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EXPERIMENTAL INVESTIGATION OF THE MOTION OF INDIVIDUAL CHARGED PARTICLES IN A MIRROR DEVICE

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A reduction in the confinement time for electrons in a trap has been observed with reduction of the magnetic field, the effect being ascribed to the nonconservation of the adiabatic invariant μ. Loss of electrons is observed in a pulsed change in the magnetic field configuration and the effect is related to the nonconservation of μ. The appearance of these effects depends on the pressure of the residual gases and on the magnetic geometry. Measurements have been made on the time dependence of the distribution of electron magnetic moment.

1. INTRODUCTION

INTEREST in the conservation of the orbital magnetic moment μ of a charged particle in a magnetic field arises in connection with work on cosmic electrodynamics and work in controlled thermonuclear reactions. One of the methods used for confining a plasma in a bounded volume depends on a trap with magnetic mirrors[1]. The finite bounds of the motion of a charged particle in such a trap depends on the conservation of the adiabatic invariant μ.

Kulsrud[2] has shown that when $\rho/R \to 0$ the ratio $\Delta\mu/\mu$ tends to zero faster than any power of ρ/R (ρ is the particle Larmor radius and R is the radius of curvature of the magnetic line of force). Using quantum-mechanical methods, A. N. Dykhne[3] has been able to establish a relation between the finite value of the small parameter ρ/R and $\Delta\mu/\mu$. Arnold[4] has shown that if the quantity ρ/R is small enough the magnetic moment becomes essentially a true adiabatic invariant and the confinement time of a charged particle in a magnetic trap becomes infinite, so long as gas scattering does not occur. Chirikov[5] has considered resonances between the Larmor gyration of a charged particle in a magnetic field and slow oscillations of the particle along the lines of force. The analysis was carried out neglecting the curvature of the magnetic lines of force. It follows from the results of this work that under certain conditions resonances can lead to an exchange of energy between the degrees of freedom of the particle and this effect can lead to particle loss from the trap.

An experimental investigation of the conservation of the magnetic moment of electrons has been reported by a number of authors.[6-8] In the earlier investigations the escape of electrons into the loss cone as a result of the nonconservation of μ and scattering on the residual gas were considered independently; the change in μ was assumed to be random and the motion of the electrons in the magnetic-moment space was described by means of a diffusion relation with the diffusion coefficient being given by $D = D_n + D_s$ where D_n is the diffusion coefficient associated with the nonconservation of magnetic moment and D_s is the coefficient associated with scattering on the residual gas. If it is also assumed that D_n and D_s (for a given value of the magnetic field) are uniform for all μ/μ_{max} (μ_{max} is the largest possible value of the magnetic moment for the electrons being studied) then the confinement time τ is given by the reciprocal relation:

$$\tau^{-1} = \tau_n^{-1} + \tau_s^{-1},$$

where $\tau_s \propto p^{-1}$ (p is the residual gas pressure). By measuring the experimental value of τ for different values of p it is possible to estimate τ_n; when this approach is used, this relation gives the quantitative characteristics of the nonconservation processes.

The method described above, however, leaves out of consideration a number of important effects: how the quantity D_n (for a given magnetic field) depends on μ/μ_{max}, how the scattering of electrons by molecules of the residual gas is related to the development of an instability (the dependence of D_n on p), whether the motion is unstable that is to say, whether the loss of particles from the trap is terminated after a long time or whether the variation in μ is bounded by some limit, and whether it is, in fact, possible to describe the change in μ within the framework of a diffusion analysis. In the present work we have attempted to investigate a number of these questions.

