MEASUREMENT OF THE THRESHOLD DENSITY DURING THE APPEARANCE OF ION-CYCLOTRON INSTABILITY IN A HOT ION PLASMA

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Threshold phenomena arising in a plasma with hot ions are studied for the case when the plasma density exceeds a certain critical value. It is found that if the lifetime of the ions is small (equal to the time of flight between the mirrors) the excess of the density with respect to the critical value leads to a sharp increase of the varying electric fields in the plasma possessing frequencies equal to that of the ion-cyclotron frequency or its harmonics. A result of these oscillations is an increase of the flux of fast ions incident on the wall and a broadening of their angular distribution, causing them to penetrate deeper into the magnetic mirror. The threshold value of the density satisfies the criterion according to which ion-cyclotron instability due to the presence of a positive derivative in the fast ion distribution function with respect to transverse energy ($\partial f_\perp/\partial\epsilon_\perp > 0$) must develop with a maximal increment (cyclotron cone instability). On trapping of the plasma (large ion lifetime), the high-frequency oscillations decay and flute instability sets in.

INTRODUCTION

EXPERIMENTS[1-6] on a plasma produced in a magnetic-mirror trap by injection of fast particles indicate that unstable oscillations, at the cyclotron frequencies of the ions and their harmonics, occur in the plasma. According to numerous theoretical investigations[7-10], the causes of the cyclotron instability in apparatus of this type are the following: the anisotropy of the distribution function of the ions captured in the trap, or the non-monotonic nature of the distribution function of their transverse energies ($\partial f_\perp/\partial\epsilon_\perp > 0$). The qualitative aspect of this cyclotron instability is by now quite clear. However, to check on the theoretical considerations, and to find ways of suppressing the cyclotron instability, it is important to perform further experiments on the dependence of the stability on the plasma density, on the ion velocity distribution anisotropy, on the width of the transverse-energy distribution peak, on the dimensions of the apparatus, and on the electron temperature.

The present investigation is devoted to the dependence of the plasma cyclotron-oscillation amplitude on the plasma density and to the influence of the cyclotron oscillations on the ion velocity distribution function.

EXPERIMENTAL CONDITIONS. APPARATUS

The experiments were made with the "AC" apparatus[11], a simplified diagram of which is shown in Fig. 1.

A long solenoid was used to produce a homogeneous magnetic field H_0. In the region D, an additional coil was placed to produce an adjustable magnetic mirror ($1.5 \geq R = H_{mir}/H_0 \gg 1$). A pulse coil placed in the region C between the solenoid and the vacuum chamber produced a quasistationary magnetic mirror ensuring the capture of the plasma. The distance between mirrors is L = 200 cm. The vacuum chamber diameter in the region CD is 20 cm. To the left of B is located the injection part of the apparatus, which contains the plasma source and the system for differential pumping of the neutral hydrogen coming from the source.

The ion source produces in the magnetic field a column (region AB) of cold plasma contained in a metallic jacket which is transparent to the neutral gas. The plasma and the jacket are under a high (positive) potential. In region B, the jacket diameter is decreased to the plasma-column diameter, and has several azimuthally distributed longitudinal slots. The jacket is surrounded by a grounded wire-mesh cylinder. The ions from the plasma column are accelerated transversely to the magnetic field by the potential difference between the jacket and the mesh cylinder. The accelerated ions move along the trajectories shown in Fig. 1. In order for the ions not to fall on the accelerating electrodes after the first revolution, they are deflected along the magnetic field by an electric field **E** produced by a parallel-plate capacitor with electrodes in the form of large-mesh grids.

The accelerated ions move along the axis to a stationary magnetic mirror, are reflected from it, return to the source, and are neutralized. The average density of the fast ions is

$$n_{av} = Jt_{mot} / V_p, \tag{1}$$

where J is the injection current, t_{mot} is the time of motion from the source to the magnetic mirror and back, and V_p is the volume of the plasma. Since

$$t_{mot} = 2L / v\cos\alpha, \quad V_p = 4\pi\rho_i^2 L, \quad \rho_i = \frac{v\sin\alpha}{\omega_i}, \quad \omega_i = \frac{eH_0}{m_i c}, \tag{2}$$

we have

$$n_{av} = \frac{J\omega_i^2}{2\pi v^3\cos\alpha\sin^2\alpha} \tag{3}$$

(α is the angle between the velocity vector and the magnetic-field force lines, and v is the total ion velocity). Thus, the average density of the fast ions depends on the injection current, on the magnetic field, and on their energy. The quantity $1/\cos\alpha\sin^2\alpha$ depends little on α in the angle range $75° \geq \alpha \geq 40°$.

