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CUTOFF OF CYCLOTRON HARMONICS IN AN UNSTABLE PLASMA

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A sharp increase of the energy losses with subsequent emission of microwave radiation whose frequencies were harmonics of the cyclotron frequency was observed during cyclotron heating of plasma electrons. The phenomena were observed at certain plasma concentrations which were close to cutoff condition (vanishing of the refractive index) for the respective harmonics. It is suggested that they can be attributed to trapping of the wave induced by the anisotropic instability inside the reflecting layer. The possibility of applying the same mechanism to other cases of double resonance in a plasma is discussed.

In experiments on electron cyclotron heating of a plasma in an adiabatic magnetic trap, we observed a sharp increase of the energy loss at definite values of the plasma concentration. Near the same values, we observed microwave radiation at the second and third harmonics of the electron cyclotron frequency (we have in mind here and throughout the cyclotron frequency in the direct field region). The indicated results can be interpreted as a direct observation of the instability of an anisotropic plasma.[1,2] The development of the instability at definite values of the concentration is explained by us as being due to the occurrence of a reflecting layer in the spatially-inhomogeneous plasma; in this layer the refractive index vanishes for the cyclotron harmonics, i.e., the cutoff condition for the waves in question is satisfied. The volume contained inside this layer has the properties of a resonator for the waves excited during the instability, thus contributing to an increase in their amplitude.

The experimental setup is shown in Fig. 1. The plasma was injected from a gun and heated by a microwave field from a magnetron of 3 kW power with a vacuum wavelength 10.7 cm. The wave penetrated into the plasma along the magnetic field in accordance with the plasma waveguide principle,[3,4] and not in accordance with the resonator principle as in most other investigations. The absence of a metallic resonator not only lifts the limitation on the concentration, but also makes it possible to separate in pure form the resonant phenomena inside the plasma, which could not be easily separated in [5,6] from effects connected with an external resonator. The energy density in the plasma was measured with a diamagnetic pickup, and the charged-particle concentration was measured with an interferometer operating at 8 mm wavelength.

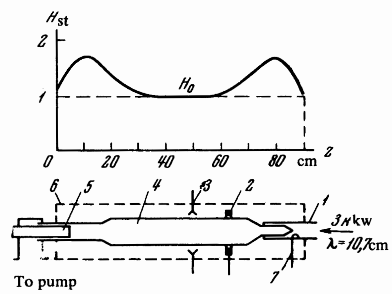

FIG. 1. Diagram of setup and distribution of the static magnetic field: 1 – magnetron waveguide, 2 – coil of diamagnetic pickup, 3 – interferometer horn antennas, λ = 8 mm. 4 – vacuum chamber (glass), 5 – titanium gun. 6 – microwave screening, 7 – radiation receiver.

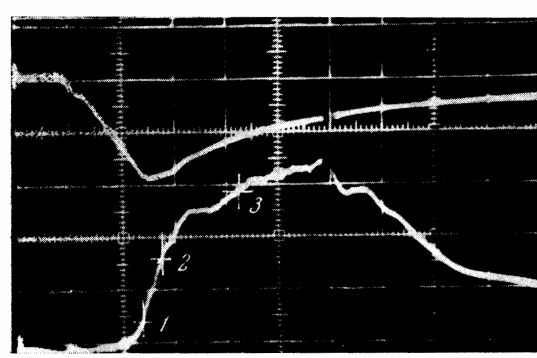

FIG. 2. Diamagnetic signal (upper curve, 0.6 × 10^{14} eV/cm³ per division the amplitude is measured downward) and concentration (lower curve): 1 – $\omega_0^2 = 2\omega_{ce}^2$, 2 – $\omega_0^2 = 6\omega_{ce}^2$, 3 – $\omega_0^2 = 12\omega_{ce}^2$; H_0 = 790 Oe, sweep rate 50 μsec per division.

Figure 2 shows typical oscillograms of the diamagnetic signal (integrated) and of the concentration. The growth of the concentration is connected with ionization of the gas, both the residual gas and that knocked out from the walls by the action of the wave. When the magnetron operates for a long time, the concentration reaches saturation, whereas the decrease observed in the oscillogram pertains to the afterglow obtained already after the magnetron is turned off.[1)] In the oscillograms of Fig. 3, the plasma concentration is compared with the radiation pulses at the second and third harmonics of the cyclotron frequency, and in Fig. 4 it is compared with the derivative of the diamagnetic signal obtained directly from the pickup without an integrating network. The latter quantity characterizes the difference between the rates at which energy is supplied and removed. In the case of stationary magnetron operation, the jumps of this derivative denotes a sharp intensification of energy removal from the plasma, i.e., the occur-

[1)]The instant when the magnetron is switched off is indicated by blacking out of the sweep line.

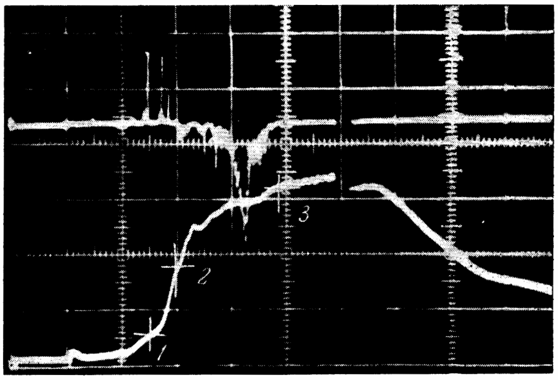

FIG. 3. Radiation at harmonics of the cyclotron frequency (upper curve, the amplitude of the second harmonic is directed upward, the amplitude of the third harmonic is directed downward from the center line) and the concentration (the points are the same as in Fig. 2); H_0 = 790 Oe; sweep rate 50 μsec per division.

