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Nonthermal Radiation from a Magnetoactive Plasma in the Field of a Microwave Pumping Wave

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The microwave radiation from a collisionless magnetized plasma interacting with an intense pumping wave in the microwave range is investigated experimentally. Red and blue satellites in the emission spectrum induced by the first harmonic of the pumping wave ω_0 are observed, which are shifted by $\Delta\omega \sim \omega_{Li}$ with respect to the central peak, ω_{Li} being the ion Langmuir frequency. This indicates that extreme shortwave ion oscillations are built up. Emission due to the second harmonic of the pumping wave ($2\omega_0$) is detected; its intensity exponentially increases with growth of intensity of the incident wave. The satellite excitation effects and emission due to the second harmonic of the pumping wave correlate with anomalous absorption and heating effects, and can be explained by parametric excitation of plasma oscillations.

THE mechanism of anomalous dissipation of the energy of an electromagnetic wave in a collisionless plasma (anomalous electron heating and anomalous absorption[1-4]) is considered to be parametric excitation of high-frequency and low-frequency plasma waves by the external pump wave[5-8]. We have previously investigated[1,4,9] the interaction of a microwave pumping wave with a magnetoactive plasma in the frequency region $\omega_{Le} < \omega_0 < \omega_{He}$ ($\omega_{He} = eH/m_ec$, $\omega_{Le} = (4\pi ne^2/m_e)^{1/2}$, ω_0 is the angular frequency of the external field). In this frequency region, as is well known[10], there are no conditions for linear transformation of waves. The frequency ν_{ei} of the electron-ion collisions in the investigated plasma was such that during the time of interaction between the microwave wave and the plasma the number of collisions was $\nu_{ei}\tau \lesssim 1$ (τ is the interaction time).

Inasmuch as linear wave excitation in the plasma is possible under the conditions of our experiments, it is important, in order to understand the anomalous dissipation of the microwave energy of the pump wave, to observe the plasma oscillations under anomalous absorption and heating of the plasma. On the basis of our earlier results[4,9], we could expect at $\omega_{He}/\omega_0 = 1.08$ parametric excitation of a non-potential electromagnetic wave at a frequency close to ω_0, propagating along the magnetic field. At $\omega_{He}/\omega_0 \approx 2$, one could expect in the plasma the excitation of a potential wave with frequency $2\omega_0$ close to the upper hybrid frequency $(\omega_{He}^2 + \omega_{Le}^2)^{1/2}$.

We have measured the radiation of these oscillations by a plasma. The apparatus was the same as in our earlier studies[4,9]. A cyclindrical plasma stream of 1.5 cm diameter flowed in and out of a rectangular waveguide, through its narrow walls, along the magnetic field. The plasma density in the experiment was maintained at the level $n = (3 - 4) \times 10^{10}$ cm^{-3}, so that $\omega_{Le}^2/\omega_0^2 \approx 0.3$. The plasma produced by the spark source was non-isothermal with a ratio of the electron and ion temperatures $T_e/T_i \approx 10$ ($T_e \approx 6$ eV). The electric field in the TE_{10} wave incident on the plasma was perpendicular to the quasi-stationary magnetic field. The plasma radiation was registered with a loop antenna located either in the vacuum chamber through which the plasma flowed, and which was separated from the waveguide by stubs tuned beyond cutoff, or directly in the waveguide by moving the antenna to a distance $3\lambda_g$ from the plasma column (λ_g is the length of the wave of frequency ω_0 in the waveguide). The microwave signal received by the loop antennas was amplified by ultrasensitive standard amplifiers of type P-5-5 (for the frequency ω_0) and P-5-8 (for $2\omega_0$). The frequency was measured accurate to 5 MHz near ω_0 and up to 10 MHz in the double-frequency region $2\omega_0$. The error in the determination of the radiation intensity did not exceed 2 dB/μW.

