

IMPACT OF A RIPPLED MAGNETIC FIELD ON FLOWS

DE LA RECHERCHE À L'INDUSTRIE



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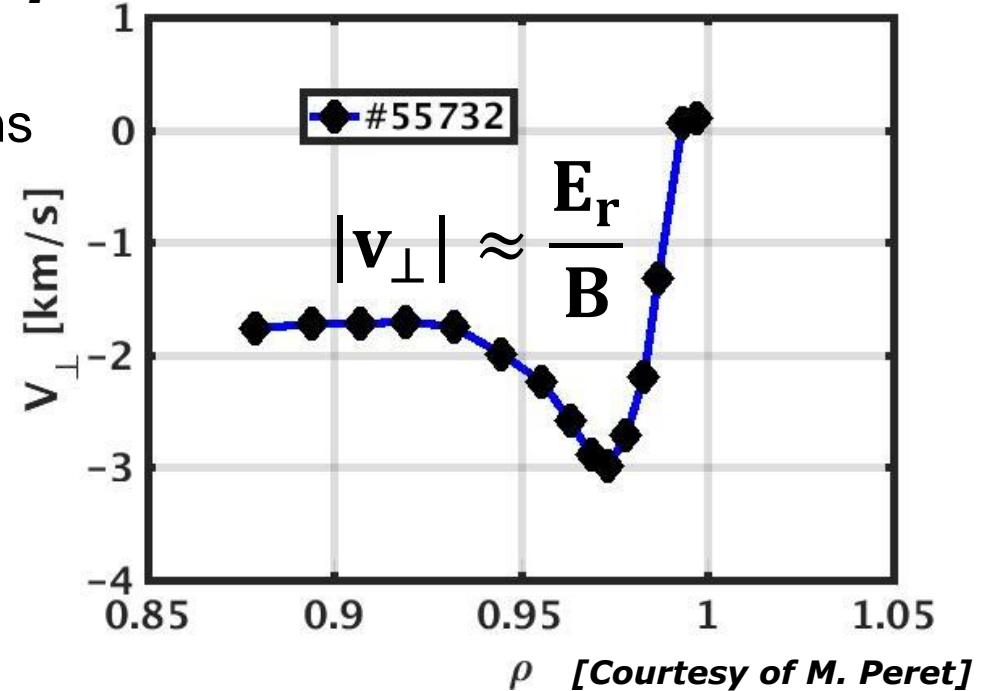
LH transition is affected by velocity shear
 [Burrell 1997] [Connor 2000] [Wagner 2007, 2018]

Ripple : magnetic field toroidal modulations
 due to finite number of coils N_{coils}

Typical values of ripple amplitude δ :

- JET : $0.08\% < \delta_{max} < 1.5\%$
- ITER : $\delta_{max} \sim 0.5\%$ (expected)
- Tore Supra : $\delta_{max} \sim 6.0\%$
- WEST : $\delta_{max} \sim 2.0\%$

