Fast wave damping on non-Maxwellian electrons

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Theoretical studies of fast wave damping on electrons are presented. Different regimes of importance for fast wave plasma heating and current drive in tokamaks are considered. Various cases of Maxwellian and multi-Maxwellian, isotropic and anisotropic electron distribution functions are investigated. In all cases, fast wave damping on electrons is due to three terms: Landau damping, transit-time magnetic pumping (TTMP), and the cross-term effect. Expressions for all these terms are derived for all regimes considered. Although in most cases Landau damping, TTMP, and the cross-term effect are the same order of magnitude, regimes are found that can be referred to as the pure Landau damping regimes, or pure TTMP regimes. A key parameter that defines the character of fast wave damping is found: $\delta_\alpha = \epsilon_2/\gamma_\alpha \epsilon\epsilon_3$. In simplified form, and far from resonances, it can be written as $\delta_\alpha \approx -2\omega^2/\Omega_i\Omega_e\beta_\alpha$, where α specifies the appropriate regime.

I. INTRODUCTION

Fast wave plasma heating is a well-known method of radio frequency (rf) plasma heating in tokamaks and other devices.[1,2] The best results for heating have been achieved in an ion cyclotron range of frequency (ICRF) in the regime of fast magnetosonic wave excitation, where significant ion and electron heating has been observed.[1,2] Moreover, in principle, fast waves can be used for the fast wave current drive (FWCD) in tokamaks. This technique has definite advantages in comparison with the other current drive schemes. Fast waves can penetrate into the dense and hot plasma of future reactors without any of the serious limitations inherent in lower-hybrid or electron cyclotron current drive schemes. However, the results of experiments on FWCD, carried out so far (see, for example, Refs. 3–7), are difficult to interpret because fast wave damping on electrons in moderate size tokamaks is weak. The most important regimes for FWCD are ones when ion absorption is not strong and wave energy goes mostly to electrons.

Collisionless damping of fast waves on electrons is due to the Čerenkov resonance $\omega = k_\parallel / v_\parallel$. However, often it is useful to consider damping from two separate mechanisms: Landau damping, where the force acting on electrons is $F_{\rm LD} = eE_\parallel$; and transit-time magnetic pumping (TTMP), in which the force is $F_{\rm MP} = -\nabla_\parallel (\mu B_\parallel)$. Here e and μ are the charge and the magnetic moment of an electron and $E_\parallel$ and $B_\parallel$ are the parallel components of the fast wave electric and magnetic field. These two mechanisms are coherent and the cross-term contribution can be very important.[8,9] Fast wave absorption on electrons has been considered in a number of papers.[8–16] The present work gives systematic extension of the theoretical consideration to multi-Maxwellian or anisotropic electron distribution functions, which could be the case for FWCD. It can be especially important in the regimes when preliminary rf heating of electrons is used, for example, via the electron cyclotron or low hybrid resonances. This paper can be considered as an extension of the analysis presented in Ref. 9. However, unlike that work, the Wentzel–Kramers–Brillouin (WKB) approximation is employed here, resulting in expressions useful and convenient for estimation of fast wave damping on electrons for many regimes of FWCD in tokamaks.

II. FAST WAVE DAMPING ON ELECTRONS IN MAXWELLIAN PLASMA

Let us consider fast wave penetration in a plasma immersed in an external magnetic field $\mathbf{B}_0$, which is directed along the z axis of Cartesian coordinate system (x,y,z): $\mathbf{B}_0 \| \hat{\mathbf{z}}$. Suppose that a wave vector $\mathbf{k}$ has only $k_x = k_\perp$ and $k_z = k_\parallel$ components. Then the corresponding WKB form for the electric and magnetic fields of a fast wave can be written as

$$\mathbf{E},\mathbf{B} \sim \exp(-i\omega t + ik_\perp x + ik_\parallel z). \tag{1}$$

In this paper we will characterize wave damping by the factor of Γ, representing the ratio of imaginary and real parts of the perpendicular refractive index

$$\Gamma = 2\,{\rm Im}(n_x)/{\rm Re}(n_x) = 2\,{\rm Im}(k_x)/{\rm Re}(k_x), \tag{2}$$

where $n_x = k_x/k_0$, $k_0 = \omega/c$.

The local power deposition of fast wave energy to electrons, P_e, can be calculated through the electron related ani-Hermitian part of the hot plasma dielectric tensor, $\boldsymbol{\epsilon}_{\rm e}^{\rm a}$,

$$P_e = \frac{\omega}{8\pi}\,\mathbf{E}^*\boldsymbol{\epsilon}_{\rm e}^{\rm a}\mathbf{E}. \tag{3}$$

