:ffect of quasilinear effects on the propagation ınd damping of lower-hybrid waves in a plasma

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The quasilinear mechanism of "trapping" of the lower-hybrid waves on the periphery of a plasma is considered.

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A strange regularity was observed in all the experiments performed to date on additional ıeating of a plasma by lower-hybrid waves ($\omega^2 \geqslant \omega_{\rm LH}^2 = \omega_{pi}^2 \omega_{Bi} \omega_{Be}/(\omega_{pi}^2 + \omega_{Bi}\omega_{Be})$, $|k_\perp| c/\omega > 1$), $k_z \| H_0$ n installations of the tokamak type.[1] Despite the high efficiency ($\gtrsim 90\%$) of RF energy input nto the plasma, absorption of the energy by the long-lifed plasma component was very small, not nore than 20% of the energy input. The greater part of the RF energy vanished "without trace," vithout increasing the energy content of the plasma. Generally speaking, this anomaly could be ttributed to the nonlinear process of conversion of the lower-hybrid waves into short-wave plasma ›scillations[2]; if the characteristic length of energy transfer turns out to be much shorter than the ›lasma dimensions, then the RF energy dissipation should occur mainly on the periphery of the ›lasma. In most experiments, however, it was noted that at a moderate ($P \leqslant 100$ kW) energy input he intensity of the scattered waves decreased rapidly with decreasing plasma density; on the other ıand, the heating efficiency was not increased thereby. The absence of nonlinear processes in lischarges with $\omega > \omega_{\rm LH}^{\rm max}$ was attributed in a number papers[3] to convective emergence of the cattered waves from the interaction zone, inasmuch as in the real experiments the decelerating ystem (and consequently also the region of localization of the lower-hybrid waves) have a finite limension along the z axis. It is clear that such a mechanism of stabilization of the nonlinear ›rocesses will operate only if the wave energy is lost on account of linear (or quasilinear) lissipation mechanisms during one passage of the wave through the plasma. In the opposite case, he energy of the oscillations has time to become uniformly distributed over the entire plasma 'olume and there will be no convective stabilization mechanism. Numerical estimates show that in he existing tokamak installations (with characteristic parameters $\overline{n}_e \sim 10^{13}$ cm^{-3}, $T_e = 1$ keV, $a \sim 10$ m, $R \sim 50$ cm) for oscillations with $\omega/|k_z| \gg V_{Te}$ (and most waves in the spectrum are of this kind) and $\omega > \omega_{LH}^{max}$ all the linear dissipation mechanisms (Landau damping, dissipation due to th electron-ion collisions and to wave reflection from the chamber walls) are negligibly small, so tha noticable energy absorption should take place after several hundred revolutions of the wave in th torus. Since experiments reveal never the less the absence of nonlinear processes at $\omega > \omega_{LH}^{max}$, i remains to assume that the lower-hybrid waves, say on account of quasilinear effects, produce o the periphery of the plasma pinch a layer of hot strongly absorbing plasma with $T_{e\,\mathrm{eff}} \sim 100$ keV The present paper is devoted to a theoretical investigation of the possible appearance of such "trapping" layer.

The problem is solved in the following formulation. A uniform plasma with temperature T_e density n_e, and $\omega_{pe} < \omega_{Be}$ occupies the half-space $x \geqslant 0$. A source of lower-hybrid waves of frequency $\omega > \omega_{LH}$ is located in the $x = 0$ plane and delivers a power P through 1 cm^2 of surface. Assume tha the decelerating system excites the wave spectrum of large width with respect to k_z, such tha $P_{k_z} = (Pk_0/k_z^2)\theta(|k_z| - k_0)$ ($k_0 \approx 2\omega/c$ is the optimal deceleration). This form of the spectrum i close enough to that obtained in modern experiments. If the conditions $\omega/|k_z| > V_{Te}$ and $\omega < \omega_{pe}$ ar satisfied, the oscillations propagate into the interior of the plasma with a group velocity $u_x = \omega^2/\omega_{pe}|k_z|$. In the absence of damping it is easy to obtain the spectral density of the energy o the waves in the plasma

$$W_{k_z} = \frac{|E|^2_{k_z}}{4\pi} = \frac{Pk_0}{\omega_{pe}|k_z|}\,\theta(|k_z| - k_0).$$

The fact that the decelerating system excites a wave spectrum that is broad with respect to k_z makes it possible to use the quasilinear theory to describe the reaction of the waves on the resonant electrons. In our case this equation can be written in the simplified form:

$$\frac{\partial f_z}{\partial t} = \frac{\partial}{\partial V_z}\int_{-\infty}^{\infty} dk_z D k_z\, \delta\left(k_z - \frac{\omega}{V_z}\right)\frac{\partial f_z}{\partial V_z} - \nu_E(f_z - f_M)\,. \quad (1$$