v_{\perp} measurement with Doppler reflectometry in WEST



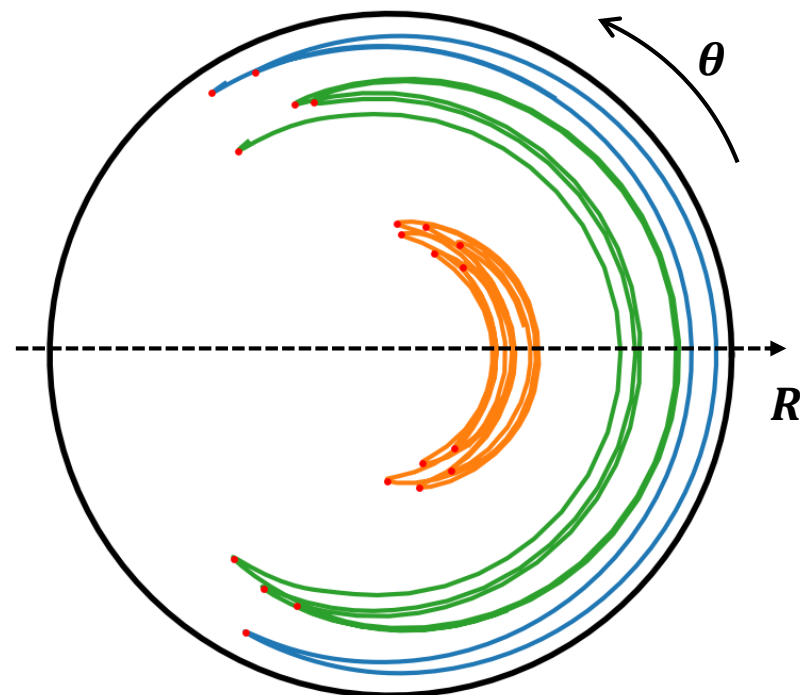
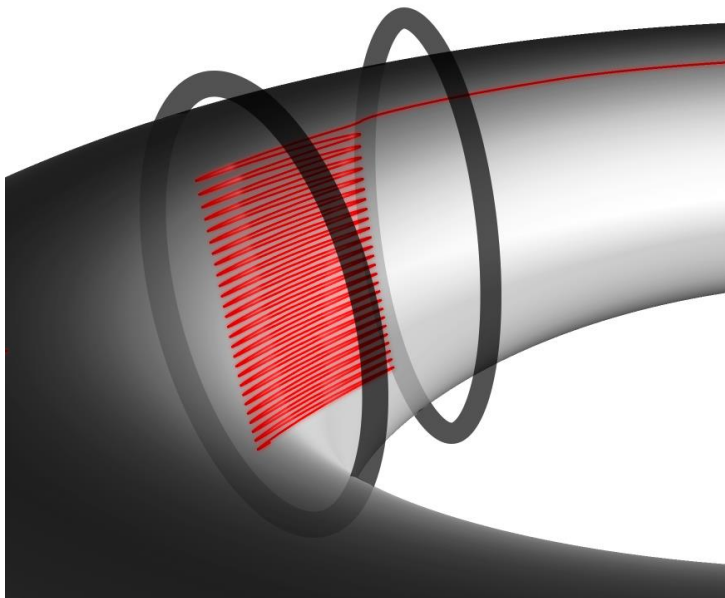
Question : How ripple impacts flows in WEST and does it

2 influence L-H transition ?

[C. Fenzi 2011] [E. Trier 2008] [B. Chouli 2014]

$$\text{Magnetic field amplitude : } B \propto 1 - \varepsilon \cos\theta + \delta \cos(N_{coils}\varphi)$$

Primary perturbation	$\delta \cos(N\varphi)$ Magnetic wells	$\varepsilon \cos(\theta)$ Banana trapping
Secondary perturbation	$\varepsilon \cos(\theta)$ Vertical drift	$\delta \cos(N\varphi)$ Drift of bounce points



Ripple induces toroidal magnetic braking

- Without toroidal constraint → no neoclassical prediction on E_r and v_T
- Ripple → toroidal magnetic braking / friction v_ϕ

$$\frac{\partial v_T}{\partial t} = -v_\phi \left(v_T - k_T \frac{\nabla T}{eB_\theta} \right)$$

$$\varepsilon_r \frac{\partial E_r}{\partial t} = e\Gamma_r^{NC}(E_r, v_T)$$

[X. Garbet 2010]

- Predicted by neoclassical theory with ripple

[J. W. Connor 1973]

- Depends mainly on $\frac{\delta}{\varepsilon}$ and v^*

[K. C. Shaing 1986]

[L. M. Kovrizhnykh 1998]

[A. B. Mikhailovskii 1995]

WEST / Tore Supra : Neoclassical + Turbulence

$$\frac{\partial v_T}{\partial t} = -v_\phi \left(v_T - k_T \frac{\nabla T}{eB_\theta} \right) \rightarrow \text{Counter-rotation (depends on } \delta)$$

+ $\nabla \cdot \Pi_{\text{turb}}$

→ Co-rotation (depends on turbulent intensity)

→ Gyrokinetic codes : both effects

[K. Kim 2014]

[S. Matsuoka 2018]

[E.J. Paul 2017]

4 taken into account

- GYSELA : full-F gyrokinetic semi-lagrangian code solving :

$$\text{Vlasov equation : } \frac{\partial F}{\partial t} + (\mathbf{v}_{\parallel} + \mathbf{v}_D^{\text{axi}} + \mathbf{v}_D^{\text{rip}} + \mathbf{v}_E) \cdot \nabla F + \frac{\partial v_{\parallel}}{\partial t} \frac{\partial F}{\partial v_{\parallel}} = \mathcal{C}(F)$$