In our analysis we will suppose that the wave frequency, ω, is much smaller than the electron cyclotron frequency, Ω_e. For a Maxwellian plasma the components of $\boldsymbol{\epsilon}_{\rm e}^{\rm a}$ are well known (see, for example, Ref. 17), and the absorbed power is given by the sum of Landau damping ($P_{\rm LD}$), TTMP ($P_{\rm MP}$), and the cross-term ($P_{\rm CR}$) contributions:

$$P_e = P_{\rm LD} + P_{\rm MP} + P_{\rm CR}, \tag{4}$$

and can be written in the form[9]

$$P_{\rm MP} = 2\gamma n_\perp^2 G |E_y|^2, \tag{5}$$

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$$P_{LD}=\frac{1}{\gamma n_\parallel^2} G|E_z|^2, \quad (6)$$

$$P_{CR}=2\frac{n_\perp}{n_\parallel} G\,\mathrm{Im}(E_y^* E_z). \quad (7)$$

Here $n_\perp$ and $n_\parallel$ are the perpendicular and parallel components of the fast wave refractive index, and γ and G are defined by the expressions

$$\gamma=\frac{\omega v_e^2}{2\Omega_e c^2}=\frac{\omega}{\Omega_e}\frac{T_e}{m_e c^2}, \quad (8)$$

$$G=\frac{\omega}{8\pi}\frac{\omega_{pe}^2}{\omega\Omega_e}\zeta_{0e}\,\mathrm{Im}\,Z(\zeta_{0e})=\frac{\omega_{pe}^2}{8\sqrt{\pi}\Omega_e}\zeta_{0e}\exp(-\zeta_{0e}^2), \quad (9)$$

where ζ_{0e} is written in place of $(\omega/k_\parallel ve)$, and v_e is the thermal electron velocity.

The value of $\mathrm{Im}(k_\perp)$ can be calculated through the expressions for absorbed power (5)–(7) and the expression for the power flux (which is equal to the Poynting flux in the case of a fast wave[18]):

$$\mathrm{Im}(k_\perp)=\frac{P_e}{2S_x}, \quad (10)$$

$$S_x=\frac{c}{8\pi} n_\perp |E_y|^2. \quad (11)$$

To find the wave damping coefficient Γ, one can use the polarization relation[9]

$$E_z=in_\perp n_\parallel \gamma(-1+\delta)E_y, \quad (12)$$

where

$$\delta=\frac{\epsilon_2}{\gamma\epsilon\epsilon_3}, \quad (13)$$

$$\epsilon=\epsilon_1-n_\parallel^2, \quad (14)$$

$$\epsilon_1=1+\sum_\alpha \frac{\omega_{p\alpha}^2}{2\omega^2}\zeta_{0\alpha}[Z(\zeta_{1\alpha})+Z(\zeta_{-1\alpha})], \quad (15)$$

$$\epsilon_2=\sum_\alpha \frac{\omega_{p\alpha}^2}{2\omega^2}\zeta_{0\alpha}[Z(\zeta_{1\alpha})-Z(\zeta_{-1\alpha})], \quad (16)$$

$$\epsilon_3=1-\sum_\alpha \frac{\omega_{p\alpha}^2}{k_\parallel^2 v_\alpha^2}Z'(\zeta_{0\alpha}), \quad (17)$$

$$\zeta_{n\alpha}=\frac{\omega-n\Omega_\alpha}{k_\parallel v_\alpha}. \quad (18)$$

More precise expressions for the dielectric tensor components could be used in calculations if one would like to include corrections caused by the second- or higher-order ion cyclotron harmonic resonances. In the case of the absence of cyclotron resonances, when $|\zeta_{n\alpha}|\gg 1$, the cold plasma expressions for ϵ_1 and ϵ_2 can be used:

$$\epsilon_1=1+\frac{\omega_{pe}^2}{\Omega_e^2}+\sum_i \frac{\omega_{pi}^2}{\Omega_i^2-\omega^2}, \quad (19)$$

$$\epsilon_2=-\frac{\omega_{pe}^2}{\omega\Omega_e}+\sum_i \frac{\omega}{\Omega_i}\frac{\omega_{pi}^2}{\Omega_i^2-\omega^2}. \quad (20)$$

The expressions for fast wave damping on electrons can be obtained from Eqs. (4)–(7), and Eqs. (10)–(12):

$$\Gamma=\Gamma_{LD}+\Gamma_{MP}+\Gamma_{CR}=(1+|\delta|^2)G_1, \quad (21)$$

$$\Gamma_{MP}=2G_1, \quad (22)$$

$$\Gamma_{LD}=|1-\delta|^2 G_1, \quad (23)$$

$$\Gamma_{CR}=-2G_1\,\mathrm{Re}(1-\delta), \quad (24)$$

$$G_1=\frac{\sqrt{\pi}}{2}\beta_e\zeta_{0e}\exp(-\zeta_{0e}^2). \quad (25)$$

If parameter δ is small, $|\delta|\ll 1$, then there is a cancellation between TTMP and the cross-term contribution, so the total electron absorption is equal to Landau damping:

$$\Gamma=\Gamma_{LD}=\tfrac{1}{2}\Gamma_{MP}=-\tfrac{1}{2}\Gamma_{CR}. \quad (26)$$

This cancellation was first mentioned in Ref. 8. In spite of this cancellation, and the equality $\Gamma=\Gamma_{LD}$, we believe that it is not correct to identify this regime as a Landau damping regime, because TTMP (although canceled by the cross-term contribution) is not small in comparison with Landau damping. On the other hand, the regime $|\delta|\gg 1$ is a true Landau damping regime, because TTMP and cross-term contributions are both small in comparison with Landau damping. In principle, one can imagine the pure TTMP regime when $\mathrm{Re}\,\delta\simeq 1$, $\mathrm{Im}\,\delta\ll 1$. However, in reality, this regime does not seem very interesting because it can be realized only in nonresonant conditions, when wave damping is very weak.