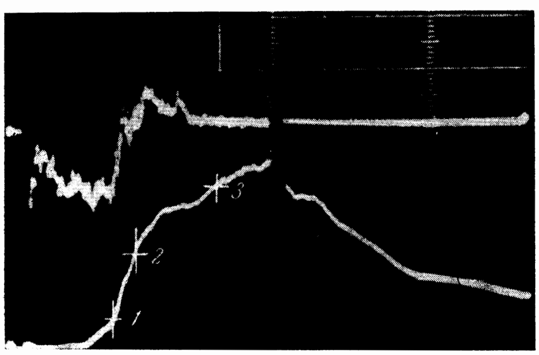

FIG. 4. Derivative of the diamagnetic signal (upper curve, the positive values are in a direction downward from the center line) and concentration (lower curve, symbol the same as in Fig. 2), H_0 = 790 Oe. Sweep rate 50 μsec per division.

rence of instability. Figure 4 shows two such jumps, preceding the cyclotron-harmonic radiation pulses shown in Fig. 3.

We propose the following explanation for the phenomena. The cyclotron heating produces a plasma in which the transverse temperature is much higher than the longitudinal one, leading to excitation of waves at the cyclotron frequency and its harmonics. At definite plasma concentrations, the refractive index of the plasma relative to these waves vanishes (the so-called cutoff condition). Of primary significance for these effects is the inhomogeneity of the concentration over the cross section of the plasma column, and in this respect they are related to the higher Tonks–Dattner resonances[7,8] or to the analogous phenomena in a magnetic field.[9] After the plasma concentration on the column axis exceeds the value corresponding to cutoff, a reflecting layer, on which this condition is satisfied, is produced around the axis. The excited waves are then locked inside the cylindrical resonator made up by this reflecting layer. The wave amplitude inside the layer increases; the charge particles interacting with the waves go off into the loss cone and carry energy out of the plasma. With increasing concentration, the reflecting layer approaches the outer boundary of the plasma. The longitudinal waves, which are then amplified to a large amplitude inside the reflecting layer, are transformed into transverse ones of the steep density gradient at the boundary, and are radiated to the outside. Photometric measurements of the light radiated by the plasma along different chords show that the concentration profile inside the column is close to the square-wave. Therefore the time of displacement of the reflecting wave from the axis to the periphery is small.

Let us turn to a quantitative verification of the developed concepts. As is well known (see, for example, [10]) the condition for the vanishing of the refractive index (cutoff) does not depend on either the propagation angle or the thermal motion, and has in the usual tensor notation the form

$$\varepsilon = \pm g, \tag{1}$$

where the values of the tensor components can be taken the same as for the cold plasma. For high-frequency oscillations, in which the ion motion can be neglected, this condition yields

$$\omega_0^2 = \frac{\omega^2 - \omega_{ce}^2}{1 \mp \omega_{ce}/\omega} = \omega^2 \pm \omega\omega_{ce}, \tag{2}$$

where ω, ω_0, and ω_{ce} are the wave, plasma, and cyclotron (electron) frequencies. For the cyclotron harmonics the cutoff condition takes the form

$$\omega_0^2 = \frac{s^2 - 1}{1 \mp 1/s}\omega_{ce}^2 = s(s \pm 1)\omega_{ce}^2, \tag{3}$$

where s is the number of the harmonics. Since the quantity ω_0^2 is proportional to the concentration, the expression (3) determines those characteristic plasma-concentration values, at which cutoff takes place. For each number s there are two such concentrations, the upper one for the given harmonic coinciding with the lower for the next harmonic.

It is seen from Fig. 4 that the jumps of the derivative of the diamagnetic signal, which offer evidence of instability bursts in the plasma, are observed at concentrations that coincide, within the limits of the experimental accuracy, with the cutoff conditions (3) for the second and third harmonic of the cyclotron frequency. By the same token this confirms our assumption that the sharp increase of the instability is connected with the locking of the waves at the cyclotron harmonics inside the reflecting layer. A particularly strong instability is observed at $\omega_0^2 = 6\omega_{ce}^2$, when the second and the third harmonics are simultaneously locked. In our experiments, the growth of the diamagnetic signal, i.e., the energy density of the plasma, was limited precisely to these values of the concentration. Similar instabilities and emission of harmonics were observed in [5,6], but were complicated there by the influence of the external metallic resonator.

In addition, in these investigations the procedure of maintaining and measuring the plasma density did not make it possible to reveal the connection between the instability and the cutoff condition. This connection was obtained by us for the first time.

In a number of investigations,[11,12] the plasma radiation at cyclotron harmonics was connected with the equality of the frequency of the harmonic and the upper hybrid frequency (double resonance). Certain theoretical considerations favoring this argument can be found in [13,14]. However, unlike cutoff, hybrid resonance occurs only for waves having a propagation direction very close to normal to the magnetic field. In anisotropic instability, only essentially oblique waves are excited ($k_{\parallel} \sim k_{\perp}$), and therefore hybrid resonance could not have any significance in the phenomena observed by us. It is possible that in other double-resonance cases the emission of cyclotron harmonics is connected with the equality of the frequency of the harmonic not with the hybrid frequency, but with the cutoff frequency, leading to the resonant wave amplification mechanism considered by us. The accuracy with which plasma concentration is measured is usually insufficient to delineate between the cutoff frequencies and the hybrid frequencies that are sufficiently close to them. If the concepts developed in this paper are valid, then double resonance should be classified as a spatial resonance peculiar to a bounded plasma, similar to magnetosonic resonance.[15]

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14