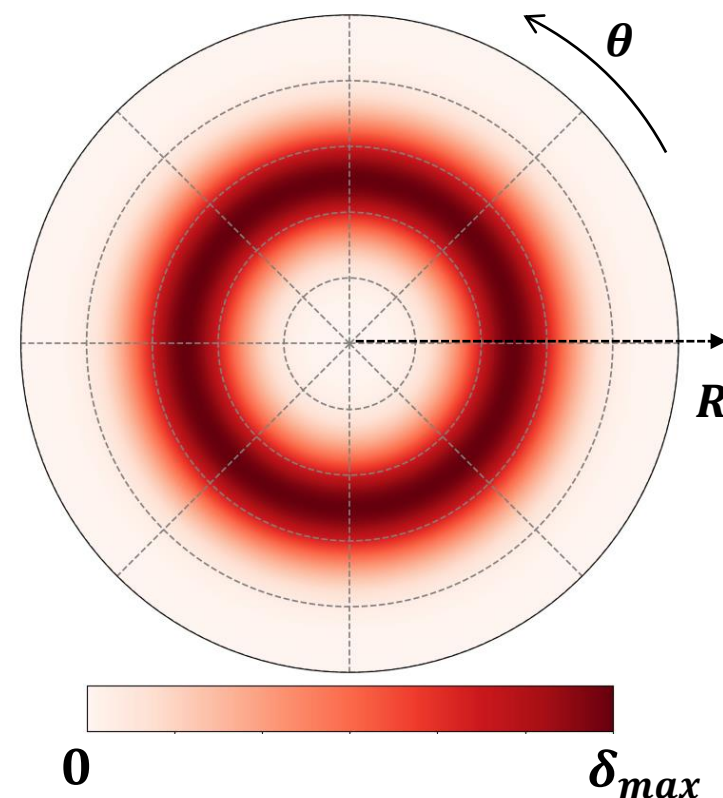
+ Poisson equation

- Current version : boundary condition acting as momentum sink
- First step : trial with radially gaussian ripple
- Realistic T, N and q profiles (similar to WEST)

- $v_{\star}(a/2) = 0.14 ; \rho_{\star}^{-1} = \frac{a}{\rho_i} = 250$

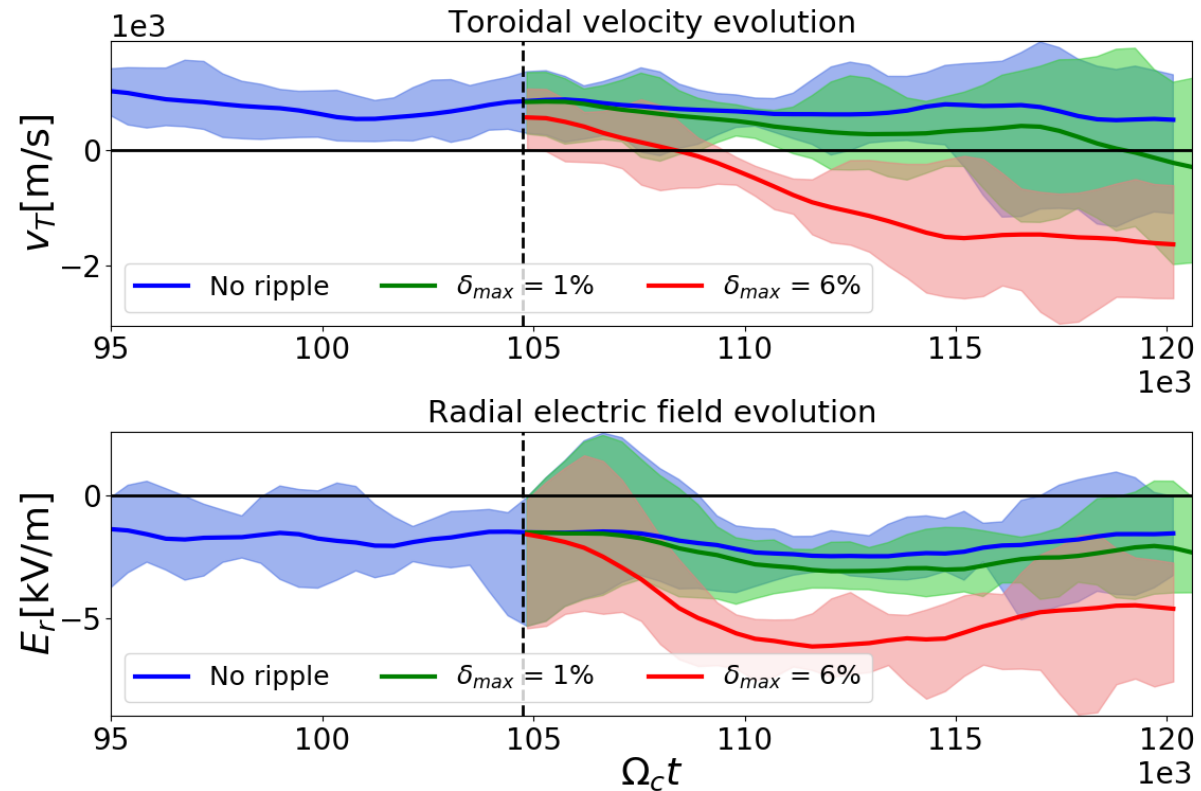
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Gaussian ripple map $\delta(r, \theta)$



