Transport and zonal flows dynamics in flux-driven interchange and drift waves turbulence

O Panico, Y Sarazin, P Hennequin, Ö Gürcan, R Bigué, G Dif-Pradalier, X Garbet, R Varennes, Y Munschy

Transport and zonal flows dynamics in flux-driven interchange & drift waves turbulence

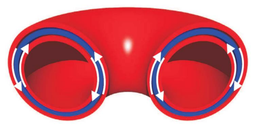
O. Panico[1,2], Y. Sarazin[2], P. Hennequin[1], Ö. Gürcan[1], R. Bigué[2], G. Dif-Pradalier[2], X. Garbet[2,3], R. Varennes[3], Y. Munschy[2]

[1] LPP, CNRS, Sorbonne Université, Ecole Polytechique, Institut Polytechnique de Paris
[2] CEA, IRFM
[3] Nanyang Technological University, Singapore

1. Motivation: zonal flows improve confinement

- Tokamak confinement: largely governed by **turbulence**
- Turbulence self-organizes at mesoscale into **zonal flows**
- Flows can structure into **staircases**: long-lived micro-barriers

[Lin 1998] [Diamond 2005] [Dif-Pradalier 2010]

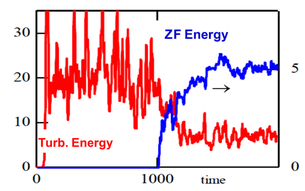


Zonal flows symmetric in poloidal and toroidal directions

Objectives:
- ✓ Nonlinear flux-driven model: turbulence and zonal flows interplay
- ✓ Physics of the flows: generation ? Impact on turbulent transport ?

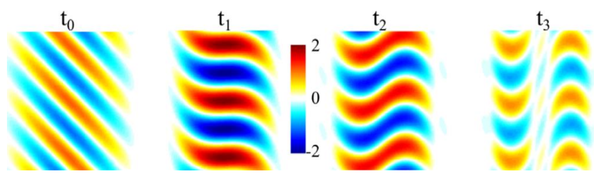
Zonal flows (ZF) regulate **turbulent transport**

- Reservoir of energy for the turbulence



[Beyer 2004]

- Sheared poloidal flow decorrelates turbulent



[Fedorczak 2013]

2. Tokam1d: reduced nonlinear flux-driven model

Assumptions:
- Flux driven: source of particles S_n
- Constant ion and electron temperatures
- Mean curvature of the magnetic field
- SLAB geometry

Dimensionless system of equations: $N = \ln N \ ; \ \phi = e\phi/T_e$

Electron density continuity equation

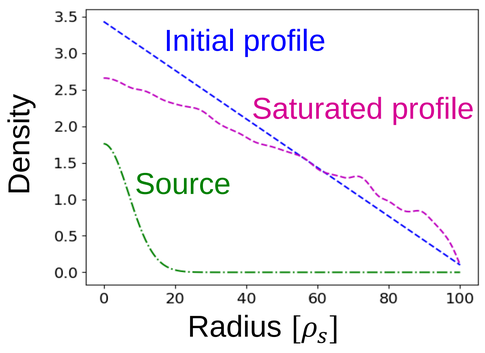
$$\partial_t N + \{\phi, N\} - g\ \partial_y(\phi - N) = \sigma\nabla_\parallel^2(N - \phi) + D\ \nabla_\perp^2 N + S_n$$

Charge balance equation (generalized vorticity $\Omega = \nabla_\perp^2(\phi + \tau N)$)

$$\partial_t \Omega + (1+\tau) g \partial_y N + \nabla_{\perp,i}\left\{\phi, \nabla_{\perp,i}\ (\phi + \tau N)\right\} = \sigma\nabla_\parallel^2(N - \phi) + \nu\nabla_\perp^2\Omega$$

- Parallel conductivity : $\sigma = \omega_{ce}/\nu_{ei}$
- **B**-field inhomogeneity: $g = 2\rho_s/R$
- Temperature ratio : $\tau = T_i/T_e$

Separation: **equilibrium (avg on y and z)** and **fluctuations** => 4 equations
Single $k_\parallel$ and k_θ mode retained for the fluctuations => **1D radial**



Equilibrium density equation

$$\partial_t N_{eq} = -\partial_x \Gamma_{ES} + D\ \partial_x^2 N_{eq} + S_n$$

Turbulent flux of particles:

$$\Gamma_{ES} = \langle n\ v_{Ex}\rangle = -2\ k_y |N_k||\phi_k| \sin\underbrace{\Delta\varphi}$$

