Unraveling the competition/synergy between turbulence and 3D magnetic perturbations

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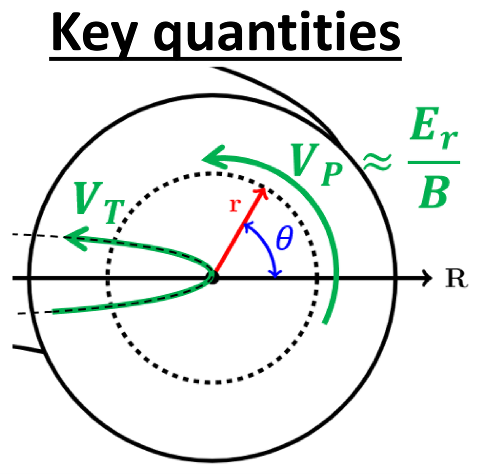
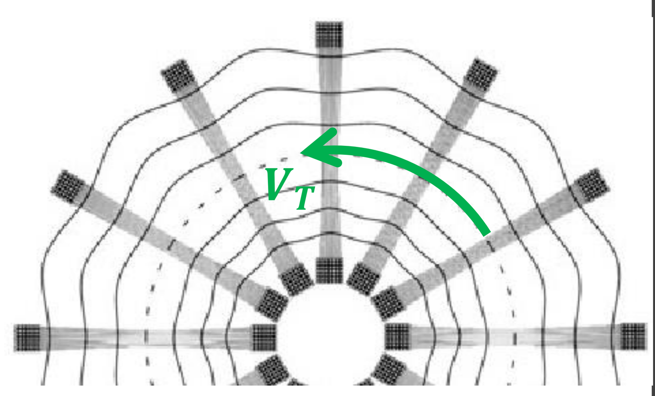
Introduction

- Plasma rotation plays a key role in plasma confinement;
- Control of plasma rotation in reactor-sized tokamak is challenging;
- Intrinsic bulk plasma rotation is driven by ***turbulence*** and ***magnetic braking*** due to ripple

Key quantities **Rippled magnetic field**





Intrinsic rotation mechanisms

- A reduced model [1] based on the mean toroidal velocity V_T reads :

$$\frac{\partial V_T}{\partial t} = \text{Magnetic braking} + \text{Turbulent torque}$$

Ripple constrains particle trajectories and collisional processes

Turbulence constrains V_T through wave-particle interactions

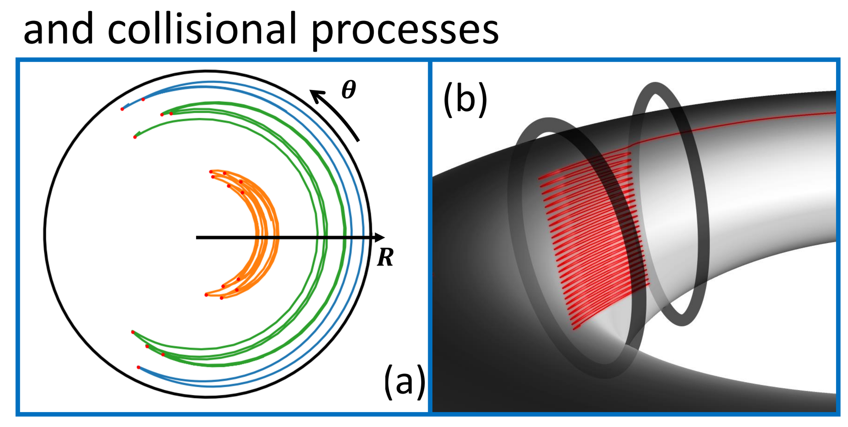


FIG.1 – Kinetic effects induced by ripple : drift of banana bounce points (a) and toroidal trapping between coils (b). Neoclassical friction ν_φ comes from the collisions between trapped particles.

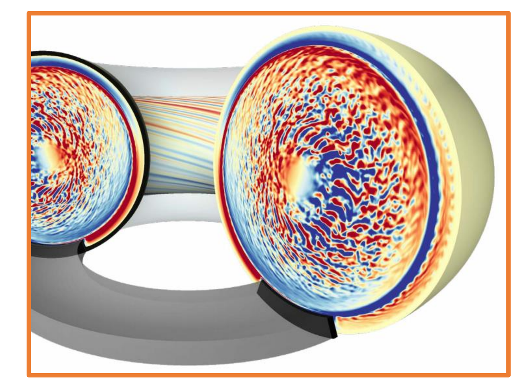


FIG.2 – Snapshot of the turbulent structures seen through a colormap on the electric potential. From rest, V_T grows due to wave-particle interactions.

