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Impact of non-axisymmetric magnetic field perturbations on flows

R.Varennes[1], X.Garbet[1], L.Vermare[2], Y.Sarazin[1], V.Grandgirard[1], G.Dif-Pradalier[1], M.Peret[2]

[1]CEA, IRFM, France [2]LPP, CNRS, Ecole polytechnique, France

Introduction

- Plasma rotation plays a key role in plasma confinement [1][2];
- Control of plasma rotation in reactor-sized tokamak is challenging [3];
- Intrinsic bulk plasma rotation is driven by turbulence and ***Neoclassical Toroidal Viscosity* (NTV)**;
- Magnetic field ripple is responsible for the NTV.

<u>Objective</u>: Understand the competition/synergy between turbulence and NTV with gyrokinetic simulations.

Theoretical model

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

$$\frac{\partial V_T}{\partial t} = \text{Neoclassical Toroidal Viscosity} + \text{Turbulent torque}$$

Ripple constrains V_T through neoclassical friction ν_φ

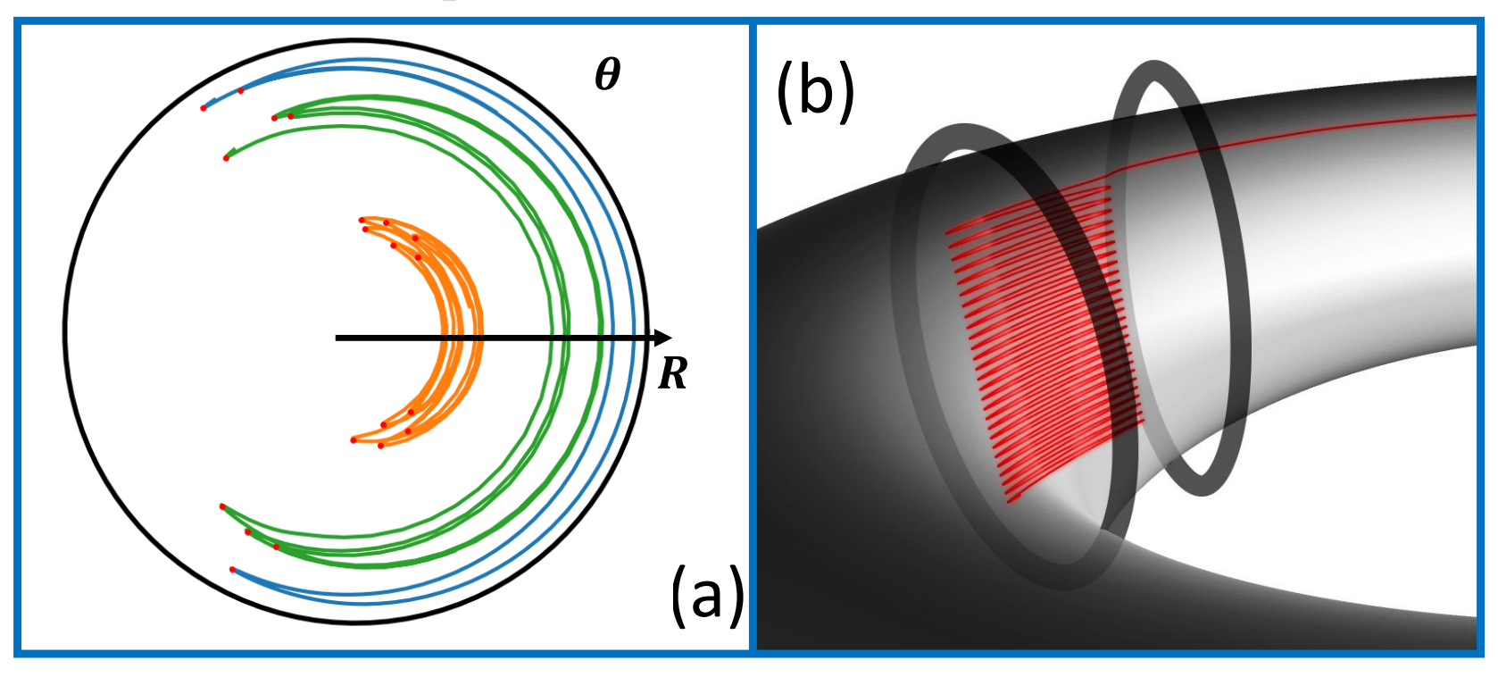

FIG.1 – Kinetic effects induced by ripple : drift of banana bounce points (a) and toroidal trapping between coils (b). Neoclassical friction ν_φ comes from the collisions between trapped populations.

