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Interplay between magnetic braking and turbulent stress tensor regarding plasma flow

R. Varennes¹

Acknowledgments:

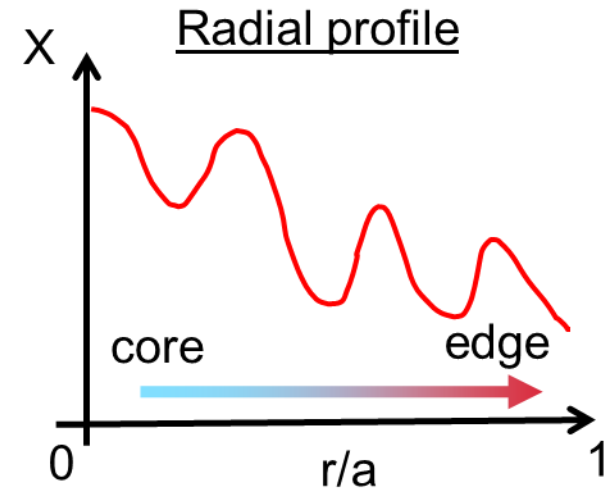
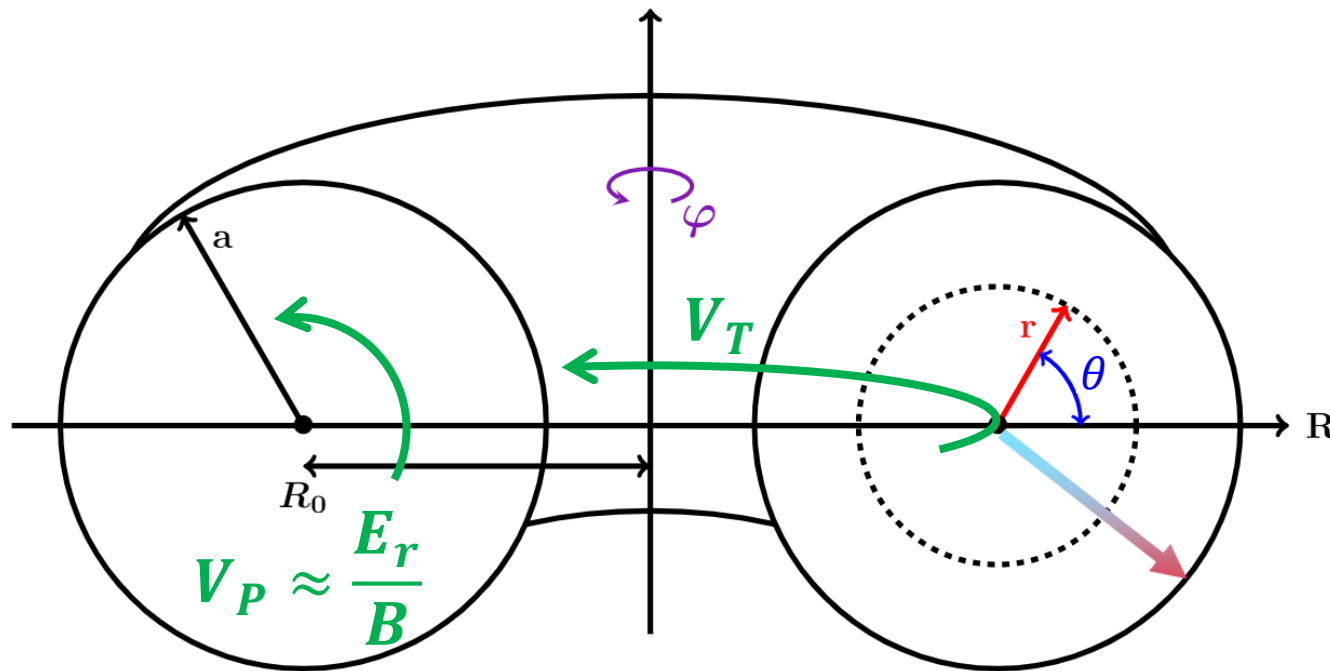
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A renewed interest for 3D magnetic perturbations



- Tokamak: magnetic configuration often considered axisymmetric
- Interest of 3D magnetic configuration: effect on the LH transition threshold, optimization of plasma stability and confinement, impact on the rotation

[J.-K. Park - PRL 2021]

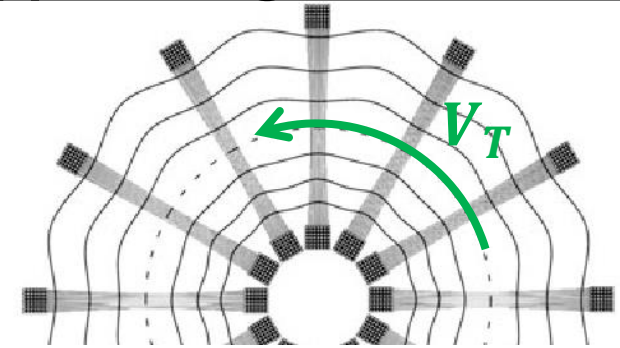
[M. Landreman - PRL 2022]

Plasma rotation → competition between magnetic braking and turbulence

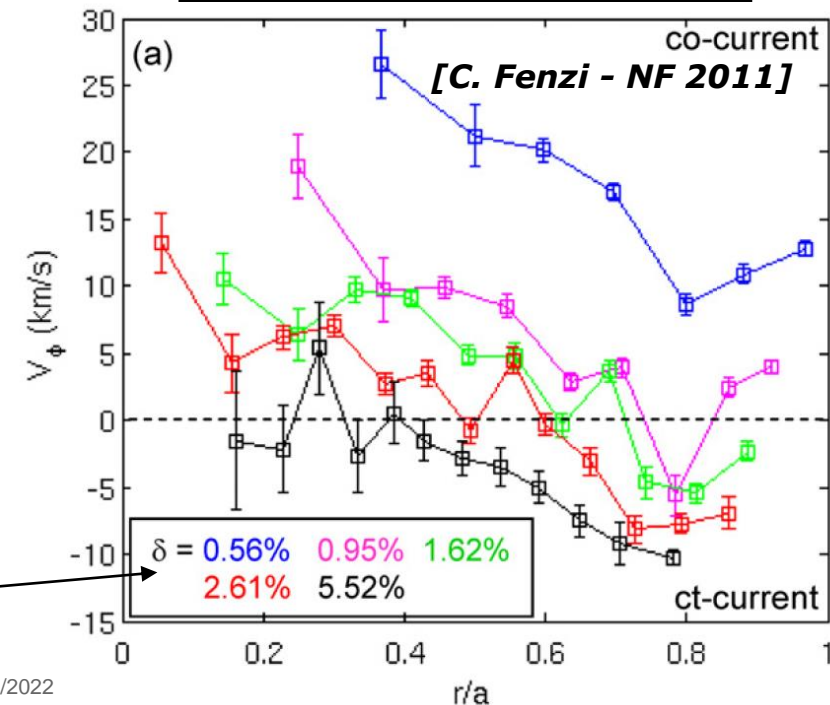
Plasma toroidal rotation V_T :

- Plays a key role in confinement
- Challenging to control in reactor-sized tokamak (e.g. ITER)
- Flows rather governed by **intrinsic rotation**
- Governed by **turbulent momentum drive** and **magnetic braking** (RMP, ripple, ...)

