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ION CYCLOTRON PLASMA INSTABILITY IN A MINIMUM-B ADIABATIC TRAP

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We have investigated an ion cyclotron instability in a dense plasma $\sim 5 \times 10^9$ cm^{-3} with ion energy of approximately 1 keV in a magnetic field of 3000 G. The instability is manifest in the form of individual bursts with duration of 30–40 μsec that are accompanied by rf oscillations and the loss of plasma to the walls. The bursts can be very different in nature. The amount of plasma lost to the walls corresponds to the observed reduction in density. The distribution of plasma flux to the walls indicates that the plasma losses along the magnetic field and across the magnetic field are of the same order of magnitude. The rotation of the velocity vector in the direction of the loss cone is also indicated by the marked longitudinal expansion of the plasma during the instability bursts. The rf signal exhibits a discrete spectrum in which the fundamental, corresponding to the ion cyclotron frequency, predominates. The magnitude of the electric field indicates that longwave oscillations, $\lambda \cong 30$ cm, are excited in the plasma; these oscillations are characterized by appreciable departures from plasma neutrality (several percent) with oscillation amplitudes for the potential being of the order of a kilovolt. A quantitative comparison of the available experimental data with the theory of cyclotron instabilities in a uniform plasma does not appear to yield consistent results.

IN earlier reports[1, 2] concerning experiments on the PR-5 system it has been indicated that under certain conditions the plasma exhibits an instability which appears in the form of a sharp discontinuous reduction in density which appears spontaneously in the quiescent, charge-exchange decay of the plasma. As has been indicated in the preliminary communication,[2] these jumps are accompanied by the expulsion of a certain amount of plasma to the walls, the appearance of rf bursts at the ion cyclotron frequency, and the acceleration of an appreciable number of ions in the trap to energies of the order of tens of kiloelectron volts. In the present work the results of a more detailed investigation of these phenomena are described.

1. EXPERIMENTAL CONDITIONS

These experiments were carried out with the PR-5 system,[3] which is a mirror device 120 cm in length and 40 cm in diameter with a mirror ratio of 1.7. The minimum-B configuration is produced by 3 pairs of longitudinal current-carrying conductors; these conductors are located at the periphery of the trap. The system is filled with a hydrogen plasma with hot ions. A schematic diagram is shown in Fig. 1.

The experiments described here were carried out with a longitudinal magnetic field of 3 kG; the radial mirror ratio in the central cross section is 1.2. The pumping is carried out by titanium sputter pumps in which titanium is sputtered on the walls of the chamber, which are maintained at room temperature. Using this system, the residual vacuum is better than 5×10^{-8} torr; however, during operation in the pulse mode the vacuum in the trap deteriorates to 10^{-7} torr because of outgassing from the walls due to the effect of the injected plasma.

The trap is filled by plasma in the following way. A plasma pinch, similar to that used earlier in magnetron injection (cf. [3]), is injected along the chamber axis by a pulse of length 300 μsec. Before the pulse is terminated there is applied to the pinch an alternating potential in the form of a burst of damped oscillations which are obtained by discharging an LC circuit which is charged to 30–35 kV. The oscillation frequency 4.5 MHz is approximately the same as the ion cyclotron frequency and the characteristic decay time is approximately 1 μsec. The load on the tank circuit due to the pinch is 1 ohm. Immediately after the decay of the rf pulse the pinch is turned off and the plasma undergoes free decay.

In the first 100–200 μsec after the termination of the injection pulse the plasma decays very rapidly; after this period the decay rate is retarded appreciably. Similar behavior has been observed earlier in [1], in which possible causes for the rapid initial density decay were discussed. After this decay (from an initial density of approximately 10^{11} cm^{-3}) the residual plasma in the trap is characterized by a density of approximately 5×10^9 cm^{-3} over a volume of several liters. The mean ion energy, as estimated from the shape of the energy spectrum of the charge exchange particles, is 1000 eV while the electron temperature is less than tens of electron volts. This plasma decays with a characteristic time of 1–3 msec which is close to the charge exchange time. However, as a rule, on this decay process

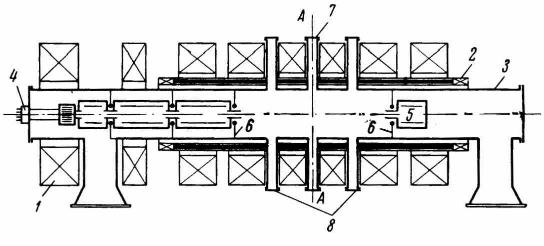

FIG. 1. Diagram of the PR-5 device: 1) longitudinal field winding, 2) stabilizing field winding, 3) vacuum chamber, 4) plasma source, 5) detector electrode, 6) limiters, 7, 8) ports for motion of the measurement apparatus in the median plane and the side planes. Central cross-section of the system.

there are superimposed instability bursts which lead to the density discontinuities mentioned above.