Turbulence constrains V_T through turbulent viscosity χ_{turb}

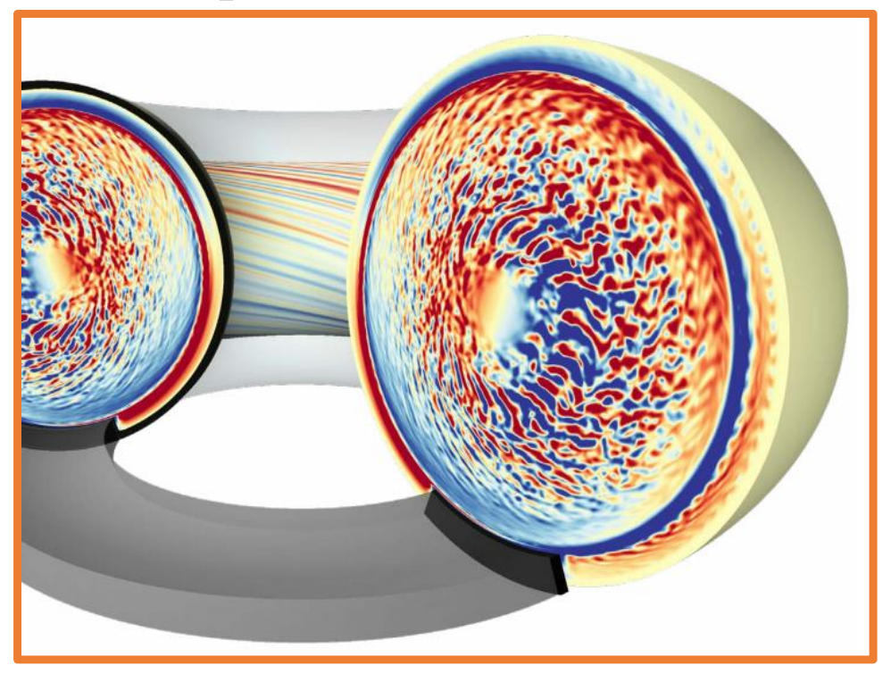

FIG.2 – Snapshot of the turbulent structures seen through a colormap on the electric potential. From rest, V_T grows due to wave-particle interactions.

<u>Goal</u>: Obtain coefficients of turbulent momentum transport <u>from simulations</u> and use neoclassical friction ν_φ predictions to find the ripple amplitude threshold for which neoclassical effects overcome turbulence.

Turbulent momentum transport

- Turbulence impacts V_T through the toroidal Reynold's stress Π_φ
- Axisymmetric theory [4][5] :

$$\Pi_\varphi = \underbrace{-\chi_{\text{turb}} \frac{\partial V_T}{\partial r}}_{\text{Viscosity}} + \underbrace{\mathcal{V} V_T}_{\text{Pinch}} + \underbrace{\Pi_{res}}_{\text{Residual}} \quad \text{(Eq.1)}$$

- Obtention of χ_{turb}, $\mathcal{V}$ and Π_{res} using gyrokinetic simulations :
  - Simulations of turbulent plasma without ripple with different initial toroidal velocity → FIG.3 shows the dominance of the viscosity : $-\chi_{\text{turb}} \frac{\partial V_T}{\partial r}$;
  - Eq.1 defines a plane in the $(\mathrm{V_T}, \partial_r \mathrm{V_T}, \Pi_\varphi)$ space;
  - Mean square plane fit using simulations output gives an estimation of χ_{turb} within a radial range (see FIG.4 for an example).