Rippled magnetic field lines



Plasma rotation in Tore Supra without momentum input



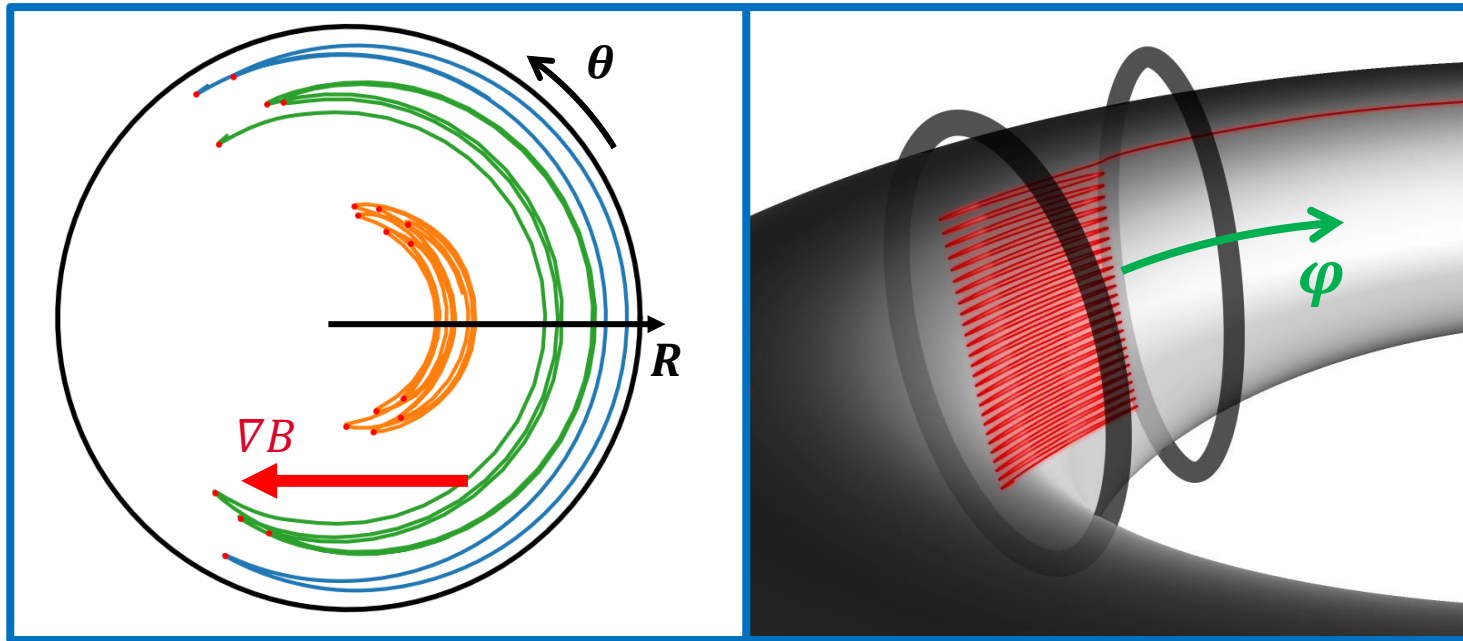
Ripple amplitude

- 1) Reduced model for the intrinsic rotation**
- 2) Validation with gyrokinetic simulations**
- 3) Synergy between turbulent drive and magnetic braking**

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Collisionnal processes lead to magnetic braking

Trapped trajectories in presence of ripple



Magnetic braking: $\mathbf{m} = -\mathbf{v}_{\text{col}}(V_T - V_{\text{col}})$

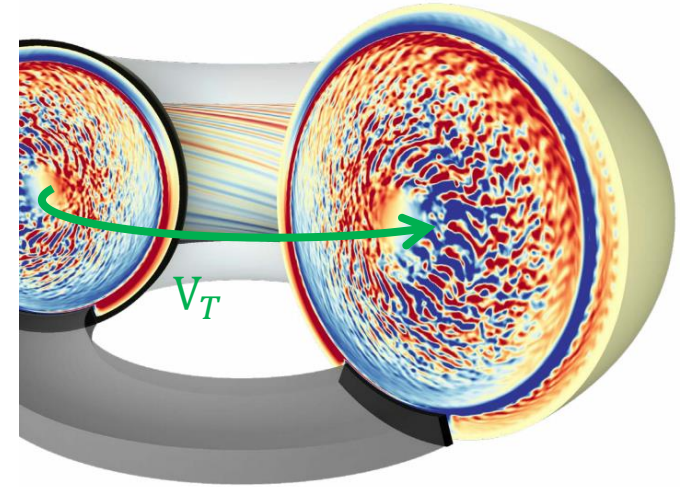
Collisional friction
Equilibrium velocity

[J. W. Connor - NF 1973]
[K. C. Shaing - PoF 1986]
[P.N. Yushmanov - NF 1983]
[L. M. Kovrizhnykh - NF 1984]
[X. Garbet - PoP 2010]

Turbulence:

- Small-scale fluctuations of the electric potential leading to macroscopic transport
- Turbulence forces rotation to finite value via wave/particle momentum transfer
- Expression of the exerted force: $-\nabla \cdot \Pi$

Turbulent structures in a tokamak



[O. Gürcan - PRL 2008]

[T. S. Hahm - PoP 2007]

[P.H. Diamond - NF 2009]

[A. Peeters - PRL 2007/ NF 2011]

[B. Chouli - PPCF 2015]

Toroidal Reynolds stress: $\Pi = \langle \tilde{v}_r \tilde{v}_\phi \rangle = -\chi \partial_r V_T + \mathcal{V} V_T + \Pi_{\text{res}}$

Turbulent viscosity

Pinch

Residual stress → Sets the equilibrium velocity

A simplified expression for the turbulent drive

$$\Pi = -\chi \partial_r V_T + \mathcal{V} V_T + \Pi_{res}$$

Turbulent drive:

$$-\nabla \cdot \Pi \approx -\nu_{turb} (V_T - V_{turb})$$

$$-\frac{\partial_r^2 V_T}{V_T} \chi + \frac{\partial_r V_T}{V_T} \mathcal{V}$$

“Effective” turbulent friction

$$\frac{\Pi_{res}}{\nu_{turb}}$$

Equilibrium velocity

A critical ripple amplitude rules the toroidal rotation

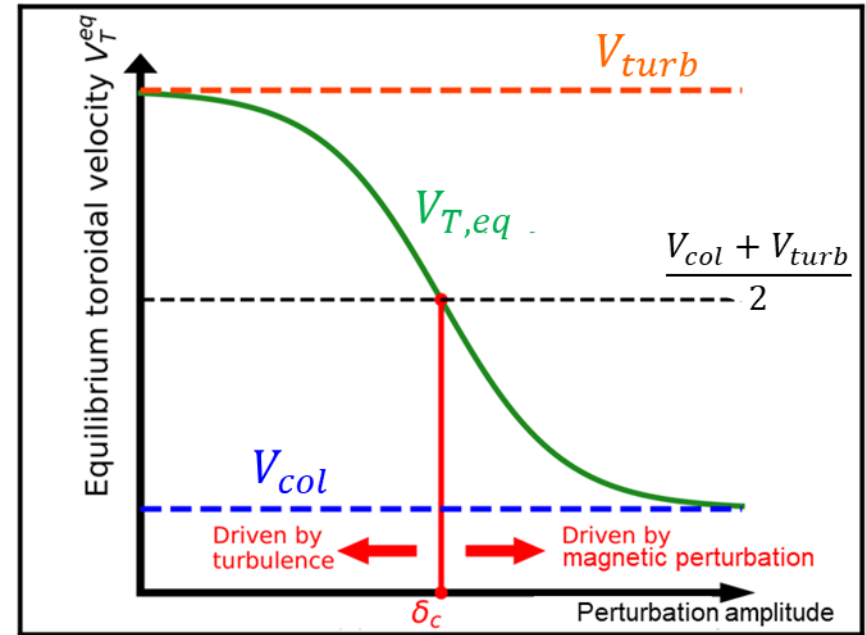
Turbulence and ripple:

