Analytical understanding of the effect of shaping on confinement in TEM regime References

X Garbet, P Donnel, Y Melka, Y Sarazin, V Grandgirard, K Obrejan, E Bourne, G Dif-Pradalier, Y Munschy

Analytical understanding of the effect of shaping on confinement in TEM regime

X, Garbet[1,2], P. Donnel[1], Y. Melka[1], Y. Sarazin[1], V. Grandgirard[1], K. Obrejan[1], E. Bourne[3], G. Dif-Pradalier[1], Y. Munschy[1]

1 CEA, IRFM, Saint-Paul-lez-Durance, F-13108
2 SPMS, NTU, 677371 Singapore
3 SCITAS, EPFL, CH-1015 Lausanne, Switzerland

Email address: xavier.garbet@cea.fr

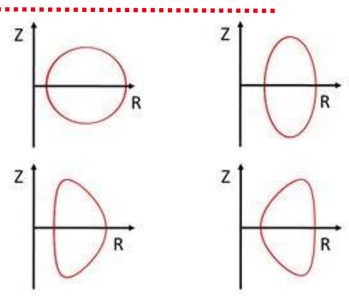
Abstract

- Analytical dispersion relation for Trapped Electron Mode (TEM) instab. → solved numerically
- Retains shaping effects ⇒ evaluation of their impact on growth rate
- Beneficial role of negative triangularity results from | finite orbit width effect and/or ballooning of the mode

Context

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

Analytical model



❖ Assumptions

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

❖ Dispersion relation

$$\mathcal{L}(\omega) = 1 - f_t \left\langle \frac{\omega_{*T}\left(\mathcal{E} - \frac{3}{2} + \frac{1}{\eta}\right) - \omega}{\omega_{dT}\bar{\Omega}_d(\lambda)\mathcal{E} - \omega - i0^+} \right\rangle_{\lambda,\mathcal{E}} = 0 \qquad \eta = d\ln T_{eq}/d\ln N_{eq}$$

Average over energy $\mathcal{E} = \frac{E}{T}$

$$\langle ... \rangle_{\mathcal{E}} = \frac{2}{\sqrt{\pi}} \int_0^{+\infty} d\mathcal{E}\mathcal{E}^{1/2} e^{-\mathcal{E}} ...$$

Average over pitch-angle $\lambda = \mu B_{\min}/E$

$$\langle ... \rangle_{\lambda} = \frac{1}{f_t} \int_{\frac{B_{min}}{B_{max}}}^{1} \frac{d\lambda}{\sqrt{2\bar{\Omega}_b(\lambda)}} ...$$

Thermal magnetic drift frequency $\omega_{dT} = n\Omega_{dT} = \frac{nq}{r_s}\frac{T}{e_a B_\Delta R_\Delta}$

Normalized bounce frequency $\bar{\Omega}_b(\lambda)$

Thermal diamagnetic frequency $\omega_{*T} = n\Omega_{*T}$ with $\Omega_{*T} = -\frac{T}{e_a}\frac{d\ln T}{d\psi}$

Trapped fraction: $f_t = \int_{\lambda_-}^{\lambda_+} \frac{d\lambda}{\sqrt{2\bar{\Omega}_b(\lambda)}}$

❖ Shaping modifies bounce & precession frequencies

Considered magnetic equilibrium = "Culham" [10] → parametrized shaping (ε,κ,δ)
Expression bounce & precession frequencies following refs. [8,9]

$$\Omega_d = \frac{1}{e_a}\frac{\left.\frac{\partial\mathcal{J}}{\partial\psi}\right|_{\mu,H}}{\left.\frac{\partial\mathcal{J}}{\partial H}\right|_{\mu,\psi}} = \Omega_{dT}\bar{\Omega}_d(\lambda)\mathcal{E} \qquad \frac{1}{\Omega_b} = \left.\frac{\partial\mathcal{J}}{\partial H}\right|_{\mu,\psi} \qquad \Omega_b = \bar{\Omega}_b(\lambda)\sqrt{\mathcal{E}}\frac{v_T}{2q_sR_{\max}}$$

$$\left.\frac{\partial\mathcal{J}}{\partial\psi}\right|_{\mu,H} = \frac{q_s}{r_s}\frac{1}{B_sR_s}\frac{1}{\pi}\int_{-\theta_b}^{\theta_b} d\theta\sqrt{g_s}\frac{B_s}{v_\parallel}\left(m_av_\parallel^2 + \mu B_s\right)\left(\frac{r_s^2}{a_s^2}\frac{1}{r_s}\frac{\partial Z_s}{\partial\theta} - \left(s_s\theta - \alpha_m\tilde{D}\right)\frac{1}{r_s}\frac{\partial R_s}{\partial\theta}\right)$$

