field became much worse, and the ratio n_L/n_L^* decreased roughly speaking like $1/n_L$, so that it was impossible to obtain in our experiments a concentration n_L greatly exceeding $(3–5) \times 10^9$ cm^{-3} at the exit from the installation. This may be due both to onset of plasma instability and to a change in the character of the processes at the ionizer with increasing plasma concentration. This question is presently under study, but we can definitely state that to attribute this effect to some instability it is necessary that the diffusion coefficient associated with this instability be larger than the Bohm coefficient.

Results qualitatively analogous to those indicated in

Fig. 3 were obtained in experiments with potassium, but since the surface recombination of potassium is larger than that of cesium, the ratio n_L/n_L^* could be maintained constant only in a narrow range of concentration, making the quantitative treatment more difficult.

We made a special study of the region of low plasma concentrations, where the transition from molecular flow to collision flow takes place. The corresponding results are illustrated in the Fig. 4, which shows this transition clearly. With the smaller base (five probkotrons), the transition occurs at a higher value of the concentration. The temperature determined from the exponential sections of the curves is 0.45 eV for a base of nine probkotrons and 0.48 eV for a base of five probkotrons. The agreement between these quantities, as before, is satisfactory. It is interesting to note that in this series of experiments the ratio n_L/n_L^* is higher than in the preceding case (at a level 1.5), as it should be at a larger value of T_i/T_0 (see Sec. 2).

The external conditions of the experiment (the tungsten temperature, the magnetic field, etc.) in the last run were the same as in the case shown in Fig. 3. This can raise the question of why the temperature determined in this case ($T_i \approx 0.45$ eV) differs from the temperature obtained from the data of Fig. 3. The reason is obviously that in our experiments the ionizer was a disk of polycrystalline tungsten. In the course of time the high temperature changed the crystal structure of the tungsten, and the crystals on its surface acquired a certain preferred orientation.

As is well known, different crystalline planes of tungsten have different work functions (ranging from 4.2 to 5.3 eV according to the data given in[9]), so that recrystallization can be the consequence of a change in the plasma ion temperatures at a constant ionizer temperature T_0 (see formulas (8) and (9)). The ion temperature determined in our experimental runs actually ranges from 0.25 to 0.5 eV, but in most cases it is close to one of two values, 0.45 or 0.35 eV.

The favorable role played by the effect noted here was that it made it possible to extend the range of plasma parameters accessible to experiment. Its unfavorable role was that if for some reason the performance of one run lasted a long time (3–4 hours), a noticeable change could take place in the plasma temperature during the course of the experiment, and the interpretation of the results was made difficult.

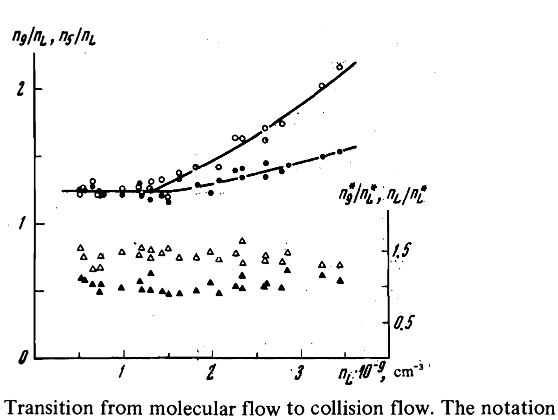

FIG. 4. Transition from molecular flow to collision flow. The notation is the same as in Fig. 3.

In measurements lasting a short time, the main source of errors was fluctuation of the ionizer temperature. Indeed, according to formula (8), the energy acquired by the ions in the Debye layer is very sensitive to the ionizer temperature, namely, when the ionizer temperature changes by an amount δT_0 the value of E changes by $\delta E \sim 20\,\delta T_0$. This leads in turn to a change in the ion temperature in the plasma by an amount $\delta T_i \sim 10\,\delta T_0$ (see (9)). Since usually $T_i \approx (2-3)T_0$, we have

$$\delta T_i / T_i \approx (3 \div 5)\delta T_0 / T_0. \tag{15}$$

The system for stabilizing the heating of the tungsten ensured constancy of the power applied to it with accuracy of approximately 10%. Since the heat was removed by radiation (the loss power was $\sim T_0^4$), the relative change in the tungsten temperature was of the order of 2%, i.e., according to (15) the spread δT_i should range from 5 to 10%, in agreement with the results of the observations.