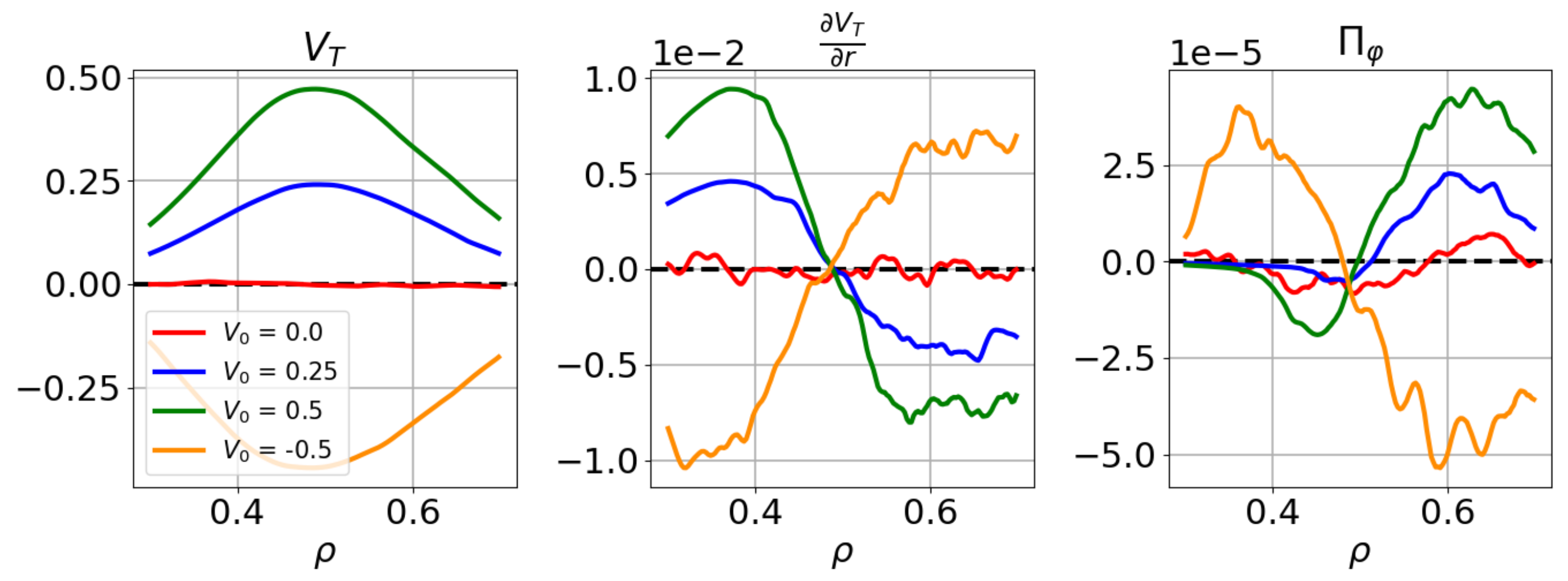

FIG.3 - Radial profiles of V_T, $\partial_r V_T$ and Π_φ taken at turbulent saturation for simulations initialized at different toroidal velocity $V_T(t=0) = V_0 e^{4(\rho-0.5)^2}$