- Activation of ripple on weak turbulent equilibria
- Counter-rotation of plasma with ripple (as observed in JET and JT60)
 - [M.F.F Nave 2010]
 - [H. Urano 2011]
- Competition between ripple NC effects and turbulence
- Increasing of $|E_r|$ as predicted by theory
- Long relaxation time ν_ϕ^{-1} of toroidal velocity

Time evolution of v_T and E_r for $0.45 < \rho < 0.55$



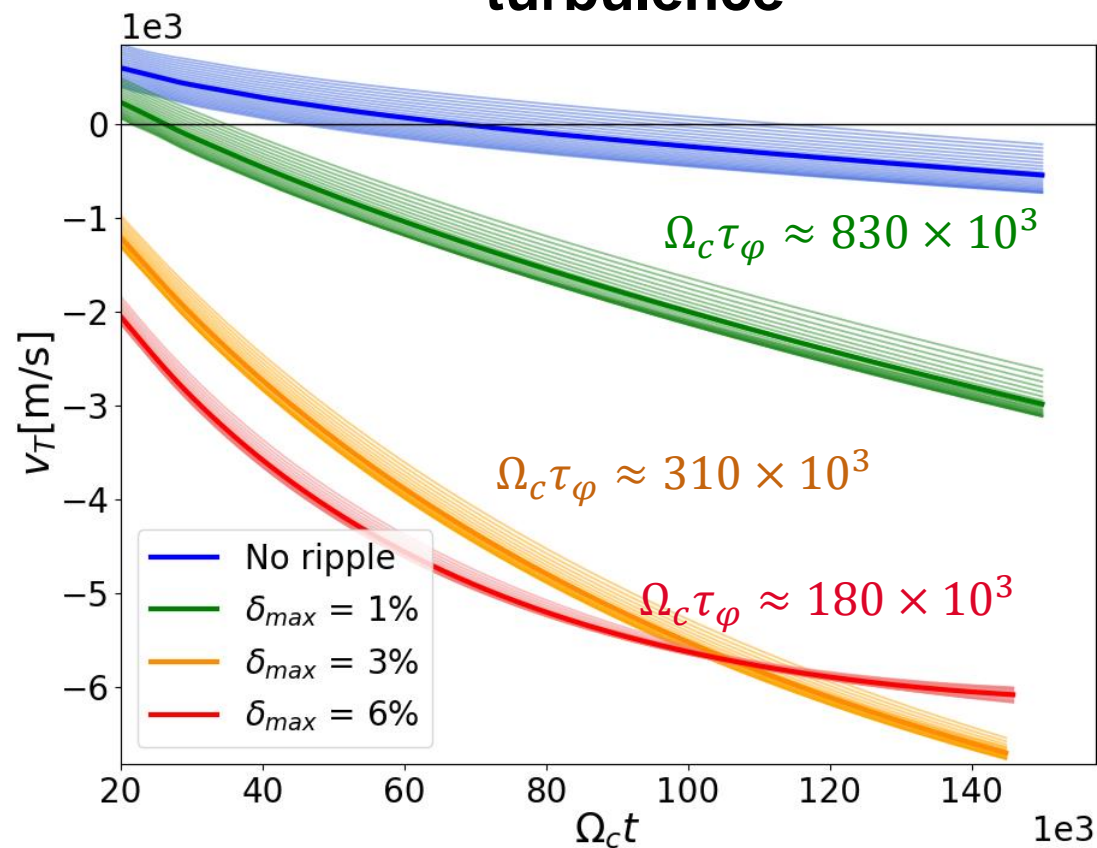
Without turbulence, $v_T \propto (1 - e^{-\nu_\phi t})$