In a highly tenuous plasma ($\lesssim 10^9$ cm^{-3}), there is also a noticeable random error in the measurement of the concentration, due to the insufficient sensitivity of the recording apparatus.

5. PULSE MEASUREMENTS

In this section we describe the results of experiments in which we investigated the behavior of a plasma after rapid turning off of the plasma flow.

The hole in the container through which the cesium was fed to the ionizer was covered with a mechanical shutter after 0.25 msec. Owing to the thermal scatter in the jet of the neutral atoms, the time required for the plasma flow to be stopped directly at the ionizer was approximate twice as long.

The measurement procedure was the following: During the course of smooth heating (cooling) of the container with the cesium, either the corrugated or the homogeneous magnetic field was turned on periodically for several seconds, and the shutter operated 1–2 seconds after turning-on the field. The signals from the two probes (one of which was a monitor) was photographed from the screen of a two-beam oscilloscope. After each frame taken in the corrugated field, a frame was photographed in a homogeneous field, making it possible to compare the character of the processes in the two cases at close values of the concentration.

Figure 5 shows oscillograms illustrating the time behavior of the plasma density after turning off the plasma flow in a corrugated magnetic field (a) and in a homogeneous field (b) (the distance between probes is nine probkotrons). The instant at which the plasma density at the ionizer begins to fall off is marked by arrows. The vertical spikes of the oscilloscope traces of the homogeneous regime correspond to turning on the corrugated field prior to start of the sweep (see Fig. 5b). Thus, the passage of the plasma could be monitored in accordance with the standard scheme described in Sec. 4, and all the relations given below could be plotted as functions of n_L. The containment of a plasma in a multimirror trap can be characterized by a "half-life" $\tau^{(1/2)}$, which means in this case the time (reckoned from the instant when the flux is turned off at the ionizer) during which the plasma concentration decreases by a factor of 2.

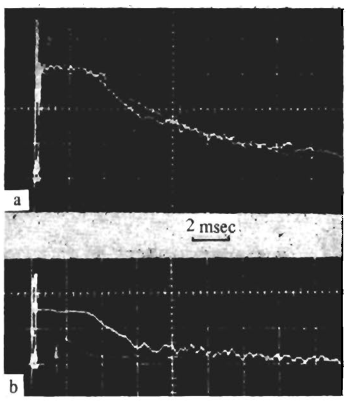

FIG. 5. Oscillograms of probe currents in pulsed switching of the plasma flux: a—corrugated magnetic field; lower trace (last probe)—relative sensitivity $S_L = 1.7 \times 10^9$ cm^{-3}/division, upper trace (probe located nine probkotrons away from the end of the system)—$S_9 = 3.15 \times 10^9$ cm^{-3}/division; b—homogeneous magnetic field; upper trace (last probe)—$S_L = 1.7 \times 10^9$ cm^{-3}/division, lower trace—$S_9 = 3.15 \times 10^9$ cm^{-3}/division. Sweep rate in both cases 2 msec/division.

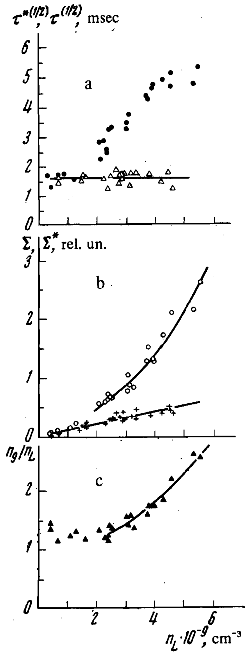

FIG. 6. Results of pulse measurements: a—dependence of plasma half-lives $\tau_9^{(1/2)}$(O) and $\tau_9^{(1/2)}(\Delta)$ on the concentration n_L at the last probe for the case of corrugated and homogeneous magnetic fields; b—plots of $\Sigma(n_L)$(O) and $\Sigma^*(n_L)$(+) obtained by graphic integration of the oscillograms; c—effect of corrugation of the magnetic field on the longitudinal density drop. (Reduction of the stationary sections of the oscillograms.)

