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Interplay between magnetic braking and turbulent stress tensor regarding plasma flow

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To cite this version:

R Varennes, P Gendrih, L. Vermare, X Garbet, Y Sarazin, et al.. Interplay between magnetic braking and turbulent stress tensor regarding plasma flow. 12ème Festival de théorie : contrôle, rétroaction et réduction de modèle, Jul 2022, Aix en provence, France. hal-03923040

HAL Id: hal-03923040

https://hal.science/hal-03923040v1

Submitted on 4 Jan 2023

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DE LA RECHERCHE À L'INDUSTRIE

Interplay between magnetic braking and turbulent stress tensor regarding plasma flow

R. Varennes[1]

Acknowledgments:

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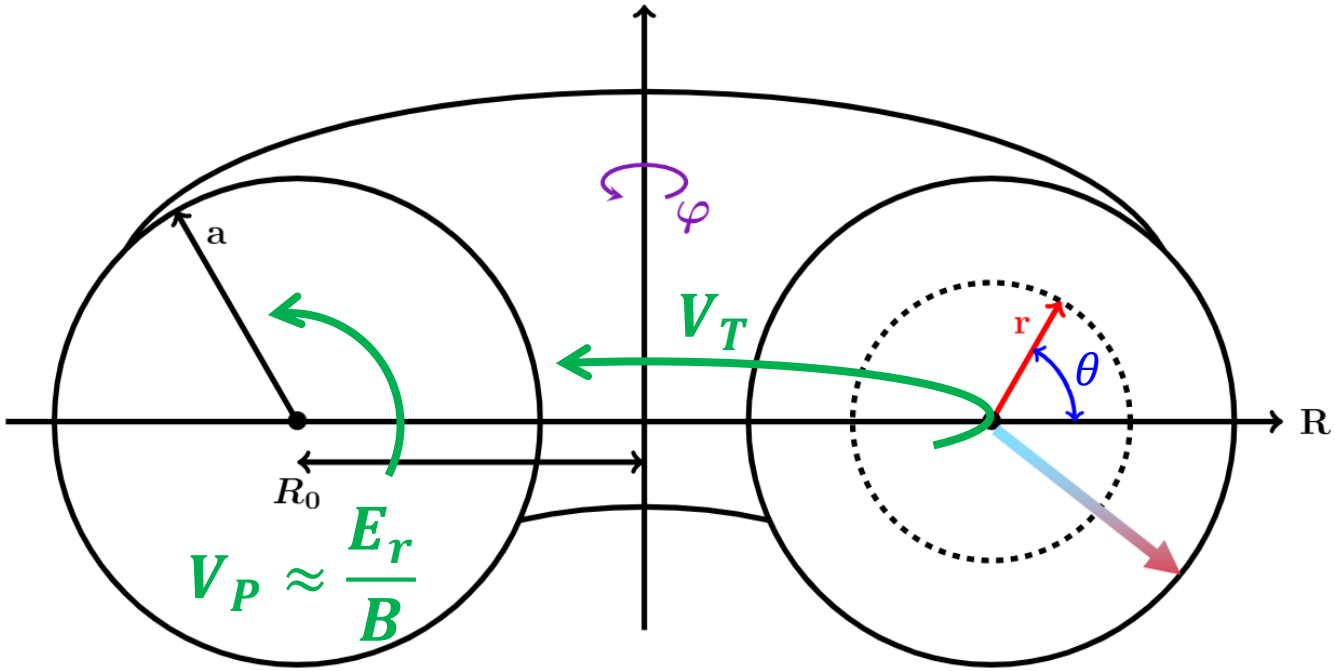
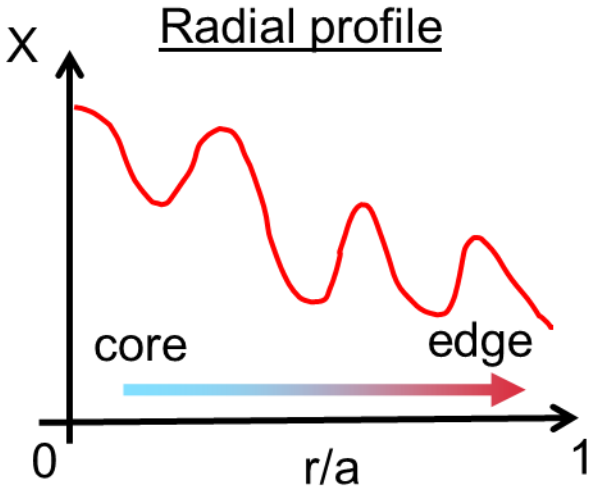
A renewed interest for 3D magnetic perturbations





- 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

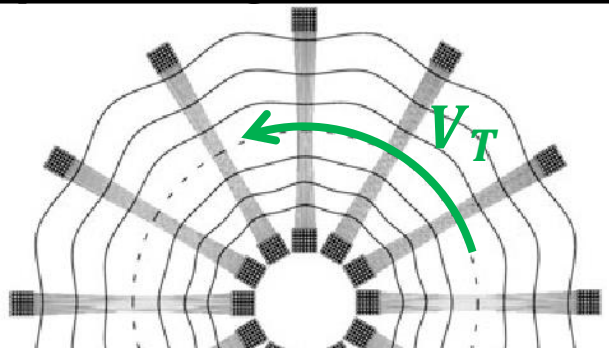
[J.-K. Park - PRL 2021]

[M. Landreman - PRL 2022]