There is another way to find the damping coefficient, Γ. Because of the weakness of fast wave electron damping in the typical tokamak conditions, $\Gamma\simeq\beta_e\ll 1$, one can find Γ from the fast wave dispersion relation, using the perturbative method for the calculation of small $\mathrm{Im}(n_\perp)$. This method has been used in Ref. 15. However, the partition of TTMP and the cross-term effect in comparison with Landau damping was not given there. For the special case, when $\zeta_{0e}\gg 1$ and

$$|\epsilon_1|\gg n_\parallel^2, \omega_{pe}^2/\Omega_e^2, \quad (27)$$

we can estimate

$$\delta\simeq -\frac{m_e c^2}{T_e}\frac{\omega^2}{\omega_{pi}^2}=-\frac{2\omega^2}{\Omega_i\Omega_e\beta_e}, \quad (28)$$

which agrees with the expression from Ref. 12.

The TTMP regime corresponds to the special case of the real δ in conditions when $\delta\simeq 1$. If, moreover, the resonance condition $\zeta_{0e}\simeq 1$ is satisfied, electron absorption will be maximal. In this case, $\mathrm{Re}(\delta)\simeq\mathrm{Im}(\delta)$, and it is difficult to have the pure TTMP regime, because, even for conditions when $\mathrm{Re}(\delta)=1$, the Landau damping term is the same order of magnitude as the TTMP absorption term. When $\mathrm{Re}(\delta)<1$, the cross-term contribution is neg-

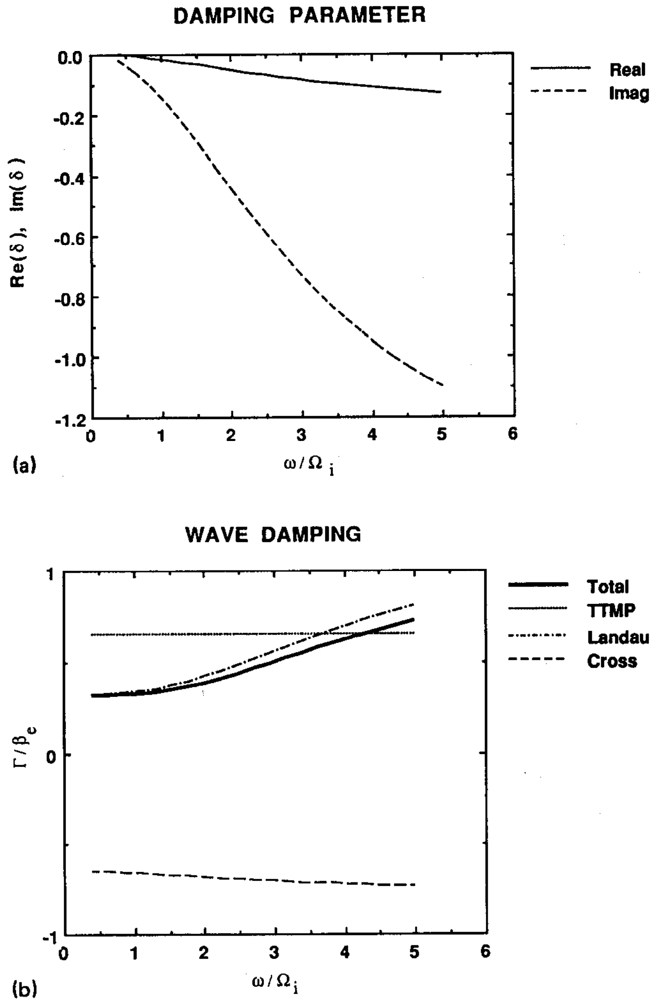


FIG. 1. (a) Damping parameter, δ, as a function of ω/Ω_i in a Maxwellian plasma. (b) Wave damping factor, Γ/β_e, as a function of ω/Ω_i in a Maxwellian plasma. Solid, dotted, dash-dotted, and dashed curves represent, respectively, the total electron absorption, TTMP, Landau damping, and the cross-term effect.

ative. In the opposite case, $\mathrm{Re}(\delta) > 1$, the cross-term contribution is positive, and hence, increases total absorption of waves.