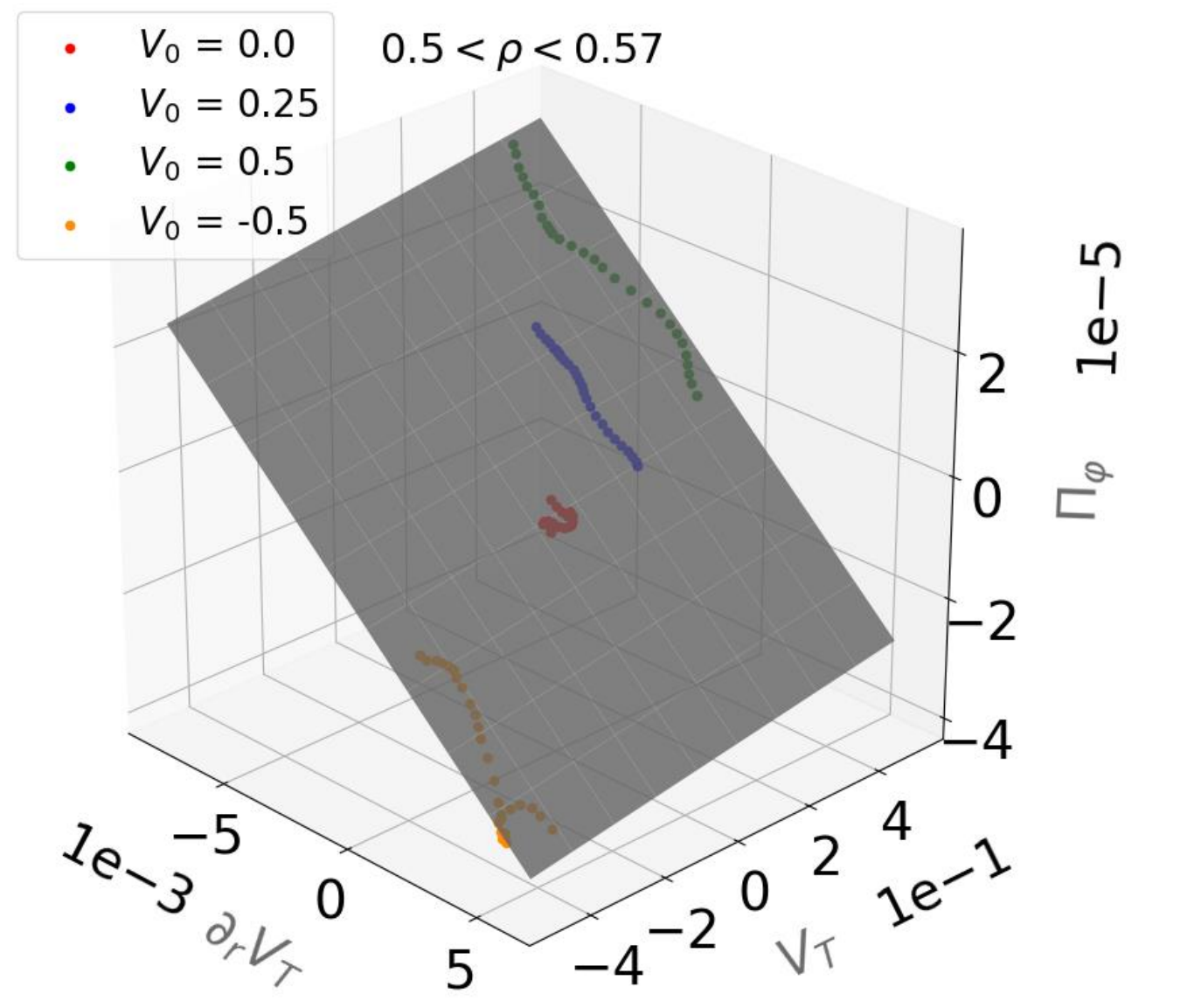

FIG.4 - Plane fit of Π_φ using point cloud from simulations giving an estimation of the turbulent viscosity within a radial range.

Neoclassical friction

- Ripple is responsible for magnetic braking $\mathcal{m}$ in the toroidal direction : the NTV;
- Neoclassical theory [6][7] with ripple gives :

$$\mathcal{m} = \underset{\text{Friction}}{-\nu_\varphi} \left(V_T - \underset{\text{Thermal drive}}{k_T \frac{\nabla T}{eB_P}} \right)$$

- GYSELA code shows good agreement with neoclassical predictions;
- ν_φ increases with the ripple amplitude.

Competition ripple/turbulence

- Complete model reads :

$$\frac{\partial V_T}{\partial t} \approx \mathcal{m} - \nabla . \Pi_\varphi \quad \Rightarrow \quad \overset{V_T\ \text{relaxation time}}{\tau_V} \sim max\left(\frac{\chi_{turb}}{\underset{V_T\ \text{gradient's length}}{L_V^2}}, \nu_\varphi \right)^{-1}$$

- Boundary physics not in the model → radially gaussian ripple (cf FIG.5)