The chamber was evacuated by diffusion pumps with a system of nitrogen traps to a pressure $P = 10^{-8}$ Torr.

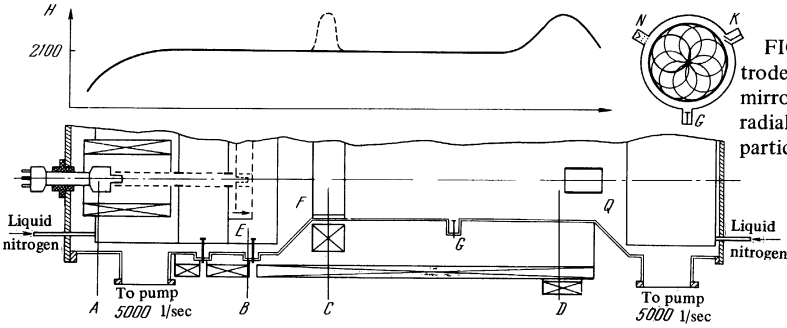

FIG. 1. Diagram of setup: A – ion source, B – accelerating electrodes, C – quasistationary magnetic mirror, D – stationary magnetic mirror, G – antenna, Q – current receiver, F – cylinder limiting the radial dimensions of the plasma, K – fast-ion collector, N – neutral-particle detector.

The ion beam was introduced in pulses of several millisecond duration. The pressure in the pulse did not exceed 5×10^{-7} Torr.

Protons were injected in the working volume (CD). The large-mass ions were trapped in region C by a cylinder F of 17 cm diameter (approximately 4 ρ_i).

The measurements were made with the following parameters: field H_0 = 2100 Oe, energy ϵ_i = 2.5 keV, injection current 0.1 mA $\leq J \leq$ 6 mA, in which case the average ion density n_{av} ranged from 4×10^5 cm^{-3} to 2.5×10^7 cm^{-3}.

The plasma was investigated both prior to its capture by the pulsed mirror (short ion lifetime mode) and after capture.

The high-frequency oscillations were registered with a plate antenna[1] (G in Fig. 1). The signal from the antenna was fed to a high-speed analyzer[12]. The time variation of the signal amplitude was measured at fixed frequency with a receiver having a bandwidth 0.5 MHz.

The flux of fast ions near the chamber wall was measured with a current collector (K in Fig. 1), the construction of which was such that ions with large Larmor radii could fall on it.

The flux of the neutral atoms was monitored with the aid of a detector whose operation was based on the secondary electron emission (N in Fig. 1).

The injected current was measured by a cylinder Q placed behind the magnetic mirror; the cylinder axis was parallel to the force lines of the magnetic field. During the time of the current measurement, a negative potential was applied to the cylinder in order to reflect the electrons that enter into the volume from the accelerating electrodes of the source.

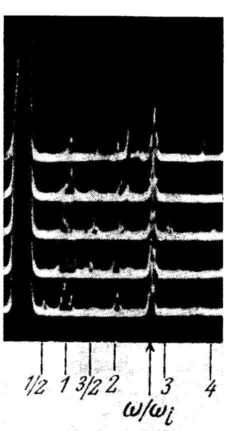

FIG. 2. Oscillogram of spectrum of the oscillations at the electrostatic antenna. The arrow shows the 10-MHz marker.

MEASUREMENT RESULTS

1. Plasma in homogeneous magnetic field. Figure 2 shows an oscillation-spectrum oscillogram obtained with the aid of a high-speed analyzer. It follows from its analysis that the oscillations produced in the plasma have frequencies ω which are multiples of the cyclotron frequency of the atomary ions ω_i. The frequencies $\omega_i/2$ and $3\,\omega_i/2$ were also observed occasionally in the spectrum. The appearance of these frequencies is apparently due to the entry of a small amount of molecular ions into the volume of the trap.

Figure 3 shows a plot of the plate-antenna signal and of the current in the collector K against the injection current at fixed values H_0 = 2100 Oe and ϵ_i = 2.5 keV. The large changes in the signals when the injection current is varied from 0.25 to 0.8 mA indicate that a plasma-density threshold must exist in order for the instability to set in. If we assume the threshold to be in the region of the largest rate of change of the quantities, then according to (3) the average ion density n_{av} lies in the range 10^6–3×10^6 cm^{-3}. Attention is called to the fact that the abrupt rise in the second-harmonic amplitude begins at a larger injection current than for the first harmonic.