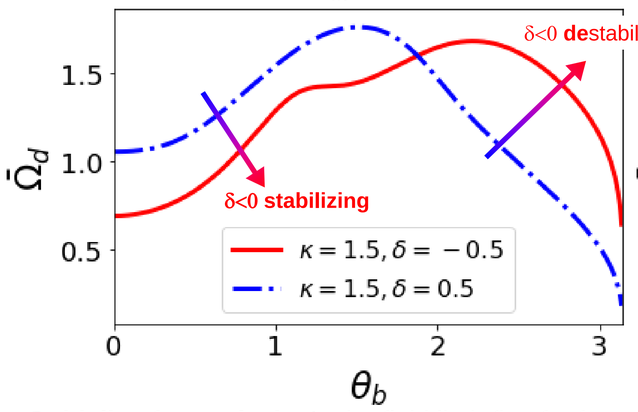
Functions of (ε,κ,δ)

$$- \frac{\alpha_m}{2q_s^2}\frac{q_s}{r_s}\frac{1}{B_sR_s}\frac{1}{\pi}\int_{-\theta_b}^{\theta_b} d\theta\sqrt{g}\frac{B_s}{v_\parallel}\mu B_s$$

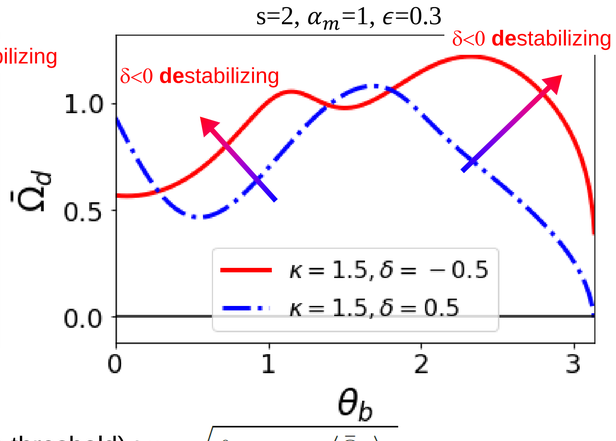
MHD pressure parameter $\alpha_m = -2\mu_0 q_s r_s R_s \frac{1}{B_s}\frac{dp_s}{d\psi}$

$$\left.\frac{\partial\mathcal{J}}{\partial H}\right|_{\mu,\psi} = \frac{1}{\pi}\int_{-\theta_b}^{\theta_b} d\theta\sqrt{g_s}\frac{B_s}{v_\parallel}$$

s=2, α_m=0, ϵ=0.3



s=2, α_m=1, ϵ=0.3



Guideline for analysis: In the fluid limit (i.e. far from threshold) : $\gamma \sim \sqrt{f_t\omega_{dT}\omega_{*T}\left\langle\bar{\Omega}_d\right\rangle_\lambda}$

Numerical results

❖ Necessity to include finite orbit width and/or ballooning of the mode

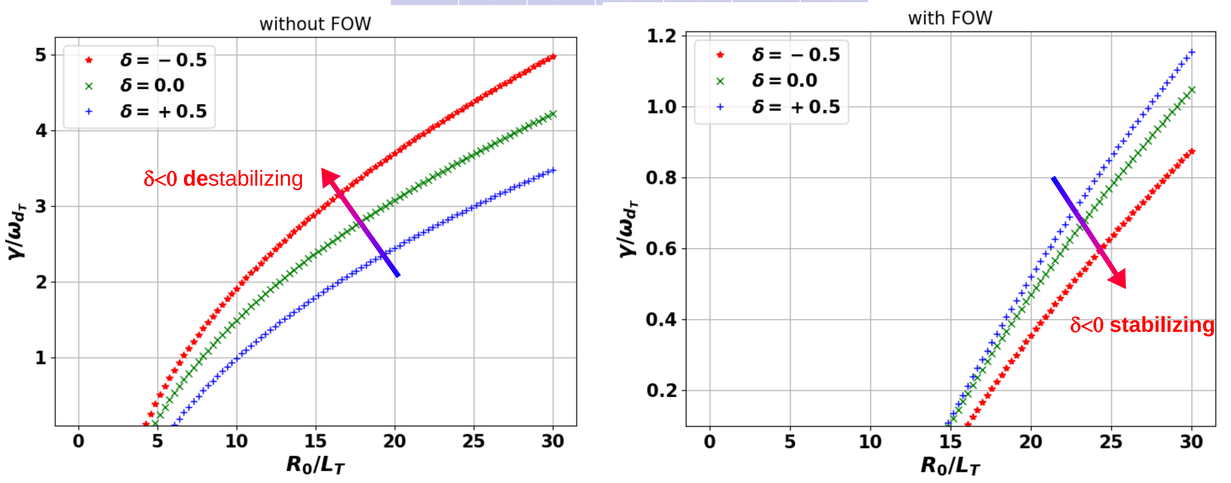
Finite Orbit Width (FOW) ⇒ modified definition of pitch-angle average
⇒ new definition of trapped fraction, accordingly