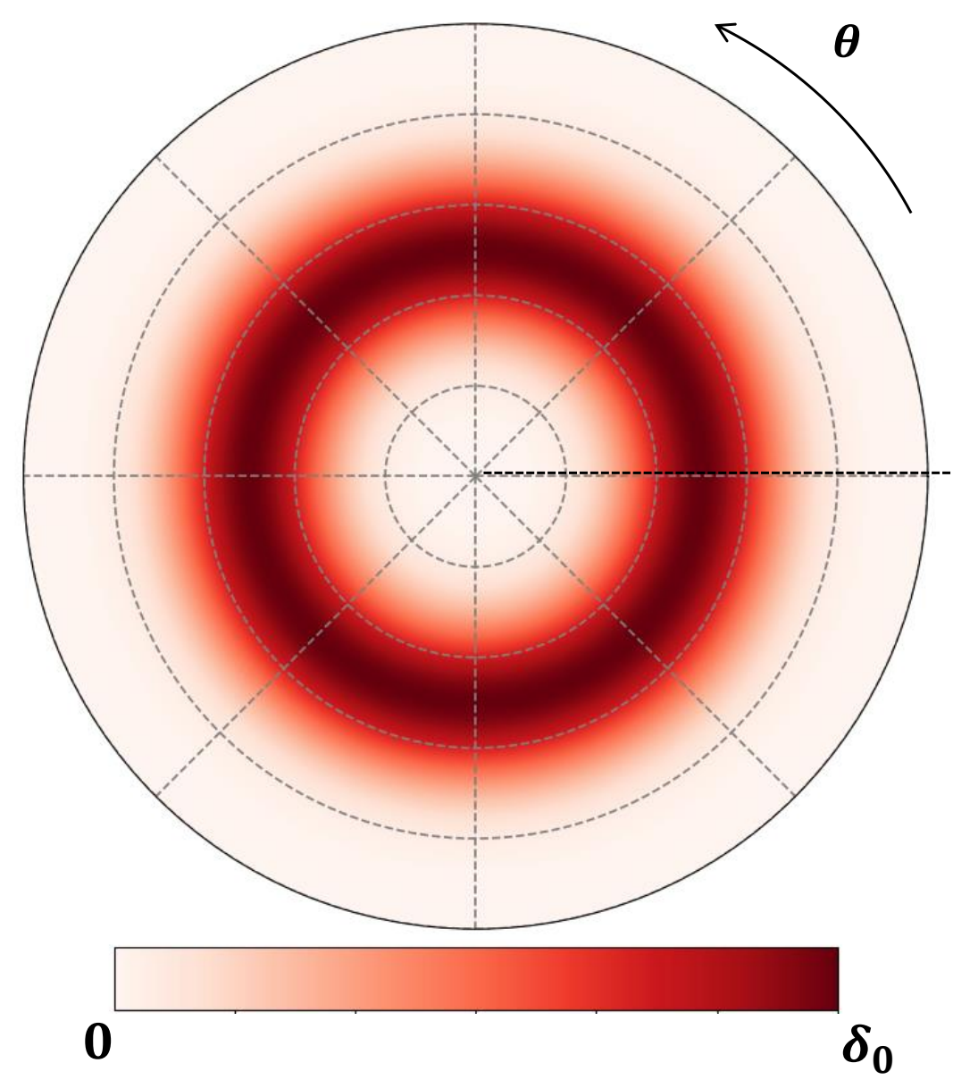

FIG.5 – Polar map of the ripple amplitude used for simulations.