Frequent discontinuities are observed if the discharge in the torus which produces the pinch is sufficiently strong so that the amplitude of the accelerating rf pulse is at least 20–25 kV and the operating vacuum is 10^{-6} torr or better. It is necessary that the frequency of the accelerating pulse coincide with the ion cyclotron frequency; these frequencies can differ by tens of percent.

2. DISCONTINUITY CHARACTERISTICS

The basic method used to observe the discontinuities in density is the detection of the flux of charge-exchange particles in the median plane of the system. It should be recalled that this signal does not represent the total density, but rather the density of the hot-ion component, the magnitude of which can change to a greater degree than the total density as a result of the jumps. The method based on probing by a potassium beam,[1] which gives information on the total density, has not been used in the present experiments since this method is characterized by a rather poor resolution time and is suitable only for rough detection of the existence of a discontinuity.

The jumps observed on the charge-exchange signal exhibit various characteristics. Most frequently they are observed in the first millisecond of free decay, but sometimes after 2–3 msec. Frequently it is possible to observe 2 or even 3 jumps on a single oscilloscope trace. The form of the discontinuities can be characterized by two basic features: the relative reduction in the signal (height of the discontinuity) and the presence of a narrow burst preceding the discontinuity (the origin of the burst is discussed in Sec. 5). The total time interval during which the anomalous charge-exchange signals are observed is always the same and is approximately 50 μsec.

In shape the jumps can be tentatively divided into three main classes. The characteristic features of the first class are shown in oscillogram 1 of Fig. 2. Before the jump there is a burst; the height of the jump is approximately 30–40%. However, this height becomes smaller and it is possible to observe a sequence of jumps of this first class with a continuous reduction toward zero of the height (1–3, Fig. 2). In the latter case the jump, as such, does not appear and the presence of the instability is only indicated by the burst in the charge-exchange signal.

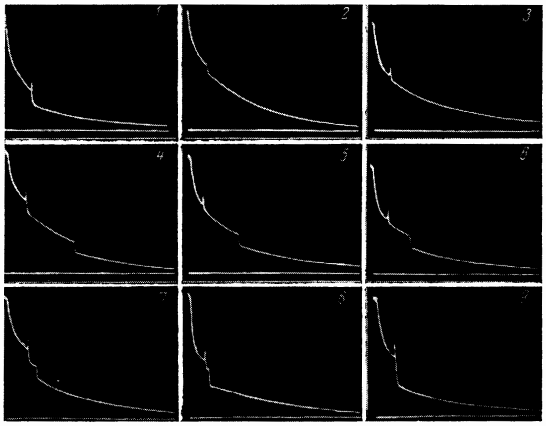

FIG. 2. Oscillogram showing the charge-exchange signals that characterize different jumps. The sweep length is 3 msec.

Another class is represented by jumps without bursts which are shown by the oscillograms 4–6 in Fig. 2. In this case the height of the jump is always 30% and the burst either does not appear or is hardly visible. A characteristic feature is the fact that the jumps that occur without bursts are always second jumps which follow a jump of the first class with the same or different height.

The jumps in the third class are larger (9, Fig. 2). This jump exhibits a burst similar to the first type, but the height of the jump is 50–80%. It appears that the large jump is a result of the superposition of several jumps of the first and second classes. This picture arises if one considers three oscillograms where the first and second jumps follow closely upon each other (7, Fig. 2) or even partially overlap (8, Fig. 2). In these cases the general form of the signal is very similar to the form of a large burst.

After the large jumps, just as after jumps of the second class, usually there are no further anomalous charge-exchange signals. The accompanying instability effects such as the expulsion of plasma from the trap and the rf signal burst are most intense for the large jump. In general, the results of the experiments described below apply to the case of the large jump unless specific indication is given otherwise.

It has not been possible to establish a relation between the observation of the various classes of jumps and the experimental conditions. Usually, in one series of identical experiments different kinds of jumps are observed at different times with the predominance of one class. In certain cases there are new varieties of anomalous charge-exchange signals which differ from those described above. However, operational regimes corresponding to these cases have not been investigated specifically.

3. RF BURSTS DURING THE JUMPS

The high-frequency electric and magnetic fields have been investigated near the walls in the median plane of the trap. The electric signals are observed by means of a disc electrode 2.5 cm in diameter, which forms part of the side wall. In this case the flux of charged particles striking the electrode does not represent the noise since its magnitude is much smaller than the rf displacement current detected during a jump. The magnetic signal is observed by means of a loop antenna which is shielded by a slotted metal shield from the electric field and the particle fluxes. The plane of the loop antenna can by oriented arbitrarily but remains perpendicular to the wall surface. Thus, the rf probes record the normal component of the electric field and the tangential component of the magnetic field (with respect to the walls). Matched transmission lines have been used to provide uniform frequency characteristics for the rf probes in the range 1–19 MHz. The rf signal from the probe is fed to a narrow-band (~0.5 MHz) tunable amplifier and then detected and displayed on the oscilloscope.