2. EXPERIMENTAL APPARATUS

In order to make a more detailed investigation of these questions the magnetic-mirror device LN, which has been described in[9], has been modified. The injector has been located on the side toward the pumping system thus making it possible to achieve a higher and more stable vacuum. The limiting vacuum in the operating volume is approximately 6×10^{-10} torr. In order to inject electrons into the trap without having the electron trajectories encircle the axis of the system (electrons which encircle the axis of symmetry are confined indefinitely if certain conditions are satisfied[10]) the injector has been mounted at a distance of 3 cm from the axis. The mean injection angle with respect to the axis is 30°. The length of the hollow cylindrical electrode (the ring), by means of which electrons are captured in the trap, has been increased to 32 cm, thus making it possible to achieve capture for low values of the positive pulse voltage applied to the ring. For electrons with energy on W the upper limit of the magnetic moment for which capture occurs for a ring voltage U is

$$\mu_{\lim} = (W - eU) / H_{max}, \tag{1}$$

where H_{max} is the maximum magnetic field in the trap.

The magnetic field configuration has been modified by the addition of three solenoids that are coaxial with the main solenoid (Fig. 1). The polarity of the field in the center solenoid is the same as the polarity of the primary field while the fields in the other two solenoids are opposed. The experiments have been carried out primarily with three different field configurations. In configuration I the field is produced only by the basic solenoids. The configurations II and III are produced by switching on the additional solenoids; in configuration III the current in the additional solenoids is twice as large as in configuration II.

In Fig. 1 we show curves of the magnetic field for all three configurations in the case in which the distance between centers in the basic solenoids l = 65 cm. Along the ordinate axis we have plotted the quantity H_z/H_{max} where H_z is the magnetic field on the axis at the point given by z. The magnetic field at the center of the mirror H_{max}, where the field is a maximum, is the same in all configurations (to within 3%) with the same current in the basic solenoids.

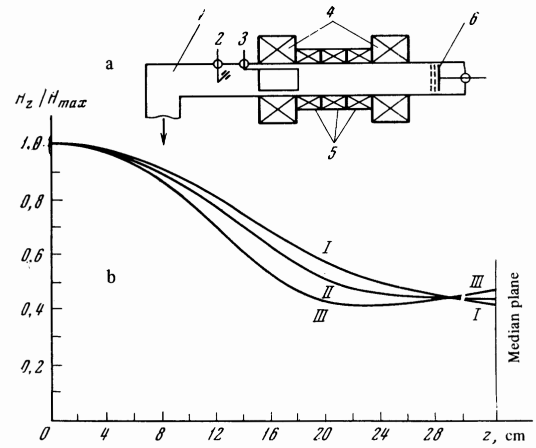


FIG. 1. a) General view of the apparatus: 1) vacuum chamber, 2) electron gun, 3) ring, 4) primary solenoids, 5) additional solenoids, 6) collector. b) magnetic field curves for the three configurations: I—γ = 2.4; II—γ = 2.3; III—γ = 2.5 ($\gamma = H_{max}/H_0$, where H_0 is the field at the center of the trap).

3. METHOD OF MEASUREMENT

These experiments have been concerned primarily with measuring the confinement time of electrons in the trap as a function of the magnetic field (in the appropriate curves the abscissa axis denotes the magnetic field H_{max} at the center of the mirror). The experiments have been carried out with different magnetic field configurations, different operating voltages on the injector and the ring, and different residual gas pressures. The density of fast electrons in the trap, which can have energies ranging from 1 to 30 keV depending on experimental conditions, is typically 10^4—10^6 particles/cm³.

The basic quantity that is investigated is the mean particle lifetime in the trap

$$\bar{\tau} = -\frac{1}{n(0)} \int_0^\infty t \frac{dn(t)}{dt} dt = \frac{1}{n(0)} \int_0^\infty n(t)\, dt,$$

where n(t) is the number of fast electrons at time t. Experimentally the quantity $\bar{\tau}$ is determined by an oscillogram of the current induced in the collector I

$$\bar{\tau} = \frac{1}{I(0)} \int_0^{\tau_c} I(t)\, dt, \tag{2}$$

where τ_c is the time for total decay of the signal on the oscillogram. The current I is approximately 95% (for W = 10 keV) secondary electrons; these are formed by the ionization of molecules of the residual gas by fast electrons. The magnitude of this current is proportional to the number of fast electrons n(t) in the operating volume at a given time.