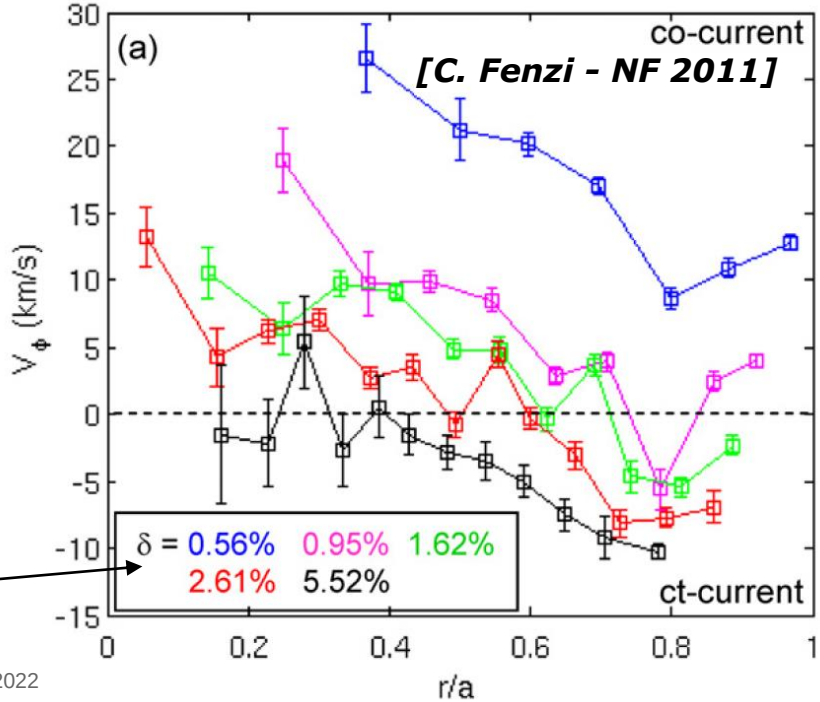
Plasma rotation → competition between magnetic braking and turbulence

- 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

Talk outline

1) **Reduced model for the intrinsic rotation**

2) **Validation with gyrokinetic simulations**

3) **Synergy between turbulent drive and magnetic braking**

Talk outline

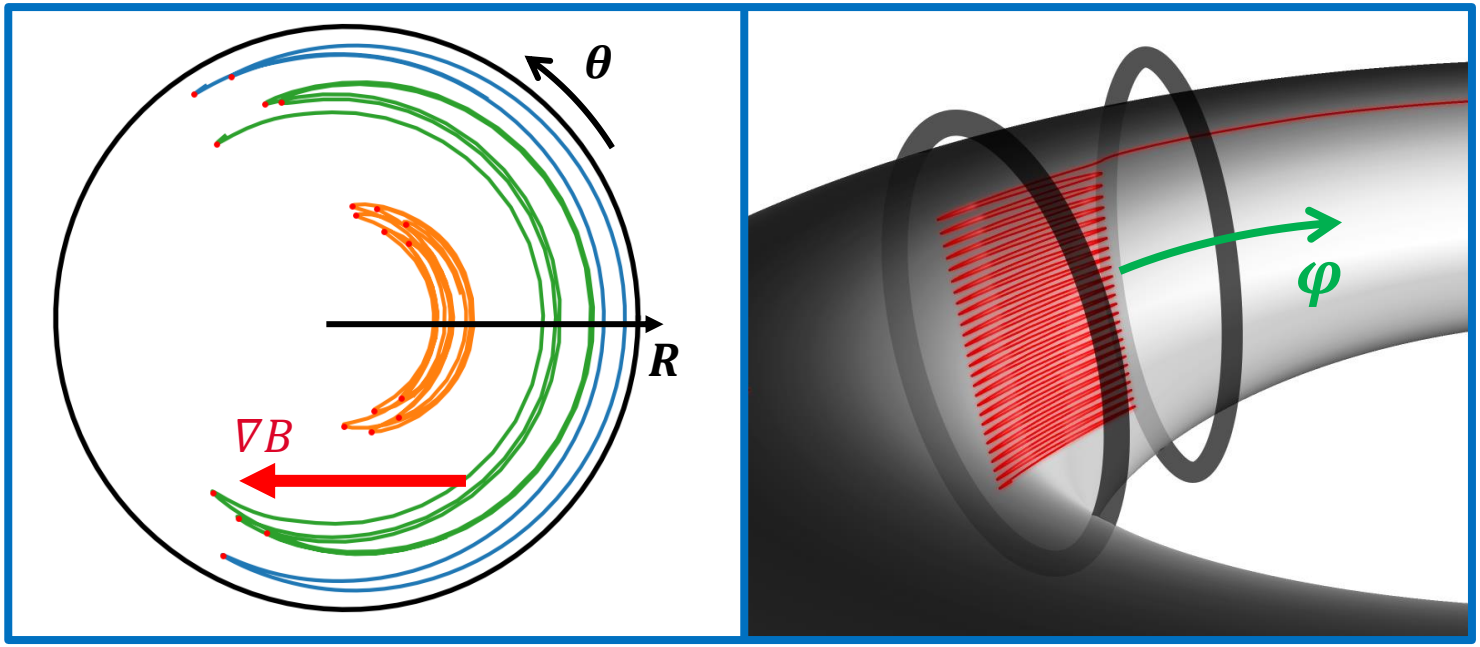
1) **Reduced model for the intrinsic rotation**

2) **Validation with gyrokinetic simulations**

3) **Synergy between turbulent drive and magnetic braking**

Collisionnal processes lead to magnetic braking

Trapped trajectories in presence of ripple



Magnetic braking: $m = -\nu_{col}(V_T - V_{col})$

Collisional friction

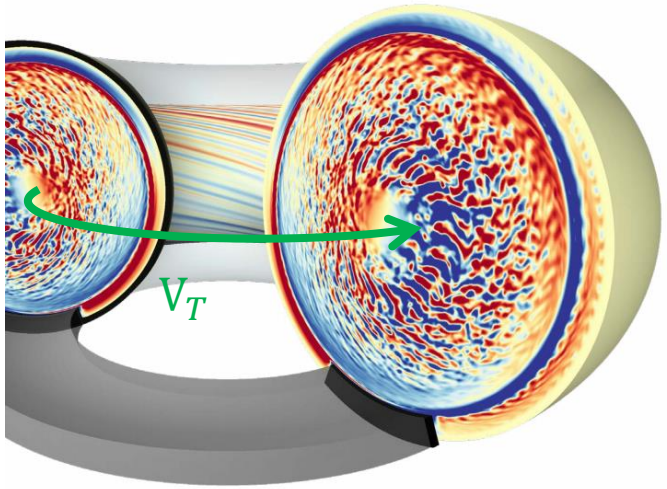
Equilibrium velocity

[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 is a source of intrinsinc rotation

- 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: $\Pi = \langle \tilde{v}_r \tilde{v}_\varphi \rangle = -\chi \partial_r V_T + \mathcal{V} V_T + \Pi_{res}$

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:

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

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

"Effective" turbulent friction

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

Equilibrium velocity

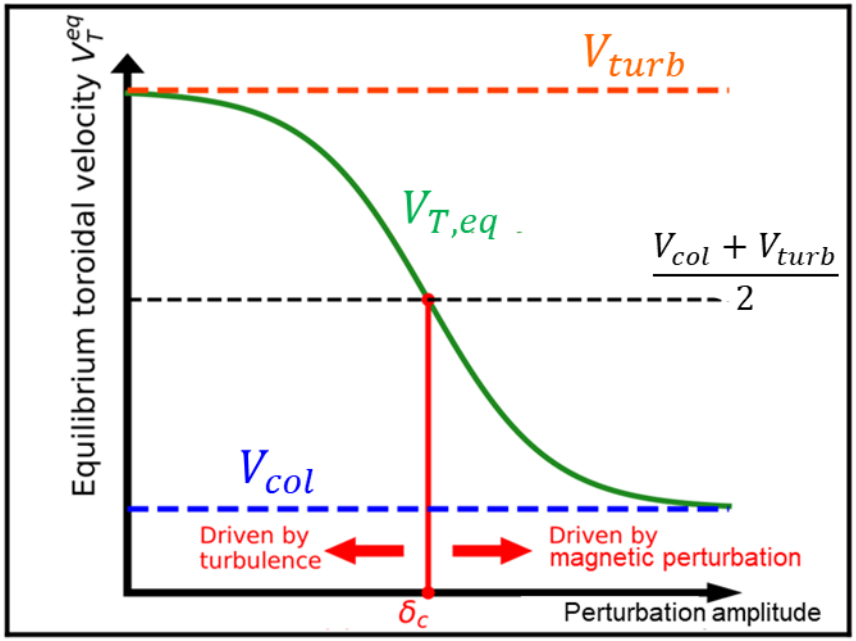
A critical ripple amplitude rules the toroidal rotation

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

$$\partial_t V_T = -(\nu_{col} + \nu_{turb})V_T + \nu_{col}V_{col} + \nu_{turb}V_{turb}$$

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

$$\nu_{col}(\delta_c) = \nu_{turb}$$



[R. Varennes - PRL 2022]

Ion Larmor radius — Coils number

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

Temperature gradient length

Application at $r/a = 0.8$:

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

Talk outline

1) **Reduced model for the intrinsic rotation**

2) **Validation with gyrokinetic simulations**

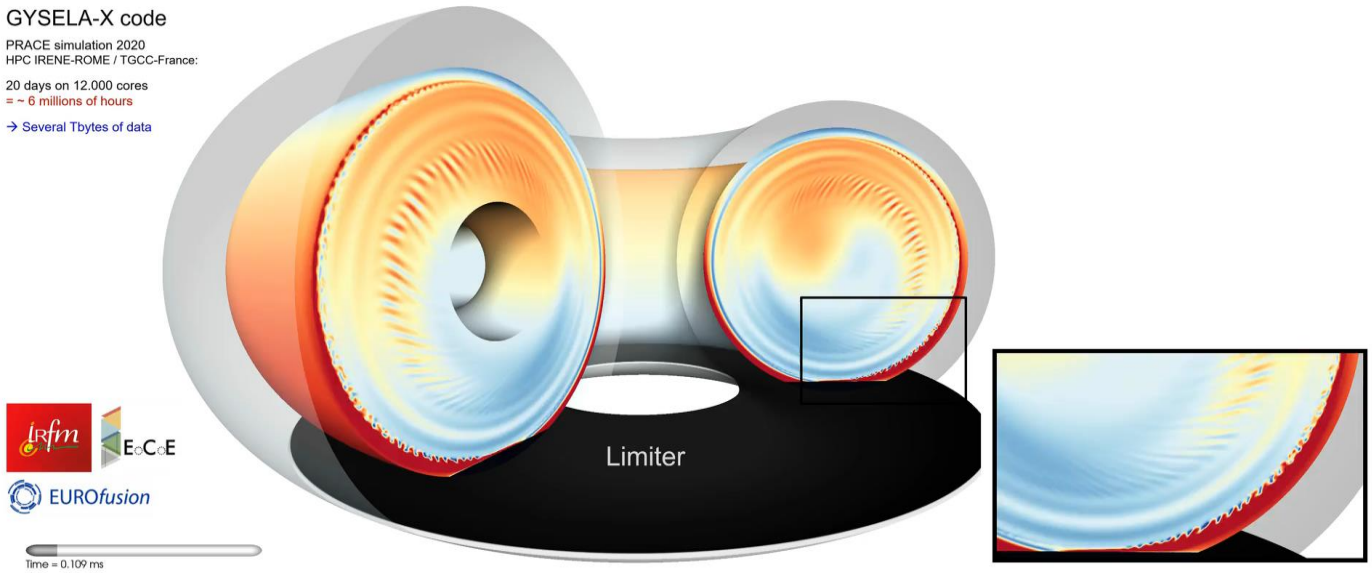
3) **Synergy between turbulent drive and magnetic braking**

Validating the model requires gyrokinetic simulations

- GYSELA: kinetic code solving

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

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



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

[V. Grandgirard – CPC 2016]

Requires 3D magnetic perturbation to be implemented

Determined for one turbulence

Using a simplified ripple amplitude shape

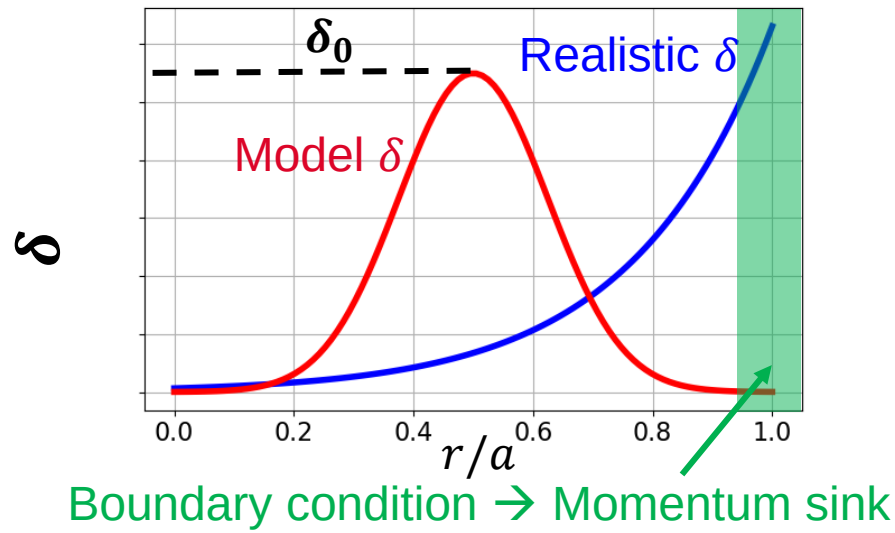
- Boundary conditions (realistic/simulated)

