A New Kinetic Mode Driven by Electron Temperature Gradient *

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A new unstable short wavelength mode is identified in sheared slab plasmas using a fully kinetic integral equation code. This mode is driven by the electron temperature gradient and propagates in the ion diamagnetic direction. The instability occurs due to the electron inverse Landau damping effect at short cross-field wavelength regions.

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Microinstabilities driven by temperature gradients are proposed as the plausible candidates responsible for anomalous thermal transport in magnetically confined plasmas.[1] The effect of the $\boldsymbol{E}\times\boldsymbol{B}$ velocity shear on the ion temperature gradient (η_i, or ITG) turbulence successfully explains the ion thermal transport reduction in improved confinement tokamak plasmas,[2] for the measured $\boldsymbol{E}\times\boldsymbol{B}$ shearing rate exceeds the maximum linear growth rate of the ITG mode. However, the electron transport is still anomalous in many cases. It is believed that the anomalous electron transport is governed by short wavelength turbulence.[3] Observations of electron temperature profile stiffness [4] in experiments also indicate that the short wavelength instability responsible for electron transport is driven by finite electron temperature gradient (η_e, ETG). Both the ITG [5–8] and ETG modes [9–11] have been extensively studied over decades. These modes are essentially acoustic waves driven by plasma compressibility and/or bad magnetic curvature. Recently, another unstable mode driven by temperature gradients in the short wavelength region $|k_\perp\rho_i|\gg 1$ has been identified both in a slab [12,13] and in a toroidal [14] configuration. This temperature-gradient-driven short wavelength ion (SWITG) mode propagates in the ion diamagnetic direction and requires both finite η_i and η_e for excitation. This instability occurs mostly due to the ion kinetic response in the short wavelength region. The SWITG mode can be strongly influenced by the electron kinetics, but still exists for adiabatic electrons. In this Letter, we identify a new kinetic mode in the short wavelength region driven by electron temperature gradient alone. This kinetic ETG (KETG) mode propagates in the ion diamagnetic direction and is destabilized by the electron inverse Landau damping effects.

In this Letter, we limit our consideration to the electrostatic case in a sheared magnetic field $\boldsymbol{B}=B_0[\hat{\boldsymbol{z}}+\hat{\boldsymbol{y}}(x/L_s)]$. The mode is described by the fully kinetic integral equation [13]

$$\frac{k_\perp^2\rho_e^2}{2}\frac{\Omega_e^2}{\omega_{pe}^2}+\sum_j\frac{Z_jT_e}{T_j}\Big\{1+\int\frac{dk'}{2\pi}\int dx\exp[i(k'-k)x]L_j\Big\}=0, \tag{1}$$

$$L_j=\Big(1-\frac{\omega_{*j}}{\omega}\Big)[\xi_jZ(\xi_j)]\Gamma_{0j}-\eta_j\frac{\omega_{*j}}{\omega}\Big[\xi_j^2+\Big(\xi_j^2-\frac{3}{2}\Big)\xi_jZ(\xi_j)\Big]\Gamma_{0j}-\eta_j\frac{\omega_{*j}}{\omega}\xi_jZ(\xi_j)[(1-b_a)\Gamma_{0j}+b_g\Gamma_{1j}].$$

Other notation is defined as follows:

$$\omega_{*j}=(k_yT_j)/(\Omega_jm_jL_n),\quad \Gamma_{nj}=I_n(b_{gj})\exp(-b_{aj}),$$
$$b_{gj}=\sqrt{b_jb_j'},\quad b_{aj}=(b_j+b_j')/2,\quad b_j=k_\perp^2\rho_j^2/2,$$
$$b_j=k_\perp^2\rho_j^2/2,\quad \rho_j=v_{tj}/\Omega_j,\quad \xi_j=\omega/|k_\parallel|v_{tj},$$
$$k_\parallel=(x/L_s)k_y,\quad k_\perp^2=k_y^2+k^2,\quad k_\perp'^2=k_y^2+k'^2,$$
$$\Omega_j=-q_jB/m_jc,\quad Z_j=-q_j/e,$$
$$\phi(x)=1/\sqrt{2\pi}\int\phi(k)\exp(ikx)dk,$$

and $Z(\xi)$ is the plasma dispersion function. This integral eigenmode equation can be applied to ITG, ETG, and SWITG modes,[8,13] as well as to the present new KETG modes.