Numerical calculations and a comparison out carried for large values of the magnetic field (in which case the electron confinement time is determined primarily by scattering on the residual gas) of the oscillograms for the collector current due to fast electrons and an oscillogram for the total collector current I shows that after a time τ_c the fast electrons have lost essentially all of their initial energy by ionization and inelastic collisions with molecules of the residual gas. Then the quantity $\bar{\tau}$ as determined by Eq. (2) is overestimated by 10—20% because the coefficient α in the relation I(t) = αn(t) increases with time.

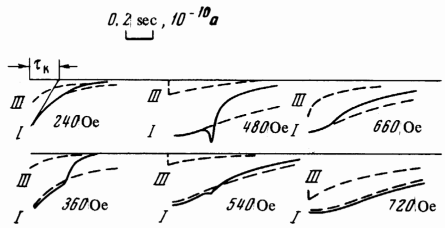


FIG. 2. Oscillograms of the collector current [$I_\infty n(t)$] for pulsed switching of the magnetic field PAMF from configuration I to configuration III for different values of the magnetic field in the mirrors (the time is plotted along the abcissa axis). The dashed curves are the oscillograms for configurations I and III; the solid curves are for PAMF.

In addition to finding the quantities $\bar{\tau}$ and τ_c, we also determined the quantity τ_k; the method by which this quantity is determined is given in Fig. 2. As is evident from Fig. 2, the quantity τ_k is determined by the distance from the origin of the collector current oscillogram to the point of intersection with the abscissa axis of the tangent dn/dt constructed at the point of maximum slope. It can be assumed that τ_k characterizes the motion of electrons with magnetic moments close to the minimum value while τ_c applies to electrons with the maximum magnetic moment. By investigating the dependence of $\bar{\tau}$, τ_k, and τ_c on H_{max}, it is possible to draw conclusions as to the motion of electrons with different values of μ.

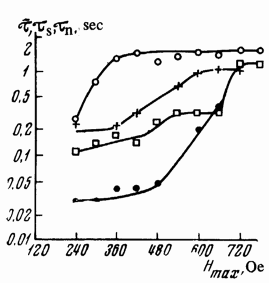


FIG. 3. The dependence on H_{max} of the quantities τ_s, τ_n and $\bar{\tau}$ obtained by graphical analysis of the oscillograms in Fig. 2: ●—$\bar{\tau}$ for configuration I, □—$\bar{\tau}$ for configuration III, O—τ_n +—τ_s; l = 65 cm, W = 9 keV, U = 15.3 kV, $p \approx 10^{-8}$ torr.

This question can be investigated further by carrying out experiments in which the distribution of magnetic moment for the electrons in the trap is investigated as a function of time. The method by which this measurement is carried out is as follows. At some given time after capture, a second pulse of positive voltage U_2 is applied to the ring (the first pulse provides the capture); under these conditions the effective potential associated with the motion of electrons along the z-axis assumes the form $\mu H_z + e\varphi$ ($\varphi \approx U_2$ in the median plane of the ring) rather than μH_z. The mirror located at the injector side is "turned off" allowing the escape of a certain fraction of the fast electrons in the direction of the injector. The secondary electrons which are completely lost from the trap are rapidly reestablished and the value of the collector current established after the pulse is determined by the number of fast electrons that remain in the trap. Thus, at any given time after capture it is possible to find the dependence of the number of fast electrons remaining in the trap as a function of the pulse voltage. The upper limit for the region of magnetic moments of electrons that escape from the trap under the effect of the pulse can be estimated from Eq.