→ momentum sink not included in the model

- Solution: radially gaussian ripple

amplitude

Ripple amplitude profile

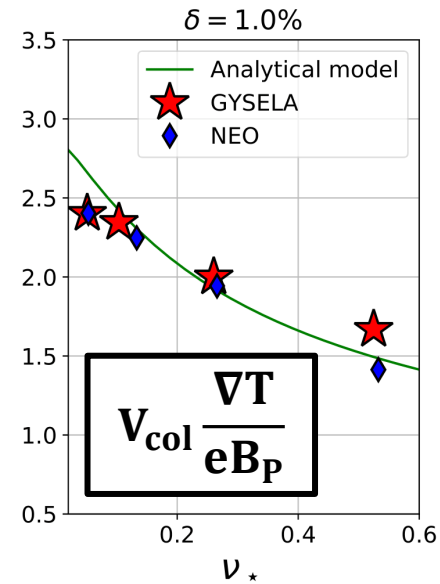


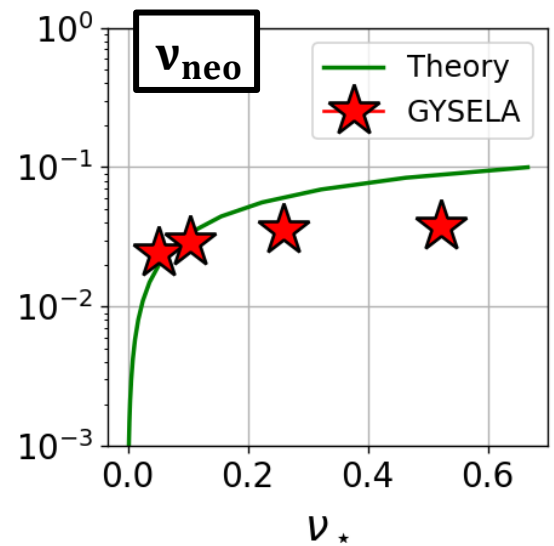
Thorough benchmark of the ripple implementation

$$m = -\nu_{col}(V_T - V_{col})$$

Depend on the collisionality $\nu_\star$ and ripple amplitude δ

- Toroidal momentum is conserved
- V_{col} → good agreement GYSELA / NEO
- Collisional friction ν_{col} → good agreement between GYSELA and the theory





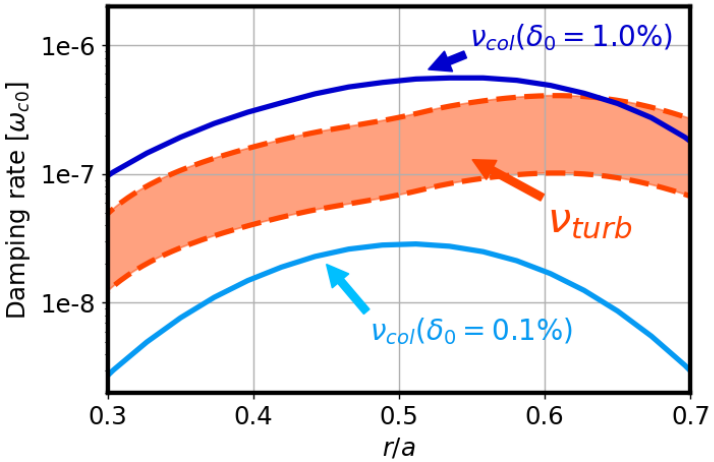
[R. Varennes – Submitted to PPCF]

The estimated critical ripple amplitude validated through simulations

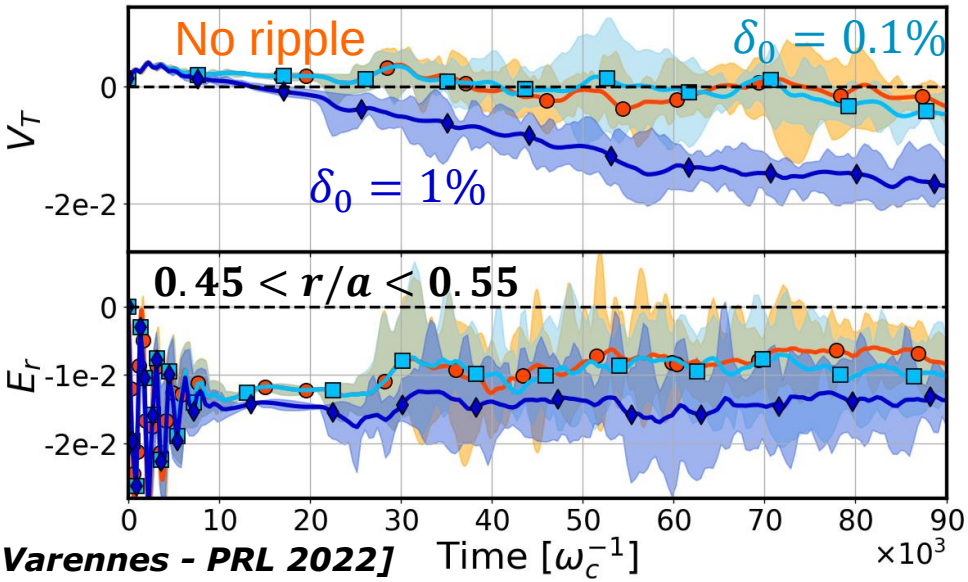
- Cases with $\delta \gg \delta_c$ and $\delta \ll \delta_c$
- No significant difference between $\delta \ll \delta_c$ case and the no ripple case
- $\delta \gg \delta_c$ case dominated by magnetic braking → similar in some experiments (TS, JET and JT60)

[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. Varennes - PRL 2022]

Talk outline

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:

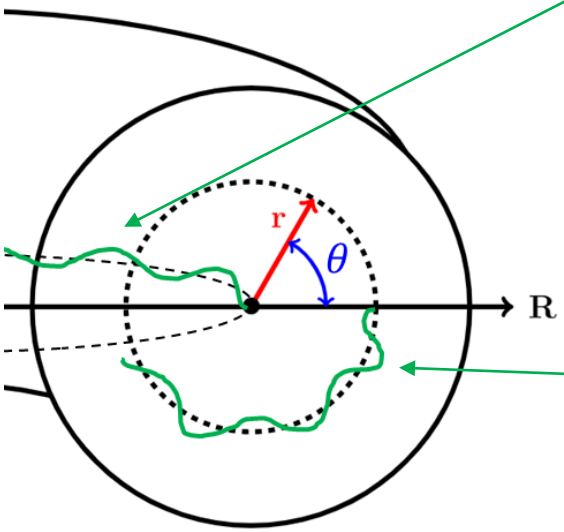
Magnetic braking ← Negligible — Turbulent drive

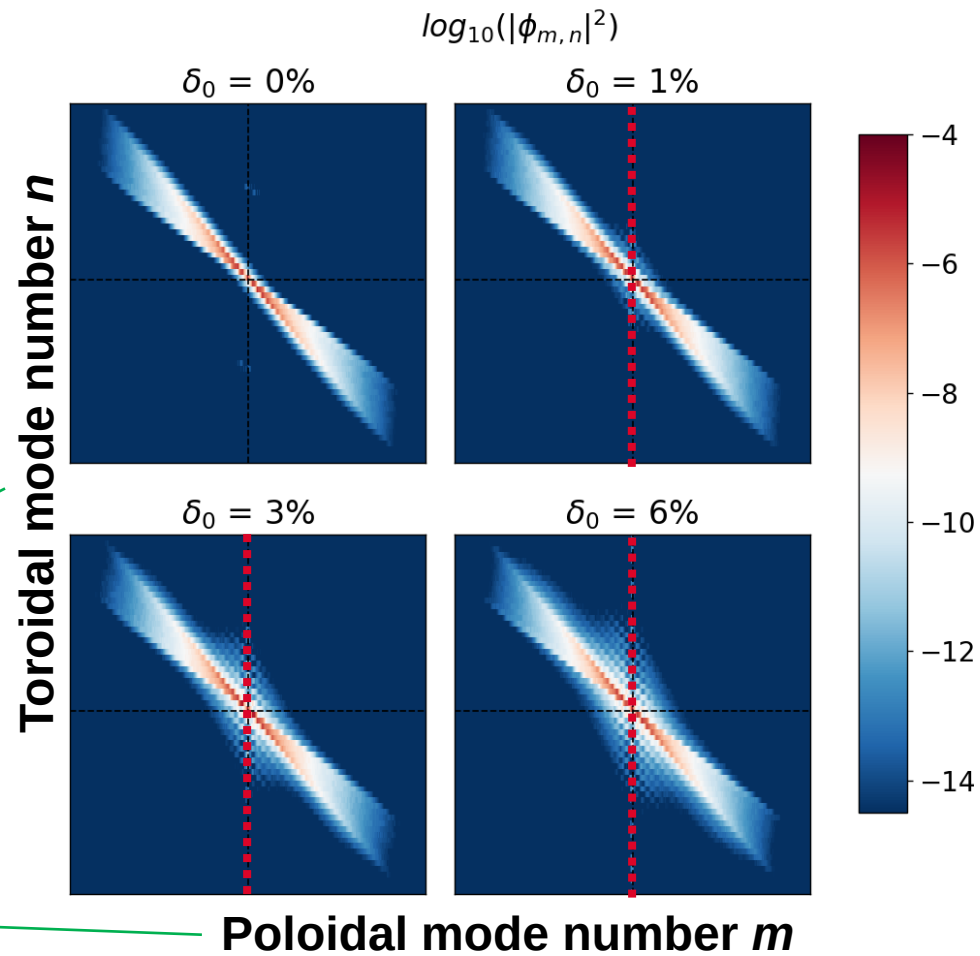
Magnetic braking → Significant — **Turbulent drive**

- 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 → $\cos(N_c\varphi)$ perturbation magnetic field → reflects on electric potential ϕ
- With turbulence, mode-coupling modifies the turbulent spectra

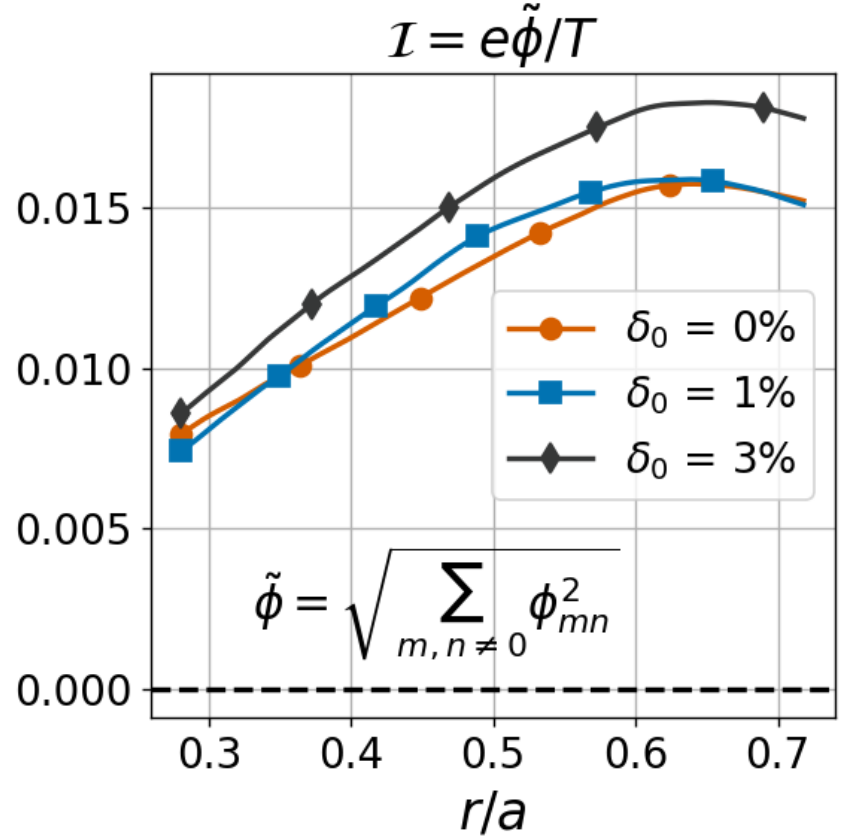




Turbulence intensity weakly impacted by ripple

- Spectral coupling → well described by the simulation code
- However, weak effect of the ripple on the turbulent intensity