Here

$$D_{kz} = \frac{4\pi^2 e^2}{m^2} W_{k_z}\frac{k_z^2}{k^2} = \frac{4\pi^2 e^2 Pk_0}{m^2\omega\omega_{pe}}\,;\quad f_z = 2\pi\int_0^{\infty} V_\perp dV_\perp f_e\,;\quad f_M$$

$$= \frac{n_e}{\sqrt{\pi}\,V_{Te}}\exp\left(-\frac{V_z^2}{V_{Te}^2}\right);\quad \frac{1}{\nu_E}$$

$1/\nu_E$ is the energy lifetime of the electrons. The quantity ν_E is obtained from experiment and ca greatly exceed the classical electronic thermal conductivity ($\nu_E \gg \chi_{e\,\mathrm{cl}}/a^2$). The stationary solutio of (1) takes the form:

$$f_z \approx \frac{n_e}{2V_b}\exp\left(-\frac{|V_z|}{V_b}\right);\qquad V_b = \sqrt{D_{kz}/\nu_E}\,. \quad (2$$

To estimate the value of V_b and to compare it with V_{Te} it is necessary to specify the numerica values of P, ν_E, n_e, T_e, etc. By way of example we have chosen the parameters of the TM-: installation in typical discharges with lower-hybrid heating, the values of n_e, T_e, and ν_e being chosen from the conditions on the pinch periphery: $P = 100$ kW, $R = 40$ cm, $a = 8$ cm, $T_e = 100$ eV $n_e = 10^{12}$ cm^{-3}, and $\nu_E = 10^4$ sec^{-1}. For these parameters it turns out that $V_b \gtrsim 10^{10}$ cm/sec. We remark immediately that the "hot" plasma layer thickness (obtained from the energy-balance equation) is less than 1 cm in this case.

At $t < 1/\nu_E$, the distribution function varies with time like $f_z \sim \exp(-|V_z|/\sqrt{D_{k_z}t})$; the characteristic time necessary to establish the stationary state is $\tau \sim 1/\nu_E$.

We have thus shown that the quasilinear effects lead to the appearance of a thin layer of hot ɛctrons, on the plasma periphery. If we estimate the decrement of the damping of the lower-ʼbrid waves by the resonant electrons in such a plasma, then we find that for waves with $/|k_z| \lesssim (3/2)V_b \approx c/2$ we have:

$$\frac{\gamma}{\omega} \approx \frac{\omega \frac{\omega_{pe}^2}{k^2 n_e} \frac{\partial f_z}{\partial V_z}\Big|_{\omega/k_z}}{\omega} \approx \frac{\omega^2}{k_z^2 V_b^2} e^{-\frac{\omega}{|k_z| V_b}} \lesssim 1, \tag{3}$$

:., the wave must lose its energy over a length on the order of the transverse wavelength:

$$\Delta x \sim \frac{1}{k_x} \sim \frac{\lambda_z}{2\pi} \frac{\omega}{\omega_{pe}} . \tag{4}$$

is interesting to note also that, in addition to the appearance of strong damping, for waves with $/|k_z| < V_b$ ($N_z = |k_z| c/\omega \gtrsim 3$) the plasma becomes altogether opaque. Indeed, when the condi-ɔns $\omega < \omega_{pe}$ and $N_z > 1$ are satisfied, the expression for the transverse refractive index is[4]

$$N_\perp^2 \approx -(N_z^2 - 1)\left(1 - \frac{4\pi e^2}{m\omega} \int_{-\infty}^{\infty} \frac{V_z \frac{\partial f_z}{\partial V_z}}{\omega - k_z V_z} dV_z\right) . \tag{5}$$

ʼhen the inequality $\omega/|k_z| < V_b$ is satisfied, it follows from (3) that

$$N_\perp^2 \approx -\frac{\omega_{pe}^2}{\omega^2} \frac{c^2}{V_b^2}\left(1 + i\sqrt{\pi}\exp\left(-\frac{\omega}{|k_z| V_b}\right)\right) . \tag{6}$$

he appearance of such an opacity zone leads to an even greater localization of the waves on the lasma periphery. Thus, we have shown in this paper that the lower-hybrid waves can produce, on ıe periphery of a plasma pinch, on account of quasilinear effects, a hot plasma thin layer, thus ading to a strong kinetic absorption of the waves on the plasma periphery. It should be noted that ıe effectiveness of such a dissipation process depends substantially on the number of short-wave ıodes in the spectrum. Namely, the electron-acceleration mechanism begins to exceed the dynam--friction force only if the oscillation energy has a sufficiently large spectral density. If the number f short-wave modes in the excited spectrum is small, then the effective acceleration will be ɛperienced only by the epithermal electrons with $V_z > V_0 > V_{Te}$, and consequently the number of ɔcelerated particles (and correspondingly the wave damping decrement) will be exponentially nall $\gamma/\omega \sim \exp(-V_0^2/V_{Te}^2)$. We note also that under certain conditions such a layer of hot plasma relative to V_z) can be unstable to buildup of oscillations via the anomalous Doppler effect.

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