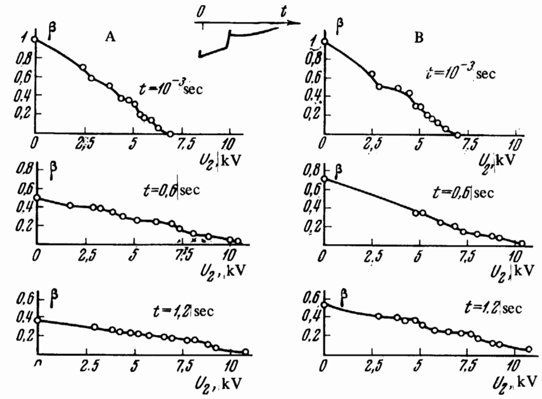


FIG. 4. The quantity β, which is the number of particles captured in the trap after the second voltage pulse is applied to the ring U_2 divided by the initial number of trapped particles, as a function of U_2 at various times t for W = 9 keV, U = 7.7 kV, p = 5 x 10^{-9} torr, l = 72 cm, H_{max} = 840 Oe. A—configuration I, B—configuration II.

(1). Thus, for any given time one can determine $N(\mu)$, the number of electrons with magnetic moments ranging from μ_{max} to μ_{min}. By differentiating the curves $N(\mu)$ it is then possible to find the distribution of electrons over magnetic moment $\rho(\mu, t)$. The length of the second pulse is 6 μsec. The variation in collector current under the effect of the pulse U_2 is shown in the oscillograms in Fig. 4.

We note that for a given $\rho(\mu, t)$ it is possible to find the coefficients in a Fokker-Planck equation for electron motion in magnetic-moment space. In the present experiments the measurements of $\rho(\mu, t)$ have not been performed with sufficient accuracy to carry out this procedure.

The last group of experiments consists of those in which investigations are made of the loss of particles from the trap upon the pulsed application of an additional magnetic field (PAMF). In these experiments electron capture in the trap is carried out using the magnetic field configuration denoted by I above. After 0.15—0.12 sec following capture the additional solenoids are switched on. The magnetic field geometry is changed adiabatically and in 10^{-2} sec the configuration denoted by III is established, this configuration having a larger value of $\nabla H/H$ than the configuration denoted by I (cf. Fig. 1). These measurements are carried out with residual gas pressures of 10^{-8}—10^{-9} torr so that at the time the additional field is switched on only a small number of electrons have escaped from the trap.

4. NONADIABATIC LOSS OF ELECTRONS ON THE TRAP

The $\bar{\tau}(H_{max})$ curves have three characteristic regions (cf. Fig. 5). For large values of H_{max} the particle lifetime in the trap $\bar{\tau}$ = const. For small values of H_{max} it is approximately an order of magnitude smaller and is a weak function of magnetic field. In the intermediate region the quantity $\bar{\tau}$ exhibits a sharp variation. The intermediate region can be conveniently characterized by the quantity H_{cr}, the value of H_{max} for which the particle containment time is 0.9 of the containment time characteristic of large fields.

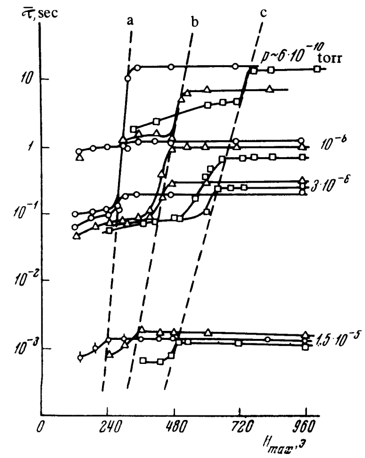


FIG. 5

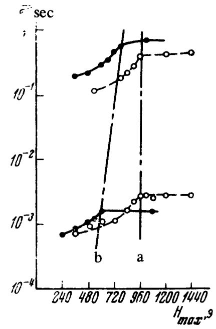


FIG. 6

FIG. 5. The functional dependence $\bar{\tau}$ (H_{max}) for various residual gas pressures in three magnetic field configurations: ○—configuration I, △—configuration II, □—configuration III, W = 9 keV, U = 4 kV, l = 65 cm.

