INVESTIGATION OF ION-CYCLOTRON INSTABILITY IN A POTASSIUM PLASMA

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Excitation of ion-cyclotron instabilities in a collisionless strongly ionized potassium plasma is investigated. The state of the plasma and the diffusion when the instability is developing are studied, as well as the interaction of the ion-cyclotron instabilities with drift and ion-acoustic instabilities.

Ion-cyclotron instabilities in a collisionless plasma were predicted and investigated theoretically in [1, 2]. It was found that in an almost isothermal plasma, instabilities are excited for electron drift speeds relative to the ions (i.e., current velocities) greater than the critical value

$$u_* = v_i \left(\frac{1}{\Gamma_1} \frac{T_i}{T_e} + 1 \right) \left(\ln \frac{M}{m} \right)^{1/2}, \quad \Gamma_1 = \frac{I_1 (k_\perp{}^2 \rho_i{}^2)}{\exp (k_\perp{}^2 \rho_i{}^2)}$$

Here I_1 is the Bessel function of imaginary argument; $k_\perp$ and $k_\|$ are the transverse and longitudinal components of the wave vector; v_i is the thermal velocity of the ions; ρ_i is the Larmor radius of the ions; T_i and T_e are the temperatures of the ions and the electrons; and M and m are the masses of the ions and the electrons.

The instability shows itself in the excitation of electrostatic almost radial waves ($k_\perp \gg k_\|$) at frequencies close to the ion-cyclotron frequency f_i. As shown in [3], at the same time as the ion-cyclotron frequency, harmonics of this frequency may also be excited.

Instabilities of this type have been observed in experiments on plasmas thermally ionized by collisions [4]. It was found that when a current passes along the axis of a plasma cylinder at drift speeds close to the calculated value [1], radial waves are excited at frequencies considerably exceeding the ion-cyclotron frequency.

1. Description of the Arrangement. Experiments were made using the arrangement [5] shown in Fig. 1, in which the plasma is formed by thermal ionization of potassium on a tungsten plate (the ionizer) of radius R = 2 cm, heated to a temperature of approximately 2,000° K. The radius of the plasma column can be reduced to 0.9 cm by means of an iris diaphragm, placed in front of the ionizer. The plasma is bounded at the other end by a collector of radius 0.5 cm and a ring plate of radius 2 cm insulated from one another. The length of the plasma column L is 36 cm.

The experiments were made with magnetic fields of 600-3,000 Oe and plasma densities of 10^9-10^{10} cm^{-3}. For such densities the mean free path $\lambda_{ei} \sim L$, so that the plasma can be regarded as collisionless.

The plasma density n and the amplitude of the density oscillation n° were measured with a Langmuir probe from the constant and varying components of the ion saturation current, while the amplitude of the potential oscillations φ° was measured from the varying component of the current in a floating probe [6]. The phase measurements were made using a system of probes in which a movable probe could be shifted along the axis and along the radius.

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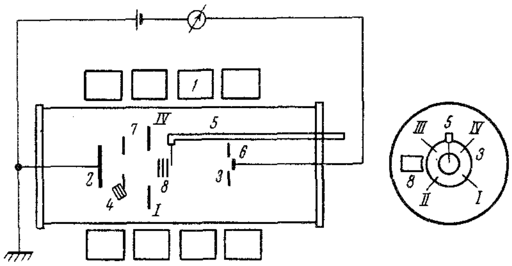

Fig. 1. Sketch of the experimental arrangement: 1) Magnetic field coil; 2) ionizer; 3) ring plate; 4) vaporizer; 5) movable probe; 6) collector; 7) iris diaphragm; 8) diffusion measurer; I-IV) isolated probes.

The spectrum of the oscillations was investigated using type S5-2 and S5-3 harmonic analyzers (passband approximately 200 cps) which recorded the effective amplitude.

When investigating the state of the plasma we made a qualitative correlation analysis [7] and we used a correlograph which measured the sign correlation function $F(\tau)$ [7, 8]. The diffusion coefficient across the magnetic field was measured using an instrument [6, 7] which recorded the transverse plasma current.