Let us consider a numerical example for the following parameters relevant to experiments on the Phaedrus-T tokamak: an electron density number, $n_e = 3 \times 10^{13}$ cm^{-3}, the toroidal magnetic field, $B_0 = 1$ T, and the ion and electron temperatures, $T_i = 400$ eV, $T_e = 500$ eV. The value of $k_\parallel$ has been chosen to satisfy the resonant condition, $\zeta_{0e} = 1$, which corresponds to maximal wave absorption. In these conditions the dependence of the complex parameter δ on the ratio of rf and ion cyclotron frequencies, ω/Ω_i, is shown in Fig. 1(a), and Fig. 1(b) represents the variation of different absorption mechanisms during changes of ω/Ω_i. As one can see, the low-frequency regime, $\omega < \Omega_i$, corresponds to the small values of $|\delta|$. In this case the relation between various absorption mechanisms, expressed by Eq. (26), holds. The high-frequency regime, $\omega \gg \Omega_i$, gives high values of $|\delta|$, and, hence, corresponds to a true Landau damping regime. In Maxwellian plasma and at the resonance conditions, as one can see from Fig. 1(a), the damping parameter, δ, is mostly imaginary.

III. DAMPING IN THE CASE OF ELECTRON DISTRIBUTION WITH A HOT RESONANT COMPONENT

Sometimes in an experiment the spectrum of excited waves can be nonresonant with the bulk electrons, because they are too cold, $\zeta_{0e} \gg 1$. In this situation, wave damping is weak, and the existence of even a small group of hot resonant electrons can change damping significantly. In our analysis, suppose that electron distribution function can be presented as a sum of a bulk nonresonant component with $\zeta_{0b} \gg 1$, and a hot tail with $\zeta_{0h} \approx 1$, so wave damping will occur mainly due to the wave–particle interaction with the hot tail component. We are using subscripts b and h, respectively, for the bulk electrons and hot tail electrons. For simplicity, in this section we assume that the hot tail has an isotropic Maxwellian distribution. For the bulk electrons the assumption of Maxwellian distribution is not so important, because only the global parameters, such as ω_{peb}^2 of β_{eb}, contribute to the expression for the dielectric tensor components or absorbed power. For example, if the bulk distribution is multi-Maxwellian,

$$f_{eb} = \sum_k f_k, \tag{29}$$

then

$$\omega_{peb}^2 = \sum_k \omega_{pek}^2, \quad \beta_{eb} = \sum_k \beta_{ek}, \tag{30}$$

where β_{ek} corresponds to the usual definition of beta:

$$\beta_{ek} = \frac{8\pi n_{ek} T_{ek}}{B^2}. \tag{31}$$

In this case, the fast wave polarization can be expressed as

$$E_z = i n_\perp n_\parallel \gamma_h (S + \delta_h) E_y, \tag{32}$$

where

$$\gamma_h = \frac{\omega}{\Omega_e} \frac{T_{eh}}{m_e c^2}, \tag{33}$$

$$\delta_h = \frac{\epsilon_2}{\gamma_h \epsilon \epsilon_3}, \tag{34}$$

$$\epsilon_3 \approx 1 - \frac{\omega_{pe}^2}{\omega^2} + q, \tag{35}$$

$$q = 2i\sqrt{\pi} \frac{\omega_{peh}^2}{\omega^2} \zeta_h^3 \exp(-\zeta_h^2), \tag{36}$$

$$\zeta_h = \frac{\omega}{k_\parallel v_{eh}}, \tag{37}$$

$$S = -[(\omega_{peh}^2/\omega^2)(\beta_e/\beta_{eh}) - q]/(\omega_{pe}^2/\omega^2 - q), \tag{38}$$

$$\omega_{pe}^2 = \omega_{peb}^2 + \omega_{peh}^2, \tag{39}$$

$$\beta_e = \beta_{eb} + \beta_{eh}. \tag{40}$$

The wave damping terms are then given by the expressions

$$\Gamma=(1+|1+S+\delta_h|^2)G_h, \tag{41}$$

$$\Gamma_{\rm MP}=2G_h, \tag{42}$$

$$\Gamma_{\rm LD}=|S+\delta_h|^2G_h, \tag{43}$$

$$\Gamma_{\rm CR}=2\,\mathrm{Re}(S+\delta_h)G_h, \tag{44}$$

where

$$G_h=\frac{\sqrt{\pi}}{2}\,\beta_{eh}\zeta_h\exp(-\zeta_h^2). \tag{45}$$

The above expressions show that in the special case,

$$|S+\delta_h|\ll 1, \tag{46}$$

wave damping occurs mostly due to TTMP. In the case, $\omega_{peb}^2\ll\omega_{peh}^2$, the expression for S goes to -1, and the bulk electrons do not play any role in wave polarization and damping. In the important opposite case, $\omega_{peb}^2\gg\omega_{peh}^2$, one gets $|S|\ll 1$, and hence, in the limit, $|\delta_h|\ll 1$, the conditions (46) are fulfilled and the absorption through TTMP will prevail, $\Gamma_{\rm MP}\gg\Gamma_{\rm LD}$, $\Gamma_{\rm CR}$. However, if $|\delta_h|\gg 1$, then again Landau damping will be the main damping process. The estimation for δ_h obtained when (27) is satisfied and $\zeta_h\gg 1$ can be written in the form analogous to (28):