We see that the cyclotron oscillations are accompanied by a loss of fast ions to the chamber wall (curve b, Fig. 3). This indicates that the cyclotron oscillations cause either a radial displacement of the fast ions, or an increase of their transverse energy.

The presence of a threshold was verified for a weaker magnetic field, H_0 = 1600 Oe. The energy of the injected ions was also lowered to 1.5 keV, in order to leave the geometric dimensions of the plasma the same as before. In this case the abrupt changes were observed at lower values of the injection current (curve b, Fig. 3).

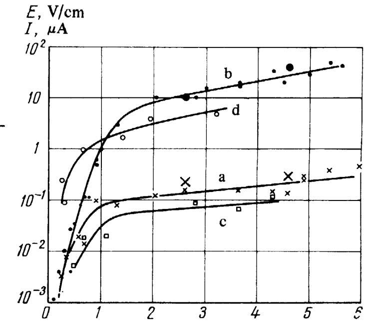

FIG. 3. Signals from the antenna (E) and from the fast-ion detector (I) vs. the injection current J. Ion energy i = 2.5 keV: a – amplitude of oscillations of frequency ω_i, b – current to K, c – amplitude of oscillations of frequency $2\,\omega_i$. Ion energy ϵ_i = 1.5 keV: d – current to K.

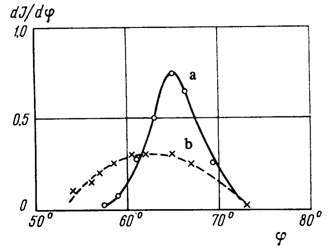

FIG. 4. Distribution of fast-ion current vs. the angle between the velocity vector and the direction of the magnetic field: a – small injection current, b – large injection current.

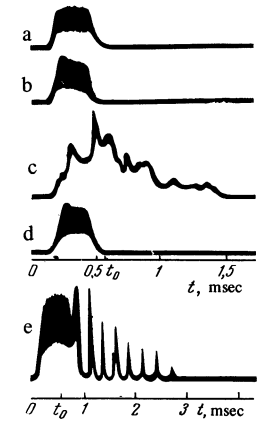

FIG. 5. Oscillograms obtained when working with a quasistationary mirror. The stationary mirror is disconnected: a – current to collector K, b – amplitude of oscillations of frequency ω_i. Stationary mirror connected: c – signal from neutral-particle detector N, d – amplitude of oscillations of frequency ω_i, e – current to K.

Figure 4 shows the distributions of the fast-ion current as functions of the angle of inclination of the velocity vector to the direction of the magnetic field in the region D. To this end, we measured the fast-ion current in the magnetic mirror at a reduced mirror ratio. The measurements were made for small and large injection currents, 0.3 and 2.5 mA, respectively. At large injection currents, the ion angular distribution function becomes very broad, so that the fast ions penetrate deeper into the magnetic mirror.

We also investigated the influence of a stationary magnetic mirror. The signals from the antenna G and from the current collector K were measured with the magnetic mirror turned on and off. In the latter case, the plasma was in a homogeneous magnetic field between the source and the current-collecting cylinder; there was no ion current in the plasma in the source direction. Turning off the magnetic mirror at a fixed injection current reduced the average plasma density by one-half. At near-threshold injection-current values, abrupt changes were observed in the signals when the magnetic mirror was turned on or off. At currents larger than threshold (at 4.6 mA, the values are denoted by the large dots in Fig. 3), turning off the magnetic mirrors reduced the signals to values corresponding to half the injection current with the magnetic mirror turned on. Such a change in the signals indicates that the level of the high-frequency oscillations depends strongly on the average plasma density, and is not connected with the reverse motion of the fast ions.

B. Plasma in trap with magnetic mirrors. To capture the plasma, a quasistationary magnetic mirror was produced in region C 1–2 msec after the start of the injection. Oscillograms a and b of Fig. 5 demonstrate the decrease of the current to the chamber wall and of the cyclotron-oscillation amplitude in the case when the right-hand stationary mirror was turned off. The instant of time t_0 corresponds to total reflection of the injected ion beam from the quasi-stationary magnetic mirror. The oscillograms e and d show the variation of the same quantities when the plasma is captured between the mirrors.