FIG. 6. The functional dependence $\bar{\tau}$ (H_{max}) for special magnetic field configurations (see text); W = 9 keV, U = 4 kV, l = 65 cm. The lines indicate the absence a) of a shift in H_{er} with pressure in the case in which the main field is distorted by a steel bar located at the side of the chamber while b) shows the presence of a bias in the case in which the field is distorted by a steel bar around the axis of the chamber. The upper and lower groups of curves are for pressures of 2 x 10^{-8} and 10^{-5} torr respectively.

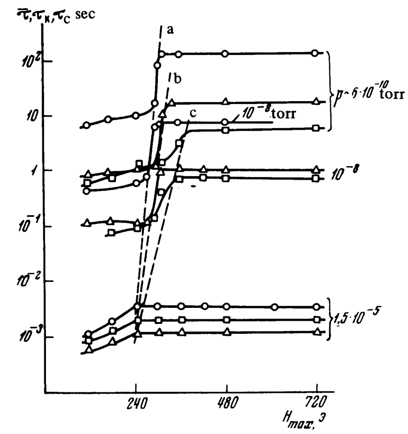


FIG. 7. The functions △—$\bar{\tau}$ (H_{max}), ○—τ_c (H_{max}), and □—τ_k (H_{max}), for various residual gas pressures; W = 9 keV, U = 4 kV, l = 65 cm, configuration I.

In addition to being reduced by the nonadiabaticity, the quantity $\bar{\tau}$ is reduced at small fields by a number of other processes. For example, as the field is reduced the Larmor radius is increased and the loss of electrons due to collisions with the chamber walls and the probe[9] increases. Furthermore, at low fields some of the electrons characterized by large values of μ can strike the chamber wall and the probe at the time of capture; another mechanism for the reduction of $\bar{\tau}$ lies in the differences in the shape of the electron distribution over magnetic moment at small fields and large fields.

If these last effects turn out to dominate, while the effect due to the loss of adiabaticity is small, the containment time measured for any value of the magnetic field H_{max} should be inversely proportional to the pressure of the residual gases. This case is shown in Fig. 6 (dashed curves). Here, the magnetic field is produced by the primary solenoids while the auxiliary solenoids are switched off and a steel bar is located at the side surface of the trap. Under these conditions the geometry of the lines of force is changed to such an extent that at low fields some of the electrons with large values of μ at capture strike the walls of the chamber. Curves measured at different residual gas pressures are found to be similar and in this case it is difficult to isolate the effects due to the lack of adiabaticity from the measured results.

The functional dependence $\bar{\tau}$ (H_{max}) is somewhat different (Fig. 6, solid curves) for an axially symmetric distortion of the primary field by a steel bar which encircles the side of the trap. With increasing pressure the reduction of $\bar{\tau}$ with reduction in H_{max} is found to be much smoother and the quantity H_{cr} is found to be reduced. The difference in the behavior of the curves indicates the existence of a mechanism for electron loss from the trap not connected with gas scattering and not due to the apparatus effects noted above.

In Fig. 5 we show the functional dependence $\bar{\tau}$ (H_{max}) for the magnetic field configurations I, II, and III for different residual gas pressures. The following conclusions are indicated: 1) the reduction in $\bar{\tau}$ becomes smoother at higher residual gas pressures; 2) as the pressure increases the quantity H_{cr} is reduced; 3) for the configuration denoted by II the value of H_{cr} is larger than for I while for III it is larger than for II. This result is due to the different value of $\nabla H/H$ in the different configurations and is not a consequence of the apparatus effects since the measurements show that for a given value of H_{max} in configurations II and III the probe currents are not larger than for I. The effects listed in 1—3 appear to indicate that under the present experimental conditions the origin of the sharp reduction in $\bar{\tau}$ at reduced values of H_{max} is the nonconservation of μ (collisionless conditions).