The eigenmode equation (1) is solved for the parameters $\eta_e=3$, $\eta_i=0$, $T_e/T_i=1$, $m_i/m_e=1836$, $L_n/L_s=0.025$, $\Omega_e^2/\omega_{pe}^2=1$ and $k_y\rho_e=0.3$ unless otherwise stated. The mode frequency and growth rate versus $k_y\rho_e$ are shown in Fig. 1. The mode has a relatively low frequency and growth rate, but persists unstable in a wide region of poloidal wavelength, from ρ_i^{-1} to ρ_e^{-1}. It is emphasized that the Debye shielding effect Ω_e^2/ω_{pe}^2 significantly influences this mode, which is the behaviour of short wavelength modes. As we know, the Debye shielding effect is proportional to $k_\perp^2$. Figure 2 shows that the KETG mode has a narrow x structure and a wide k-spectrum with the order ρ_e^{-1}. Similar to the plasma response to the SWITG mode,

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$\Gamma_{0,1}(b_i)$ is decaying as $1/\sqrt{b_i}$ for large b_i. Although ω_*/ω, which increases with k_y, can partly compensate for the decaying from $\Gamma_{0,1}(b_i)$, this compensation is also given to the electron response. As a result, the ion response is reduced in short wavelength regions and may be comparable with the electron response, especially in the case of zero η_i.

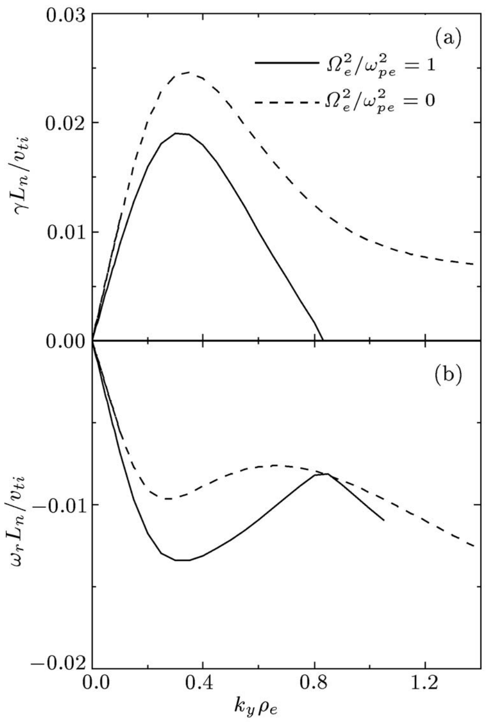

Fig. 1. Mode growth rate (a) and frequency (b) of the KETG mode versus $k_y\rho_e$ for $\eta_e = 3.0$, $\eta_i = 0$, $m_i/m_e = 1836$, $T_e/T_i = 1$, $L_n/L_s = 0.025$. The solid and dashed lines denote the results for $\Omega_e^2/\omega_{pe}^2 = 1$ and 0, respectively.

Local analysis ($k = k'$, $k_\parallel = \text{const}$) can explain this mechanism more clearly. For simplicity, $\Omega_e^2/\omega_{pe}^2 = 0$ and $ZT_e/T_i = 1$ are used. When the assumption $v_{te} > |\omega|/k_\parallel > v_{ti}$ is valid, we can neglect the terms of order $(k_\parallel^3 v_{ti}^3/\omega^3)$ and order $(\omega^3/k_\parallel^3 v_{te}^3)$ and obtain the dispersion relation in the region $\rho_e^{-1} > k_\perp \gg \rho_i^{-1}$,

$$2 + \frac{\omega_{*i}}{\omega}\Gamma_{0i} - \frac{k_\parallel^2 v_{ti}^2}{2\omega^2}\Gamma_{0i} + \frac{2\omega_{*e}\omega}{k_\parallel^2 v_{te}^2}(1-\eta_e)\Gamma_{0e} + i\sqrt{\pi}\frac{\omega_{*e}}{k_\parallel v_{te}}\Big[\frac{\eta_e}{2} - 1\Big] = 0. \quad (2)$$

As $\Gamma_{0i} \to 1$, the first three terms are just the well-known dispersion relation, which introduce two branches of acoustic waves modified by the drift wave. However, as $b_i \gg 1$, the ion response is reduced due to $\Gamma_{0i} \to 1\sqrt{2\pi b_i}$ and the electron response can effectively influence the acoustic wave. On the other hand, the electron Landau damping effect, the last term in Eq. (2), can be comparable with the fluid terms. Assuming $\gamma \ll \omega_r$, in the leading order we have

$$\omega = -\Big[\frac{k_\parallel^4 v_{ti}^2 v_{te}^2 \Gamma_{0i}}{4\omega_{*e}(\eta_e - 1)}\Big]^{1/3} + i\frac{\sqrt{\pi}k_\parallel v_{te}(\eta_e - 2)}{12(\eta_e - 1)}. \quad (3)$$