- Theoretical model: $\partial_t V_T = m - \nabla \cdot \Pi$

$$\partial_t V_T = -(\mathbf{v}_{col} + \mathbf{v}_{turb})V_T + \mathbf{v}_{col}V_{col} + \mathbf{v}_{turb}V_{turb}$$

- Dominating drive depends on a **critical ripple amplitude** δ_c such that

$$\mathbf{v}_{col}(\delta_c) = \mathbf{v}_{turb}$$



[R. Varennes - PRL 2022]

Rule of thumb: $\delta_c \sim \frac{\rho_i}{R_0} \sqrt{N_c} \left(\frac{R}{L_T} \right)^{-3/2}$

Ion Larmor radius ρ_i (points to ρ_i)
Coils number N_c (points to N_c)
Temperature gradient length L_T (points to L_T)

Application at $r/a = 0.8$:

- Tore Supra typical discharge $\rightarrow \delta_c \approx 0.4\%$
- Same with ITER geometry $\rightarrow \delta_c \approx 0.15\%$

- 1) Reduced model for the intrinsic rotation
- 2) Validation with gyrokinetic simulations
- 3) Synergy between turbulent drive and magnetic braking

Validating the model requires gyrokinetic simulations

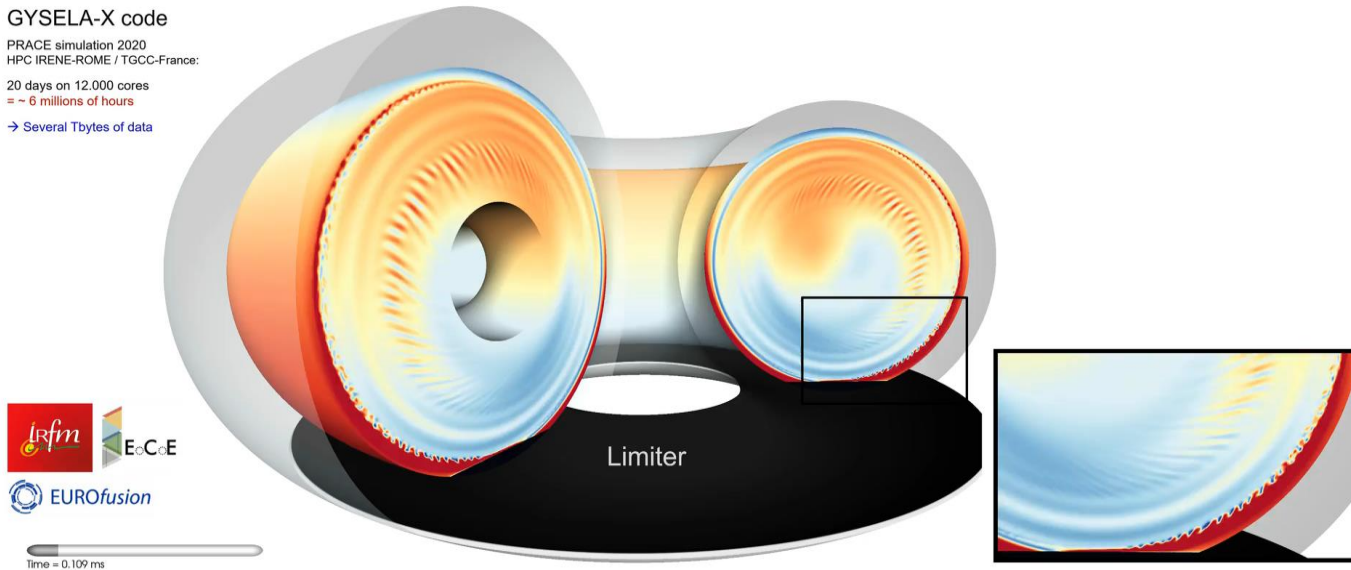
- GYSELA: kinetic code solving

$$\text{Fokker-Planck: } \frac{dF}{dt} = \mathcal{C}(F)$$

$$\text{Poisson: } \varepsilon_R \nabla^2 \phi = - \sum_{\text{species}} e \int F d^3 v$$

GYSELA-X code

PRACE simulation 2020
HPC IRENE-ROME / TGCC-France:
20 days on 12,000 cores
= ~ 6 millions of hours
→ Several Tbytes of data



$$v_{\text{col}}(\delta_c) \approx v_{\text{turb}}$$

[V. Grandgirard – CPC 2016]

Requires 3D magnetic perturbation to be implemented

Determined for one turbulence

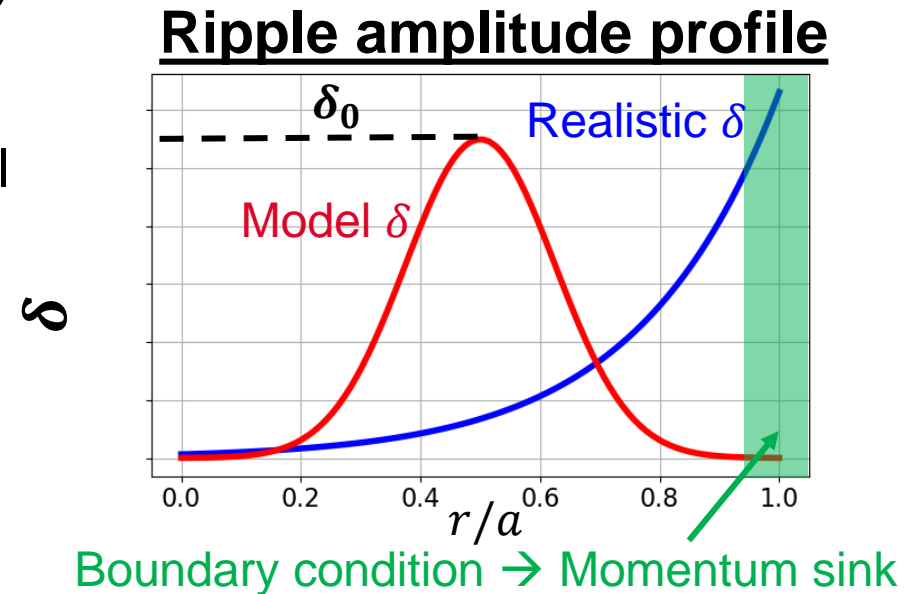
Using a simplified ripple amplitude shape

■ Boundary conditions (realistic/simulated)