$$\langle ... \rangle_\lambda = \frac{1}{f_t}\int_{\lambda_-}^{\lambda_+}\frac{d\lambda}{\sqrt{2\bar{\Omega}_b(\lambda)}}J_0^2\left(C\theta_b\right)... \qquad f_t = \int_{\lambda_-}^{\lambda_+}\frac{d\lambda}{\sqrt{2\bar{\Omega}_b(\lambda)}}J_0^2\left(C\theta_b(\lambda)\right)$$

FOW ⇒ more weight on **deeply trapped particles** that are **stabilized by negative triangularity**

Consequence: **Negative triangularity becomes stabilizing when including FOW effects**

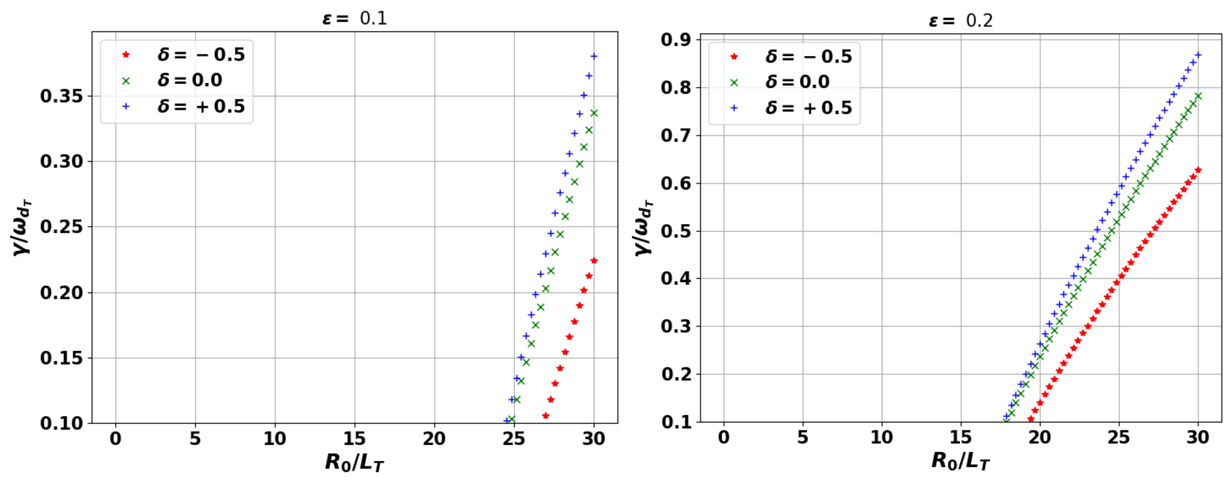
C	ε	κ	q	s	η	α_m
scan	0,3	1,75	2,0	2,0	1000	0,0



Similar effect expected from **mode ballooning** (puts more weight on stabilized deeply trapped particles)