$$\delta_h\approx-\frac{2\omega^2}{\Omega_i\Omega_e\beta_{eh}}. \tag{47}$$

Again, let us present a numerical example for the same basic parameters of the Phaedrus-T tokamak, as in Figs. 1(a) and 1(b). However, now we suppose that the electron distribution function has the hot resonant component: $T_{eh}=3T_e$, $n_{he}/n_e=0.1$, and $\zeta_h=1$. Figure 2(a) shows the dependence of δ_h on ω/Ω_i, and Fig. 2(b) represents the dependence of Γ/β_{eh} on ω/Ω_i. As one can see from Fig. 2(a), in this regime the damping parameter, δ_h, is mostly real. At low frequencies, $\omega<\Omega_i$, the parameter δ_h is small and the condition, Eq. (46), is satisfied, which corresponds to damping mostly due to TTMP. At high frequencies, $\omega\gg\Omega_i$, the value of $|\delta_h|$ increases with the frequency, and Landau damping becomes the main damping process. Comparison with the results for the regime of a pure Maxwellian plasma [presented in Figs. 1(a) and 1(b)] shows the striking difference between these two regimes.

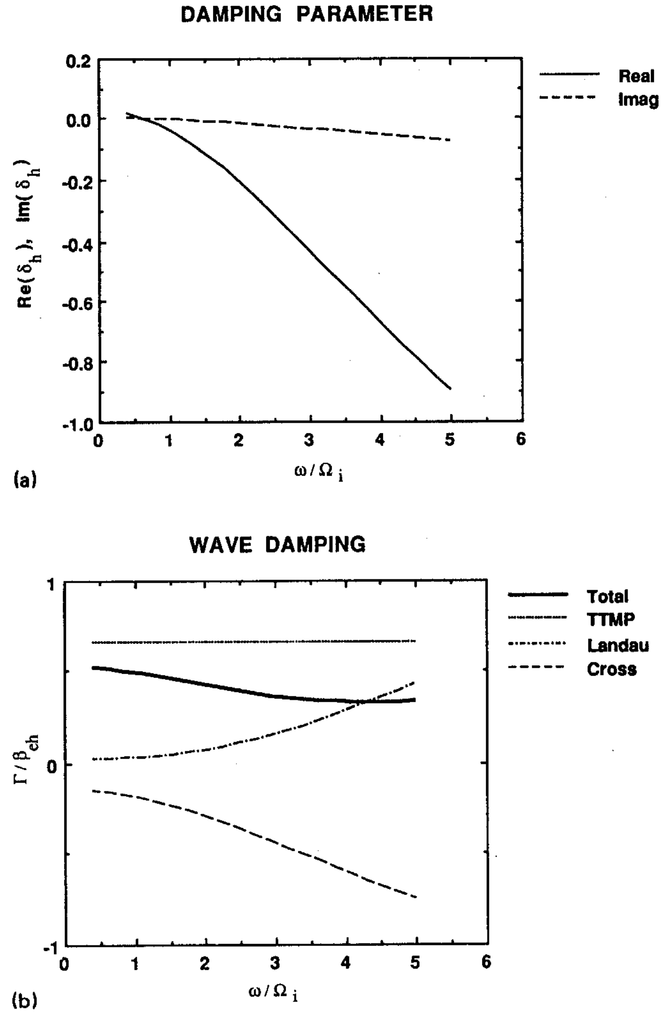


FIG. 2. (a) Damping parameter, δ_h, as a function of ω/Ω_i in a plasma with a hot resonant component ($T_{eh}=3T_e$, $n_{eh}=0.1\,n_e$). (b) Wave damping factor, Γ/β_{eh}, as a function of ω/Ω_i in a plasma with a hot resonant component ($T_{eh}=3T_e$, $n_{eh}=0.1n_e$). Solid, dotted, dash-dotted, and dashed curves represent, respectively, the total electron absorption, TTMP, Landau damping, and the cross-term effect.

IV. DAMPING IN THE CASE OF NONISOTROPIC DISTRIBUTION

The electron distribution function can easily be nonisotropic under the presence of rf plasma heating. In this case fast wave damping is different. Additional electron heating, for example, via electron cyclotron resonance or lower-hybrid (LH) resonance heating, has been recently proposed with the goal of increasing electron temperature and, hence, the rf current drive efficiency. The experiments on fast wave current drive in the DIII-D tokamaks,[5] for example, imply powerful electron cyclotron heating. The experiments in the joint European torus (JET) tokamak[7] have found synergistic LH and fast wave current drive effects. The electron distribution function, created during the heating process, may have $T_\perp>T_\parallel$, or $T_\perp<T_\parallel$, or may have some directional flow with a drift velocity, v_{e0}. Let us consider these cases.

