Parametric absorption of h-f radiation by the magnetoactive plasma

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Parametric absorption of high-frequency (h-f) radiation in the millimeter range is shown to be an effective method of plasma heating in a thermonuclear reactor.

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As is known,[1] absorption of h-f radiation (pumping wave)—dependent on the linear transformation of radiation into palsma waves—occurs in a narrow plasma layer in which the corresponding resonance condition is satisfied. On the other hand, nonlinear absorption mechanisms—associated with parametric instabilities—may lead to absorption of the pumping wave energy and, thus plasma heating, in a large volume

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of a plasma. This suggests a possibility of increasing the yield of a thermonuclear reaction.

In existing works (see, e.g., Refs. 2 and 3), the possibility of absorption of h-f radiation in the millimeter range due to electron cyclotron resonance and the absorption of h-f radiation in the decimeter range with a frequency similar to frequency of lower-hybrid (LH) resonance $\omega_{Li}(1+\omega_{Le}^2\Omega_e^{-2})^{-1/2}$ (ω_{La} and Ω_a are the Langmuir and cyclotron frequencies of a-brand plasma particles) is usually discussed. In our work, we focus on a possibility of strong parametric absorption of h-f millimeter radiation with a frequency of the order of the transverse Langmuir wave (LH wave). Absorption of this magnitude is associated with excitation in a plasma of a turbulent internal field due to the processes of nonlinear transformation of a pumping wave into plasma waves.

We shall examine the mechanisms of absorption of an extraordinary electromagnetic pumping wave that propagates along the x-axis of a plasma inhomogeneity resulting from the parametric disintegration into two LH waves ($\omega_0 \approx 2\omega_{Le}$).

To analyze the linear stage of such a parametric instability we shall use the eikonal equation (comp. with Ref. 4 for a case of isotropic plasma) which under conditions of future thermonuclear reactors—discussed in Ref. 3 where $\Omega_e > \omega_{Le} > \omega_{Li} > \Omega_i$ has the following form

$$k_x^2(x) = -k_y^2 - k_z^2 + k_z^2 \frac{\omega_{Le}^2(x)}{\omega^2}\left[1 + \frac{1}{2}\sqrt{\frac{k_0^2 v_E^2}{\Omega_e^2} - 64\left(\frac{\gamma+\tilde{\gamma}}{\omega_0}\right)^2}\,\right]\ldots \quad (1)$$

Here, $\mathbf{k} = (k_x(x), k_y, k_z)$ is the wave vector of the LH wave, $v_E = eE_0/m\omega_0$, E_0 is the amplitude, y are the electric field components of the pumping wave, e and m are the electron charge and mass, respectively, $\tilde{\gamma}$ and ω are damping constant and frequency of the LH wave ($\omega \approx \omega_0/2$), respectively, and γ is the instability increment. The z-axis is directed along the vector of external magnetic field **B**.

The electron density distribution may be approximated by the following function of the coordinate x: $n_e(x) = n_m(1 - x^2L^{-2})$, where n_m is the electron density in the plasma center ($x = 0$). Therefore, Eq. (1) allows for a possibility of excitation in the plasma of trapped LH waves whose amplitudes, in the linear approximation, increase exponentially with time. This situation corresponds to an absolute instability with the threshold given by the following formula:

$$\frac{k_0^2 v_{E\,\mathrm{thr}}^2}{\Omega_e^2} = 16\left(\frac{\nu_{ei}}{\omega_0}\right)^2 + 4\frac{(2n+1)^2 r_D^2}{L^2}\ln\left[\frac{4L^2}{(2n+1)^2 r_D^2}\right], \quad (2)$$

where r_D is the Debye radius of electron, k_0 ($\approx \omega_0/c$) is the pumping wave number, ν_{ei} is the electron-ion collision frequency. The first term in Eq. (2)—dependent on the collisional dispersion of LH waves—corresponds to results in Ref. 5. The second term—associated with inhomogeneity—is central to the necessary conditions for future thermonuclear reactors (see, e.g., Ref. 3) and it corresponds to the threshold value of the pumping field intensity ~ 1 kV/cm (at $T_e \approx 1$ keV, $n_e \approx 10^{14}$ cm^{-3}, $B = 5\times 10^4$ gauss, $L \approx 200$ cm).

At amplitudes higher than the threshold value [Eq. (2)] the size of a region to which the absolute instability of decay into two LH waves is confined is $\Delta x \approx 2L\{3/\ln[8(2\pi)^{1/2}\Omega_e/k_0 v_E]^2\}^{1/2}$, its size being comparable with the dimension of plasma inhomogeneity L.

Let us determine the power absorbed in the plasma as the discussed absolute instability develops. By generalizing Bychenkov's results[6] for the case of a magnetoactive plasma, we get the following expression for the value of power absorbed per unit volume of anisothermal plasma: $Q = 32 n_e T_e \gamma^3 (\omega_{Li}\omega_{Le} k_d r_D)^{-1}$, where $k_d = r_D^{-1}\ln^{-1/2}(L^2/r_D^2)$ is the disintegration wave number. In the case of isothermal plasma, $Q = 32 n_e T_e \gamma^2/\omega_{Le}$. In determining Q, we allowed for the fact that the saturation of parametric instability occurs due to secondary disintegration of the LH wave into a second LH wave and an ionoacoustic wave.

Knowing Q, we may evaluate the effective radiation relaxation length $l_{\text{eff}} = cE_0^2/4\pi Q$ that characterizes absorption of the pumping wave. Assuming that at values several-fold higher than threshold [Eq. (2)] $\gamma = k_0 v_E(\omega_0/8\Omega_e)$, we find that in an anisothermal plasma

$$l_{\text{eff}} = 4\frac{c}{\omega_0}\left(\frac{B}{E_0}\right)\sqrt{\frac{m}{M}}\left(\frac{B^2}{4\pi n_m T_e}\right)\ln^{-1/2}\left(\frac{L^2}{r_D^2}\right), \tag{3}$$

where T_e is the electron temperature and M is the ion mass. In terms of the necessary conditions for a thermonuclear reactor,[3] the value of l_{eff} (Eq. (3)) is less than $|\Delta x|$ for pumping field intensity ~ 10 kV/cm and $T_e > 3$ keV which points to a possibility of an effective absorption of millimeter radiation. For the case of isothermal plasma

$$l_{\text{eff}} = (c/\omega_0)(B^2/4\pi n_m T_e). \tag{4}$$

The value above also corresponds to the possibility of a near-total absorption of h-f radiation since under the foregoing conditions $\Delta x \gg l_{\text{eff}}$.

Inasmuch as the effective relaxation length increases with temperature—according to Eqs. (3) and (4)—the effectiveness of parametric absorption increases in proportion to plasma heating.

In conclusion, we showed that the parametric transformation of an extraordinary wave in the millimeter region into an LH wave constitutes an effective heating mechanism of a plasma to temperatures that are necessary for sustaining a thermonuclear reaction. We also note that the use of h-f pumping as described requires no special devices for the coupling of h-f radiation to the plasma (see also Ref. 3).

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