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Effect of shaping on Trapped Electron Mode instability: an analytical model

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Abstract

- Analytical dispersion relation for Trapped Electron Mode (TEM) instab. → solved numerically
- Retains shaping effects ⇒ evaluation of their impact on growth rate
- Ballooning of mode plays a critical role to explain the stabilization at negative triangularity

Context

- Negative triangularity $\delta < 0 \Rightarrow$ lower turbulence \Rightarrow better confinement [1,2,3]
- Recovered in gyrokinetic (GK) simulations provided enough physical ingredients are included [4,5,6]
- Beneficial role of $\delta < 0$ depends particularly on aspect ratio [7] & magnetic shearing [8]
- Extensive parametric exploration remains to be done – numerically expensive with GK codes
- TEM modes = key players to explain the difference between positive/negative triangularity
- This work: **Usage of an analytical prediction of the TEM growth rate [9]**
Inputs = magnetic topology (aspect ratio, elongation, triangularity, safety factor, magnetic shearing) density & temperature gradients, poloidal wavenumber ($k_\theta \rho_{Ti}$)

Results

Assumptions

- Adiabatic ions & passing electrons
- Trapped electrons only (no passing)
- Collisionless

Dispersion relation [9]

$$1 + \sqrt{\frac{2}{\pi}} \int_0^\pi \frac{d\theta_b}{\Omega_b} \frac{d\lambda}{d\theta_b} W^2(\theta_b) \int_0^\infty d\epsilon \sqrt{\epsilon} e^{-\epsilon} \frac{\omega_{*T} \left(\epsilon - \frac{3}{2} \right) + \omega_{*N} - \omega}{\omega_d \epsilon - \omega} = 0$$

Average over bounce-angle θ_b Average over energy $\epsilon = \frac{E}{T}$

- Drive of the instability: Thermal diamagnetic frequency due to temperature gradient ω_{*T} and density gradient ω_{*N}
 - Normalized bounce frequency Ω_b
 - Precession frequency ω_d
- Function of shaping

W represents Finite Mode Width effects (FMW)=ballooning

$$W(D, \theta_b) \sim \exp\left(-\frac{D}{2} \theta_b^2\right) I_0\left(-\frac{D}{2} \theta_b^2\right)$$

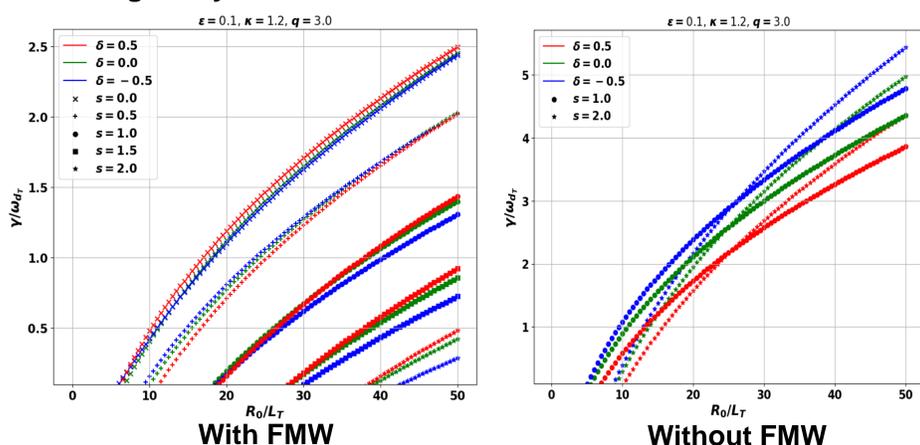
$$\text{with } D = \text{sq}(k_\theta \rho_{Ti})^2$$

Guideline for analysis of the results

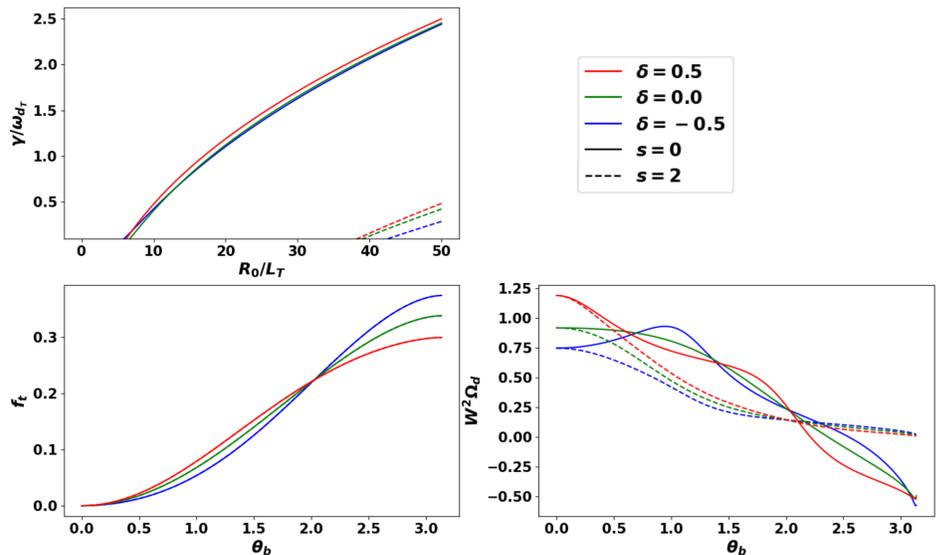
- In the fluid limit (i.e. far from threshold) : $\gamma \sim \sqrt{\omega_{*T} \langle W^2 \Omega_d \rangle_{\theta_b}}$ (for $\omega_{*N}=0$)
- Ω_d is a function of plasma shaping, in particular of triangularity
- $W(D, \theta_b)$ is a function that is maximum for deeply trapped particles ($\theta_b \ll 1$) and decreases with θ_b . The typical width of the function is $1/D$