Simulations without turbulence \rightarrow

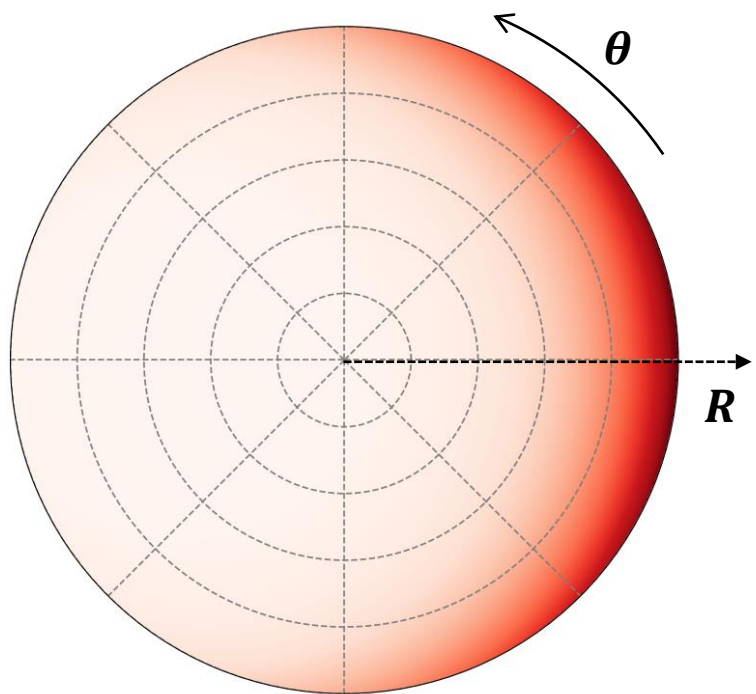
$$\nu_\phi^{-1} = \tau_\phi \propto \delta^{-1}$$

Convergence time for low (realistic) ripple requires important computational resources