→ momentum sink not included in the model

■ Solution: radially gaussian ripple

amplitude



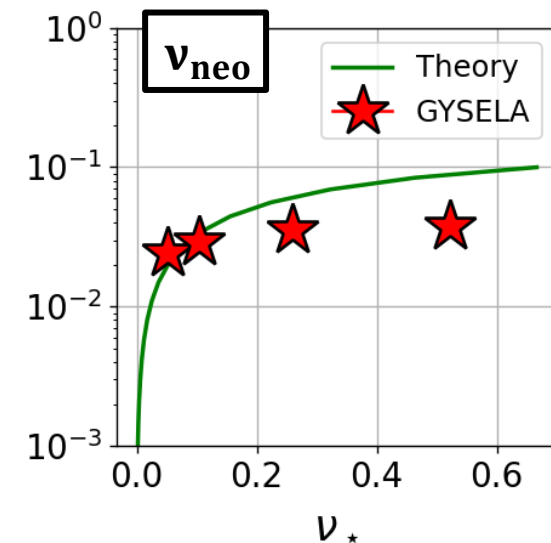
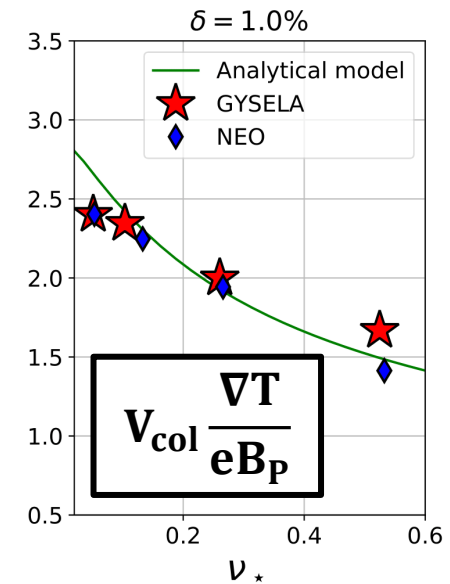
Thorough benchmark of the ripple implementation

$$m = -v_{\text{col}}(V_{\text{T}} - V_{\text{col}})$$

Depend on the collisionality ν_* and ripple amplitude δ

- Toroidal momentum is conserved
- $V_{\text{col}} \rightarrow$ good agreement GYSELA / NEO
- Collisional friction $v_{\text{col}} \rightarrow$ good

agreement between GYSELA and the theory



[R. Varennes – Submitted to PPCF]

The estimated critical ripple amplitude validated through simulations

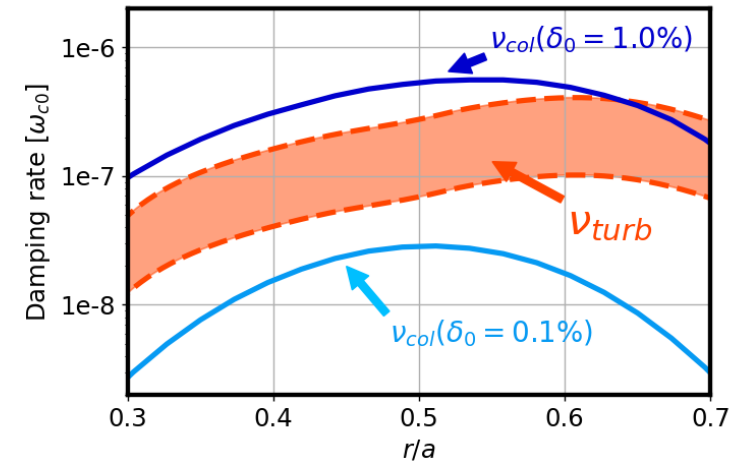
- Cases with $\delta \gg \delta_c$ and $\delta \ll \delta_c$
- No significant difference between $\delta \ll \delta_c$ case and the **no ripple** case
- $\delta \gg \delta_c$ case dominated by magnetic braking \rightarrow similar in some experiments (TS, JET and JT60)

[H. Urano – NF 2011]

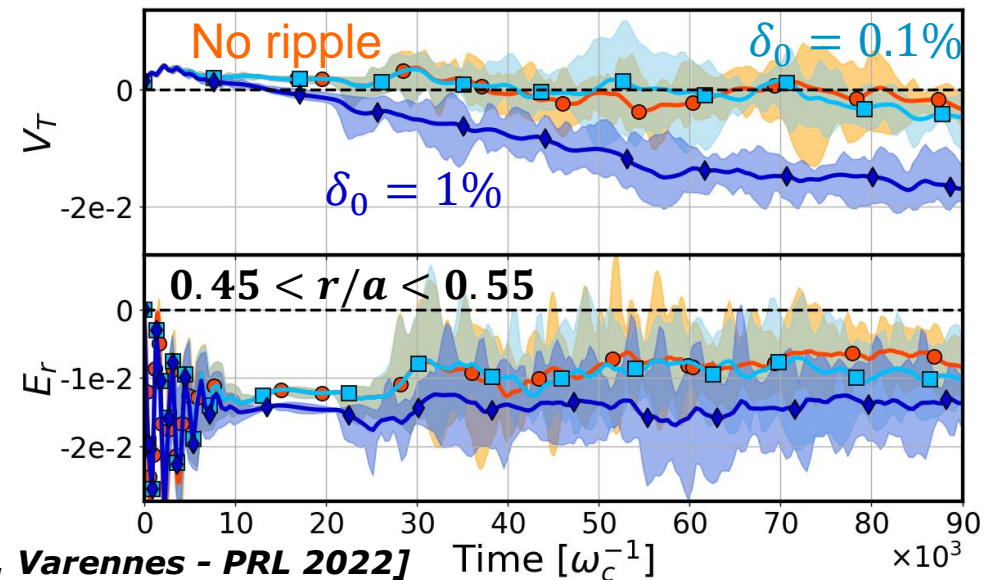
[M.F.F Nave – PRL 2010]

[C. Fenzi – NF 2011]

Radial profiles of ν_ϕ and χ



Time evolution of V_T and E_r



[R. Varenes – PRL 2022]

- 1) Reduced model for the intrinsic rotation
- 2) Validation with gyrokinetic simulations
- 3) Synergy between turbulent drive and magnetic braking

A step further : the magnetic braking impact on toroidal Reynold stress

Synergy observed in simulations:

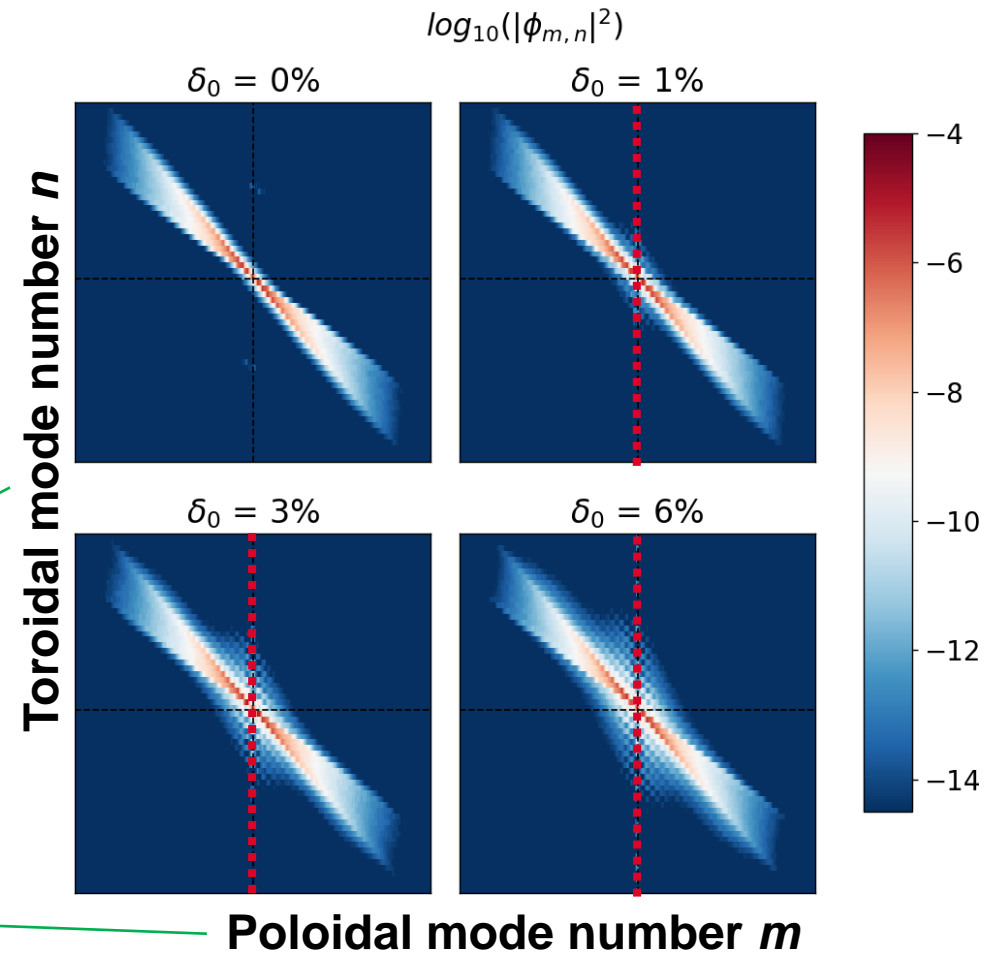
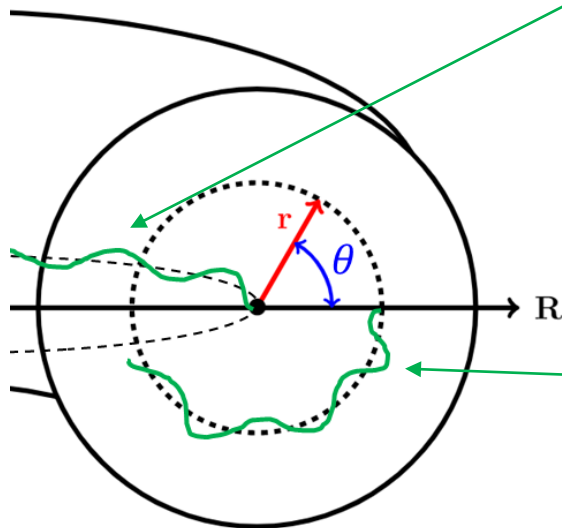


Possible synergy mechanisms:

- Up-down asymmetry of magnetic surfaces ✗ [Y. Camenen - PRL 2009]
- Stochasticity of magnetic field lines ✗ [C.-C Chen - PoP 2021]
- Modification of the turbulent intensity radial shear ✓ [O. Gürcan - PRL 2008]
- Modification of the E_r radial shear ✓ [P.H. Diamond – IAEA Vienna 1994]

Ripple changes turbulence intensity through mode-coupling

- Turbulent intensity defined as $I = \frac{e\tilde{\phi}}{T}$
- Ripple $\rightarrow \cos(N_c\varphi)$ perturbation magnetic field \rightarrow reflects on electric potential ϕ
- With turbulence, mode-coupling modifies the turbulent spectra

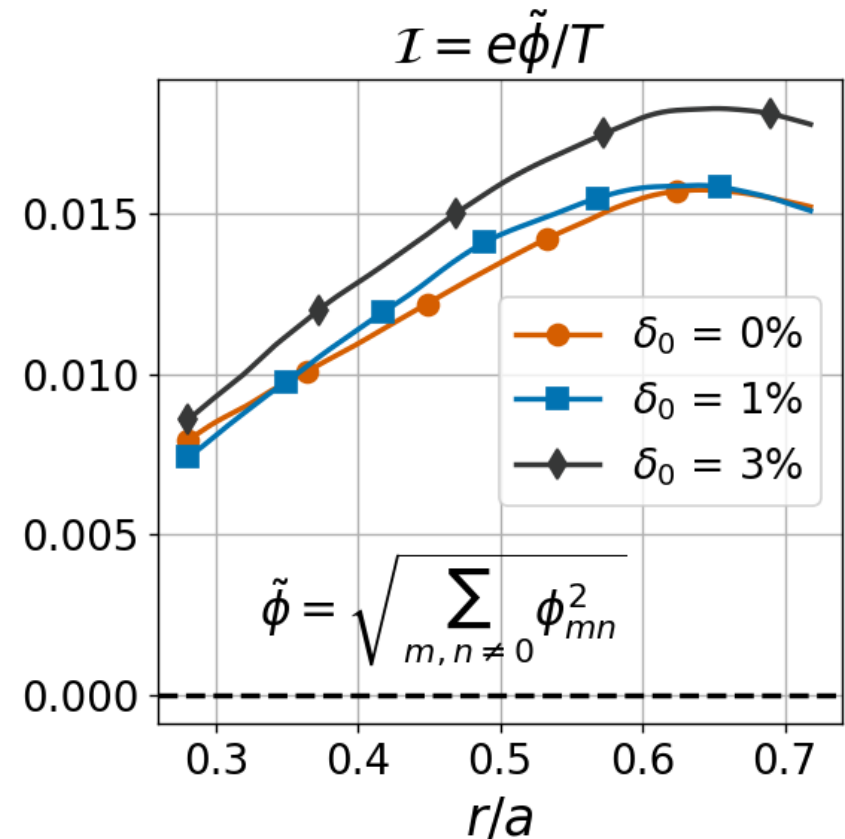


Turbulence intensity weakly impacted by ripple

Spectral coupling → well described by the simulation code

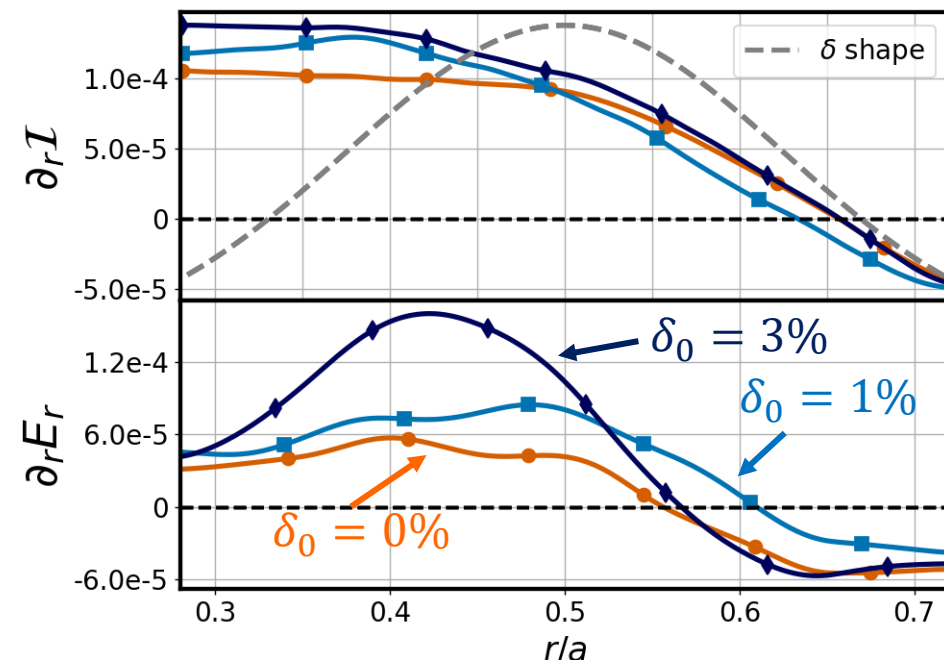
However, weak effect of the ripple on the turbulent intensity