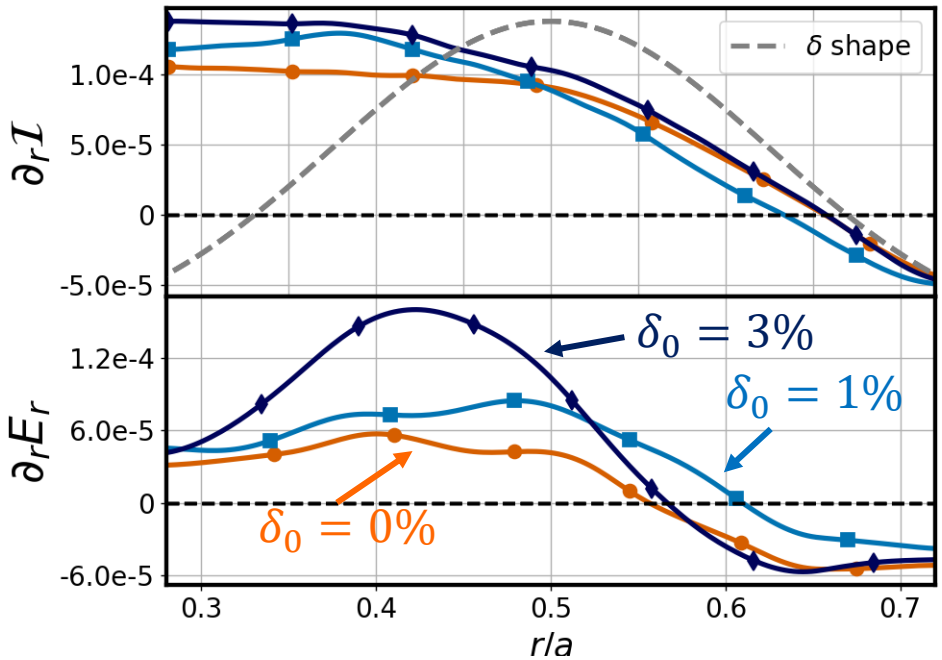
Coarse-grained turbulent intensity



Radial shear of E_r correlated with Π

- $\partial_r E_r$ expected to impact Π
- Ripple → 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]

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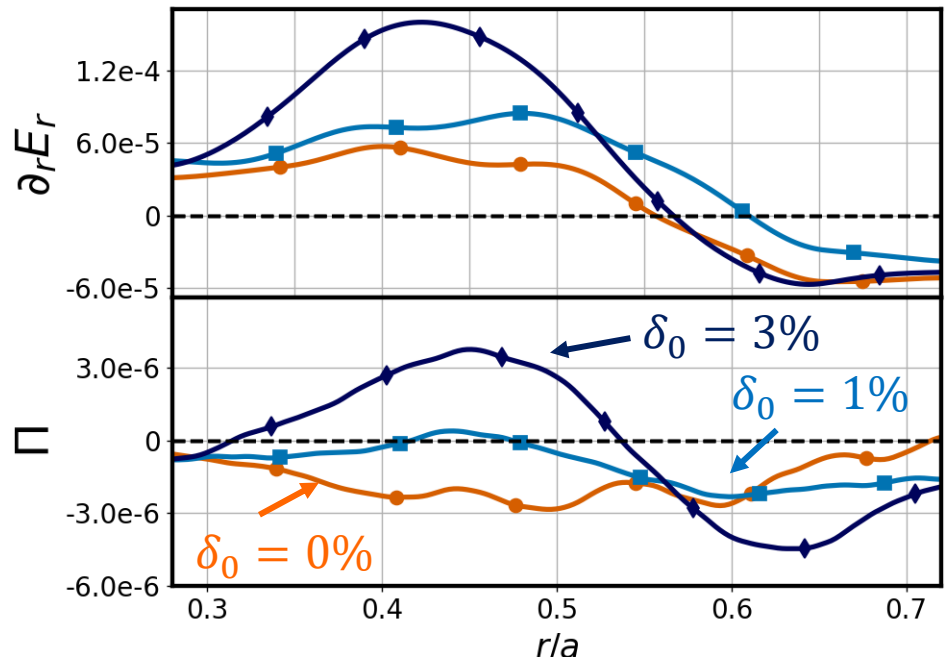


[R. Varennes - PRL 2022]

Conclusion

- 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

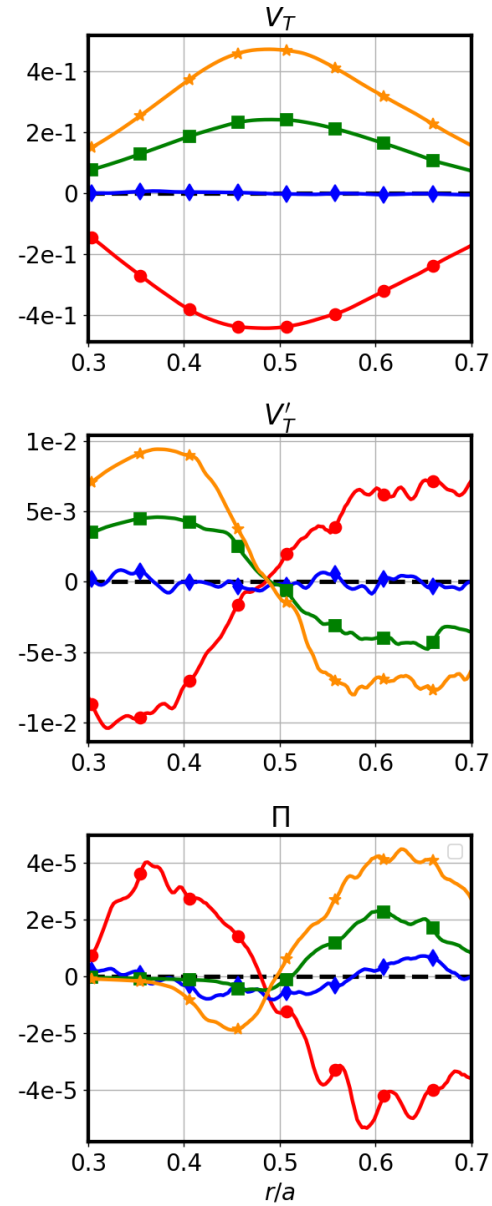
Evalutating the turbulent viscosity with gyrokinetic code