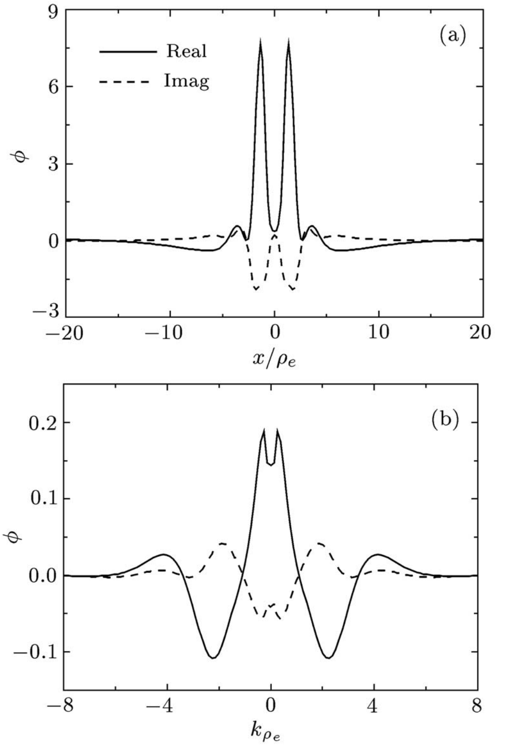

Fig. 2. Mode structure for $k_y\rho_e = 0.3$: (a) $\phi(x)$ versus x/ρ_e; (b) $\phi(k)$ versus $k\rho_e$. The other parameters are the same as those in Fig. 1.

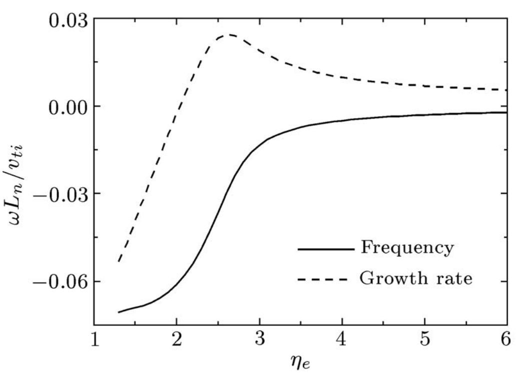

Fig. 3. Mode frequency (solid) and growth rate (dashed) of the KETG mode versus η_e. The parameters are the same as those in Fig. 1.

The above analysis is rather rough for this kinetic instability, but two characters are consistent with the numerical results: (1) the mode propagates in the ion diamagnetic direction and the frequency decreases towards zero as η_e increases; (2) the mode is destabilized when η_e exceeds the threshold of about 2. Figure 3 shows the mode frequency and growth rate versus

η_e and confirms the analytical conclusion. When η_e is very large, the mode frequency reaches a very large value and the growth rate decays as the order $\exp(-\omega^2/k_\parallel^2 v_t^2)$.

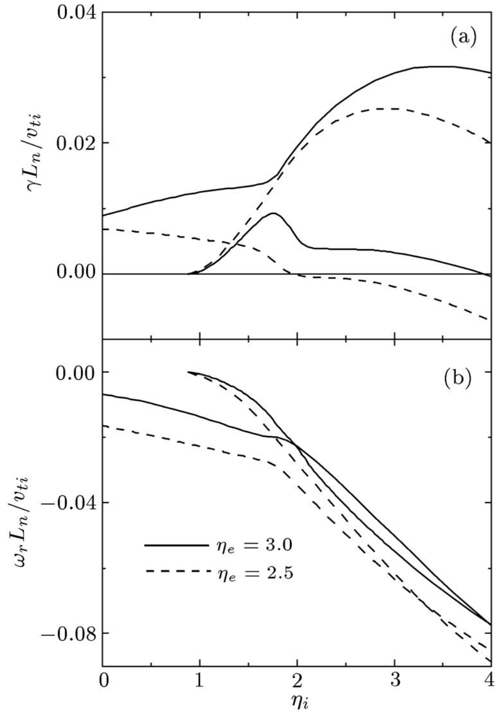

Fig. 4. Mode growth rate (a) and frequency (b) of the KETG and SWITG modes versus η_i. The solid and dashed lines denote the results for $\eta_e = 3.0$ and 2.5, respectively. The mode with higher growth rate is the SWITG mode described in Ref. [12]. Here $k_y\rho_e = 0.1$ and the other parameters are the same as those in Fig. 1.

The mechanism of the new KETG mode is similar to that of the SWITG mode,[13] except that the ion response is dominant for the latter. The mode frequency and growth rate are shown as functions of η_i at $k_y\rho_e = 0.1$ in Fig. 4. When η_i increases, the KETG mode couples to the SWITG mode and the SWITG mode usually has a higher growth rate.

In summary, we have identified a new unstable branch of temperature gradient driven modes in sheared slab plasmas using a fully kinetic integral equation code. This mode is driven by a finite electron temperature gradient and propagates in the ion diamagnetic direction. The instability occurs due to the electron inverse Landau damping effect when the cross-field wavelength is short. This unstable mode grows slowly but it provides a possible way in which the electron temperature gradient can drive negative direction fluctuations. More details on this mode, especially whether this mode exists in the toroidal geometry or not, need to be further investigated in the future.

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