Coarse-grained turbulent intensity



- $\partial_r E_r$ expected to impact Π
- Ripple $\rightarrow E_r$ enhancement through collisional processes
- Increasing of Π associated with an increase in $\partial_r E_r$ in simulations

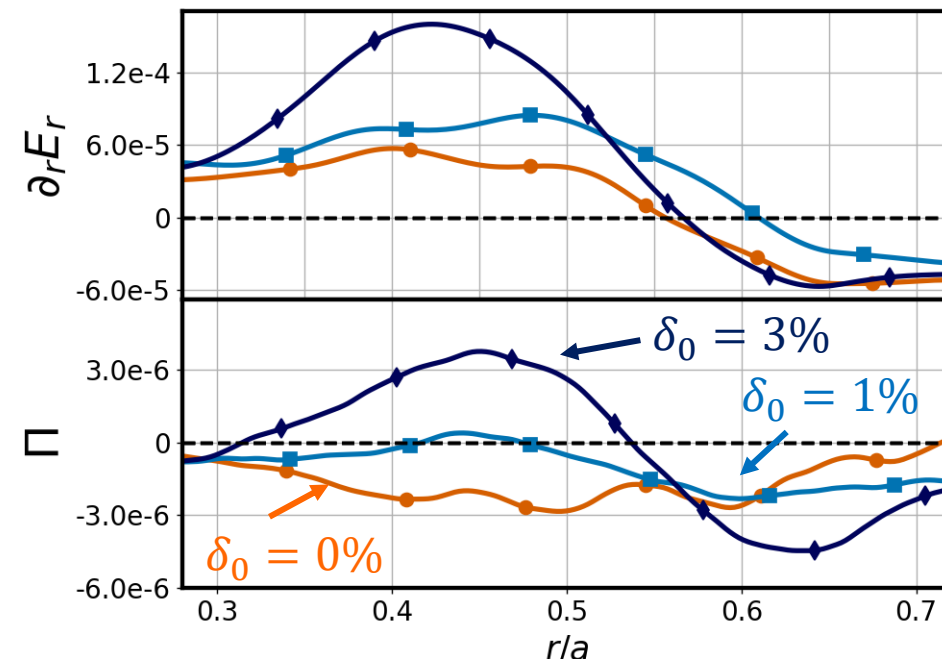
Coarse-grained profiles



[R. Varennes - PRL 2022]

- $\partial_r E_r$ expected to impact Π
- Ripple $\rightarrow E_r$ enhancement through collisional processes
- Increasing of Π associated with an increase in $\partial_r E_r$ in simulations

Coarse-grained profiles



[R. Varennes - PRL 2022]

- Plasma rotation → driven by a **competition** between **turbulence** and **magnetic braking**
- Magnetic braking overcomes turbulence above a **critical amplitude** of magnetic ripple
- Toroidal Reynold stress → **strongly impacted by ripple**
- Synergy mechanism → **Enhancement of $\partial_r E_r$ due to ripple** which in turn modifies Π

[R. Varennes - PRL 2022]

[R. Varennes - Submitted to PPCF]

Backup slides

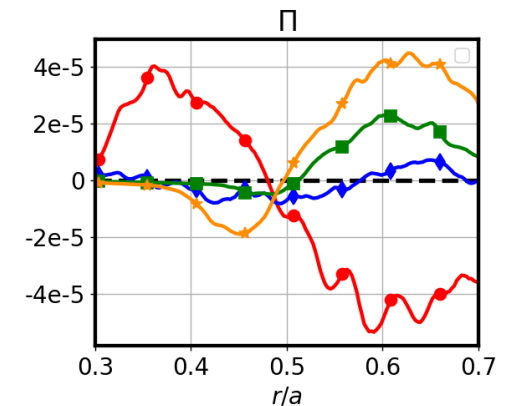
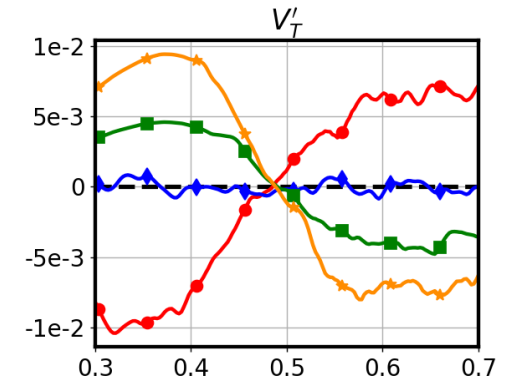
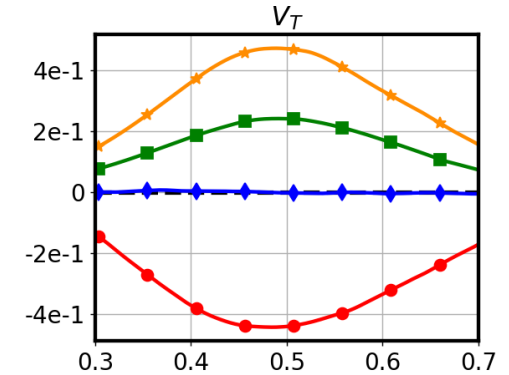
Evaluating the turbulent viscosity with gyrokinetic code

$$\Pi = -\chi \partial_r V_T + \mathcal{V} V_T + \Pi_{res}$$

Unknowns

GYSELA outputs

- Simulations of ITG turbulence with different initial V_T
- Enough equation to deconvolve χ , \mathcal{V} and Π_{res}
- Pinch \mathcal{V} found negligible



A simple expression for the critical ripple amplitude

$$\delta_c \text{ defined by } v_\phi(\delta_c) = |\lambda_v| \underbrace{\left(\chi + \frac{\kappa_v}{\lambda_v} \mathcal{V} \right)}_{\chi_{\text{eff}}}$$

Toroidal harmonic of the perturbation \rightarrow Thermal velocity

- Ripple-plateau regime (relevant for most tokamaks): $v_\phi \sim \frac{N_c V_{th}}{R} \delta^2$ (robust)

Ion Larmor radius \rightarrow

- Gyrobohm scaling: $\chi_{\text{eff}} \sim \chi_{GB} = \frac{\rho_i^2 V_{th}}{L_T}$ (debatable, but verified in our simulations)

Temperature gradient length \rightarrow

- $\lambda_v = -\frac{(r\chi V_{Teq})'}{r\chi V_{Teq}} \sim L_T^{-2}$ (ok in order of magnitude)

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

Application with magnetic ripple at $r/a = 0.8$:

- Tore Supra typical discharge $\rightarrow \delta_c \approx 0.4\%$
- Same with ITER geometry $\rightarrow \delta_c \approx 0.15\%$