Unknowns

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

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

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

Toroidal harmonic of the perturbation

Thermal velocity

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

Ion Larmor radius

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

Temperature gradient length

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

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

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

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

Evalutating the turbulent viscosity with gyrokinetic code

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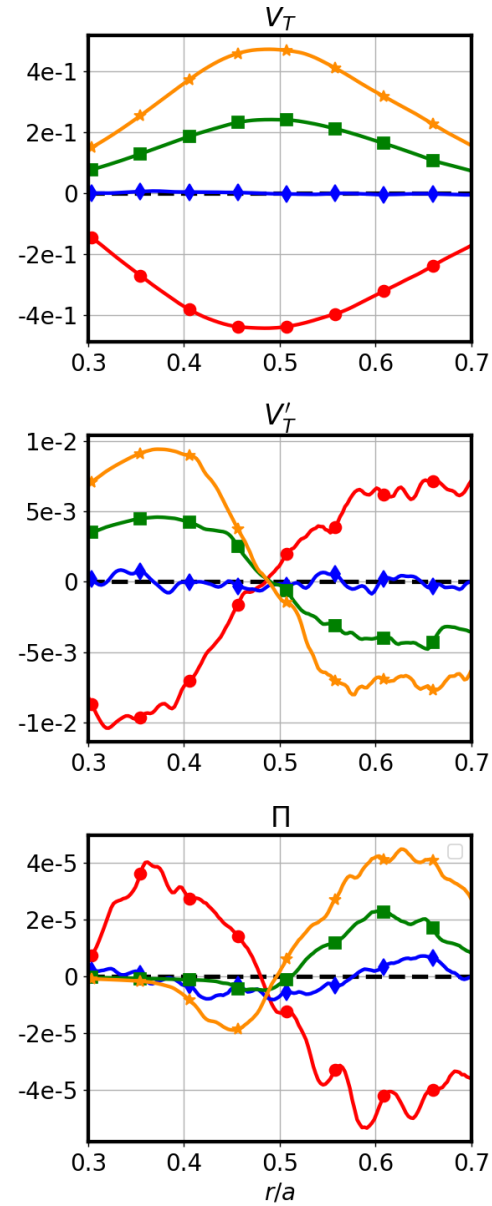
GYSELA outputs



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

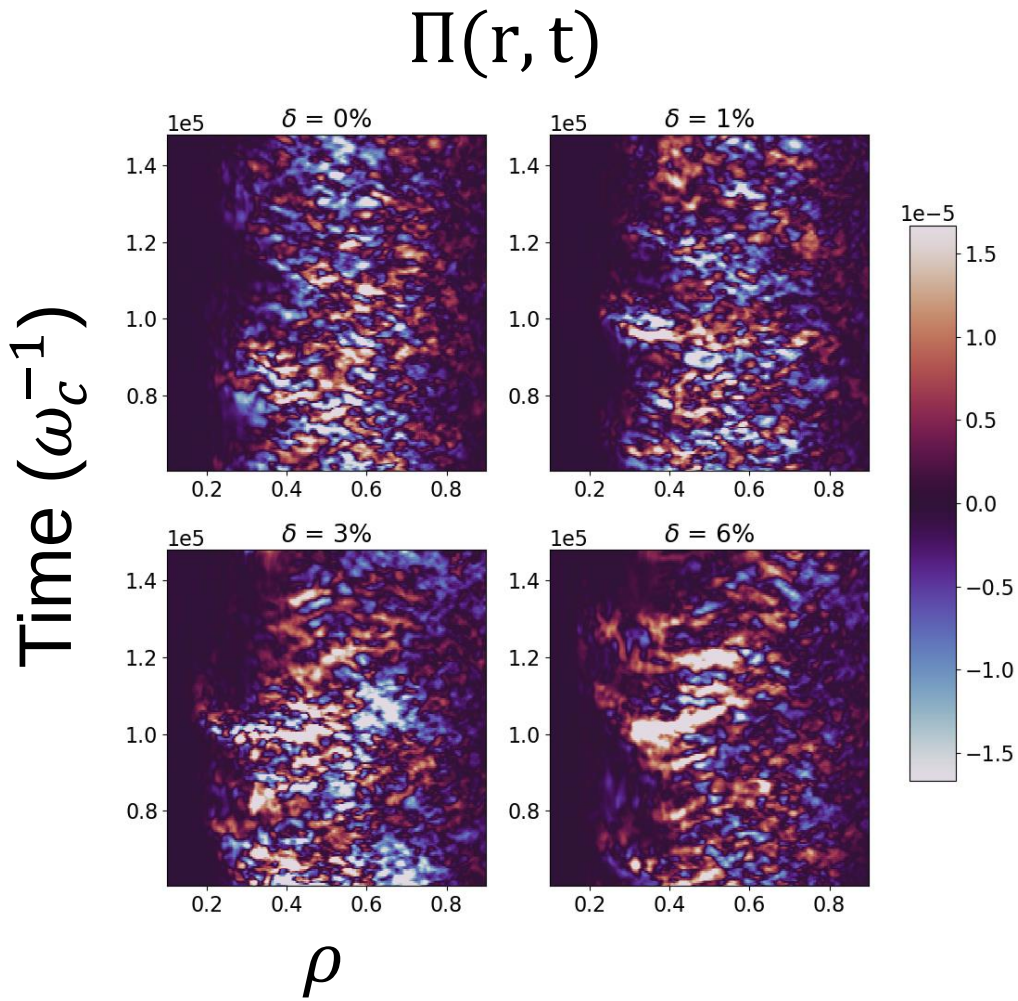
[A. Peeters - NF 2011]

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 :

$$(\boldsymbol{v}_{\parallel} + \boldsymbol{v}_{\boldsymbol{D}}) \,.\, \boldsymbol{\nabla}(\ F_{eq} + \delta \mathrm{F}\ ) = \mathcal{C}(\delta F)$$

Ripple → $\boldsymbol{v}_{\parallel}$; Banana → F_{eq}

$\boldsymbol{v}_{\boldsymbol{D}}$ → $\boldsymbol{\nabla}\mathbf{B}$; $\delta \mathrm{F}$ → Local trapping

→ Drifting banana

→ Magnetic wells

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

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

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

(Also valid for RMPs !)