Suppose that the electron distribution function is bi-Maxwellian (in the sense that it is characterized by the two different temperatures, $T_{e\perp}$ and $T_{e\parallel}$), and a drift velocity, v_{e0}, directed along the z axis (i.e., along the external magnetic field):

$$f_e(v_\perp,v_\parallel)=\frac{1}{\pi^{3/2}v_{e\perp}^2v_{e\parallel}}\exp\left(-\frac{v_\perp^2}{v_{e\perp}^2}-\frac{(v_\parallel-v_{e0})^2}{v_{e\parallel}^2}\right). \tag{48}$$

In this situation, TTMP absorption, Landau damping, and cross-term contributions read as the following:

$$P_{\rm MP}=2\gamma_\perp n_\perp^2 G_\parallel\left(\frac{T_{e\perp}}{T_{e\parallel}}-\frac{k_\parallel v_{e0}}{\omega}\right)|E_y|^2, \tag{49}$$

$$P_{LD}=2\frac{\Omega^e}{\omega}\zeta_{e\parallel}^2 G_\parallel |E_z|^2, \quad (50)$$

$$P_{CR}=2\frac{n_\perp}{n_\parallel}\frac{T_{e\perp}}{T_{e\parallel}} G_\parallel \text{Im}(E_y^* E_z), \quad (51)$$

where

$$\zeta_{e\parallel}=\frac{\omega}{k_\parallel v_{e\parallel}}, \quad (52)$$

$$G_\parallel=\frac{\omega_{pe}^2}{8\sqrt{\pi}\Omega_e}\zeta_{e\parallel}\exp(-\zeta_{e\parallel}^2), \quad (53)$$

$$\gamma_\perp=\frac{\omega}{\Omega_e}\frac{T_{e\perp}}{m_e c^2}. \quad (54)$$

The corresponding wave damping coefficients can be expressed as

$$\Gamma=(2\xi-1+|\delta_\perp|^2)G_2, \quad (55)$$

$$\Gamma_{MP}=2G_2\xi, \quad (56)$$

$$\Gamma_{LD}=|1-\delta_\perp|^2 G_2, \quad (57)$$

$$\Gamma_{CR}=-2G_2(1-\delta_\perp), \quad (58)$$

where

$$G_2=\frac{\sqrt{\pi}}{2}\frac{T_{e\perp}}{T_{e\parallel}}\beta_{e\perp}\zeta_{e\parallel}\exp(-\zeta_{e\parallel}^2), \quad (59)$$

$$\delta_\perp=\frac{\epsilon_2}{\gamma_\perp\epsilon\epsilon_3}, \quad (60)$$

$$\beta_{e\perp}=\frac{8\pi n_e T_{e\perp}}{B^2}, \quad (61)$$

$$\xi=1-\frac{T_{e\parallel}}{T_{e\perp}}\frac{k_\parallel v_{e0}}{\omega}. \quad (62)$$

In Eq. (60) the value of ϵ_3 is given by Eq. (17), with parameters v_e and ζ_{0e} changed, respectively, to $v_{e\parallel}$ and $\zeta_{e\parallel}$.

Almost the same conclusions, as in the case of isotropic Maxwellian plasma, can be obtained from the above expressions, if the direction flow is absent, i.e., $v_{e0}=0$. Namely, if parameter $\delta_\perp$ is small, $|\delta_\perp|\ll 1$, then TTMP is canceled by the cross-term effect, total damping corresponds to Landau damping, and the relations (26) hold. Again, the large parameter $\delta_\perp$, $|\delta_\perp|\gg 1$, corresponds to the pure Landau damping regime, when $\Gamma_{LD}\gg\Gamma_{MP}$, Γ_{CR}. However, the regime of small $\delta_\perp$ is essentially different, in comparison with the isotropic plasma: the wave damping grows significantly with increasing perpendicular temperature, $T_{e\perp}$ (the parallel temperature, $T_{e\parallel}$, is supposed to be constant).

The directional flow can also have an effect on wave damping if the ratio of directional velocity, v_{e0}, and the parallel phase velocity, $\omega/k_\parallel$, is not too small, so the parameter ξ is different from 1.

Again, when (27) holds and $\zeta_{e\parallel}\gg 1$, the important parameter $\delta_\perp$ has the form similar to (28) or (47):

$$\delta_\perp\approx-\frac{2\omega^2}{\Omega_i\Omega_e\beta_{e\perp}}. \quad (63)$$

V. DAMPING IN THE CASE OF ELECTRON DISTRIBUTION WITH THE HOT RESONANT NONISOTROPIC COMPONENT

In this section we combine the results of the two last sections for the case of electron distribution with a hot resonant nonisotropic component. As in Sec. III we will suppose that the electron distribution function can be presented as the sum of a nonresonant bulk multi-Maxwellian distribution (29) and a nonisotropic hot resonant component with the distribution (48), with the subscript e changed to h. Here, we will use the subscripts b and h, respectively, for the bulk electrons and the hot tail electrons. In this case the fast wave polarization is given by the expression

$$E_z=in_\perp n_\parallel\gamma_{h\perp}(S_\perp+\delta_{h\perp})E_y, \quad (64)$$

where

$$\gamma_{h\perp}=\frac{\omega}{\Omega_e}\frac{T_{h\perp}}{m_e c^2}, \quad (65)$$

