Effect of trapped electrons on ITG modes and occurrence of TEM instabilities in RFP plasmas

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The significant progress recently made in Reversed Field Pinch (RFP) experiments has shown a strong reduction of the stochastic nature of the magnetic field [1]. These results suggest a possible transition from global MHD turbulence transport to a regime likely dominated by microturbulence. Recent studies on Ion Temperature Gradient (ITG) driven modes [2] have shown that the RFP configuration requires very steep ion temperature profiles for such modes to be excited, a condition difficult to find in current experiments. However, such conclusions arose from assuming an adiabatic electron response. In the RFP community the influence of a trapped particle population has been investigated in the past only for its role on neoclassical transport, by means of test-particle simulations [3]. Conversely, its effect on microinstabilities, which may lead to anomalous transport, is still an open issue. In this work we address this problem, and in particular we study the effects of trapped electrons on the ITG mode and the Trapped Electron Mode (TEM) instability in the framework of gyrokinetic theory. Two approaches have been applied: analyses by solving the differential eigenmode equation and simulations with the GS2 flux tube gyrokinetic code. Some preliminary results are presented in the paper.

The fraction of Trapped Electrons (TE) in a large volume of core RFP plasmas can almost reach the same value as the TE fraction in tokamaks (which is estimated as $O((2\varepsilon)^{1/2})$). In the RFP the poloidal magnetic field B_θ is of the same order as the toroidal magnetic field B_φ and the magnetic mirror effect results from both fields: in the core the contribution of B_θ is small, while in the edge the mirror effects mainly results from B_θ, due to the toroidal field reversal. As a consequence, the TE fraction decreases in the edge of RFP plasmas and becomes smaller than that in the edge of a tokamak. The trapped particle fraction is estimated as $f = (2\delta)^{1/2}$, with δ defined in [4].

Differential eigenmode equation

The eigenmode equation is derived by quasi-neutrality condition, written as

$$[\frac{d^2}{dz^2} + Q(z)]\psi(z) = 0 \qquad (1)$$

with $Q(z) = \frac{A(z) - [1 + (1 + D_T)/\tau]}{b\hat{s}^2 B(z)} - \frac{1}{\hat{s}^2} + \frac{1}{4}(\frac{B'(z)}{B(z)})^2$

$$A(z) = \pi \int_{-\infty}^{+\infty} d\hat{v}_{\|} \int_0^{\infty} d\hat{v}_{\perp}^2 \frac{\Omega - \Omega_{*i}[1 + \eta_i(\hat{v}_{\perp}^2 + \hat{v}_{\|}^2 - 3/2)]F_{Mi}}{\Omega - \Omega_{di} - z\hat{v}_{\|}}$$

$$B(z) = \pi \int_{-\infty}^{+\infty} d\hat{v}_{\|} \int_0^{\infty} d\hat{v}_{\perp}^2 \frac{\Omega - \Omega_{*i}[1 + \eta_i(\hat{v}_{\perp}^2 + \hat{v}_{\|}^2 - 3/2)]\hat{v}_{\perp}^2 F_{Mi}}{\Omega - \Omega_{di} - z\hat{v}_{\|}} \; ;$$

$$D_T = -\frac{2}{\sqrt{\pi}}\sqrt{2\delta}\int_0^{\infty} dE\, E \frac{\Omega - \Omega_{*e}[1 + \eta_e(E - \frac{3}{2})]}{\Omega - \langle \Omega_{de} \rangle + i\nu_{eff} E^{-3/2}} e^{-E}, \qquad (2)$$

$$\Omega_{di} = \frac{\omega_{di}}{\omega_{ti}} = \frac{\hat{k}_\theta v_{tj}^2}{\Omega_{cj}}[\frac{1}{L_B}(\frac{v_{\perp}^2}{2}) - \frac{1}{r}(\frac{\varepsilon^2}{q^2\alpha^2})\hat{v}_{\|}^2], \quad \Omega = \frac{\omega}{\omega_{ti}}, \qquad \omega_{ti} = v_{ti}/(Rq\alpha) \quad , \nu_{eff} = (\nu_{ei}/\delta)/\omega_{ti}$$

$$\langle \Omega_{de} \rangle = \frac{\langle \omega_{de} \rangle}{\omega_{ti}} = \int_{-\theta_0}^{+\theta_0} d\theta \frac{\omega_{de}}{|v_{\|}|} / \int_{-\theta_0}^{+\theta_0} \frac{d\theta}{|v_{\|}|}\omega_{ti} \approx \frac{1}{\omega_{ti}}\left\{\omega_{deB} E + \omega_{dec} E \cdot [4\delta(\kappa^2 - 1 + \frac{E(\kappa)}{K(\kappa)})]\right\}$$

