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ABSORPTION OF LOWER HYBRID AND UPPER HYBRID PUMP WAVES IN MAGNETIZED PLASMA

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The kinetic theory of fluctuations in the spatially homogeneous and inhomogeneous magnetized plasma in the presence of a HF pump wave field with frequencies near the lower hybrid and upper hybrid frequencies is developed. The effective absorption length is calculated. It is shown that for the thermonuclear plasma the effective absorption length is of the same scale as plasma dimension that ensures effective dissipation of the HF pump power.

In [1 - 4], on the basis of the kinetic theory of fluctuations, the anomalous absorption of the RF wave in a nonequilibrium homogeneous plasma was studied and the expressions for the absorbed RF power in the lower and upper hybrid frequency ranges were derived.

In this paper the RF power absorbed in the plasma is determined under the conditions characteristic of the parametric decay of the LH and UH wave into the secondary and electron-drift wave. It is assumed that the mechanism for the saturation of the parametric turbulence is the scattering of charged particles by the turbulent fluctuations of the electric field. The efficiency of this mechanism was discussed in detail in [5].

The expression for the effective absorption length of an external RF wave as a function of the density, temperature, plasma-density gradient frequency, and amplitude of the pump wave is derived. It is shown that for the typical parameters of thermonuclear plasmas the absorption length is comparable with the plasma size which results in efficient dissipation of the RF power.

Let us consider a magnetized electron-ion plasma (the constant magnetic field $\vec{B}_0$ is directed along the z-axis) under the action of the external RF electric field $\vec{E}_0(t) = E_0\vec{y}\cos\omega_0 t$ with the frequency ω_0 lying in the LH frequency range $\Omega_i << \omega_0 \sim \omega_{LH} << \Omega_e$, where $\omega_{LH} \approx \omega_{pi}(1+\omega_{pe}^2/\Omega_e^2)^{-1/2}$ is the LH resonance frequency and $\omega_{p\alpha}$ and Ω_α are the plasma frequency and cyclotron frequency, respectively, of the particle of α species ($\alpha = e, i$).

The distribution function (which is Maxwellian in the absence of the density gradient) can be written as

$$f_{0\alpha}(p,y) = \frac{n_0}{(2\pi m_\alpha T_\alpha)^{3/2}} \exp(-\alpha(\frac{p_x}{m_\alpha \Omega_\alpha} - y)^2)\exp(-p^2/2m_\alpha T_\alpha), \qquad (1)$$

where $p^2 = p_x^2 + p_y^2 + p_z^2$ and $\alpha = \frac{1}{n_0}\frac{dn_0}{dy}$ is the parameter characterizing the plasma density inhomogeneity. We note that, although below we neglect the temperature gradients, the longitudinal and transverse (with respect to the magnetic field) inhomogeneities of the particle temperature can be easily included into consideration by substituting $\alpha \to \alpha + \delta_\perp \upsilon_\perp^2 + \delta_{II}\upsilon_{II}^2$.

We obtain the expressions for the real part of the frequency and the damping rate of electron-drift oscillations ($\omega = \omega_r + i\gamma_r$) [6, 7]

$$\omega_r = \omega_{de}(1 - k_\perp^2 \rho_i^2 (1 + T_e/T_i)), \qquad (2)$$

$$\gamma_r = (\pi/2)^{1/2}\left(\frac{\omega_r - \omega_{de}}{k_{II}\upsilon_{Te}} + \frac{T_e}{T_i}\frac{\omega_r - \omega_{di}}{k_{II}\upsilon_{Ti}}\right)\exp\left(\frac{\omega_r^2}{2k_{II}^2\upsilon_{Ti}^2}\right). \quad (3)$$

In formulas (2) and (3), $\omega_{de} = -k_x kT_e / m_e\Omega_e$ is the electron-drift frequency and $\omega_{di} = -(T_i/T_e)\omega_{de}$. We note that, when deriving (2), we assumed $z_{e,i} << 1$; i.e., $A_0(z_e) = 1$ for electrons and $A_0(z_i) \approx 1 - z_i$ for ions. Thus, we incorporate the effect of a finite Larmour radius.

It is seen from (2) that $\omega_r < \omega_{de}$. As a result, the interaction of plasma eigenmodes with electrons is a destabilizing factor; I.e., oscillations build up due to convection of resonant electrons, because, according to (3), the ion damping is exponentially small [6, 7].