Unlike the data of our preceding paper [1], the attenuation of the cyclotron oscillations is much faster than the decrease of the plasma density (oscillogram c in Fig. 5). An appreciable change takes place in the form of the current to the collector K; the loss of the fast ions to the chamber wall becomes intermittent, and the repetition frequency of the peaks is several kHz. An analysis of the longitudinal and azimuthal correlations of the loss of the fast ions to the wall has shown that the plasma has the form of an eccentric that rotates around the axis of the apparatus.

Thus, as expected, flute instability develops in the plasma after it is captured in the trap. The lifetime of the plasma (~ 1 msec) is shorter than the time due to the charge transfer from the fast ions to the residual gas, and is determined apparently by the loss of fast ions due to the flute instability. The question of the cause of the rapid attenuation of the ion-cyclotron oscillations (they vanish as the result of the appearance of flutes or for other reasons) calls for additional experimental research.

DISCUSSION OF RESULTS

The aggregate of the experimental data indicates that ion-cyclotron oscillations develop in a plasma produced by high-energy ions, starting with a certain threshold density. These oscillations cause a radial displacement of the fast ions and a broadening of their distribution angle, as a result of which the ions penetrate deeply into the magnetic mirror. The threshold density, which is given in our case by formula (3), satisfies the condition $\omega_{pe}^2/\omega_i^2 \approx 8-24$, where $\omega_{pe}^2 = 4\pi ne^2/m_e$ is the Langmuir frequency of the electrons. The determination of the threshold density is of interest in that respect, that it makes it possible to compare experiment with theory and by the same token indicates the cause of the ion-cyclotron oscillations.

An attempt can be made to set the buildup of the ion-cyclotron oscillations observed by us in correspondence with the following two types of theoretically-obtained instabilities. First, the anisotropy of the velocity distribution could serve as a cause of the buildup of cyclotron oscillations [2,7], since the plasma is anisotropic in our case. However, as follows from a number of investigations [8,9,13], the anisotropy can play the main role in the buildup of oscillations at a plasma density satisfying the condition

$$\left(\frac{m_i}{m_e}\right)^{1/3} \geqslant \frac{\omega_{pe}^2}{\omega_i^2} \geqslant 1.$$

Pistunovich has shown, using the "Ogra" installation [2], that the right-hand side of this condition ($\omega_{pe}^2/\omega_i^2 \sim 1$) determines the lower density limit for the occurrence of an anisotropic ion-cyclotron instability.

It is more probable that we have observed another instability, which appears at a higher plasma density, when the decisive factor is the nonmonotonic character of the distribution function of the ions relative to the transverse energy component (the presence of a section with $\partial f_\perp/\partial\epsilon_\perp > 0$ in the distribution). For a δ-like distribution function, this factor becomes significant when the plasma density is such that the following condition is satisfied

$$\frac{\omega_{pe}^2}{\omega_i^2} \geqslant \left(\frac{m_i}{m_e}\right)^{1/3}.$$

this condition agrees quite well with the threshold values of the fast-ion density observed by us.

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[1] A. V. Bortnikov, N. N. Brevnov, V. G. Zhukovskii, and M. K. Romanovskii, Plasma Physics, 1967 (in press).

[2] V. I. Pistunovich, Atomnaya énergiya 14, 72 (1963).

[3] A. H. Fitch et al., Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Culham, 1965, Paper CN-21/234.

[4] L. I. Artemenkov et al., ibid, Paper CN-21/238.

[5] G. L. Dunlap, G. R. Haste, C. E. Nielsen, H. Postma, and L. H. Reber, Phys. of Fluids 9, 199 (1966).

[6] L. A. Kuo, E. A. Murphy, M. Petravic, and D. R. Sweetman, ibid. 7, 988 (1964).

[7] E. A. Harris, Phys. Rev. Lett. 2, 34 (1959).

[8] Yu. N. Dnestrovskiĭ, D. P. Kostomarov, and V. I. Pistunovich, Nuclear Fusion 3, 30 (1963); Yu. N. Dnestrovskiĭ, ibid. 3, 259 (1963).

[9] A. B. Mikhaĭlovskiĭ, ibid. 5, 125 (1965).

[10] M. N. Rosenbluth and R. F. Post, Phys. of Fluids 8, 547 (1965).

[11] A. V. Bortnikov, N. N. Brevnov, V. G. Zhukovskiĭ, and M. K. Romanovskiĭ, Atomnaya énergiya 18, 3 (1965).

[12] Collection: Diagnostika plazmy (Plasma Diagnostics), Part II, Atomizdat, 1967.

[13] A. V. Timofeev and V. I. Pistunovich, in: Voprosy teorii plazmy (Problems of Plasma Theory) 5, Atomizdat, 1967.

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