2. Experimental Results. The experiments were made under conditions in which there was a layer of electrons close to the ionizer, so that when there is no current in the plasma there are no instabilities [7]. When a current flows along the axis of the plasma cylinder (a voltage is applied to the collector and the potential of the ring plate is floating) instabilities are excited. A typical spectrum of the oscillations, in which several harmonics are clearly visible, is shown in Fig. 2. The frequency of the first harmonic is close to the ion-cyclotron frequency and increases with the magnetic field (Fig. 3).

In the phase measurements, carried out with H=1,000 Oe, we did not observe an azimuthal and longitudinal phase shift (in the latter case the movable probe was moved within the limits 10-32 cm from the ionizer). The radial phase shift changed when the distance between the probes was changed and amounted to approximately π at a distance of .5 R. Hence, the instability shows itself in the excitation of radial waves with a wavelength $\lambda_r \sim R$ without an azimuthal component. The absence of a longitudinal phase shift suggests that a standing wave with a wavelength $\lambda_z \gtrsim 2L$ is set up or that there is no longitudinal component.

It was found that the amplitudes of the density and potential oscillations are connected by the relation $n^\circ / n \sim e\varphi^\circ / T$, i.e., the observed oscillations are potential oscillations.

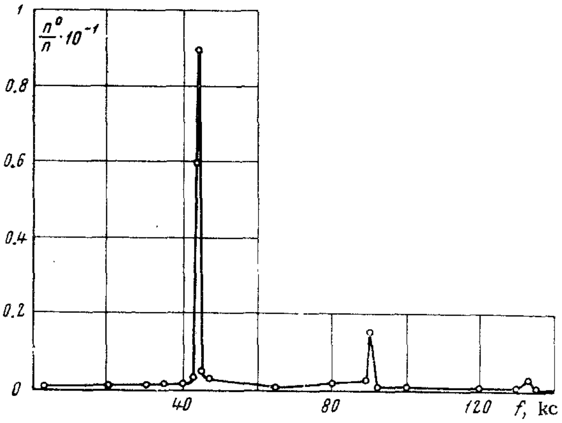

Fig. 2. Spectrum of the oscillations. H=1,000 Oe and $n=5\times10^9$ cm^{-3}.

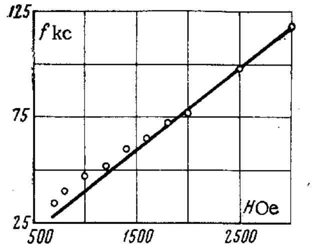

Fig. 3

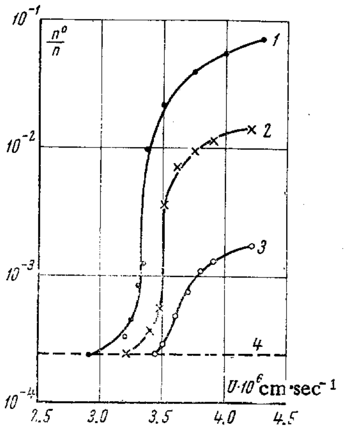

Fig. 4

Fig. 3. Frequency of the first harmonic as a function of the magnetic field: $n=5\times10^9$ cm^{-3}

Fig. 4. The amplitudes of the harmonics as a function of the electron drift speed; curves 1, 2, and 3 correspond to the first, second and third harmonics; the broken line is the initial level of the noise; H=1,000 Oe; $n=5\times10^9$ cm^{-3}.

The critical electron drift velocity u_*, required to excite instabilities, is given by the equation [9]

$$u_* = v_i I_* / I_i$$

Here I_i is the saturation ion current at the collector and I_* is the critical current. It is assumed in this formula that the plasma moves from the hot ionizer to the cold end with a speed of approximately v_i [10, 11], as a result of which $I_i \sim nv_i$. It was found that the critical drift velocity does not depend on the magnetic field and its value is

$$u_* = (3.5 \pm 0.6)\cdot10^6 \text{cm/sec} \sim 40\ v_i$$

It was found that the sharp maxima in the spectrum are only observed for fairly large magnetic fields $H > H_*$. When $H < H_*$ only a noise spectrum is excited in the frequency range $\sim f_i$-$4f_i$, and the amplitude of the oscillations is an order less than the amplitude of the first harmonic when $H > H_*$. When the radius of the plasma column is reduced it was found that the value of H_* increases. The critical values of H_* corresponding to the different column radii R are given in the following table.