where A(z) and B(z) come from the ion kinetic response, and D_T is due to the trapped-electron response, Ω_{di} is the lowest order of the normalized ion magnetic drift frequency and $\langle\Omega_{de}\rangle$ is the electron precession frequency, $\eta_i = L_{ni}/L_{Ti}$, (L_{ni} and L_{Ti} are the gradient scale lengths of ion density and temperature profiles respectively). The other definitions and details of notation can be found in [2] and [5]. In the derivation of Eq.(1), the assumptions $b = k_\theta^2\rho_i^2/2 \ll 1$ and $\omega \ll \omega_{be}$ (ω_{be} is electron bounce frequency) have been used. A Krook collision operator is adopted.

In the ITG mode study, the trapped-electron effect has not significant influence on the mode behavior. This is expected since the mode propagates in the ion diamagnetic drift direction: Ω has a opposite sign with respect to $\langle\Omega_{de}\rangle$ in Eq.(2), and there is no resonance in TE response. The strong ion Landau damping is still a dominant effect in ITG modes of the RFP. Fig.1 shows the modification of the ITG stability threshold ε_{Tc} by trapped electron effect for TE fraction δ = 0.1 and υ_{eff} = 0.5. $\varepsilon_{Tc} = L_{Tc}/R$, L_{Tc} is the critical gradient scale length of ion temperature.

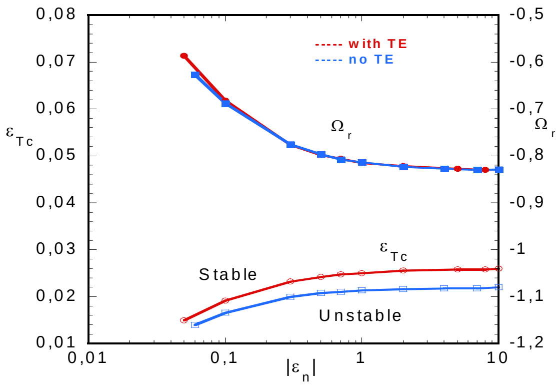

Fig.1 Comparison of the ITG threshold ε_{Tc} and corresponding real frequency Ω_r between the cases with and without TE.

Trapped electrons play a small destabilizing role; however, they can not significantly modify the ITG thresholds.

The TEM instability can be driven in RFP plasmas. The analytical analysis has been made by taking fluid ions (by ignoring the ion kinetic resonant effects) and a flat ion temperature gradient (η_i<<1). It is found that, when υ_{eff}=0, the $\Omega \sim \langle\Omega_{de}\rangle$ resonance can destabilize the electron drift wave when L_B/L_n >3 approximately, where L_B and L_n are the scale lengths of the magnetic field gradient and density gradient. In the limit $\upsilon_{eff} >> \Omega$, $\langle\Omega_{de}\rangle$, the trapped electrons can also destabilize the mode, with a larger υ_{eff} leading to a smaller growth rate. Fig.2 is the plot of the frequencies and growth rates of TEM instabilities for fluid ions obtained solving Eq.(1) for L_B/R=-0.4 and $\eta_i \approx 0$. It shows that the peaked density gradient leads to a large frequency, and the larger collisionality leads to the small growth rates. The mode has been justified as TEM by taking $\delta \rightarrow 0$ and resulting to be stable. When the kinetic ion effect is taken into account, the unstable TEM can still occur, this study being currently in progress.

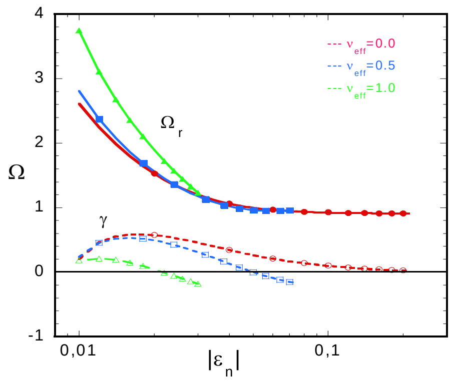

Fig.2 The frequency Ω_r and the growth rate γ are plotted as functions of $|\varepsilon_n|$ ($\varepsilon_n=L_n/R$) for different collision frequencies for ε_{te}=-0.025, q=ε=0.1, τ=2.0 s=-0.5, $k_\theta\rho_i$=0.45.