The observations indicate the absence of appreciable rf signals over the entire tail of the decay following the termination of injection, with the exception of the times corresponding to the jumps, during which intense rf bursts are observed (cf. Fig. 6 below). The spectral composition of the rf signals as averaged over a large number of pulses is shown in Fig. 3. One can see the sharply defined discrete nature of the spectrum with rapidly decaying harmonics. The frequency of the fundamental corresponds to the ion cyclotron frequency at the center of the trap. The amplitude of the rf electric field at the wall is approximately 50–70 V/cm for the fundamental; the amplitude of the longitudinal component of the magnetic field, parallel to the axis, as measured 2–3 cm from the wall is found to be approximately 3×10^{-3} G. The qualitative features of the spectra remain unchanged for different kinds of jumps.

Attempts have also been made to establish the direction of flow of the rf current in the plasma by determining the orientation of the rf magnetic field component parallel to the wall. These experiments have not given reproducible results but in some cases the magnetic field appears to be circularly polarized.

The spectra that have been obtained indicate that the instabilities leading to the density jump are expressed in the excitation of oscillations at the ion-cyclotron frequency. Although the signal spectra exhibit higher harmonics of the ion cyclotron frequency, it is probable that the actual excitation does not occur at these frequencies since the field amplitudes of the harmonics are small compared with the fields at the fundamental frequency. The higher harmonics could be secondary in origin and are probably related, for example, to the nonlinear electrical properties of the medium (plasma) which lies between the rf field source and the point of observation. It is also possible that the oscillations themselves are anharmonic as a consequence of the nonlinear effects that arise at large amplitudes.

As has been reported earlier,[2] after the burst of instability in the trap there is a small number of ions with energies of tens of kiloelectron volts. Evidently this energy is acquired as a result of cyclotron acceleration of individual ions in the resonance electric field observed in the experiments that have been described.

The magnitude of the observed rf electric field allows us to estimate the wavelength of the unstable oscillations. The fact that the amplitude of the electric field is somewhat greater than the amplitude of the magnetic field indicates that the electric field is not solenoidal, but that it is of a potential character; it is an electrostatic field produced by a system of polarized charges which form in plasma bunches with partial separation of the ion and electron components. If a is a characteristic dimension of the plasma (for example the radius of the plasmoid) while $\lambdabar$ is the quantity that characterizes the wavelength of the oscillation and also determines the dimensions of the region containing the excess charge of one sign, then the number $m = a/\lambdabar$ obviously corresponds to the number of pairs of regions with charges of the opposite sign which form in the polarization of the bunch. Knowing the intensity of the rf electric field at the walls and knowing the quantity a and assigning a given number of waves m, it is not difficult to estimate the magnitude $\pm Q$ of the excess charge lying within one-half wavelength.

For example, in the case of azimuthal waves of lower mode number one can invoke the simplification that the charge in a half-wavelength is localized in the form of a uniformly charged filament oriented parallel to the axis approximately at half the radius of the plasma and with a length equal to the length of the pinch. For this system of m linear dipoles one can solve the electrostatic problem of determining the value of the field at the surface of the metal walls of the vacuum chamber (taking account of the image charges); from a comparison with the experimentally measured field at the walls one can then determine the appropriate value of Q for given values of m. Then, the linear localization of the charges can be replaced by the volume distribution which is harmonic in azimuth ($\cos m\theta$, where θ is the azimuth angle) and one can compute the maximum value of the potential φ and the field E in the plasma as well as the departure from neutrality $\Delta n/n$ (n is the plasma density and Δn is the excess charge density of one sign) which can be regarded as the peak values of these quantities in the wave.

We present below the results of the calculation of this kind under the assumption that $a \approx 10$ cm $\approx L/2$ (L is the length of the plasma), $E_{\text{wall}} \approx 70$ V/cm and $n \approx 5 \times 10^9$ cm^{-3}. In order to be definite we consider the case of azimuthal polarization of the plasmoid; however the results will be similar for other oscillation configurations. We have

m:	1	2	3
$\lambdabar$, cm	10	5	3
φ, kV	2.5	6.2	17
E, kV/cm	0.5	2.5	10
$\Delta n/n$, %:	1.6	7	27

It is evident from the data given above that if one assumes two or three wavelengths around the periphery of the plasmoid one must have extremely high oscillation amplitudes for the potential within the plasma. This possibility, however, will tend to be limited by the rough condition that the energy of the electric field in the wave cannot exceed the initial energy stored in the plasma. If $\mathscr{E}$ is the initial mean ion energy then the condition given above obviously requires that $E^2/8\pi < \mathscr{E}n$. It is evident that even when $m = 2$ this condition is almost violated, the more so, since we are dealing with oscillation energy and the efficiency of transfer from the ion energy is not complete but must always be a fraction, indeed generally a small fraction, of this latter quantity.