Measurements outside the waveguide (curve 1, Fig. 1) show that the dependence of the radiation intensity at the frequency ω_0 on the magnetic field has a resonant character, similar to the dependence of the electron current in anomalous heating[9]. Thus, the peak at $\omega_{He}/\omega_0 = 1.08$ corresponds to excitation of a non-potential wave propagating along H, and of an acoustic wave[7]. The peaks at $\omega_{He}/\omega_0 = 1.4$ and 1.65 are apparently due to resonances of Bernstein waves at the harmonics of the external frequency ($3\omega_0 \approx 2\omega_{He}$

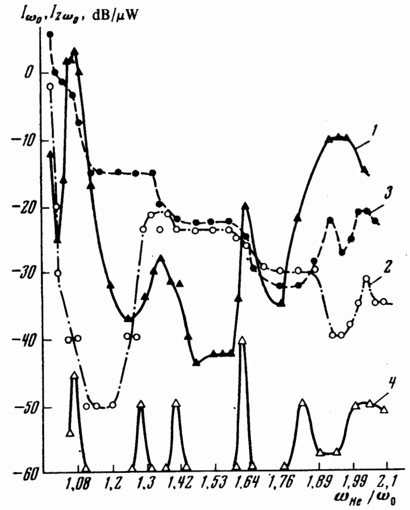

FIG. 1. Plots of the radiation intensity at frequencies ω_0 and $2\omega_0$ against the magnetic field. 1) Radiation at ω_0, E = 2.7 kV/cm, attenuation 30 dB. 2) Radiation at $2\omega_0$, E = 2.7 kV/cm. Measurement outside the waveguide. 3) Radiation at $2\omega_0$, E = 2.7 kV/cm. Measurements in the waveguide. 4) Radiation at ω_0, E = 0.7 kV/cm, attenuation 60 dB.

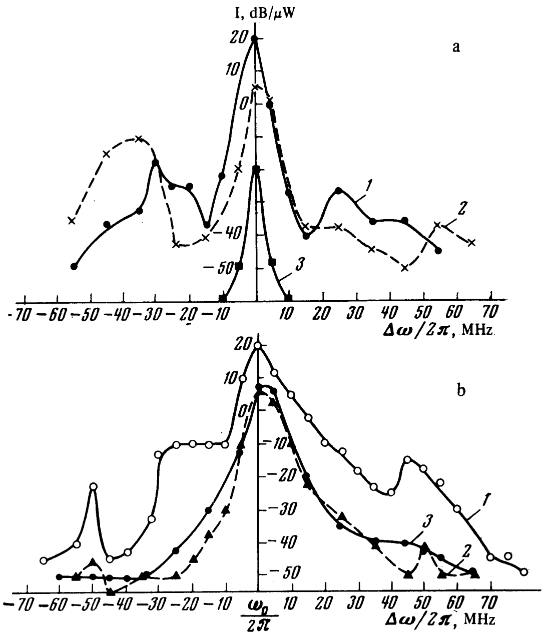

FIG. 2. Radiation spectra at the frequency ω_0: a) $\omega_{He}/\omega_0 = 1.08$; curves: 1) E = 1.1 kV/cm, 2) E = 250 V/cm, 3) E = 25 V/cm; b) $\omega_{He}/\omega_0 = 2$; curves: 1) E = 1.4 kV/cm, 2) E = 650 V/cm, 3) E = 240 V/cm.

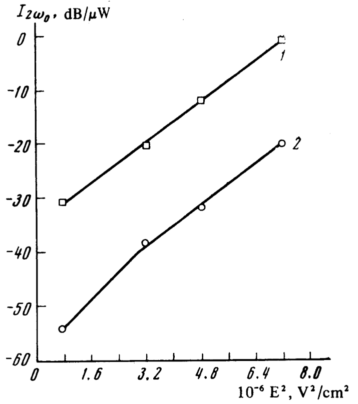

FIG. 3. Radiation intensity in the waveguide at frequency $2\omega_0$ vs. pump-wave electric field intensity. Curves: 1) $\omega_{He}/\omega_0 = 1.05$; 2) $\omega_{He}/\omega_0 = 2$.