Time evolution of v_T without turbulence



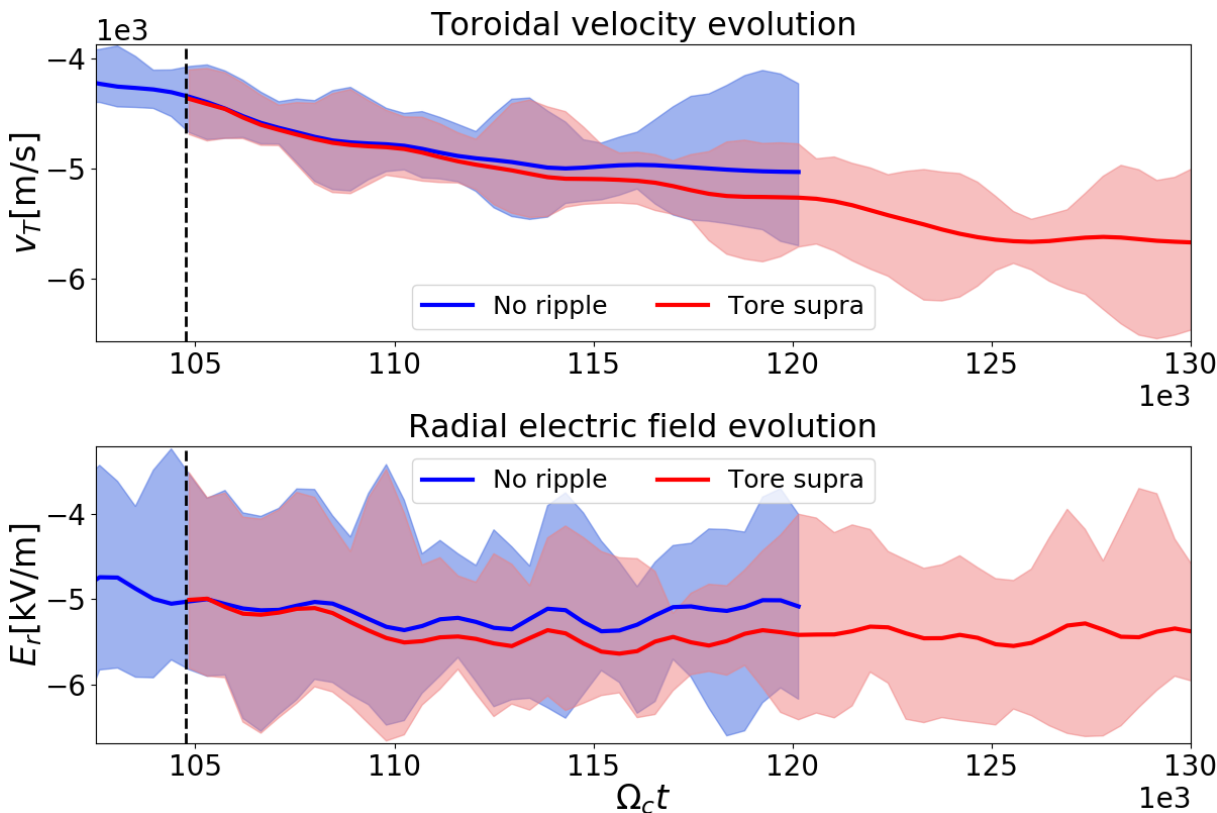
Tore Supra ripple amplitude



[P.N. Yushmanov 1987]

- As expected, long convergence of v_T
- Increasing of E_r amplitude observed

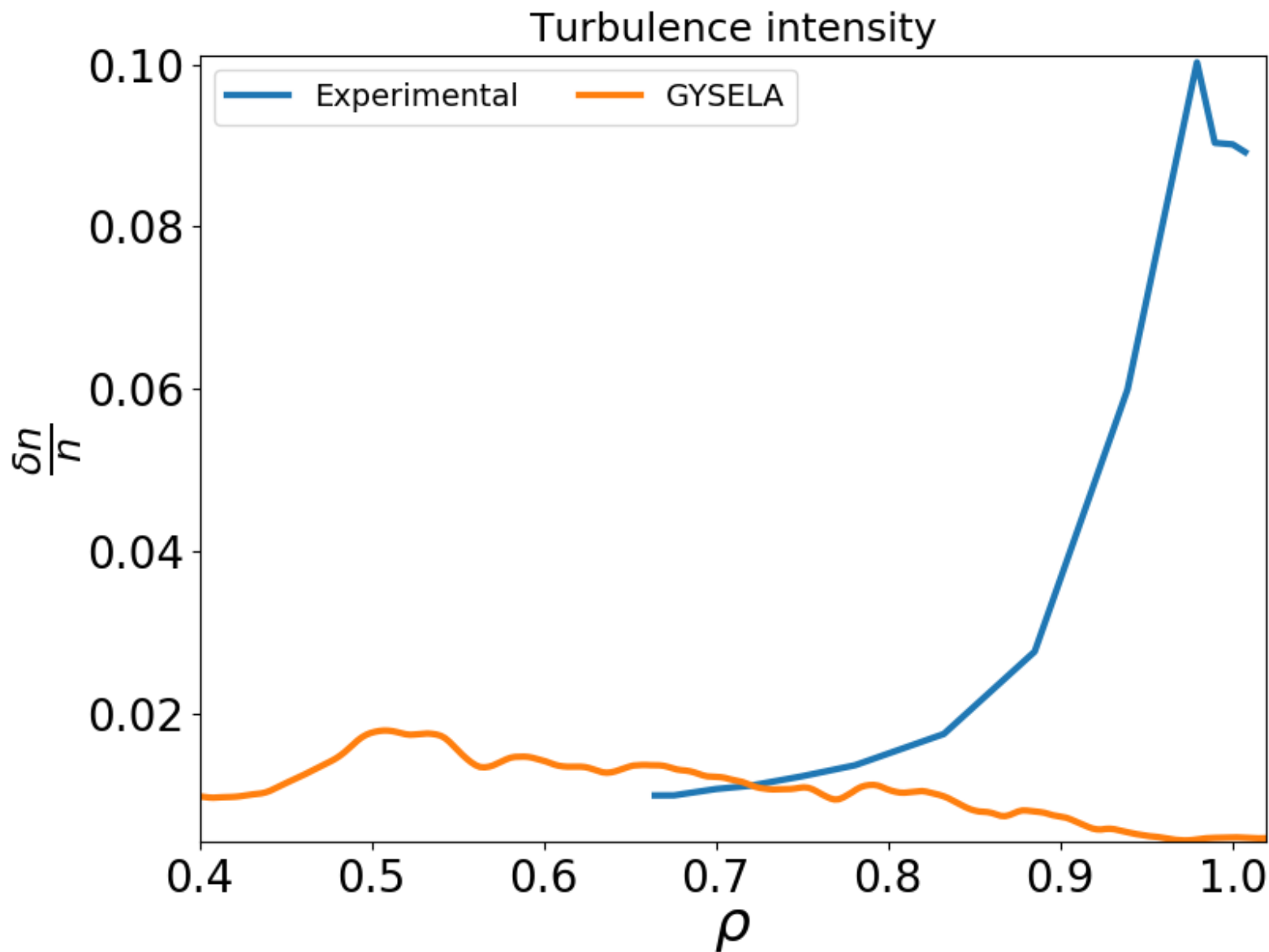
Time evolution of v_T and E_r for $0.75 < \rho < 0.85$ ($\delta \sim 1\%$)