5. FEATURES OF THE ELECTRON LOSS FROM THE TRAP

A preliminary analysis of the feature of the electron motion for electrons with different values of μ can be carried out on the basis of the measured results shown in Figs. 5 and 7. In Fig. 7, where we show the curves $\bar{\tau}$, τ_K and τ_c obtained from the same oscillogram, it is evident that as the magnetic field is reduced the reduction in τ_k starts at larger values of the magnetic field than for $\bar{\tau}$. For τ_c the reduction starts at lower values of the magnetic field. It then may be assumed that for electrons with small values of μ the appearance of nonadiabatic effects in the motion starts at higher magnetic fields.

At low fields the containment time is a weak function of the magnetic field (Figs. 5, 7). This indicates the existence of regions in magnetic-moment space in which the motion is stable and in which the nonadiabatic effects are small. It may be assumed that in these field regions the containment is, to a considerable degree, determined by the dimensions of the indicated magnetic-moment regions.

The relatively rapid loss of electrons with small

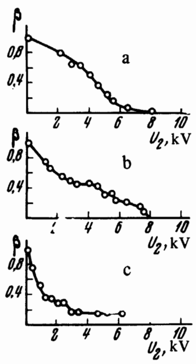


FIG. 8

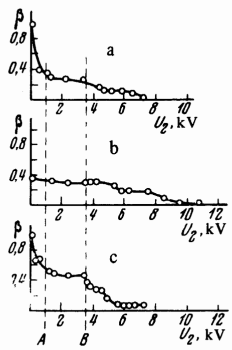


FIG. 9

FIG. 8. Spectra taken 10^{-3} sec after electron capture in the trap for different magnetic field strengths in configuration I: a–H_{max} = 720 Oe, b–H_{max} = 420 Oe, c–H_{max} = 300 Oe; W = 9 keV, U = 7.7 kV, p = 5 x 10^{-9} torr, l = 77 cm, H_{cr} = 480 Oe.

FIG. 9. Spectra taken a–10^{-3} sec and b–3.4 sec after electron capture (W = 9 keV, U = 7.7 kV, p = 5 x 10^{-9} torr, l = 65 cm) PAMF from configuration I to configuration III; c–spectrum taken 10^{-3} sec after capture under the same conditions as in a, but with U = 15.4 kV.

values of μ as well as the motion of electrons in the region $\mu > \mu_{lim}$ can be observed directly by spectral measurements. An increase in the number of electrons in the region μ_{lim} to μ can be attributed to scattering on the residual gas since the observed characteristic times for this process are approximately equal to $\bar{\tau}$ at large fields, in which case $\bar{\tau} \propto p^{-1}$ (Fig. 5). Nonetheless, even in regions of high field one observes in the spectral measurements slow changes in magnetic moment that are not due to gas scattering. These are evident in the formation, in the magnetic-moment space, of a number of regions with highly different density (Fig. 4). It is possible that in this case the changes in magnetic moment do not lead to the loss of electrons from the trap but that these effects are bounded by limits corresponding to the maximum density.

Spectra taken with $H_{max} < H_{cr}$ some 10^{-3} sec after capture are of a nonmonotonic nature (Fig. 8). These spectra exhibit a number of regions with anomalously low electron density (the region denoted by AB in Fig. 9). As the confinement is reduced the spectra do not disappear and the origin of this complex shape is not understood at the present time.

It has been noted in the spectral measurements that the magnetic-moment space can be divided into two regions (μ_{min}, μ^*) and (μ^*, μ_{max}), $\mu_{min} < \mu^* < \mu_{max}$ in which the electron behavior is completely different: the time for electrons capture in the region (μ_{min}, μ^*) is much smaller than the containment time for electrons captured in the region (μ^*, μ_{max}). In Fig. 9 the boundary between the regions corresponds to the dashed line B. In view of this difference the time dependence of the number of particles in the trap can be approximated by the expression

$$n(t) \approx n(0)\,[A \exp(-t/\tau_s) + B \exp(-t/\tau_n)], \qquad (3)$$

where τ_s is the containment time for electrons captured in the region (μ_{max}, μ^*), and τ_n is the containment time for electrons captured in the region (μ^*, μ_{min}). The approximation in (3) is a fairly good fit with the form of the oscillogram in Fig. 2.