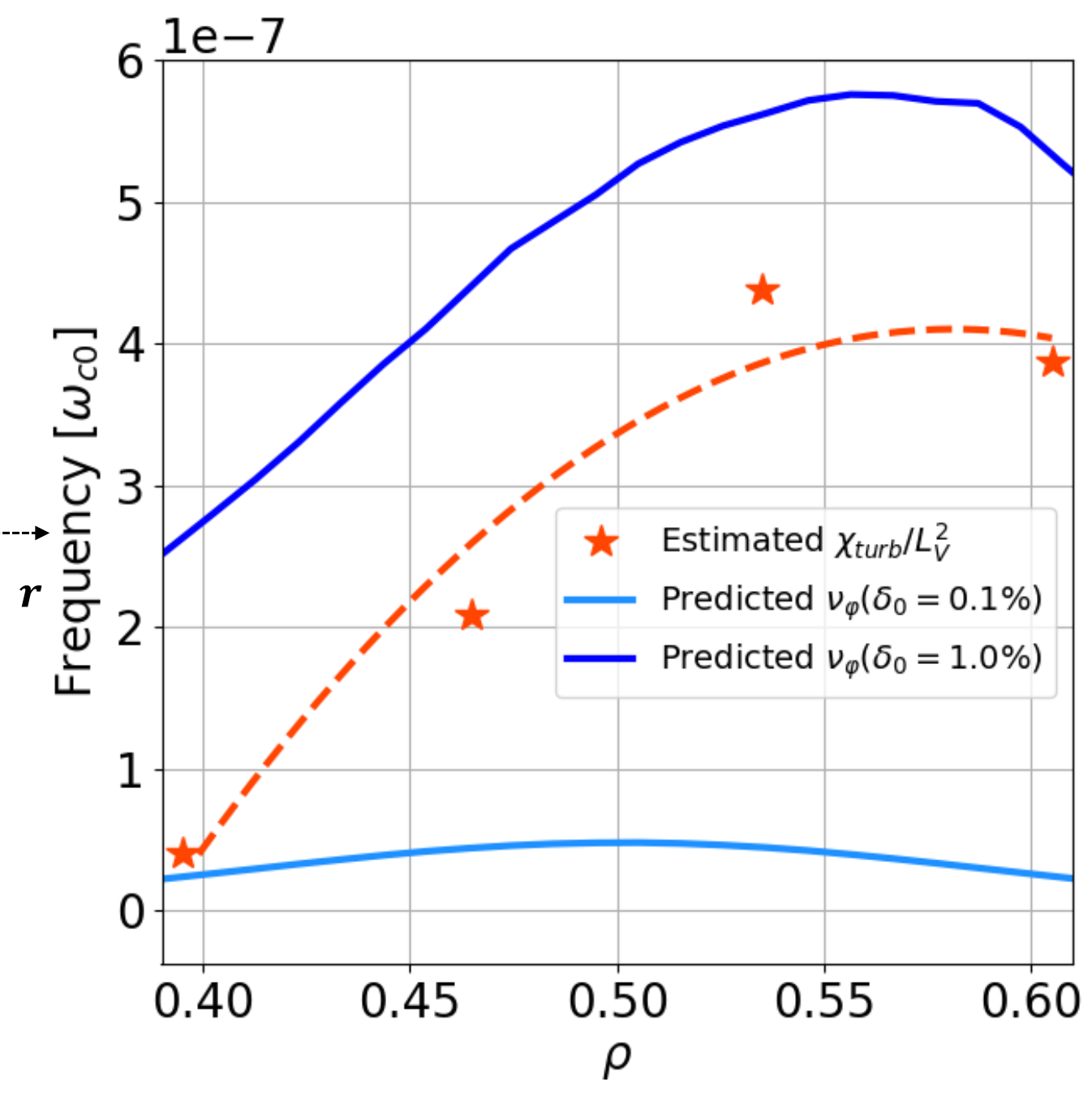

FIG.6 – Radial profiles of estimated turbulent relaxation frequency and predicted neoclassical frictions.