Turbulence / Ripple competition

- Magnetic braking m imposes a finite velocity V_{neo} [2,3] $m = -\nu_\varphi (V_T - V_{neo})$ Collisional friction
- Turbulence, through toroidal Reynold stress Π, also imposes a finite velocity V_{turb} [4,5] due to particle-waves interactions:

$$\Pi = \underbrace{-\chi \frac{\partial V_T}{\partial r}}_{\text{Viscosity}} + \underbrace{\mathcal{V} V_T}_{\text{Pinch}} + \underbrace{\Pi_{res}}_{\text{Residual}}$$

- Competing forces $\partial_t V_T = m - r^{-1}(r\Pi)'$

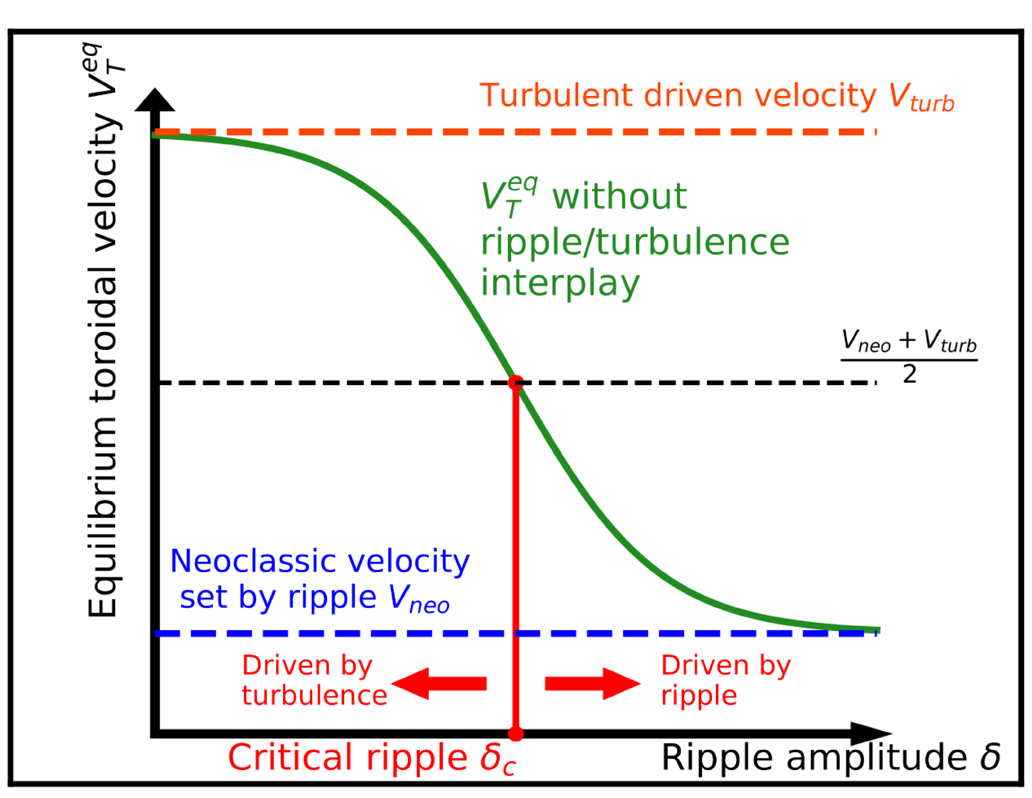


FIG.3 – Sketch of the modelled ripple/turbulence competition on the equilibrium toroidal velocity.