$$\delta_{h\perp}=\frac{\epsilon_2}{\gamma_{h\perp}\epsilon\epsilon_3}, \quad (66)$$

$$\epsilon_3\approx 1-\frac{\omega_{pe}^2}{\omega^2}+q_\parallel, \quad (67)$$

$$q_\parallel=2i\sqrt{\pi}\frac{\omega_{peh}^2}{\omega^2}\zeta_{h\parallel}^3\exp(-\zeta_{h\parallel}^2), \quad (68)$$

$$\zeta_{h\parallel}=\frac{\omega}{k_\parallel v_{h\parallel}}, \quad (69)$$

$$S_\perp=-\frac{[(\omega_{peh}^2/\omega^2)/(\beta_{e\perp}/\beta_{h\perp})-q_\parallel]}{(\omega_{pe}^2/\omega^2-q_\parallel)}, \quad (70)$$

$$\beta_{e\perp}=\beta_{eb}+\beta_{h\perp}. \quad (71)$$

The wave damping terms are then given by the expressions

$$\Gamma=(2\xi_h-1+|1+S_\perp+\delta_{h\perp}|^2)G_{2h}, \quad (72)$$

$$\Gamma_{MP}=2G_{2h}\xi_h, \quad (73)$$

$$\Gamma_{LD}=|S_\perp+\delta_{h\perp}|^2 G_{2h}, \quad (74)$$

$$\Gamma_{CR}=2G_{2h}\text{Re}(S_\perp+\delta_{h\perp}), \quad (75)$$

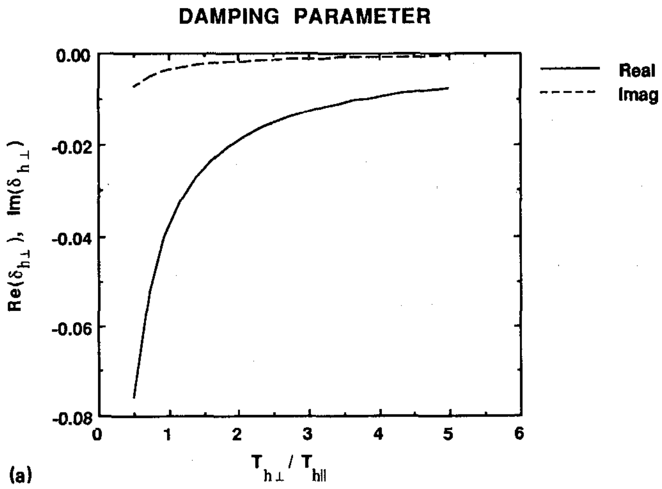
where

$$G_{2h}=\frac{\sqrt{\pi}}{2}\frac{T_{h\perp}}{T_{h\parallel}}\beta_{h\perp}\zeta_{h\parallel}\exp(-\zeta_{h\parallel}^2), \quad (76)$$

$$\xi_h=1-\frac{T_{h\parallel}}{T_{h\perp}}\frac{k_\parallel v_{0h}}{\omega}. \quad (77)$$

This case is interesting because one can easily obtain the pure TTMP damping regime if

$$|S_\perp+\delta_{h\perp}|\ll 1. \quad (78)$$



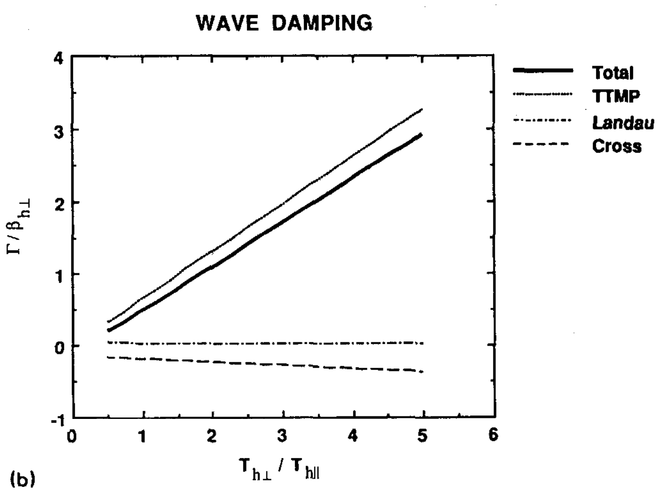


FIG. 3. (a) Effect of electron temperature anisotropy, $T_{h\perp}/T_{h\parallel}$, on the damping parameter, $\delta_{h\perp}$, in a plasma with a hot resonant component ($T_{h\parallel}=3T_e$, $n_{eh}=0.1n_e$). (b) Wave damping factor, $\Gamma/\beta_{h\perp}$, as a function of electron temperature anisotropy, $T_{h\perp}/T_{h\parallel}$, in a plasma with a hot resonant component ($T_{h\parallel}=3T_e$, $n_{eh}=0.1n_e$). Solid, dotted, dash-dotted, and dashed curves represent, respectively, the total electron absorption, TTMP, Landau damping, and the cross-term effect.