The plasma half-lives determined from the oscillograms of the probe currents are shown in Fig. 6a as functions of the corresponding stationary values of the plasma concentration n_L. The same figure shows the dependence of the plasma half-life $\tau^{*(1/2)}$ in a homogeneous magnetic field on n_L. For the case of a plasma in a homogeneous magnetic field we have $\tau^{*(1/2)} \approx 1.6$ msec, a value independent of n_L. In the corrugated magnetic field one can clearly see the growth of the plasma containment time with increasing n_L. At low concentrations ($n_L < 2 \times 10^9$ cm^{-3}), where molecular plasma flow is realized, the half-lives in the corrugated and homogeneous fields are equal. The region of molecular flow is clearly seen also in Fig. 6c, which shows the results of a reduction of the oscillograms for the stationary values of the concentrations immediately before the flow is turned off. The continuous curve in Fig. 6c, for the region $n_L > 2-10^9$ cm^{-3}, is an exponential obtained, as in the preceding figures, by least squares. The temperature calculated from the argument of the exponential is $T_i = 0.46$ eV. The increase of the half-life with increasing density is evidence of improved efficiency of the plasma containment in the multimirror trap with decreasing ion mean free path.

Pulse measurements make it possible to compare independently once more the predictions of the theory with the experimental data. Indeed, by graphically integrating the oscillograms, we obtain the quantity

$$\Sigma_{\exp} = \int_{t_0}^{\infty} n_L(t)\,dt, \tag{16}$$

where t_0 is the instant when the plasma flow is turned off. In the absence of transverse losses, this quantity is proportional to the number of particles contained in the near-axis magnetic tube at the instant when the flow is turned off (the quantity n_L is proportional to the plasma flow at the exit from the installation). At the same time, the number of particles in the near-axis magnetic tube can be calculated by integrating formulas (4) with respect to z, which yields

$$\Sigma_{\text{theor}} = C[\exp(\gamma_N n_L) - 1], \tag{17}$$

where the factor C, at a given magnetic configuration, depends only on the plasma temperature. The solid line in Fig. 6b is the plot of a function of the type (17), and is drawn through the experimental points by least squares. The value of the ion temperature calculated from the argument of the exponential ($T_i = 0.45$ eV) is almost exactly equal to the temperature $T_i = 0.46$ eV obtained by reducing the stationary sections of the oscillograms (Fig. 6c), thus demonstrating the correctness of formula (4).

To compare the effects of plasma containment in corrugated and homogeneous fields, Fig. 6b shows the results of a reduction of the oscillograms for a homogeneous field. As seen from the figure, the function $\Sigma^*_{\exp}(n_L)$ is linear with good accuracy.

6. CONCLUSION

In conclusion, we present the main results of the study.

First, experiments have shown that the dependence of the plasma density on the coordinate (relation (4)), in the case of flows that are not too large, is well described by an exponential law, and the maximum observed longitudinal concentration drop is close to that predicted by the theory ($\sim N/(2 \ln N)^{1/2}$).

Second, we have observed an appreciable increase in the plasma lifetime on going from a homogeneous magnetic field to a corrugated one (under optimal conditions, the time increases approximately fourfold).

The results agree with the theory of plasma containment in a multimirror magnetic trap not only qualitatively but to a considerable degree also quantitatively, so that this theory can be employed with assurance in a wide group of problems connected with containment of thermonuclear plasma in a multimirror trap.

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1)A brief report of these experiments was published earlier (see [3]).
2)We neglect the contribution made to the concentration by particles captured in the last probkotron. This can be done because the point where the flux is monitored is close to the mirror ($H_L/H_{max} \approx 0.7$).
3)We note that a recent paper [6] likewise devoted to a check on plasma

containment by a multimirror field contains the inaccurate statement that the concentration drop δn per probkotron is constant along the apparatus. What is actually constant is the ratio $\delta n/n$.

4)The asterisk denotes here and below the quantities pertaining to the homogeneous field.

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