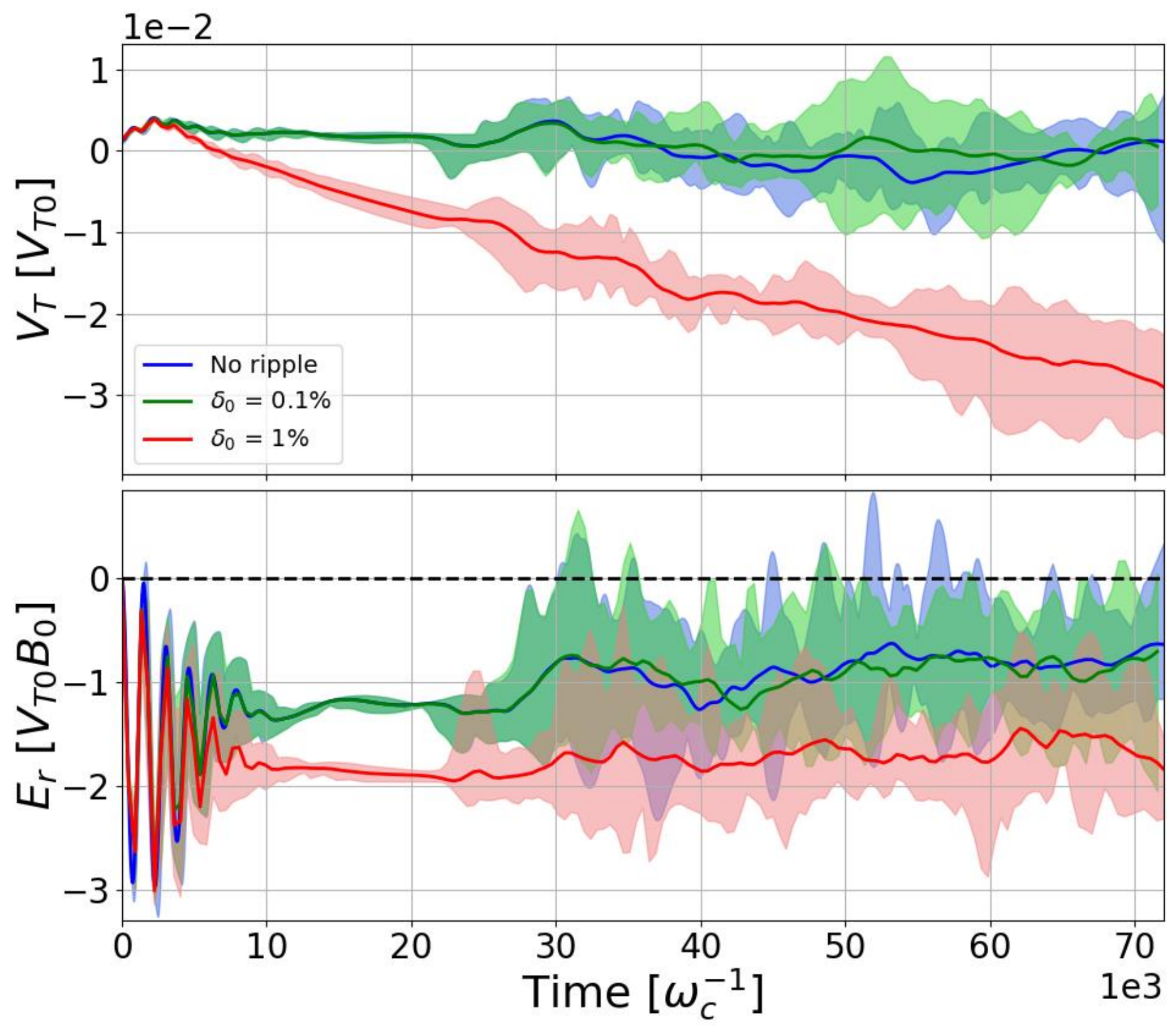

FIG.7 – Time evolution of V_T and E_r in the range $0.45 < \rho < 0.55$ for different ripple amplitudes.

- Model verification using 2 simulations :
  - With dominant neoclassical friction
  - With dominant turbulent viscosity

  See FIG.6
- Main result FIG.7
  - $\delta_0 = 0.1\%$ case dominated by turbulence
  - $\delta_0 = 1.0\%$ case driven by neoclassical friction → increase of E_r to fulfill force balance

Conclusion

- Ripple is responsible for a neoclassical friction that constrains the toroidal velocity;
- Turbulence is a source of intrinsic rotation;
- Evolution of mean toroidal flow ruled by competing turbulent stress and ripple drag forces;
- The radial electric field grows in response to the modification of the toroidal velocity;
- Simulations suggest that neoclassic drag overcomes turbulent stress for typical realistic ripple amplitudes in WEST;
- Future work taking into account boundary physics with realistic WEST ripple amplitude is necessary to understand the shape of $\frac{dE_r}{dr}$ and the transition toward high-confinement modes.

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