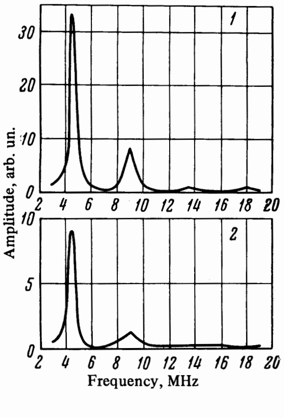

FIG. 3. rf spectra observed during instability bursts: 1) spectrum derived from the electric signal, 2) spectrum derived from the magnetic signal.

Taking account of these estimates one sees that for the azimuthal waves the experimental results indicate that one is looking at the first modes of the oscillations. Thus, the wavelength at the outer perimeter of the plasmoid will be measured in tens of centimeters while the characteristic parameter $k\rho_i$ which appears in the theoretical calculations (k is the wave number, ρ_i is the ion Larmor radius) amounts to several tenths. It should also be noted that these conclusions apply qualitatively in the general case regardless of the direction of the wave vector for the instability.

The conclusions as to the wavelengths can, in principle, also be verified from the observed intensity of the rf magnetic field which, like the electric field, is related in a definite way to the magnitude of polarized charges and the wavelength. However, in this case the verification is not entirely unambiguous because one must also have information on the mechanism by which the oscillations are generated and this information is as yet not available. We can note, that at least for several kinds of waves, the longitudinal component of the magnetic field must be of an order of magnitude such as that corresponding to production by the azimuthal rotation of the polarized charges, that is to say, $H_{||} \approx Ev/c$ where v is the apparent rotational velocity, equal to $\omega_i a/m$ (ω_i is the ion-Larmor frequency). This estimate is also in agreement with experimental result if one assumes low values of m.

4. PLASMA EXPULSION FROM THE TRAP DURING A JUMP

The plasma flux from the trap is recorded by measuring the ion current to special electrodes which are located at the surfaces of the chamber walls. At the ends the current is measured by means of two concentric planar rings which intersect a large part of the area of one of the diaphragms. At the side wall the topology of the current distribution over a segment of the surface is measured; this surface is bounded in azimuth by the angle measured from the center of the space between two neighboring longitudinal conductors to the center of one of the conductors and in length by the distance from the median plane to the end. Measurements within the boundaries of this segment, carried out with current flowing in opposite directions in the stabilizing winding, make it possible to obtain the complete pattern of the plasma flux at the side wall. In order to carry out these measurements at this surface we make use of 24 plane electrodes, 2 cm in diameter, which are arranged in three series: along the center of the conductor, along the center of the gap, and in an intermediate position.

In measurements of the flux of escaping plasma a negative bias is applied to the electrodes, this bias being sufficient to retard plasma electrons.

The measurements indicate a strong loss of plasma from the trap during the time of the injection pulse and in the subsequent transient process. During the slow exponential decay stage there is essentially no current to the walls. However, at the time of a jump one always observes a sharp current peak (cf. below Fig. 6). The nature of the plasma expulsion from the trap in the instability burst is related to the height of the indicated peak.

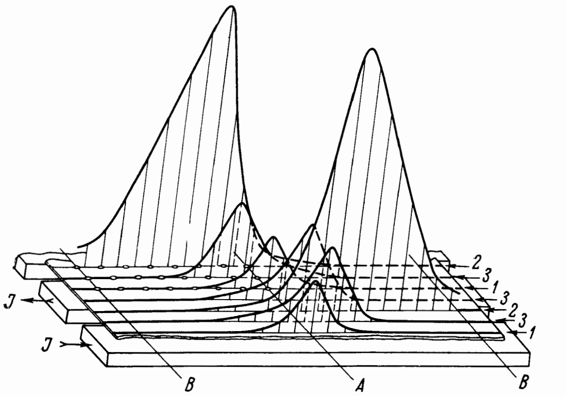

FIG. 4. Pattern showing the side surface of the vacuum chamber together with the stabilizing conductor windings. The figure illustrates the distribution of ion current at the sides of the chamber for different values of azimuth. The circles denote the measurement electrodes: 1) azimuth corresponding to the center of the stabilizing winding conductor, 2) azimuth corresponding to the center of the gap between conductors, 3) intermediate value of the azimuth. A) central cross-section of the trap, B) cross-section at the maximum of the longitudinal mirrors.

In Fig. 4 we show the current distribution at the surface of the side walls during a jump, as averaged over a large number of measurements. It is evident that the maxima in plasma flux are localized in the spaces between the conductors and that these are displaced from the median plane toward the mirrors.

The measured plasma flux at the ends during the time of a jump is 15 to 20 times smaller than at the side wall. The total number of ions expelled from the trap in a jump is $(5-10) \times 10^{12}$, which is two or three times greater than the estimate based on the height of the jump in the charge-exchange signal. This discrepancy might be due to the presence, in the plasma flux leaving the trap, of an appreciable amount of relatively slow ions which yield a small contribution to the charge-exchange signal.