and $5\omega_0 \approx 3\omega_{He}$)[8], and the peak at $\omega_{He}/\omega_0 \approx 2$ is due to the resonance of the second harmonic of the external frequency with the upper hybrid frequency. A decrease of the electric field of the external wave changes the form of the observed dependence (curve 4, Fig. 1), and splitting and narrowing of the individual peaks takes place. Even this circumstance itself indicates that the radiation at frequency ω_0 is due to a nonlinear mechanism. This is also evidenced by the emission spectra near ω_0 (Fig. 2). With increasing field intensity, a broadening of the central minimum takes place, corresponding to excitation in the plasma of long-wave acoustic oscillations, after which red and blue satellites appear in the spectrum, shifted relative to the central peak by $\Delta\omega/2\pi = \pm(40-60)$ MHz. It turns out that $\Delta\omega \approx \omega_{Li}$ (ω_{Li} is the ion Langmuir frequency), i.e., excitation of the shortest-wavelength acoustic oscillations also takes place.

In the case $\omega_{He}/\omega_0 = 2$, the intensity of the peaks at the combination frequencies $\omega_0 \pm \omega_{Li}$ increases with increasing power of the external wave more rapidly than the intensity of the central maximum. In addition, a strong increase takes place in the intensity of the radiation at frequencies smaller than ω_0 by (10–30) MHz. In the case $\omega_{He}/\omega_0 = 1.08$ the radiation at the combination frequencies occurs at lower field intensities ($eE/m_e\omega_0 v_{Te} \sim 0.2$) than at $\omega_{He}/\omega_0 = 2$, and the red satellite turns out to be more intense by three orders of magnitude than the blue one, in qualitative agreement with the theoretical predictions. An increase of the field intensity by 4.6 times leads to an equalization of the intensities of both satellites and to their shift towards ω_0. No such shift was observed in the case $\omega_{He}/\omega_0 \approx 2$.

Besides the radiation at the first harmonic of the external signal, radiation is observed also at its second harmonic (curves 2 and 3, Fig. 1), at an intensity which is lower on the average by three orders of magnitude than the intensity of the radiation at ω_0. The intensity of the radiation registered both in the waveguide and outside it is of the same order of magnitude, but the dependences on the magnetic field are strongly different. Thus, in the region $\omega_{He}/\omega_0 \approx 2$, two peaks are observed in the case of the measurements in the waveguide. The first corresponds to the resonance of the second harmonic with the upper hybrid frequency, and the second to resonance with the cyclotron frequency. In the measurements outside the waveguide we observed only the second peak. These differences are apparently connected with the dependence of the plasma-oscillation spectra on the angle between the wave vector and the magnetic field, which is equal to zero for the oscillations of frequency ω_{He} and to $\pi/2$ for the oscillations of frequency $(\omega_{He}^2 + \omega_{Le}^2)^{1/2}$.

The dependence of the intensity of the plasma radiation at the second harmonic on the power of the pump wave is essentially nonlinear (Fig. 3). Both near the cyclotron resonance ($\omega_{He}/\omega_0 = 1.05$) and far from it ($\omega_{He}/\omega_0 = 2$) there is observed an exponential growth of the radiation intensity with increasing power of the external wave. Thus, the behavior of the transverse wave radiated by a plasma situated in the field of a strong microwave shows that the plasma waves build up nonlinearly. A comparison of the results of the present paper with our earlier results[1,4,9] shows that the effects of the anomalous wave absorption and electron heating occur at field intensities at which the shortest-wavelength ion-acoustic oscillations develop in the plasma. Thus, the threshold field intensity for anomalous absorption at $\omega_{He}/\omega_0 = 1.08$ is (60–100) V/cm ($eE/m_e\omega_0 v_{Te} \sim 0.1$). This field corresponds also to the appearance of satellites in the emission spectrum at ω_0, and the threshold intensity at which the satellites appear at $\omega_{He}/\omega_0 = 2$ is ~400 V/cm, which coincides with the threshold for the anomalous heating of the electrons. This allows us to relate the effects of the anomalous energy dissipation of the pump wave with the parametric excitation of the plasma waves.

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197