Note that the ion Landau damping can become substantial for plasmas in small devices in which the longitudinal component of the wave vector k_{II} can be relatively large [8]. Moreover, in magnetic-shear devices, the damping is associated with convection of ions toward the region with large k_{II} and regions with small k_{II} are relatively narrow [8, 9].

In this work, we conquered only the case when the drift oscillations are damped, i.e., when the contribution from the second (ion) term in formula (3) is dominant.

1. The action of the external electric field with the frequency ω_0 on the order of the LH frequency on the inhomogeneous magnetized plasma results in the onset of the parametric instability. Let us examine the influence of the plasma density gradient on the threshold for this instability. The pump wave is assumed to be homogeneous, because the plasma parameters typical of laboratory devices satisfy the condition

$$\frac{k_0}{k_\perp} << 1. \quad (4)$$

Here, $k_0 = \omega_0 / c$ is the wave vector of the pump LH wave, $k_\perp = \omega_{de}\, m_e L \Omega_e / T_e$ is the transverse component of the wave vector of the electron-drift wave, and $L = 1/\alpha$ is the characteristic scale length of the plasma inhomogeneity. It should be noted that the condition under which the plasma can be considered weakly inhomogeneous assumes that the inequality $\lambda / L << 1$ is satisfied, where $\lambda = 2\pi / k_\perp$ is the wavelength of drift plasma oscillations.

When the decay condition

$$\omega_0 = \omega_r + \omega_l \quad (5)$$

is fulfilled (the frequency ω_l lies in the LH range; i.e., $\omega_l \approx \omega_{LH}(1 + (m_i/m_e)\cos^2\theta)^{1/2}$ [10] and ω_r is defined by formula (2)), it is easy to obtain the threshold electric field E_* for the decay instability in question [1, 11]

$$E_*^2 = \frac{8\omega_o^2 B_o^2 \gamma_r \gamma_l}{k_\perp^2 c^2 \omega_r \omega_l}(kr_{De})^2 . \quad (6)$$

In expression (6) γ_r is the damping rate of drift oscillations, which is determined by the second term in formula (3), and γ_l is the damping rate of the wave ω_l

$$\gamma_l = \left(\frac{\pi}{8}\right)^{1/2} \frac{m_i}{m_e} \frac{\omega_l^2 \omega_{LH}^2}{k^3 \upsilon_{Te}^3 \cos\theta} \exp\left(-\frac{\omega_l^2}{2k_{II}^2 \upsilon_{Te}^2}\right), \tag{7}$$

where θ is the angle between the wave vector $\vec{k}$ and the magnetic field $\vec{B}_0$. We note that, in a plasma device with a sufficiently large shear, E_*^2 is determined by the global value of the damping rate rather than by its local value (3).

Let us consider the case when the external electric field exceeds the threshold for the parametric instability and fluctuations resulting from this instability are well developed. We will assume that the instability saturates due to the stabilization mechanism associated with the scattering of charged particles by turbulent fluctuations of the electric field. We characterize this scattering by the effective collision frequency ν_{eff} [12], which determines the rate of plasma heating by RF waves. By using the analogy between the pair particle collisions and scattering of the particles by fluctuations [13], we express ν_{eff} in terms of the turbulent plasma conductivity σ_{turb}

$$\nu_{eff} = (m_e \omega_0^2 / e^2 n_e)\sigma_{turb} \tag{8}$$

In turn, the plasma conductivity in the pump RF field can be obtained from the energy balance equation [6, 8]

$$\frac{1}{2}\sigma_{turb} E_o^2 = \sum_\alpha n_\alpha \int d\vec{p} \frac{p^2}{2m_\alpha} I_\alpha(\vec{p}), \tag{9}$$

where $I_\alpha(\vec{p})$ is the collision integral for the charged plasma particles.

Under the conditions of the onset of the parametric instability, the main contribution to the collision integral $I_\alpha(\vec{p})$ comes from the term related to the diffusion of particles in velocity space. Hence, for ν_{eff}, we have the following expression:

$$\nu_{eff} = \frac{2m_e\omega_0^2}{e^2 n_e E_0^2} \int \frac{d\omega}{2\pi} \int \frac{d\vec{k}}{(2\pi)^3} \frac{\omega}{4\pi} < \delta\vec{E}\delta\vec{E} >_{\omega,\vec{k}} \sum_\alpha \operatorname{Im} \chi_\alpha^0, \tag{10}$$

where $< \delta\vec{E}\delta\vec{E} >_{\omega,\vec{k}}$ is the spectral density of turbulent electric-field fluctuations in the inhomogeneous plasma at $E_0 > E_*$.