Evaluating the turbulent viscosity with gyrokinetic code

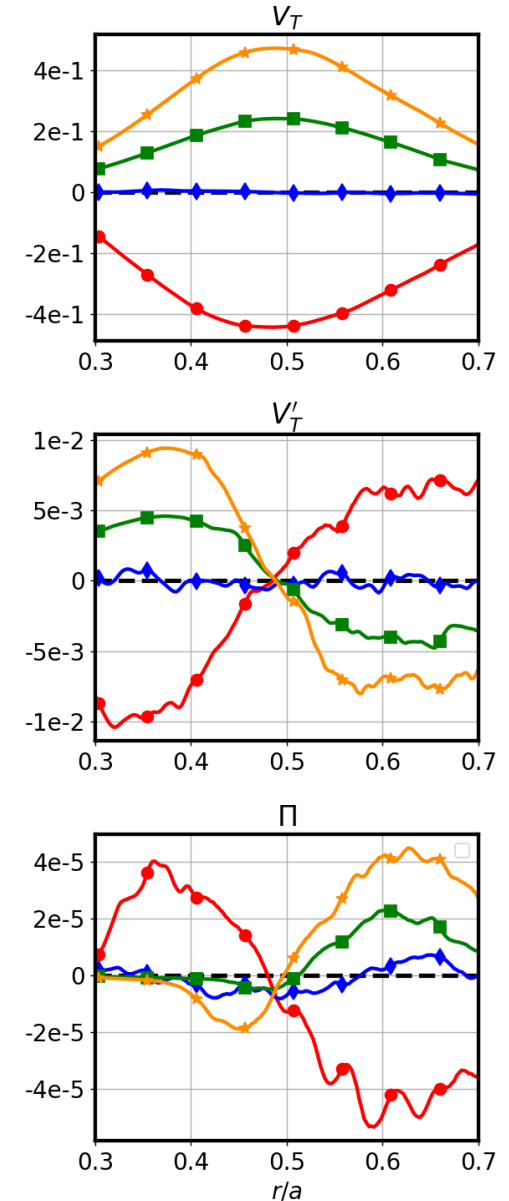
$$\Pi = -\chi \partial_r V_T + \mathcal{V} V_T + \Pi_{res}$$

Unknowns

GYSELA outputs

- Simulations with different initial $V_T \rightarrow$ get enough equation to deconvolve χ , \mathcal{V} and Π_{res}
- ITG turbulence with adiabatic e^-
- Pinch \mathcal{V} found negligible \rightarrow already observed adiabatic e^-

[A. Peeters - NF 2011]



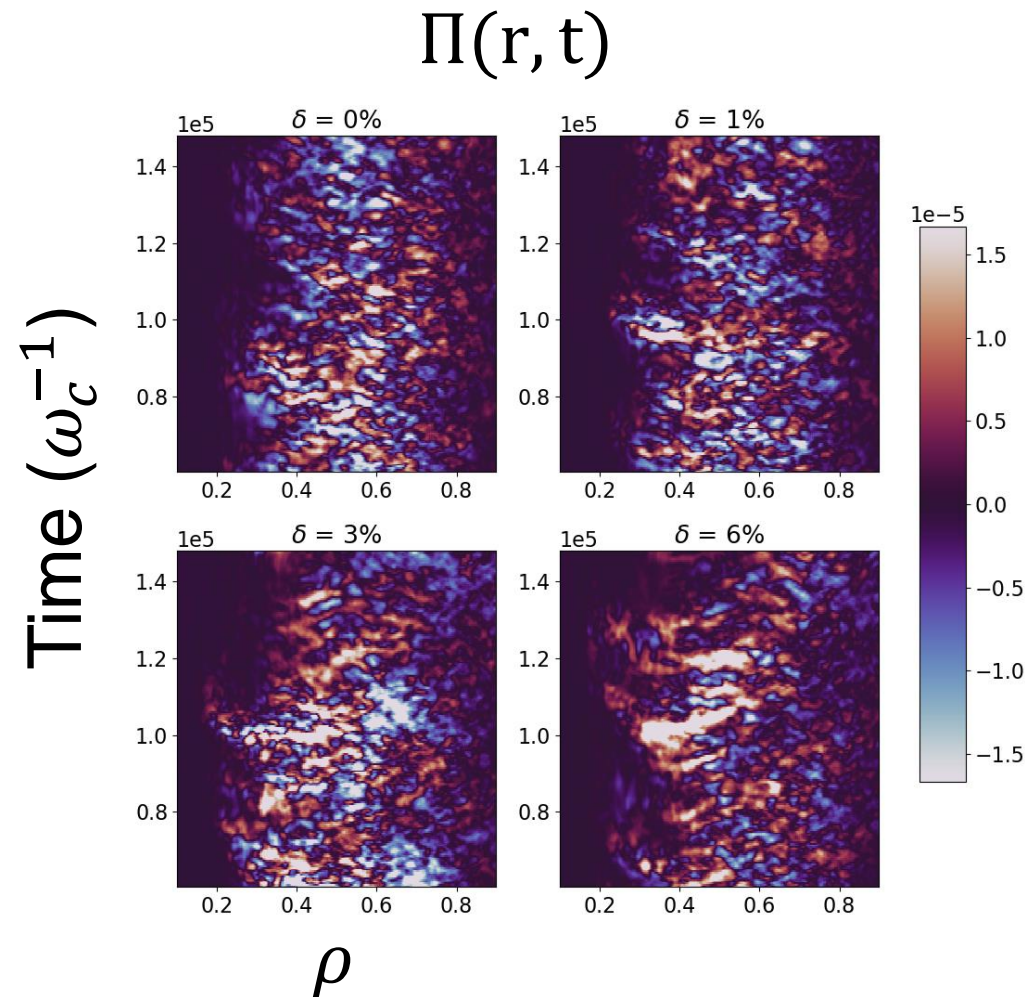
A step further : the ripple impact on toroidal Reynold stress

Synergy between ripple and turbulence:

- Turbulence impact on magnetic braking
found negligible (not tested with RMPs)
- However magnetic braking strongly
modifies Π

Mechanisms considered:

- 1) Modification of the turbulent intensity
shear
- 2) Modification of the $E \times B$ shear



Neoclassical theory gives access to fluxes and forces

- Toroidal symmetry → degeneracy on E_r and V_T (linked by force balance)
- Ripple → toroidal magnetic braking / friction

Drift kinetic equation : $(\mathbf{v}_{\parallel} + \mathbf{v}_D) \cdot \nabla (F_{eq} + \delta F) = \mathcal{C}(\delta F)$

Diagram illustrating the drift kinetic equation with annotations:

- Ripple** (red arrow) points from \mathbf{v}_D to ∇ .
- Banana** (green arrow) points from ∇ to F_{eq} .
- ∇B** (green arrow) points from ∇ to F_{eq} .
- Local trapping** (red arrow) points from F_{eq} to $\mathcal{C}(\delta F)$.

→ Drifting banana

→ Magnetic wells

⇒ $\begin{matrix} \text{Particle flux} \rightarrow \\ \text{Magnetic braking} \rightarrow \\ \text{Heat flux} \rightarrow \end{matrix} \begin{pmatrix} \frac{\Gamma}{N} \\ \frac{\mathcal{M}}{NeB_p} \\ \frac{Q}{NT} \end{pmatrix} = \underbrace{\begin{pmatrix} d_{NN} & d_{NV} & d_{NT} \\ d_{VN} & d_{VV} & d_{VT} \\ d_{TN} & d_{TV} & d_{TT} \end{pmatrix}}_{\text{Depends on}} \begin{pmatrix} \frac{dN}{Ndr} - \frac{eE_r}{T} \\ \frac{eB_p}{T} V_T \\ \frac{dT}{Tdr} \end{pmatrix}$

Depends on $\begin{cases} \delta : \text{ripple amplitude} \\ \varepsilon : \nabla B \text{ amplitude} \\ \nu^* : \text{collisionnality} \end{cases}$

(Also valid for RMPs !)