If we suppose $\omega_{peb}^2 \gg \omega_{peh}^2$, then one will have $|S_\perp| \ll 1$, and the conditions (78) can be rewritten in the more simpler manner

$$|\delta_{h\perp}| \ll 1. \tag{79}$$

In the opposite case, $|\delta_{h\perp}| \gg 1$, Landau damping will be the main damping process. An approximate expression for $\delta_{h\perp}$, assuming (27) and $\zeta_{h\parallel} \gg 1$, is similar to (63),

$$\delta_{h\perp} \approx -\frac{2\omega^2}{\Omega_i \Omega_e \beta_{h\perp}}. \tag{80}$$

To illustrate the effect of increasing anisotropy of the electron distribution function on the damping due to the various absorption processes, we present, in Fig. 3(a), the dependence of $\delta_{h\perp}$ on the ratio of the perpendicular and parallel temperatures, $T_{h\perp}/T_{h\parallel}$, and in Fig. 3(b) the dependence of $\Gamma/\beta_{h\perp}$ on $T_{h\perp}/T_{h\parallel}$. All plasma parameters have been chosen to be the same as for the case presented in Figs. 2(a) and 2(b), and the resonance condition, $\zeta_{h\parallel}=1$, holds. One can see that increasing of electron distribution anisotropy, $T_{h\perp}/T_{h\parallel}$, leads to decreasing of $|\delta_{h\perp}|$, and the absorption regime becomes the more and more pure TTMP regime, $\Gamma_{MP} \gg \Gamma_{LD}, \Gamma_{CR}$.

VI. SUMMARY AND CONCLUSIONS

The theory of fast wave damping on electrons is considered for different regimes relevant to fast wave plasma heating and current drive. Special attention is paid to the regimes with preheated electrons, which could be helpful for increasing fast wave current drive efficiency. During such preheating, the electron distribution function can be multi-Maxwellian or may have a hot nonisotropic tail with either $T_{h\parallel} > T_{h\perp}$ or $T_{h\parallel} < T_{h\perp}$, depending on the heating method. In all cases, fast wave damping on electrons is due to the three terms: Landau damping, TTMP, and the cross-term effect. The general expressions for all these terms are derived for all regimes considered. It is found that in most cases, Landau damping, TTMP, and the cross-term effect are the same order of magnitude. However, regimes are found when fast wave damping occurs, mostly due to Landau damping or TTMP. There are also regimes where TTMP, although not small in comparison with Landau damping, is canceled by the cross-term contribution. From the analysis presented, the following main qualitative conclusions can be extracted.

(1) For each regime there is a key parameter that defines the character of fast wave damping: δ—for the regime with Maxwellian electron distribution; δ_h—for the regime with a Maxwellian hot plasma component; $\delta_\perp$—for the nonisotropic plasma; and $\delta_{h\perp}$—for the plasma with the hot nonisotropic tail. This parameter, $\delta_\alpha = \epsilon_2/\gamma_\alpha \epsilon \epsilon_3$, generally a complex number, in nonresonant conditions. $|\epsilon_1| \gg n_\parallel^2$, $\zeta_\alpha \gg 1$, can be approximated by $\delta_\alpha \approx -2\omega^2/\Omega_i \Omega_e \beta_\alpha$, where α specifies the appropriate regime.

(2) In the Maxwellian plasma, the condition $|\delta| \ll 1$ corresponds to cancellation between TTMP and the cross-term contribution. The opposite case, $|\delta| \gg 1$, corresponds to the Landau damping regime, $\Gamma_{LD} \gg \Gamma_{MP}, \Gamma_{CR}$. In practice, the pure TTMP regime cannot be realized in a Maxwellian plasma.

(3) For the case of the nonisotropic electron distribution function with the different temperatures $T_{h\parallel}$ and $T_{h\perp}$, the condition $|\delta_\perp| \ll 1$, again, corresponds to the abovementioned cancellation between TTMP and the cross-term effect, and the condition $|\delta_\perp| \gg 1$ corresponds to the Landau damping regime. However, there is one essential difference, in comparison with the isotropic plasma: in the regime of small $\delta_\perp$ the wave damping increases significantly with increasing perpendicular temperature $T_{h\perp}$ ($T_{h\parallel}$ is kept constant). The TTMP regime is again almost impossible for realization.

(4) In the case of an electron distribution with a small group of hot resonant electrons, it is easy to obtain the TTMP damping regime. It corresponds to small δ_h, $|\delta_h| \ll 1$. The opposite case, when $|\delta_h| \gg 1$, gives the Landau damping regime again.

(5) If a small group of the hot resonant electrons is not isotropic, $T_{h\parallel} \neq T_{h\perp}$, then in addition to the results given in the preceding paragraph, one will have a strong dependence of wave damping on $T_{h\perp}$ (damping increases with increasing $T_{h\perp}$ at constant $T_{h\parallel}$).

(6) The directional flow of some group of electrons may have an effect on wave damping if the ratio of the drift velocity and the parallel phase velocity is not too small, so the parameter ξ (or ξ_h for the regime with the hot resonant component) differs essentially from 1.

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