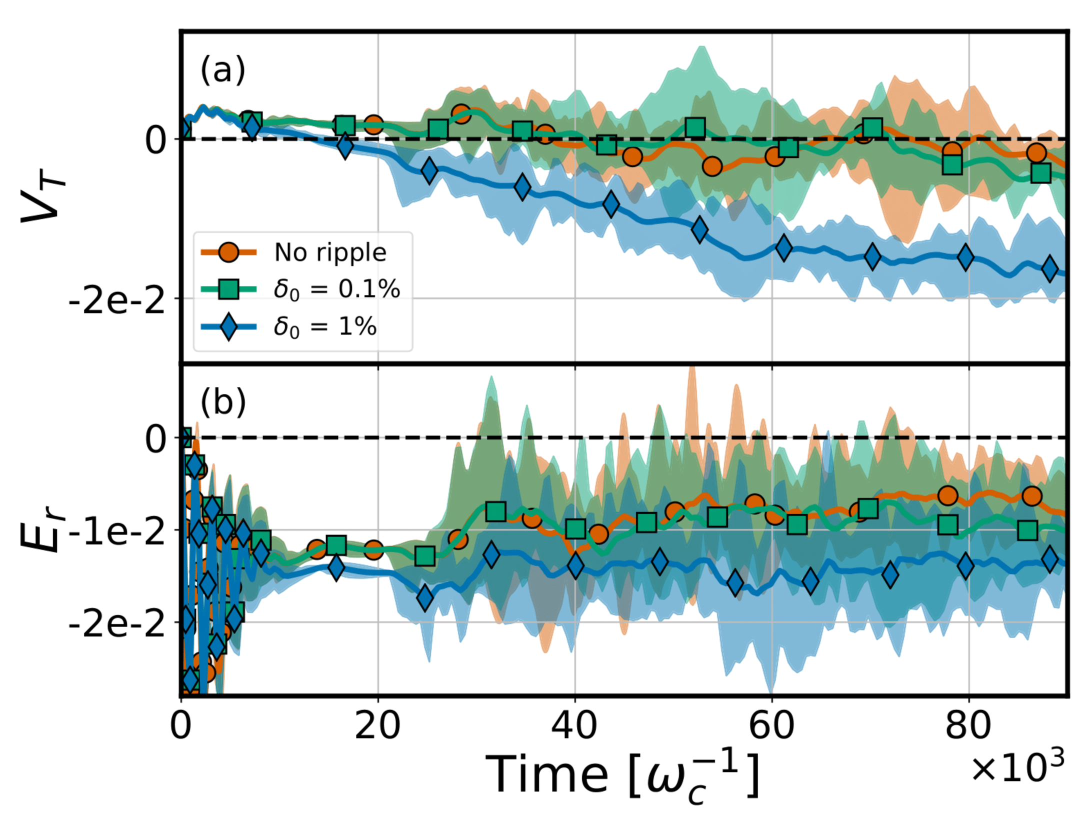


FIG.4 – Time evolution of V_T and E_r in the range $0.45 < \rho < 0.55$ for different ripple amplitudes.

Critical ripple amplitude

- NTV controls the plasma rotation above a critical ripple amplitude δ_c
- Complete model gives the relation:

$$\nu_\varphi(\delta_c) \simeq \chi_{eff}/L_T^2$$

Temperature gradient's length

With $\chi_{eff} \simeq \chi + L_T \mathcal{V}$

- A simplified equation can be devised considering
  - the gyroBohm scaling for χ_{eff}
  - The ripple-plateau scaling for ν_φ

$$\delta_c \sim \sqrt{N_c} \left(\frac{R}{L_T}\right)^{-3/2} \frac{\rho_i}{R}$$

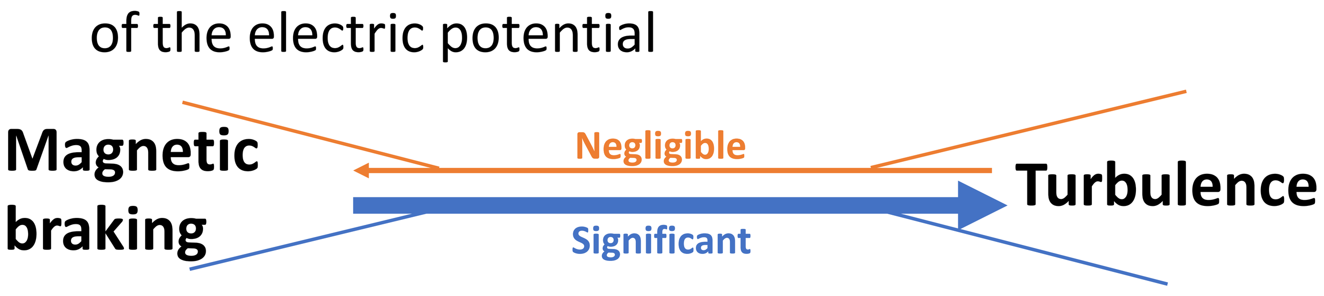
Number of coils; Ion Larmor radius; Major radius

Conclusion

- Ripple → responsible for a collisional friction that causes magnetic braking;
- Turbulence → source of intrinsic rotation;
- Evolution of mean toroidal flow ruled by competing turbulent stress and ripple drag forces;
- Magnetic braking overcomes turbulent drive above a critical ripple amplitude δ_c
- Analytical prediction of δ_c, and simplified expression, are derived and validated numerically
- Main synergy comes from neoclassical effect on E_r' in presence of ripple, in turn modifying Π