- As observed experimentally, ripple induces counter-rotation
- Competition between turbulence and ripple neoclassical effects
- Weak ripple does increases $|E_r|$ → potential effect on LH threshold ?
- Long relaxation time requires heavy computational resources

Work in progress

- Quantify ripple impact for strongly turbulent plasmas
- Better assesment of neoclassical flows in GYSELA



Goal : Obtain theoretical predictions for E_r, v_p, v_T

Step 1 : Derive the distribution function F satisfying ∇B and ripple constraint

Stationary guiding-center Vlasov equation : $(v_{\parallel} + v_D^{axi} + v_D^{rip}) \cdot \nabla F = \mathcal{C}(\delta F) \rightarrow$ Basically intractable

$$\left(v_{\parallel} + \begin{matrix} v_D^{axi} \\ v_D^{rip} \end{matrix} \right) \cdot \nabla F = \mathcal{C}(\delta F) \rightarrow \begin{matrix} F^{axi} \rightarrow \text{banana trapped} \\ F^{rip} \rightarrow \text{magnetic wells} \end{matrix}$$

Different regimes:

$$(v_{\parallel} + v_D^{rip}) \cdot \nabla (F^{axi} + \delta F) = \mathcal{C}(\delta F) \quad (v_{\parallel} + v_D^{axi}) \cdot (\nabla F^{rip} + \delta F) = \mathcal{C}(F^{rip})$$