The solution to equation (10), provided that the condition

$$\gamma_r, \gamma_l < \nu_{eff} < \omega_r \tag{11}$$

is satisfied, gives the effective collision frequency

$$\nu_{eff} \approx \gamma(k^*) \frac{E_0^2}{E_*^2(k^*)}, \tag{12}$$

where k^* is the wavenumber satisfying the decay condition (11):

$$k^* = \frac{(\omega - \omega) m_e \Omega_e}{k T_e}\ , \qquad k^*_{II} < k^*_{\perp}\ .$$

From condition (11), it is easy to find the values of the pump-field amplitude under which expression (12) is valid.

We obtain that the RF power density absorbed in the plasma is determined by the formula

$$W = \frac{1}{16} \frac{e^2 n_e \omega_l(k^*) \omega_r(k^*)}{m_e \omega_0^4 \gamma_l(k^*)} \frac{E_0^4}{B_0^2} \frac{(k_\perp^* c)^2}{(k^* r_{De})^2}\ . \qquad (13)$$

As was pointed out in [5], to make use of the parametric instability in plasma heating, it is desirable that the pump energy be absorbed uniformly over the entire plasma cross section. This is possible if the effective absorption length l_{eff} is comparable to plasma size in the direction of pump-wave propagation. Therefore, to analyze the efficiency of parametric absorption of RF energy in the inhomogeneous plasma, we must obtain the expression for l_{eff} and estimate its value.

Following [5], we characterize the absorption efficiency by scale length

$$l_{eff} = \upsilon_{gr} E_0^2 / 4\pi W\ , \qquad (14)$$

where υ_{gr} is the group velocity of the pump wave. In view of the formula for the group velocity $\upsilon_{gr} \approx \omega_0 c / \omega_{pe}$ [14] of the wave with the frequency on the order of the LH frequency $\omega \approx \omega_{LH}$ and also expression (13) for the absorbed RF power, we obtain the following expression for l_{eff} in the inhomogeneous plasma

$$l_{eff} \approx 16 \frac{c}{\omega_{pe}} \left(\frac{B_0}{E_0} \right)^2 (k r_{De})^2 \frac{\omega_0^5 \gamma_l}{\omega_{pe}^2 \omega_r \omega_l (k_\perp c)^2}\ . \qquad (15)$$

As is seen from (15), the effective absorption length increases as either the pump power or the plasma density decrease. We note that the absorption length depends strongly on the pump field frequency and plasma density ($l_{eff} \sim n_e^{-3}$) and the efficiency of the RF power absorption decreases as the density gradient increases.

Let us estimate expression (15). Note that the resonant decay takes place at $\omega_0 > 2\omega_{LH}$, and, for typical plasmas, we have $k r_{De} \sim 10^{-1}$ [5, 10]. If we use the pump field with the frequency $\omega_0 = 3\omega_{LH}$, the energy flux density 50 kW/cm^2, and the ratio $\gamma_l / \omega_l \sim 10^{-3}$ (which is characteristic of LH waves) then we obtain that, in a hot plasma with thermonuclear parameters ($n_e = 5 \cdot 10^{13}\, cm^{-3}$, $T_e = 1\, keV$, $B_0 = 5 \cdot 10^4\, Gauss$) the effective absorption length is $l_{eff} \approx 3\, m$; i.e., this length is comparable to the plasma size.

Consider the parametric decay of pump wave into upper hybrid and electron drift wave

$$\omega_0 = \omega_u + \omega_D\ . \qquad (16)$$

In the region above threshold ($E_0 > E_{th}$), where

$$E^2 = 8\omega_0^2 B_0^2 \omega_{pe}^2 (kr_{De})^2 \frac{\nu_{ei}\gamma_{De}}{k^2 c^2 \Omega_e^3 \omega_D} \tag{17}$$

plasma becomes turbulent.

Under assumption $\gamma_D, \gamma_U < \nu_{eff} < \omega_{De}$ we find

$$\nu_{eff} \approx \frac{k_0^2 c^2}{8\omega_0^2 B_0^2} \frac{\omega_D \Omega_e^3 E_o^2}{(k_0 r_{De})^2 \omega_{pe}^2 \nu_{ei}}, \tag{19}$$

where k_0 is defined by decay condition (17).

It can be seen from (19) that ν_{eff} grows with increasing density gradient and the intensity of pump wave.