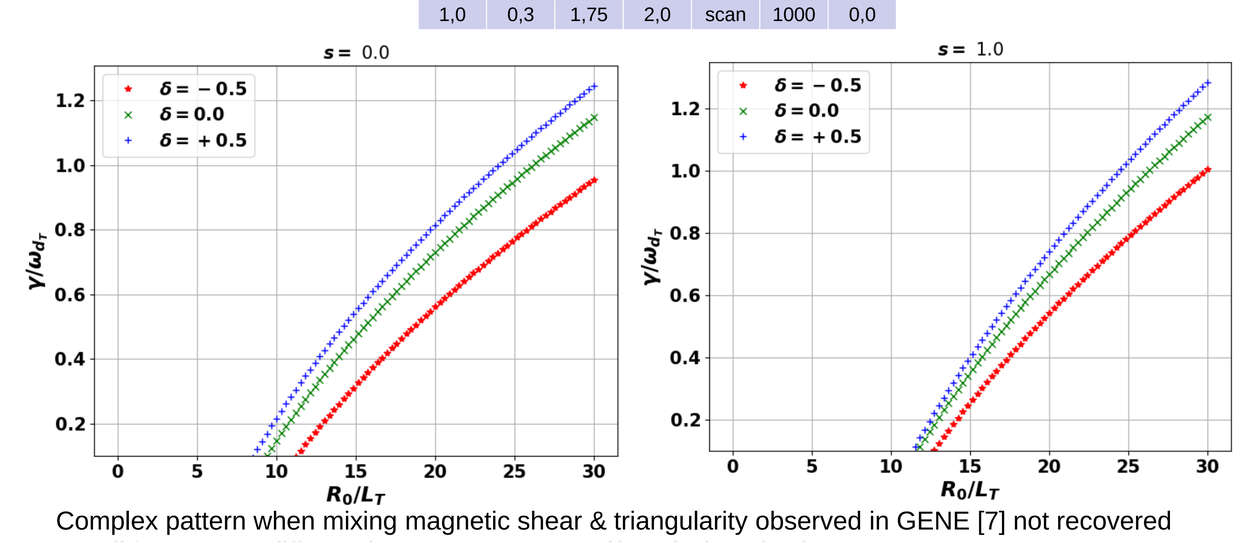
❖ Large aspect ratio is stabilizing due to a reduction of trapped fraction

C	ε	κ	q	s	η	α_m
1,0	scan	1,75	2,0	2,0	1000	0,0



❖ Magnetic shear is stabilizing as expected

C	ε	κ	q	s	η	α_m
1,0	0,3	1,75	2,0	scan	1000	0,0



Complex pattern when mixing magnetic shear & triangularity observed in GENE [7] not recovered
Possible reasons: different input parameters and/or missing physics

Conclusion & Perspectives

- Analytical dispersion relation for TEM instability
  → enables fast estimate of growth rate as function of shaping parameters
- Stabilizing effect of negative triangularity recovered **ONLY IF** a physical mechanism puts more weight on deeply trapped electrons → FOW and/or ballooning
- More systematic parameter scan under way (PhD starting end of 2023)
- Quantitative comparison with GK simulations → upgrade of model (collisions, ions) if necessary
- If successful comparison model-simulations → derivation of quasi-linear estimate of transport

References

1 Y. Camenen *et al.*, "Impact of plasma triangularity and collisionality on electron heat transport in tcv l-mode plasmas". Nuclear Fusion (2007)
2 M. E. Austin *et al.*, "Achievement of reactor-relevant performance in negative triangularity shape in the diii-d tokamak". Phys. Rev. Lett. (2019).
3 A. Marinoni *et al.*, " A brief history of negative triangularity tokamak plasmas". Reviews of modern plasma physics (2021)
4 G, Merlo *et al.*, "Investigating profile stiffness and critical gradients in shaped tcv discharges using local gyrokinetic simulations of turbulent transport". Plasma Physics and Controlled Fusion (2015).
5 G. Di Giannatale *et al.*, "Triangularity effects on global flux-driven gyrokinetic simulations", Journal of Physics: Conference Series (2022)
6 A. Balestri *et al.*, "The aspect ratio dependence on confinement enhancement in negative triangularity plasmas", EPS 2023
7 Gabriele Merlo *et al.*, " Interplay between magnetic shear and triangularity in ion temperature gradient and trapped electron mode dominated plasmas" . Journal of Plasma Physics (2023).
8 C. C. Hegna, "The effect of three-dimensional fields on bounce averaged particle drifts in a tokamak". Physics of Plasmas (2015).
9 Zhangsheng Huang *et al.*, "The synergetic effects of three dimensional magnetic perturbations and finite beta on collisionless trapped electron mode in tokamak plasmas". Nuclear Fusion (2022).
10 J. W. Connor *et al.*, . Report No. CLM-M106. Culham Laboratory Report (1985)