R mm	=20	20	14	10	9	15	15
H_* Oe	=800	700	1600	~2000	≥2000	1770	3500
R/ρ_i	=4	4	6	5	5	7	7

The last two values for R=15 mm are taken from [4] for potassium and cesium respectively. The table also gives the values of the ratio of the column radius to the Larmor radius of the ions for $H=H_*$.

We investigated the nature of the excitation of the instabilities. As can be seen from Fig. 4, which shows how the amplitudes of the harmonics depend on the electron drift velocity u, the excitation is "soft" [12]. In fact as the drift velocity changes,the amplitude changes smoothly, as u is increased and decreased the points lie on a single curve, and for $u < u_*$ the amplitude is zero. As u increases the instability harmonics are excited in succession.

When the instabilities were excited we obtained the time taken for the amplitude of the oscillations to grow to their maximum value. The voltage on the collector was supplied by rectangular pulses,the leading edge of which was small compared with the period of the oscillations. It can be seen from the oscillogram of Fig. 5 that this time is approximately 15 periods of the oscillations.

A measurement of the distribution of the oscillation amplitude over the radius showed that the oscillations are localized within the current filament and have a maximum amplitude on its axis. Outside the

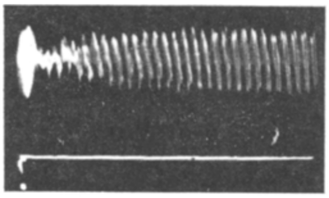

Fig. 5

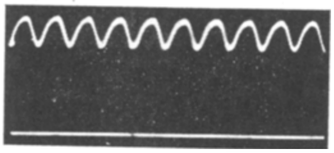

Fig. 6

Fig. 5. Development of the instability. The upper beam shows the density oscillations and the lower beam shows the potential of the collector. H=1200 Oe; $n=5\times10^9$ cm^{-3}; the time base is 50 msec/cm.

Fig. 6. Oscillogram of the current to the probe (density oscillations) when the instability is developing. The straight line shows the zero level of the density. H=1,000 Oe; $n=5\times10^9$ cm^{-3}; f=44 kHz.

current filament the amplitude falls off approximately by an order of magnitude. We can judge the value of the amplitude from the oscillogram of the density oscillations (Fig. 6). It can be seen that the amplitude is small. Direct measurements show that when the instabilities are developing the amplitude of the oscillations on the axis do not exceed the value $n^{\circ}/n\sim0.1$.

We investigated the state of the plasma while the instabilities are growing. We see from the spectrum of Fig. 2 that the amplitude of the harmonics is approximately two orders greater than the amplitude of the noise oscillations at intermediate frequencies. The oscillograms in Figs. 6 and 7 show that the oscillations excited have a regular form and their phases do not get out of step for a very large number of oscillations, at least about 100 periods. This can also be seen from the autocorrelation function $F(\tau)$ of the density oscillations, which does not differ from the autocorrelation function of the sinusoidal signal from the generator (Fig. 8). The correlation function plotted from two probes does not change when the distance between the probes is changed (in particular, the longitudinal distance), whence it follows that the phases of the oscillations at all points of the plasma column are correlated.

A measurement of the diffusion coefficient when an electron layer was present but no current and when there were no instabilities gave a value $D\lessgtr 20$ cm^2/sec^{-1} (the classical value of D is 1 cm^2/sec^{-1}). As was shown in [7], this value is obviously determined by the parasitic currents and gives the limit of the sensitivity of the measuring instrument. When the ion-cyclotron instabilities were excited no increase in the diffusion coefficient was observed. We can conclude from this that if the instabilities also lead to an increase in diffusion then $D\ll20$ cm^2/sec^{-1}.