These results agree with experimental data of the anomalous absorption of electromagnetic wave energy in a turbulent magnetized plasma [14]. We note, that for typical hot plasma parameters $kr_{De} = 0{,}2$, $B_0 = 5 \cdot 10^4 Gauss$, $n_0 = 10^{14}\ cm^{-3}, T_e = 5keV$ the present value of ν_{eff} is much grater than ν_{ei}. We have thus deduced the efficiency for the absorption of upper hybrid wave energy in a plasma, as the absorbed power is proportional to $\nu_{eff} E_0^2$.

Our results can thus be of interest for lower and upper hybrid heating of plasmas.

We note that kinetic fluctuation theory in the present time in connection with the problems of HF plasma heating, transport and scattering phenomena in plasma is extensively developed [15-17].

REFERENCES

1. *Pavlenko V.N., Panchenko V.G., Revenchuk S.M.* // Plasma Phys. and Contr. Fusion. - 1984. - Vol. 26. - P. 1221.
2. *Pavlenko V.N., Panchenko V.G., Shukla P.K.* // Fiz. Plasmy. - 1989. - Vol. 15. - P. 919.
3. *Pavlenko V.N., Panchenko V.G., Stenflo L., Wilhelmsson H.* // Phys. Scripta. - 1992. - Vol. 75. - P. 237.
4. *Pavlenko V.N., Panchenko V.G.* // Plasma Phys. Reports. - 1999. – Vol. 25. - P. 288.
5. *Krupnova L.V., Tikhonchuf V.T.* // Zh. Eksp. Teor. Fiz. - 1979. - Vol. 77. - P. 1933.
6. *Krall N.A., Trivelpiece A.W.* Principles of Plasma Physics. – New York: Academic, 1973.
7. *Mikhailovskii A.V.* Teoriya plasmenikh neustoichevostei (Theory of Plasma Instabilities). - Moskow: Atomizdat, 1977.
8. *Hasegava A.* // Phys. Fluids. - 1979. - Vol. 22. - P. 1988.
9. *Gary S.P., Sanderson J.* // Phys. Fluids. - 1978. - Vol. 21. - P. 1181.
10. *Porcolab M.* // Phys. Fluids. - 1974. - Vol. 17. - P. 1432.
11. *Kindel J.M., Okuda H., Dawson J.M.* // Phys. Rev. Letters. - 1972. - Vol. 29. - P. 995.
12. *Pavlenko V.N., Panchenko V.G., Revenchuk S.M.* // Zh. Eksp. Teor. Fiz. - 1986. - Vol. 91. - P. 86.
13. *Lominadze D.S.* // Zh. Eksp. Teor. Fiz. - 1972. - Vol. 63. - P. 1300.
14. *Golant V.E.* // Zh. Tekh. Fiz. - 1971. - Vol. 41. - P. 2492.
15. *Sitenko A. G.* ICPP-98 combined with 25th Europ. Phys. Soc. Contr. Fusion Plasma Phys. – 1998. - Vol. 22C. – P. 1643 - 1646.
16. *Sitenko A.G.* Abstracts of contributed papers ICPP2000. – Canada. – P. 120.
17. *Pavlenko V.N., Panchenko V.G., Nazarenko S.A.* // Ibid. – P. 245.

ПОГЛИНАННЯ ВЕРХНЬО- ТА НИЖНЬОГІБРИДНОЇ ХВИЛЬ НАКАЧКИ В ЗАМАГНІЧЕНІЙ ПЛАЗМІ

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Розвинуто кінетичну теорію флуктуацій для однорідної та неоднорідної замагніченої плазми в присутності ВЧ поля хвилі накачки з частотою в області нижньо- та верхньогібридних частот. Обчислено ефективну довжину поглинання та показано, що для термоядерної плазми ефективна довжина поглинання порівнянна із розмірами плазми, що призводить до ефективної дисипації потужності ВЧ накачки.

ПОГЛОЩЕНИЕ ВЕРХНЕ- И НИЖНЕГИБРИДНОЙ ВОЛН НАКАЧКИ В ЗАМАГНИЧЕНОЙ ПЛАЗМЕ

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Развита кинетическая теория флуктуаций для однородной и неоднородной замагниченой плазмы в присутствии ВЧ поля волны накачки с частотой в области нижне- и верхнегибридных частот. Вычислена эффективная длина поглощения и показано, что для термоядерной плазмы эффективная длина поглощения сравнима с размерами плазмы, что приводит к эффективной диссипации мощности ВЧ накачки.