The functions $\tau_n(H_{max})$ and $\tau_s(H_{max})$, which are shown in Fig. 3, are obtained by graphical analysis of the oscillograms of the collector electron current (Fig. 2) in the experiments with PAMF. It is evident from Fig. 2 that after PAMF there is a sharp reduction in electron signal. The effect becomes noticeable when $H_{max} < H_{cr}$ in the configuration noted by III, that is to say, in the field region in which lack of adiabaticity in configuration III leads to a reduction in $\bar{\tau}$. The absence of the effect when $H_{max} > H_{cr}$ in configuration III indicates that we can exclude adiabatic cooling of electrons during the change in magnetic field configuration as the reason for the rapid escape of electrons from the trap following PAMF.

Measurements of the current of primary electrons have shown that the strong burst of total collector current, which is observed on some oscillograms, is due to primary electrons; in certain cases, during the time in which the field configuration is changing (10^{-2} sec) instead of one burst sometimes there are several peaks.

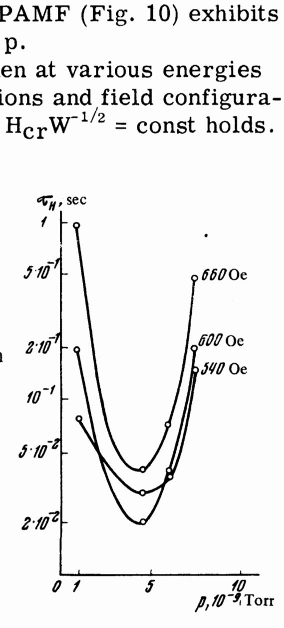
In cases in which H_{max} is much smaller than H_{cr} in configuration I the effect of PAMF from configuration I to configuration III is not observable. This can be explained by the fact that in this region the containment time in configurations I and III is approximately the same (Fig. 5); furthermore, an appreciable fraction of the electrons leave the trap before PAMF. We may also indicate that when $H_{max} > H_{cr}$ in configuration I we obtain an almost uniform distribution of electrons in the region (μ_{min}, μ_{lim}) and when $H_{max} < H_{cr}$ the configuration in I leads to a rather complex spectrum.

In a number of experiments PAMF was carried out after a number of electrons were expelled by application of a second pulse to the ring (the first pulse provides capture). Under these conditions the effect of PAMF is reduced and becomes hardly noticeable at certain values of the second pulse; this result indicates the absence of cooling of electrons at the chamber walls after PAMF and suggests the existence of a region of magnetic moments in which the lack of adiabaticity of the motion is highly pronounced.

We may also note that the dependence of τ_n on p found in the measurements with PAMF (Fig. 10) exhibits a minimum in certain regions of p.

From the $\tau(H_{max})$ curves taken at various energies but with the same vacuum conditions and field configurations it is found that the relation $H_{cr}W^{-1/2}$ = const holds.

FIG. 10. The quantity τ_n as a function of residual gas pressure for different values of H_{max}; W = 9 keV, U = 4 kV, l = 65 cm. PAMF from configuration I to configuration III.



The nonadiabaticity parameter $a_{\parallel}$ for $H_{max} = H_{cr}$, as a function of the residual gas pressure for the curves $\tau_c(H_{max})$, $\tau_k(H_{max})$ and $\bar{\tau}(H_{max})$ for various magnetic field configurations.

p, torr	τ_c			τ_k			$\bar{\tau}$		
	I	II	III	I	II	III	I	II	III
$6 \cdot 10^{-9}$	0,065	0,041	0,053	0.053	0,038	0,050	0,064	0,040	0.052
10^{-8}	0.069	0,047	0,063	0.056	0,043	0,055	0,068	0,044	0.059
$3 \cdot 10^{-8}$	0,075	0,050	0,063	0,058	0,043	0,055	0,068	0.045	0,063
$1.5 \cdot 10^{-5}$	0,115	0,063	0,080	0,087	0,057	0.056	0,087	0.063	0,080