[J. W. Connor 1973]
[K. C. Shaing 1986]
[P.N. Yushmanov 1987]
[A. B. Mikhailovskii 1995]
[L. M. Kovrizhnykh 1998]
[X. Garbet 2010]

Magnetic braking force dominates the toroidal force balance

Neoclassical non-axisymmetric toroidal momentum conservation :

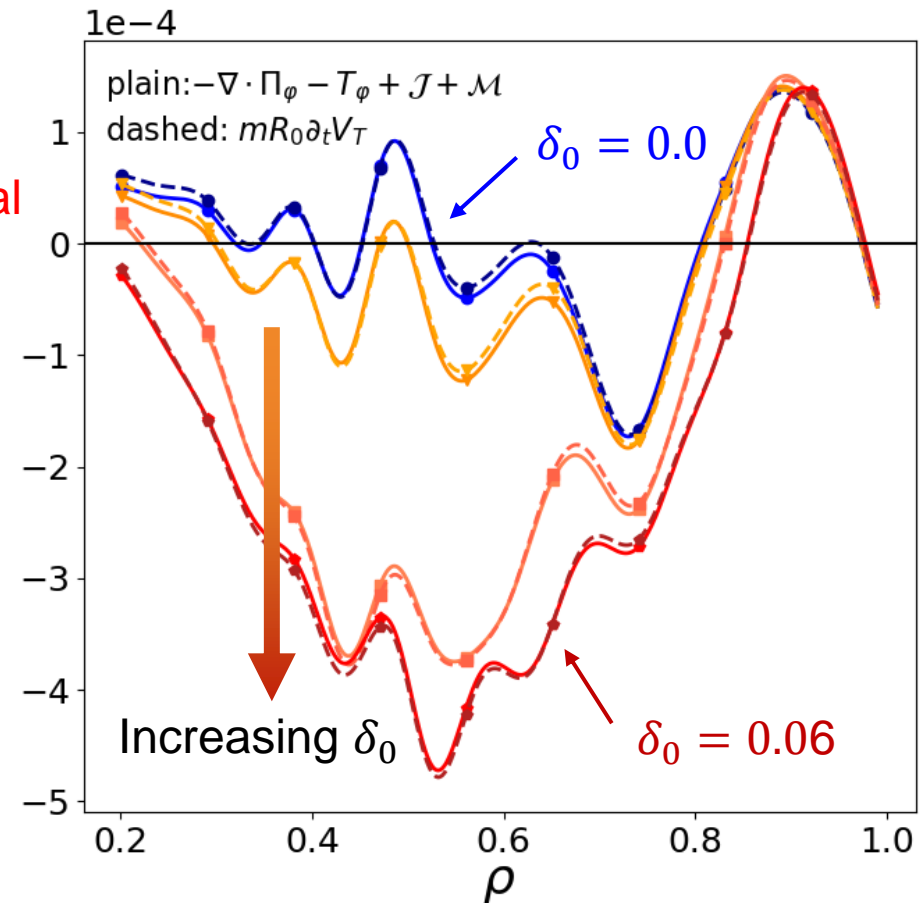
$$NmR_0 \frac{\partial V_T}{\partial t} = \underbrace{-\nabla \cdot \Pi_{turb}}_{\text{Turbulence (=0)}} - \underbrace{T_\phi}_{\text{Polarization}} + \underbrace{J}_{\text{Current}} + \underbrace{\mathcal{M}}_{\text{Neoclassical Toroidal Viscosity}}$$

[J. Abiteboul 2011]

$$\mathcal{M} = - \int \frac{d\theta d\varphi}{4\pi^2} \int d\mathbf{v} F \left\{ \mu \frac{\partial \tilde{B}}{\partial \varphi} \right\}$$

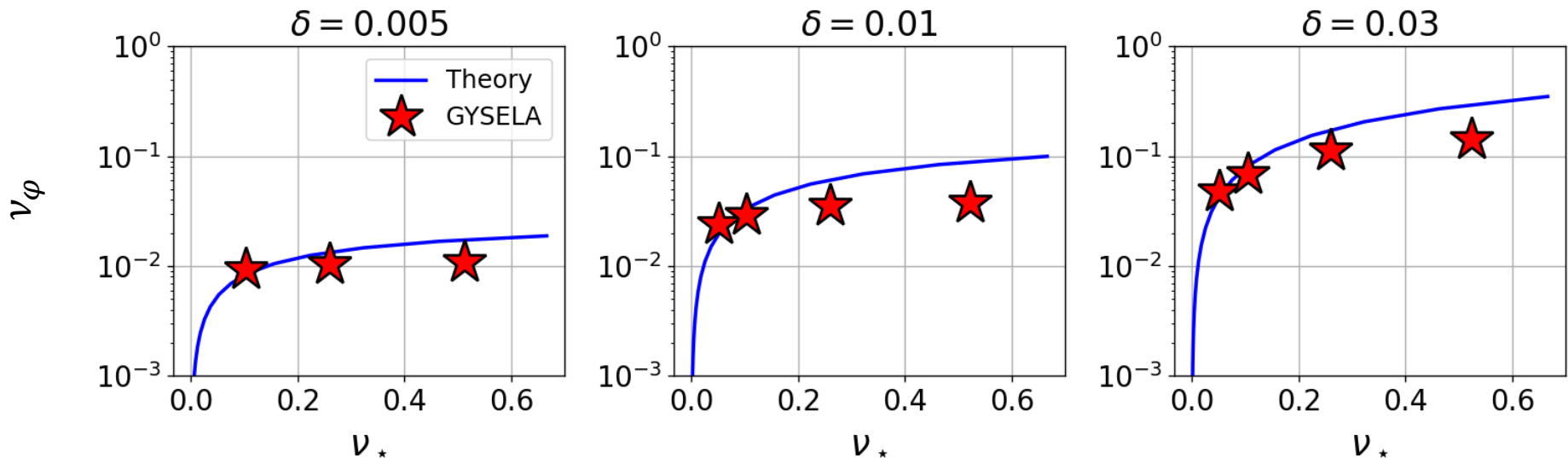
$$\mathcal{M} \text{ dominating} \rightarrow NmR_0 \frac{\partial V_T}{\partial t} \approx \mathcal{M}$$

Radial profile of the LHS and RHS of the conservation of L



- Toroidal momentum with magnetic braking is conserved
- Neoclassical target velocity V_{neo} in good agreement between GYSELA and NEO
- Neoclassical friction ν_ϕ in good agreement between GYSELA and the theory

Neoclassical friction vs ripple amplitude and collisionality



Magnetic braking is induced by 3D magnetic perturbations

Magnetic braking:

- Resulting force coming from B inhomogeneity on particle magnetic moments μ
- Magnetic braking force expression: $\mathcal{M} = - \int d^3v \left(\mu \frac{\partial B}{\partial \varphi} F \right)$
- 3D magnetic perturbations in tokamaks \rightarrow external, magnetic ripple
- Constrains the particle trajectories \rightarrow results in finite plasma toroidal velocity V_T

$$\Pi_{\text{res}} = \sum_k k_{\parallel} k_{\theta} \left| \frac{e\phi_k}{T} \right|^2 \tau_k$$