Turbulence / Ripple synergy

- Only possible mechanism: mode coupling on the electric potential
- However, ripple only impacts non-resonant modes of the electric potential



- Strong impact of ripple on Π in simulation
- Π expected to vary with turbulent intensity shear I' and radial electric field shear E_r'
- In simulations, ripple weakly impacts I through mode-coupling of the electric potential
- Ripple changes E_r through collisional effects → strong correlation with Π

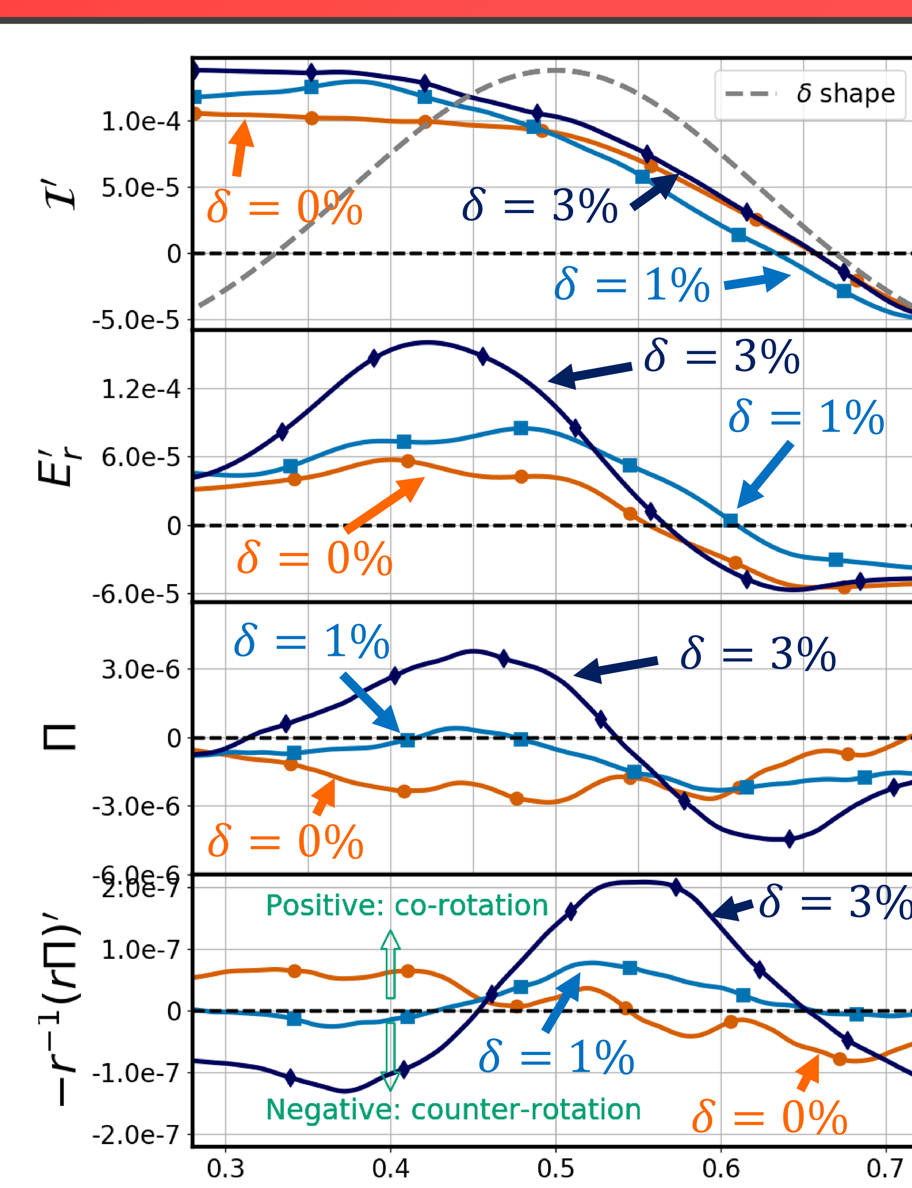


FIG.4 – Radial profiles of turbulent intensity shear, E_r shear, residual stress and its divergence. These profiles are coarse-grained as detailed in [1].

References

[1] R. Varennes, PRL 2022
[2] X. Garbet, PoP 2010
[3] R. Varennes, Submitted PPCF
[4] A. Peeters, NF 2011
[5] P. Diamond, NF 2009
[6] Ö. D. Gürcan, PRL 2008
[7] P. Diamond, 1994