The distribution of expelled plasma at the surface of the trap can be judged more accurately on the basis of Fig. 5, which shows the region of overlap of the lines of force which pass through the central part of the trap to the walls. It follows from a comparison of Figs. 4 and 5 that the largest current density is to be found at those sections of the wall which intersect the lines of force that pass through the region in which the plasma density is highest.

However, the strong loss of plasma along the magnetic field cannot be regarded as proof of the predominant role of loss through the loss cone. The point here is that in traps of the kind being considered the transverse diffusion of the plasma can not be separated from loss along the field. Particles which undergo transverse fusion only will move to the peripheral lines of force where the mirror ratio is smaller and, ultimately be lost to the side walls along the lines of force. Hence, the observation of dense flux in regions at which the lines of force go to the side walls does not exclude transverse diffusion.

A direct indication of the existence of transverse diffusion is given by the appreciable amount of current at the sections of the wall which are located under the conductors close to the median plane. At these points the lines of force are parallel to the wall and the observed current can only be due to transverse displacement of the ions. The total magnitude of the transverse flux computed from the current density at the electrodes under the conductor is approximately one third of the total amount. It is evident that this large fraction cannot be due to random trajectories of ions, the Larmor radius of which is highly increased as a consequence of acceleration due to instabilities. This explanation does not hold because the energy excess in the plasma is not sufficient for accelerating the required number of ions. Thus, it is concluded that there is a strong transverse diffusion at the time of a jump.

The presence of loss due to loss cone is also directly indicated in the form of an appreciable plasma flux to the ends of the trap and to the contiguous regions of the side walls. The magnitude of the mirror ratio is a maximum for the lines of force at this point and ion loss is only possible as a consequence of a rather large increase in an angle of inclination of the velocity vector toward the magnetic field. A direct illustration of this change in the direction of velocity as a result of the instability is also found in the longitudinal expansion of the plasma described in Sec. 6.

The measurements that have been carried out indicate that the longitudinal and transverse losses are of the same order of magnitude. With the presently available data it is difficult to provide a more exact relation between these quantities in the overall loss pattern.

5. TIME RELATION OF THE JUMP TO THE rf SIGNAL AND PLASMA EXPULSION, AND CORRELATION BETWEEN THESE QUANTITIES

A typical example of simultaneous oscillograms from three transducers is shown in Fig. 6. To within the limits of accuracy of approximately 10 μsec the rise times and peaks of these signals coincide. Consequently the growing instability is accompanied, from its very onset, by a change in the flux of charge-exchange particles in the median plane and the expulsion of plasma from the trap. The termination of the jump in the charge-exchange signal and the termination of the wall current signal are coincident with the rf signal to within 20–30 μsec.

Attention is directed to the increase in the charge-exchange signal in the first part of the instability burst. The magnitude of this increase is approximately 20–30% and, in certain cases, as high as 100%. Other observations (cf. Section 6) indicate that the charge-exchange signal increases at the sides of the trap as well as the center, indicating an absolute increase in the flux of charge-exchange particles at the time of the burst. It appears that the total flux grows by a factor of 2 or 3. This effect can be explained by an increase in the population or mean energy of those ion classes which make the basic contribution to the charge-exchange signal. This change in the spectrum is effective, as far as can be seen, only during the time of the instability, that is to say, it seems to be a feedback effect.[1) This forces us to assume that the energy increment acquired by the ions is of an ordered nature characteristic of collective oscillations or drift motion in the strong fields that arise in the instability. In the damping of the instability these fields also decay and the ordered component of the velocity disappears. According to this explanation we would also assume that the source of energy that drives the instability does not lie in that ion class which yields the charge-exchange signal, but rather in a colder portion of the spectrum.

The qualitative relation between the height of the jump and the charge-exchange signal, the expulsion of plasma to the wall, and the amplitude of the rf signals depend strongly on the nature of the jump. In different jumps the relations between the magnitudes of these four signals is found to be different; however, within the limits of any one class there is a tendency toward approximately uniform changes of all these signals in a given direction. Inasmuch as the classification of the signal types is largely provisional, one observes exceptions to these general tendencies.

The simplest pattern is found for jumps of the third class, the largest ones. For these, both the rf signal and the current to the walls is largest and changes the least from shot to shot.

A comparison of jumps of different kinds indicates a strong relation between the height of the burst on the charge-exchange signal and the intensity of the plasma expulsion from the trap to the wall. One of the manifestations of this relation is the fact that in jumps of the second kind (repeatable without expulsion) the current to the walls is a minimum. It is also interesting to note that an appreciable loss of plasma is accompanied by an anomalous charge-exchange signal which does not yield a jump like the current signal (3, Fig. 2). Evidently, in these cases only some number of relatively slow ions are expelled and these do not make a contribution to the charge-exchange signal.