A rule thumb to predict the most unstable is to compare $\langle W^2 \Omega_d \rangle_{\theta_b}$. When the ballooning is important, i.e. $D = \text{sq}(k_\theta \rho_{Ti})^2 > 1$, one needs to compare the precession frequencies of deeply trapped particles ($\theta_b \ll 1$).

Critical role played by FMW to explain stabilization by negative triangularity

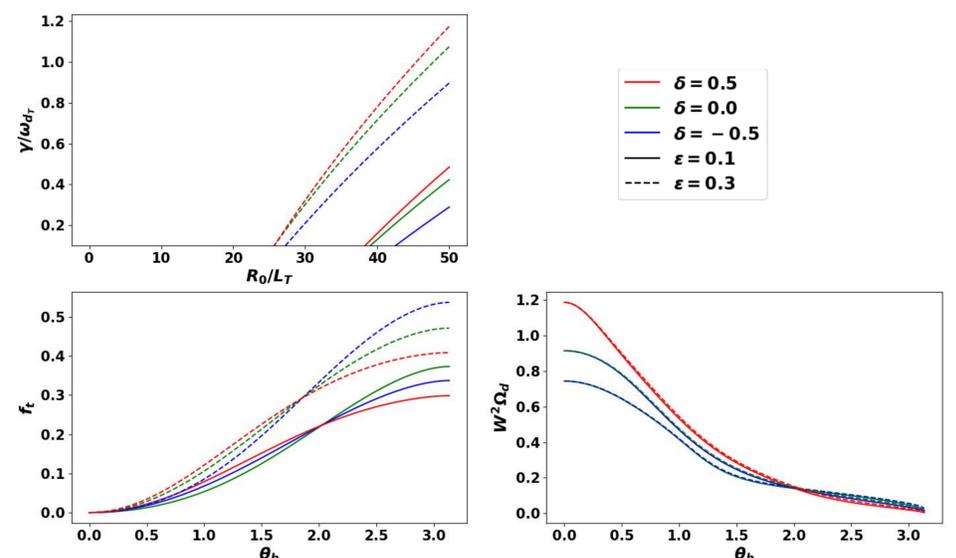


Magnetic shear is stabilizing as expected.



- Trapping is insensitive to the magnetic shear s
- The magnetic shear stabilizes more efficiently negative triangularity than positive triangularity, in agreement with gyrokinetic simulations [8]. This is due to the FMW that become more important when increasing the magnetic shear s , putting more weight on deeply trapped particles whose precession frequencies are lower for negative triangularities

Aspect ratio is stabilizing due to a reduction of trapped fraction



- Rule of thumb not sufficient to understand the aspect ratio dependence (but it is still critical to understand the triangularity dependence) as $\langle W^2 \Omega_d \rangle_{\theta_b}$ is insensitive to the magnetic shear
- The trapped fraction $f_t(\theta_b) = -\int_0^{\theta_b} \frac{d\theta}{\sqrt{2}\Omega_b} \frac{d\lambda}{d\theta}$ plays a critical role to understand the aspect ratio dependence. Indeed the drive of the TEM instability increases with f_t
- Trend observed in gyrokinetic simulation [7] (inversion of triangularity effect when going from large aspect ratio to tight aspect ratio) is not retrieved. Due to different parameters or missing ingredients?

Conclusion & Perspectives

- Analytical dispersion relation for TEM instability \Rightarrow enables fast estimate of growth rate as function of shaping parameters.
- Stabilizing effect of negative triangularity recovered **only** if FMW (ballooning) effects are taken into account.
- Critical gradients are too large when comparing with gyrokinetic simulations \rightarrow need to include ion response in the dispersion relation.
- A quantitative comparison with dedicated gyrokinetic simulations is ongoing.

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