Magnetic braking force dominates the toroidal force balance

- Neoclassical non-axisymmetric toroidal momentum conservation :

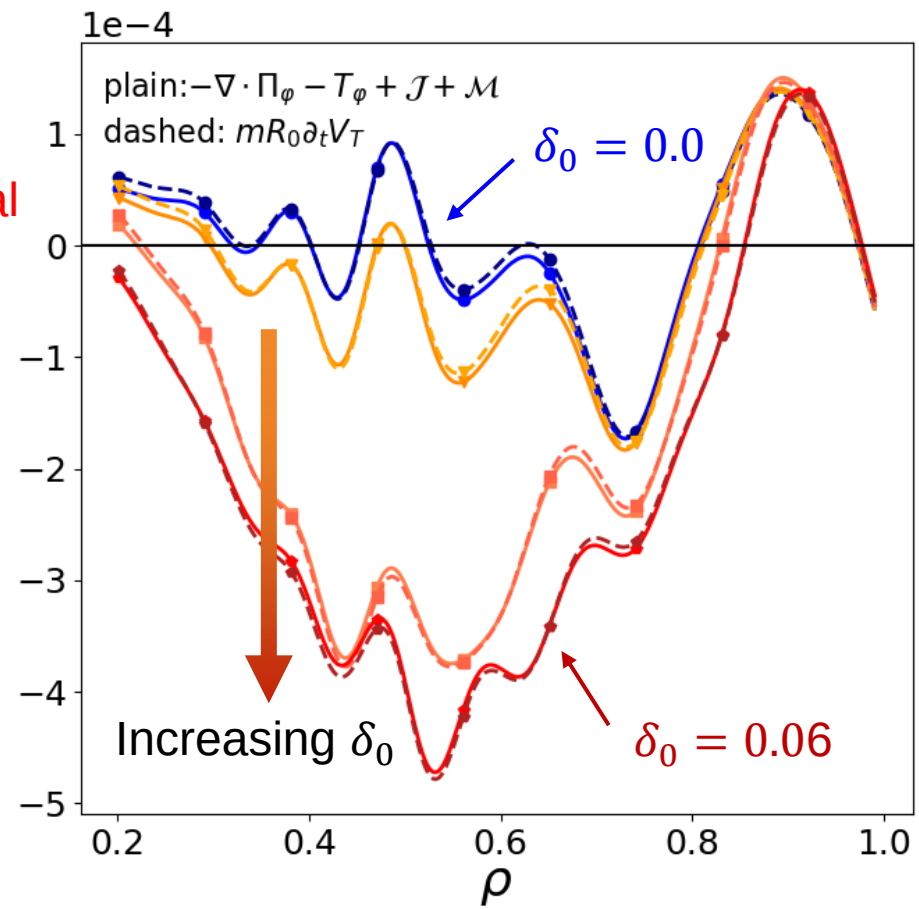
$$NmR_0 \frac{\partial V_T}{\partial t} = \overbrace{-\nabla \cdot \Pi_{turb}}^{\text{Turbulence (=0)}} - \underbrace{T_\varphi}_{\text{Polarization}} + \overbrace{J}^{\text{Current}} + \underbrace{\mathcal{M}}_{\text{Neoclassical Toroidal Viscosity}}$$

[J. Abiteboul 2011]

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

- $\mathcal{M}$ dominating → $NmR_0 \frac{\partial V_T}{\partial t} \approx \mathcal{M}$

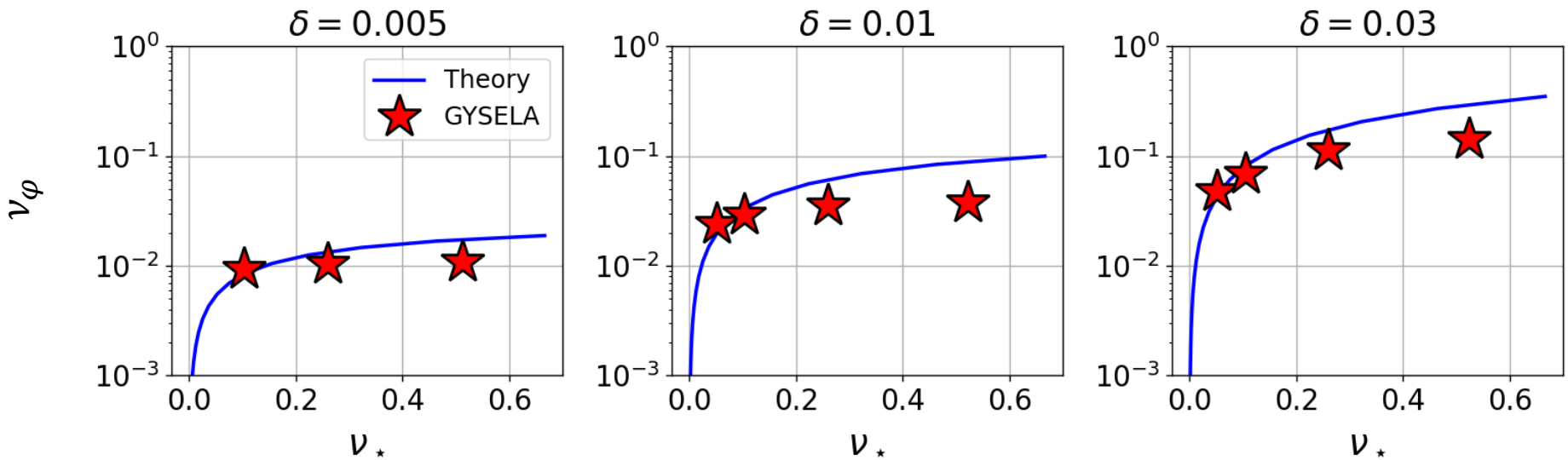
Radial profile of the LHS and RHS of the conservation of L



GYSELA recovers neoclassical predictions

- 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



[R. Varennes – Submitted to PPCF]

Magnetic braking is induced by 3D magnetic perturbations

- <u>Magnetic braking:</u>
  - 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 → external, magnetic ripple
  - Constrains the particle trajectories → results in finite plasma toroidal velocity V_T

Structure of the residual stress

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