6. LONGITUDINAL EXPANSION OF THE PLASMA DURING COMPRESSION

In addition to the measurements carried out in the median plane, we have detected the flux of charge-exchange particles in cross-sections located 30 cm closer to the mirror, where the magnitude of the longitudinal mirror ratio is 1.3. It has been established that in the quiescent state of the plasma the charge-exchange signal to the side detector is essentially zero, indicating a small longitudinal dimension for the plasma object. However, at the time of a jump one observes a strong signal indicating the presence of plasma in the side regions. The flux density of charge-exchange particles in the side region is 10–20% of the flux density at the center.

The observed dependence of the signal magnitude on the direction of current flow in the stabilizing winding and on the degree of collimation of the detector are compatible with the notion that during the time of an instability burst the plasma occupies a region which, in transverse cross-section, is in the nature of a three-point star (Fig. 5). Under these conditions the basic part of the plasma is evidently concentrated in the points.

[1)] We are not considering here the very fast ions, with energies of tens of kiloelectron volts, which appear after the jump since these represent a negligible fraction and do not make a significant contribution to the charge-exchange signal.

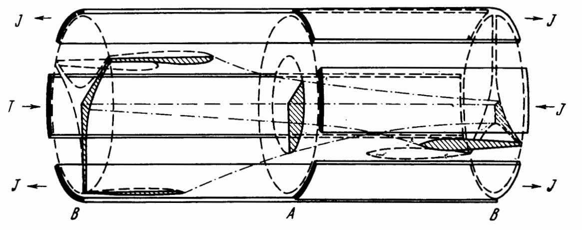

FIG. 5. Diagram showing the intersection of lines of force bounded within the center of the trap by a circle with the walls of the vacuum chamber. A) central cross-section of the trap, B) cross-section at the maximum of the longitudinal mirrors.

The charge-exchange signal observed in the side cross-sections cannot be explained as the "track" of the trajectory of those ions which are expelled from the trap during a jump. A quantitative estimate shows that in this case the charge-exchange signal could only be several percent of that which is actually measured. Thus, the basic contribution of the plasma in the side regions is due to ions which move into the acceptance region of the side detector many times. This could mean that the ions leaving the trap first undergo multiple oscillations between the mirrors and gradually move into the loss cone.

It should be noted that the charge-exchange signal in the side cross-sections is lost after the instability burst. The presence of a loss mechanism for the side regions after the termination of the instability and the absence of such a mechanism during the stable state have not been investigated specifically. One can postulate a relation between these factors and the fact that in general fast ions cannot be contained in the side regions of the combined trap because of the properties of the field configuration itself. Another possibility for explaining the plasma loss from the side regions after the jump is the fact that the longitudinal expansion of the plasma occurs under the effects of the high positive potential which can be acquired by the plasma as a consequence of the instability. At the end of the instability burst the potential of the plasmoid returns to the initial value within a short time (10–20 μsec) because of the loss of slow ions formed in charge-exchange. In this case the plasma from the side regions is again collected in the central part of the trap.

7. DISCUSSION OF RESULTS

Before discussing these experiments we wish to consider briefly the basic results obtained in observations of ion-cyclotron instabilities in other mirror devices.

The excitation of rf oscillations at the ion-cyclotron frequency and its harmonics has been observed in all devices with external injection of fast charged particles and fast neutral particles.[4–10] The strong anisotropy and monoenergetic nature of the ions in these devices favors the excitation of oscillations starting at some low plasma density $\sim 10^6$ cm^{-3}. As the density increases the amplitude of the oscillations increases as does the relative intensity at the higher harmonics. Frequently the oscillations appear in the form of discrete irregular bursts with lifetimes ranging from fractions of a millisecond to hundreds of milliseconds. The bursts are accompanied by the expulsion of electrons along the magnetic lines of force and a corresponding rise in plasma potential.

In going from the simple mirror configuration to the combined or minimum-B configuration one notices a strong reduction in the amplitude of the cyclotron oscillations and a reduction in the lifetime of the bursts. It appears reasonable that the weakening of the oscillations is due to the expansion of the angular distribution of the trapped ions with respect to the lines of force of the combined or minimum-B field, that is to say, a reduction in the degree of anisotropy.[5, 9]

Notwithstanding the various details in the oscillation behavior in various devices, a general feature of all appears to be the smearing out of the ion energy spectrum under the effect of the rf fields that arise in the plasma.

As far as the effect of cyclotron oscillations on plasma confinement is concerned, we find that the nature of the experimental information is rather unclear and in a number of cases actually ambiguous. Of the experiments carried out in simple mirror devices, the loss of plasma due to instabilities of the ion-cyclotron type has only been observed in DCX-1[7] and in DCX-2;[8] in all the other devices either this loss has not been observed[1, 10] or has been difficult to distinguish against the background of stronger losses caused by hydromagnetic flute instabilities.[5, 6] Three experiments relating to minimum-B configurations in this connection are those on Phoenix,[6] Alice[5] and Ogra-2.[9] In the first of these no loss due to cyclotron oscillations has been observed at all over the whole range of plasma density up to the maximum value that could be achieved 10^9 cm^{-3}. In the other two cases, even at the low densities $10^7 - 10^8$ cm^{-3} one observed a deviation from the linear growth of density in the median plane of the system with increasing injection current and it may be assumed that this is due to the presence of weak cyclotron oscillations. However, it is still not clear whether this deviation is due to real losses or only due to expansion of the region occupied by the plasma.