Numerical simulations by means of GS2

A parametric study has been carried out by means of the gyrokinetic flux tube code GS2 [6], with the typical mid-radius parameters of the RFP magnetic configuration, magnetic shear s ~ -0.5 and safety factor q ~ 0.1. The electron to ion temperature ratio is fixed, T_e/T_i = 2. Furthermore, we assume equal ion/electron temperature gradients, $a/L_{Ti} = a/L_{Te} \equiv a/L_T$, varying in the range [0,10], and the density gradient a/L_n in the range [0,6]. The way we carry out such a parametric study is to start with adiabatic electrons, to add kinetic electrons and subsequently to turn off their trapped fraction. The latter is done either keeping B(θ) constant along the field line, or (almost equivalently) increasing the torus major radius R by one order of magnitude, so as to reduce the field ripple. As a general result we can confirm that on the ion Larmor radius scale the major instabilities are ITG modes when the temperature gradient is large enough. As a rule of thumb, the condition a/L_T > 4-6 must be satisfied for $k_y\rho_i$ < 0.6-0.7. In case the density is peaked and the temperatures are rather flat, $a/L_n \geq 4$, $a/L_T < 4$, the dominant modes have TEM nature.

In Fig.3 (a) and (b) we show growth rate and real frequency for three different cases, when the dominant instability is an ITG mode. This is obtained for a/L_n = 2, a/L_T = 6. The inclusion of kinetic electrons has the effect to increase the growth rate of the ITG mode, and to slightly

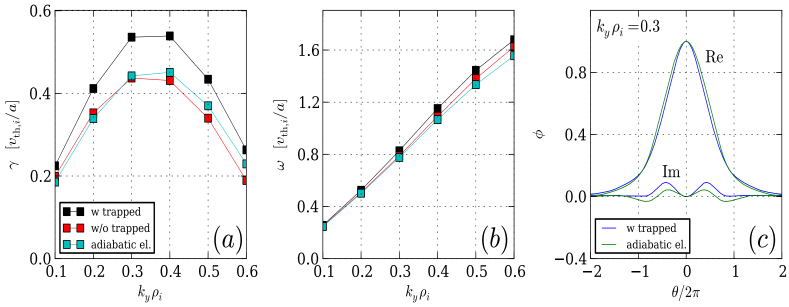

Fig.3: Growth rate (a) and real frequency (b) as a function of the wavenumber in the ITG range of parameters, a/L_n=2 and a/L_T=6, with adiabatic electrons, and with kinetic electrons with/without a trapped electron fraction. In (c) two examples of eigenmodes are shown.

increase its real frequency. Turning off the trapped fraction drops the respective values to the adiabatic-electron case. In frame (c) we show the eigenmodes at the same wavenumber for two different cases, with adiabatic electrons and with trapped electrons. The shape of the eigenmode is almost the same.

Swapping the values of the two gradients, i.e., $a/L_n = 6$, $a/L_T = 2$, a TEM branch clearly stands out. In Fig.4 (a) and (b) growth rate and frequency are plotted for such parameters. Switching off the trapped particle fraction causes the emergence of instabilities with very low growth rate and frequency, whose nature is under investigation. In frame (c) the narrow structure of the eigenmode is plotted versus the poloidal angle θ.

To conclude, TEMs are shown to be excited in RFP core plasmas in case L_n is small enough. The condition $L_n < L_B/3$ found for fluid ions is roughly in agreement with full gyrokinetic simulations. However, a more careful comparison of the two approaches has to be carried out for a full characterization of TEMs in the RFP.

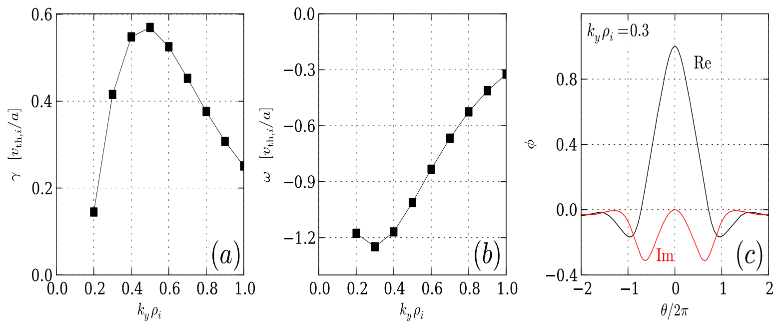

Fig.4: Growth rate (a) and real frequency (b) spectra for a TEM branch originating at a/L_n=6 and a/L_T=2, and eigenmode structure along the field line for $k_y\rho_i$= 0.3 (c).

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