Ripple-plateau regime

Banana particles perturbed by ripple
→ drift of bounce points

Local trapping regime

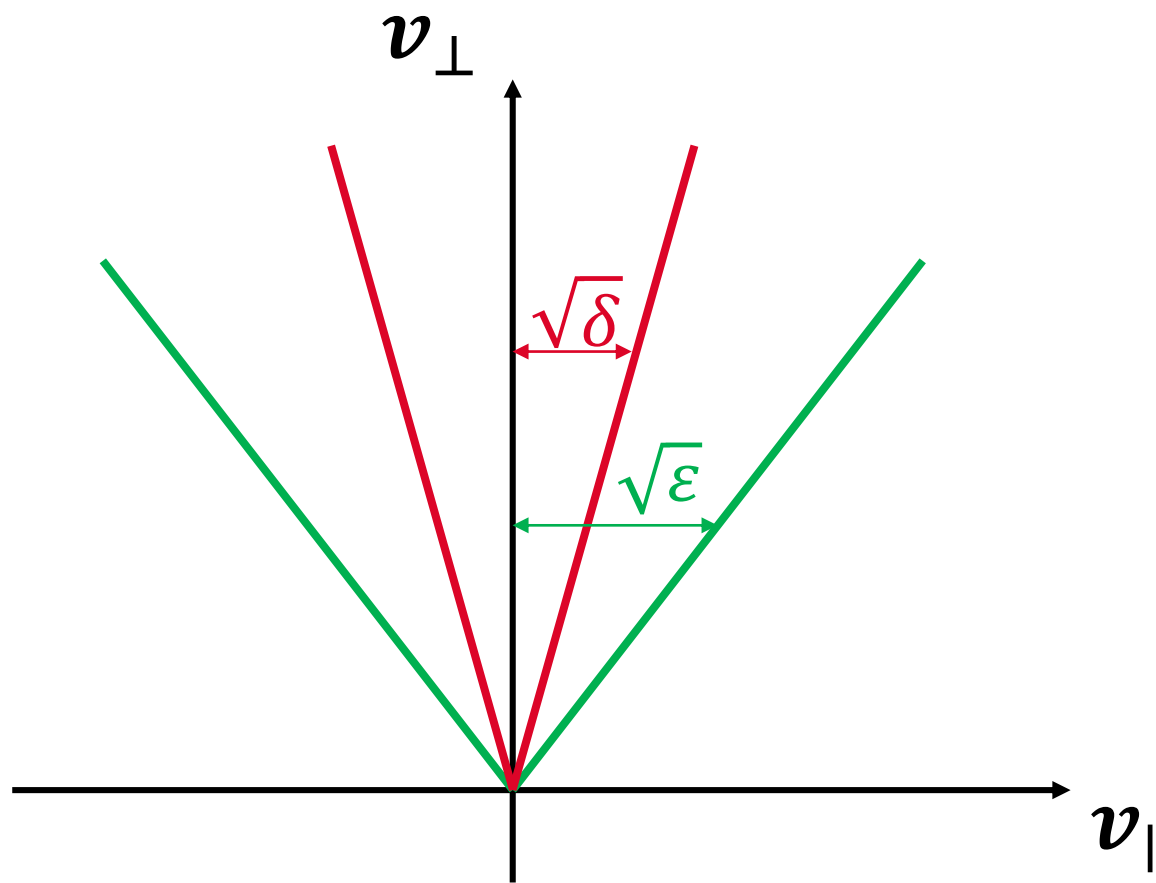
Locally trapped particle drifting vertically

Step 2 : Use the ambipolarity constraint

$$\begin{aligned}
\frac{eE_r}{\nabla_r T} - \frac{\nabla_r \ln T}{\nabla_r \ln N} &= \frac{1}{\Delta} \left\{ \left[\sqrt{\frac{\pi}{2}} (N_b q) \left(\frac{\bar{\delta}}{\epsilon} \right)^2 \int_0^{+\infty} du e^{-u} u^2 K_{rip,I}(r, u) + \sqrt{\frac{\pi}{2}} \int_0^{+\infty} du e^{-u} u^2 K_{tor,I}(r, u) \right] \right. \\
&\quad * \left[\sqrt{\frac{\pi}{2}} \int_0^{+\infty} du e^{-u} u^2 K_{tor,I}(r, u) \left(u - \frac{3}{2} \right) \right. \\
&\quad + \frac{16}{9} \left(\frac{2}{\pi} \right)^{3/2} \left(\frac{\bar{\delta}}{\epsilon} \right)^{3/2} \frac{G_1}{\nu^*} \int_0^{+\infty} du e^{-u} u^{5/2} \frac{1}{\bar{\nu}(u)} \left(u - \frac{3}{2} \right) \\
&\quad \left. \left. + \left(\frac{2}{\pi} \right)^{3/2} \frac{2}{N_b q} \left(\frac{\bar{\delta}}{\epsilon} \right)^2 \frac{1}{\nu^*} \int_0^{+\infty} du e^{-u} u^{5/2} \frac{1}{\bar{\nu}(u)} K_{rip,II}(r, u) \left(u - \frac{3}{2} \right) \right] \right\} \\
&- \frac{1}{\Delta} \left\{ \sqrt{\frac{\pi}{2}} \int_0^{+\infty} du e^{-u} u^2 K_{tor,I}(r, u) * \sqrt{\frac{\pi}{2}} \int_0^{+\infty} du e^{-u} u^2 K_{tor,I}(r, u) \left(u - \frac{3}{2} \right) \right\}
\end{aligned}$$

[X. Garbet 2010]

Trapping cones



- Simulation time : ~2 000 000h monoprocessor on 12288 processors

- Grid : $Nr * N\theta * N\varphi * Nv_{\parallel} * N\mu = 511 * 1024 * 64 * 127 * 47 \approx 10^{11}$

- ~6 days to run