The experiments reported in the present paper are of interest in this connection as an example of a very strong ion-cyclotron instability in a minimum-B system. These experiments show that oscillations can be excited in these traps under certain conditions and that the intensity of the oscillations can be so strong as to lead to the expulsion of an appreciable fraction of the

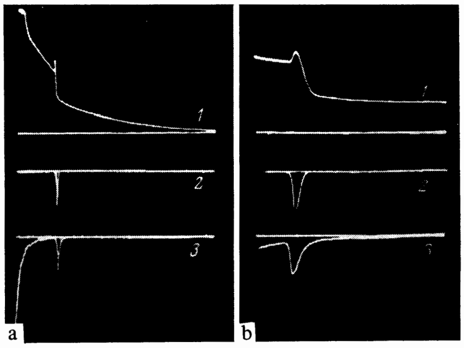

FIGURE 6. Simultaneous oscillograms of the charge-exchange signal (1), the rf signal (2) and the current to the side walls of the vacuum chamber (3). a) sweep length 3 mse, b) sweep length 0.5 msec.

plasma in the course of a single short-lived instability burst.

We now wish to make a more detailed analysis of these experiments. The excitation of instabilities in a combined minimum-B field is not surprising from the point of view of theory if one takes account of the fact that the excitation of cyclotron oscillations need not only be caused by an anisotropy in the ion velocity but can be caused by any nonmonotonic variation in the ion distribution function for the transverse velocity component $f(v_\perp)$ (the existence of a region in which $\partial f(v_\perp)/\partial v_\perp > 0$). It has been shown in [11] that the anisotropy can play a basic role in the excitation of oscillations at relatively low plasma densities: $1 < \omega_{pe}^2/\omega_{Bi}^2 < (M/m)^{1/3}$ (ω_{pe} is the electron plasma frequency, ω_{Bi} is the ion-cyclotron frequency, M is the ion mass and m is the electron mass). At higher densities the decisive factor is the nonmonotonic variation in $f(v_\perp)$. Hence, a possible weakening of the anisotropy in the transition from a simple mirror field to a combined field does not, in general, guarantee protection against cyclotron instabilities. Attempts to identify the observed instabilities with one of the kinds of ion-cyclotron instabilities that have been investigated theoretically[11-13] are, however, extremely difficult.

We now present a list of values of the plasma parameters, on the basis of which one can hope to make a comparison of experiment with theory: the plasma density $n = 5 \times 10^9\ \text{cm}^{-3}$ ($\omega_{pe} = 4 \times 10^9\ \text{sec}^{-1}$), the mean transverse ion energy $\mathcal{E}_{\perp i} \approx 1000$ eV, the anisotropy $\mathcal{E}_{\perp i}/\mathcal{E}_{\parallel i} = 10-15$, the electron temperature $T_e = 25-50$ eV, the magnetic field $H = 3000$ G ($\omega_{Bi} = 3 \times 10^7\ \text{sec}^{-1}$) the plasma length $L = 20-30$ cm, the plasma radius $a = 5-10$ cm and the shift of the oscillations frequency with respect to the ion-cyclotron frequency in the median plane of the trap $\Delta\omega = \omega - \omega_{Bi} \leq 5 \times 10^{-2}\,\omega_{Bi}$ while the mode number for the most intense cyclotron harmonic is $m = 1$.

Following the classification scheme given in [12] it may be assumed that for these plasma parameters the most probable instability is a hydrodynamic type due to the nonmonotonic variation of $f(v_\perp)$. In this case the oscillations can be excited in the form of oblique electrostatic waves in which a resonance obtains between the Larmor gyration of the ions and the longitudinal (magnetized) Langmuir oscillations of the electrons. In a uniform plasma, for these waves the relation between the components of the wave vectors $k_\parallel$ and $k_\perp$, the intensity of the magnetic field, the plasma density and the ion energy is given by

$$\frac{\omega_{pe}^2}{m^2\omega_{Bi}^2} \approx \frac{k_\perp^2 + k_\parallel^2}{k_\parallel^2} \approx \frac{k_\perp^2}{k_\parallel^2}, \quad k_\perp \rho_i \gtrsim 1,$$

where ρ_i is the ion-Larmor radius, the transverse energy of these ions corresponding to the region $\partial f(v_\perp)/\partial v_\perp > 0$ (since the oscillations are excited by virtue of the energy of this ion class only).