6. DISCUSSION AND CONCLUSIONS

A. By measuring the functional dependence $\bar{\tau}(H_{max})$ for any given field configuration with different residual gas pressures we obtain several values of H_{cr} and $\tau(H_{cr})$. It is evident from Fig. 5 that the inflection points on the curves $\bar{\tau}(H_{max})$, where $H_{max} = H_{cr}$ for each configuration, lie approximately on the lines denoted by a, b, and c respectively for configurations I, II, and III. We can then conclude that under the experimental conditions which apply to this figure $\Delta\mu/\mu$ ($\Delta\mu$ is the nonadiabatic change of μ in one longitudinal oscillation) exhibits a functional dependence on H_{max} of the form $\exp(-\chi H_{max})$. The maximum value of H_{cr} at which the measurements were carried out was determined by the minimum allowable residual pressure, this quantity being approximately 6×10^{-10} torr.

B. In the table we show the maximum values of the parameter $a_{\parallel} = (mcv_{\parallel}/eH)\nabla H/H$[11] at $H_{max} = H_{cr}$ for the functions $\bar{\tau}(H_{max})$, $\tau_c(H_{max})$ and $\tau_k(H_{max})$ in different field configurations. It is evident that the critical value of the adiabaticity parameter depends on the magnetic field configuration. The nonadiabaticity is largest in configuration I, where the dependence of field on the longitudinal coordinate is approximately parabolic.

Thus, the behavior of the nonadiabatic processes does not only depend on the nonadiabaticity parameter, but also depends on the field geometry. This conclusion is also supported by the different depth of the drops in the $\bar{\tau}(H_{max})$ curves as the field is reduced. The greatest depth is observed in configuration I and the smallest in configuration III (Fig. 5).

C. The different slope of the curves $\tau_k(H_{max})$, $\bar{\tau}(H_{max})$ and $\tau_c(H_{max})$ (Fig. 7) indicates differences in the nonadiabatic processes for electrons characterized by different values of μ. In this work we have discovered a region (μ_{min}, μ^*) in which the nonadiabatic effects are expressed most strongly. In the region (μ^*, μ_{max}) the appearance of nonadiabatic effects starts at lower values of the field. The dependence of the relative parameters of these regions on H_{max} has not been investigated in detail; the experimental results lead to the conclusion that as the field is reduced the relative dimensions of the region (μ_{min}, μ^*) are increased.

The accumulation of electrons near the loss cone in the spectra as measured 10^{-3} sec after capture, when $H_{max} < H_{cr}$, can be explained as follows. When $\mu \to \mu_{min}$ the period of the longitudinal oscillations approaches infinity and electrons near the loss cone spend a large part of the period close to the center of the mirror, where the field is essentially uniform. Hence it is expected that in the region (μ_{min}, μ^*) a narrow range of magnetic moments close to the loss cone will be relatively stable. For a given interval of time electrons in this zone will execute a smaller number of longitudinal oscillations than electrons with larger values of μ; consequently they will make a smaller number of passes through the field region where $a_{\parallel}$ is large.

D. The existence of a minimum in τ_c observed in the experiments with PAMF in certain ranges of values leads to the conclusion that the change in μ due to gas scattering and the change in μ due to the nonadiabatic effects are not independent processes. In Fig. 10 it is evident that the random collisions with molecules of residual gas at pressures of approximately 5×10^{-9} torr favor the development of an instability while an increase in pressure hinders this mechanism.

E. The effects listed in C and D show that the assumptions from which we have derived the formula for the "reciprocal time" are actually not satisfied; the formula actually should be used only for rough calculations of the containment time of charged particles in magnetic traps. The authors are indebted to B. V. Chirikov for discussion and to V. I. Potapov, Yu. N. Yudin and L. B. Krasitskaya for help with the experiments.

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