We investigated the interaction of the ion-cyclotron instabilities with the drift and ion-acoustic instabilities. As has been shown previously using the same experimental arrangement [13, 14], drift instabilities are excited when there is a layer of ions on the surface of the ionizer. The amplitude of the drift oscillations increases when the layer changes from an electron layer to an ion layer (by reducing the temperature of the ionizer for constant deposition) [14]. If ion-cyclotron instabilities are excited with an electron layer when there are no drift instabilities (Fig. 9, spectrum a), and the temperature of the ionizer is then reduced thereby changing to an ion layer, drift instabilities are excited at the same time as ion-cyclotron instabilities. For small amplitudes of the drift waves ($n^{\circ}/n\lesssim10^{-2}$) drift and ion-

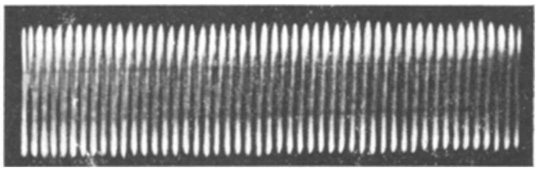

Fig. 7. Density oscillations (multiple triggering). H=1,000 Oe; $n=5\times10^9$ cm^{-3}; f=44.5 kHz.

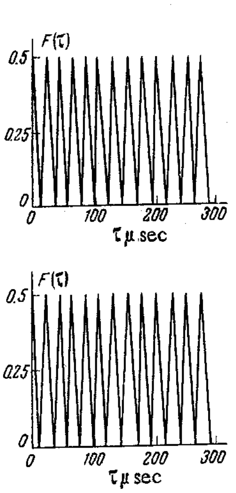

Fig. 8

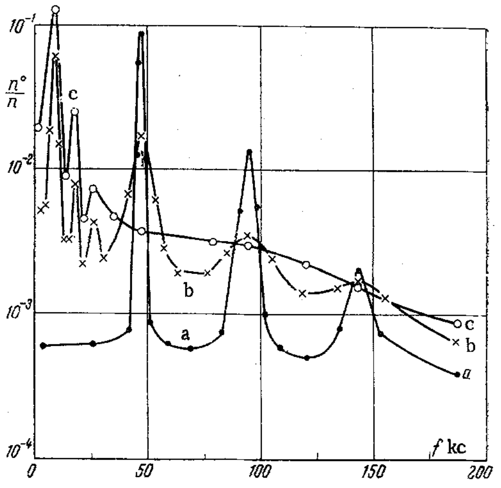

Fig. 9

Fig. 8. The autocorrelation function of the density oscillations. The upper figure is the autocorrelation function of the sinusoidal signal from the generator (f=45 kc); H=1, 000 Oe; $n = 5 \times 10^9$ cm^{-3}.

Fig. 9. Spectra of the oscillations when ion-cyclotron and drift instabilities are excited simultaneously. Curves a, b, and c, correspond to the values T=2300, 2100, and 1900° K for H=1200 Oe.

cyclotron instabilities are excited independently. As the amplitude of the drift oscillations increases the maxima of the ion-cyclotron harmonics are broadened, and their amplitude falls (Fig. 9, spectrum b). If the amplitude of the drift oscillations is fairly large ($n°/n > 7 \times 10^{-2}$) separate ion-cyclotron maxima are not observed in the spectrum (Fig. 9, spectrum c).

When a current is flowing over the whole cross section of the plasma column under conditions when there is a layer of electrons, for a certain critical velocity of the electrons ion-acoustic instabilities are excited [7]. When the instabilities are excited the amplitude abruptly increases to a value of $n°/n \sim 1$ ("hard" excitation), so that when investigating the interaction of the instabilities one can only observe the case of interaction with ion-acoustic oscillations of large amplitude. If ion-cyclotron instabilities are excited and a current is then passed to the ring plate, exciting ion-acoustic oscillations (frequency of the first harmonic ~ 5 kHz), the ion-cyclotron oscillations disappear from the spectrum and only ion-acoustic oscillations are observed. Figure 10 shows an oscillogram of the density oscillations taken at a constant collector potential and with a saw-tooth voltage on the ring plate. It can be seen that at the instant when ion-acoustic oscillations are excited, marked with an arrow, the ion-cyclotron oscillations disappear. Hence, drift and ion-acoustic oscillations of fairly large amplitude practically completely suppress the ion-cyclotron oscillations.