In order to make a direct verification, in order to see whether these relations hold in the experiment, it would be necessary to give additional results of the direct measurements of $k_\parallel$ and $k_\perp$ as well as the distribution function $f(v_\perp)$ starting at a sufficiently low value of $v_\perp$. Measurements of this kind have not been carried out at the present time. However, using the known values of ω_{pe}, ω_{Bi}, and m it is possible to find the ratio $k_\perp/k_\parallel$: furthermore, taking as the minimum value of $k_\parallel$ the quantity π/L, we can determine $k_{\perp\,\min}$ (or $\lambda_{\perp\,\max} = 2\pi/k_{\perp\,\min}$) and then make a comparison with experiment.

For the values of ω_{pe}, ω_{Bi}, m and L given above, the quantity $\lambda_\perp$ must be 0.5–0.6 cm. This estimate is in sharp contradiction with the conclusion as to the value of $\lambda_\perp$ which can be made on the basis of an analysis of the results of measurements of the amplitude of the rf electric field. As we have already noted (cf. Sec. 3) the presence, at the walls of the vacuum chamber, of fields of 50–70 V/cm can only be explained if one assumes that only the lowest modes are excited, corresponding to $\lambda_\perp \sim 30$ cm. It is easy to see that when $\lambda_\perp = 0.5-0.6$ cm the rf field cannot reach this value even with complete violation of the neutrality of the plasma in the wave (that is to say, for 100% separation of the ions and electrons). Independently of these considerations it is difficult to reconcile the small value of $\lambda_\perp$ with the condition $k_\perp\rho_i \gtrsim 1$. If $\lambda_\perp = 0.5-0.6$ cm this means that the section $\partial f(v_\perp)/\partial v_\perp > 0$ must lie in the ion energy region of several electron volts or, in an extreme case, several tens of electron volts. This is evidently not realistic since ions with such low energies will not in general be confined in the trap for any appreciable length of time.

In [14] the possibility has been discussed that the observed instabilities are excited by nonresonance oscillations in which the rigorous relation between the quantities $k_\parallel$, $k_\perp$ and ω_{pe}/ω_{Bi} $[(\omega_{pe}^2/\omega_{Bi}^2)(k_\parallel^2/k^2) > 1]$ is not satisfied. But for these oscillations as well we must still keep in mind the compatibility conditions for the transverse wavelength and the ion-Larmor radius $k_\perp\rho_i \sim 1$. This condition cannot be reconciled with the large values of $\lambda_\perp$ which are assumed because of the strong rf fields far from the plasma as we indicated earlier.

Dnestrovskiĭ and Kostomarov, using a method developed by themselves[15] have solved the numerical problem of cyclotron instability in a uniform plasma with parameter values approximately those of the present experiment. The results of these more exact calculations do not differ fundamentally from those given in the estimates above: the instability can only be explained if one assumes shortwave oscillations with $k_\perp\rho_i \approx 2-3$.

Thus, if one uses the notion of a uniform plasma it is not possible to establish satisfactory agreement between theory and experiment. It is possible that the reason is that the model of an infinite plasma with a uniform magnetic field is oversimplified as far as the present case is concerned. Actually, the plasma is in a non-uniform field of complex configuration, the plasma is inhomogeneous in density in both the axial and radial directions and is surrounded by conducting walls. Any of these factors can be important as far as excitation and other features of the instabilities are concerned.

We emphasize that the conclusion relating to disagreement between theory and experiment is based primarily on the indirect evidence concerning the magnitude of $\lambda_\perp$ which, in turn, is based on measurements of the amplitude of the rf electric field. At the present time arrangements are being made to make direct measurements of the spatial structure of the oscillations during the instability bursts.

In addition to the existence of the instability itself, another interesting aspect of the problem is that of determining the exact time at which the instability arises. Here, there appear to be two possibilities:

a) During the quiescent decay of the plasma due to charge exchange its parameters (density, dimensions, ion distribution function) change gradually and reach critical values at which the instabilities develop.

b) During the period of quiescent decay the plasma is in a metastable state and requires a finite amplitude random perturbation in order to be driven away from this state (so-called hard excitation).

The available experimental data do not allow us to decide which of these two pictures is correct. We can only introduce certain indirect factors which seem to indicate that the second possibility is the appropriate one. In the first place, with all external conditions being the same, the injection instability is not observed in every decay cycle. In the second place there is no clearly defined correlation between the time at which the instability burst appears and the initial injection conditions. Thirdly, along with the highly developed random instability which is observed in the present work, one frequently observes weak instabilities. These give rise to very weak signals at the rf probes and the electrodes which measure the wall current and also give rise to marginally discernible distortion on the charge-exchange oscillograms (Fig. 7). These cases might be characterized as unsuccessful attempts to drive the system from its metastable state.

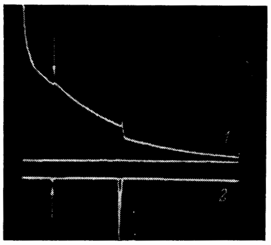

FIG. 7. Oscillograms showing the charge-exchange signal (1) and the rf signal (2). The arrows denote unsuccessful attempts at the development of instability. The sweep length is 3 msec.

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