3. Discussion of the Results. The results obtained are in qualitative agreement with the results of previous experiments [4] and theory [1]. In fact, the observed instabilities manifest themselves in the excitation of electrostatic radial waves at the ion-cyclotron frequency and its harmonics. The critical drift velocity $u_* \sim 40\ v_i$ at H=1, 000 Oe is close to the calculated value $u_* \sim 20\ v_i$. The disagreement between the experimental value of u_* and the results obtained in [4] ($u_* \sim 10\ v_i$) is due to the fact that in calculating u_* in [4] the motion of the plasma with a velocity of approximately v_i was ignored. If this motion is taken into account one obtains the value $u_* \sim 40\ v_i$.

It should be noted that according to [1] the critical velocity u_* should increase as H increases. However, experiment shows that u_* does not depend on the magnetic field. This result is obtained in experiments with a plasma in which collisions occur [15]. In [15] a theory is constructed which takes into account the role of the space charge layer on the surface of the collector. It is found that the presence of this layer leads to some change in u_*, in particular, in this case u_* should not depend on the magnetic field. One obviously cannot apply the results of the calculations given in [15] to a collisionless plasma. However, it cannot be ruled out that in this case the presence of a layer leads to a change in the critical velocity.

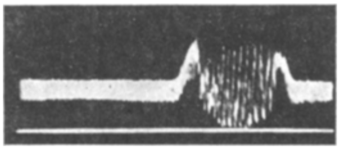

Fig. 10. Density oscillations when ion-cyclotron and ion-acoustic instabilities are excited. The straight line shows the zero density level. $H=1,000$ Oe; $n=5\times10^9$ cm^{-3}.

The presence of a magnetic field below which separate maxima at harmonics of the cyclotron frequency are not observed, and its increase in inverse proportion to R shows that to excite ion-cyclotron instabilities it is necessary for the Larmor radius of the ions to be fairly small in comparison with the radius of the plasma column. From the data given in our table it can be seen that the minimum ratio is $R/\rho_i \sim 5\pm1$. This agrees with the results obtained in [4], from which it can be found that the minimum $R/\rho_i \sim 7$.

When the instabilities are excited the harmonics are excited in succession and the excitation has a "soft" character. The time taken for the amplitude to grow when the instabilities are excited is approximately 15 periods of the oscillations, so that the increment of the instabilities is obviously small. The amplitude of the oscillations when the instabilities are growing does not exceed the value $n^\circ/n \sim 0.1$. A correlation analysis shows that the state of the plasma is not turbulent. In fact the oscillations are regular and their phases are correlated at different points of the plasma column, and the phase correlation is maintained for a large number of oscillation periods. Hence, the state of the plasma when the ion-cyclotron instabilities are developing is laminar.

Estimates were made in [1] of the diffusion coefficient across the magnetic field for a turbulent plasma. These results are obviously not applicable to the case of a plasma in a laminar state since it can be expected that regular almost sinusoidal oscillations will not lead to a drift of the plasma across the field. The experimental results confirm the fact that diffusion across the field either does not occur or, in any case, is very small.

Ion-acoustic and drift oscillations of sufficiently large amplitude practically completely suppress the ion-cyclotron oscillations, and for the drift oscillations the limiting amplitude is comparable with the amplitude of the ion-cyclotron oscillations. For small drift oscillation amplitudes the ion-cyclotron and drift instabilities develop independently. Hence, we can conclude that the suppression of the ion-cyclotron oscillations is a nonlinear effect. The nature of this effect is not at present clear.

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