Cross-phase density – potential fluctuations

Self consistent evolution of density profile:
- ❖ Particle source & turbulent transport
- ❖ Self-organization of flows ⇒ corrugation of profile

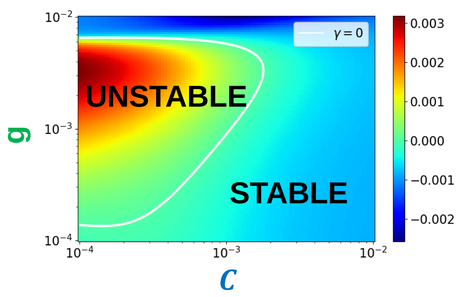
3. Two linear instabilities

[Hasegawa-Wakatani 1983]

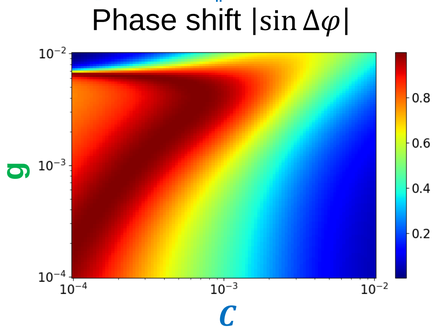
Two different instability drives:
- **magnetic curvature $g = 2\rho_s/R$**
- **parallel conductivity C = $\sigma k_\parallel^2$**

[Sarazin 1998]

Growth rate



Phase shift $|\sin\Delta\varphi|$



- ❖ Compressibility terms ⇒ stabilisation at high g
- ❖ $|\sin\Delta\varphi|$ min at high C ⇒ less efficient transport

4. Flows structure into staircases at high g

$V_{eq} \approx -\langle E_r\rangle$: **equilibrium poloidal flow** (averaged on y-axis)

$$\partial_t V_{eq} = -\partial_x \Pi_{RS} + \nu\partial_x^2 V_{eq} - \mu V_{eq}$$

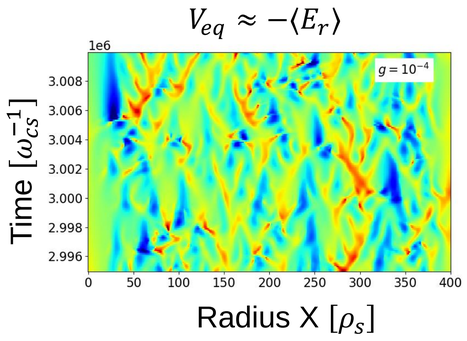
[Sarazin 2021]

Turbulent drive: Reynolds stresses — Viscous & friction damping

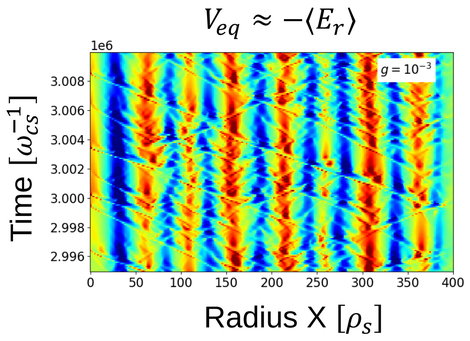
Electric: $\Pi_E = \langle\widetilde{v_{Er}}\ \widetilde{v_{E\theta}}\rangle = -2k_y\Im(\phi_k^*\partial_x\phi_k)$

Diamagnetic: $\Pi_* = \langle\widetilde{v_*}\ \widetilde{v_{E\theta}}\rangle = -2k_y\Im(\tau N_k^*\partial_x\phi_k)$

$V_{eq} \approx -\langle E_r\rangle$

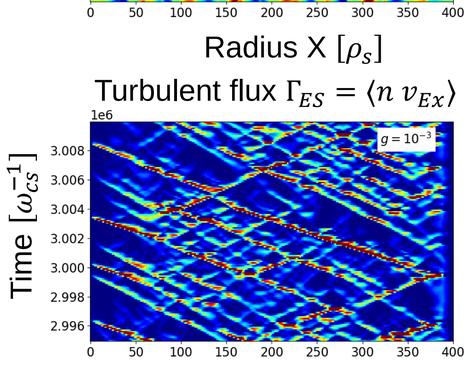


$V_{eq} \approx -\langle E_r\rangle$



- ❖ Flows structured into staircases in interchange dominated regimes
- ❖ **Avalanche**-like transport propagating both up and downwards

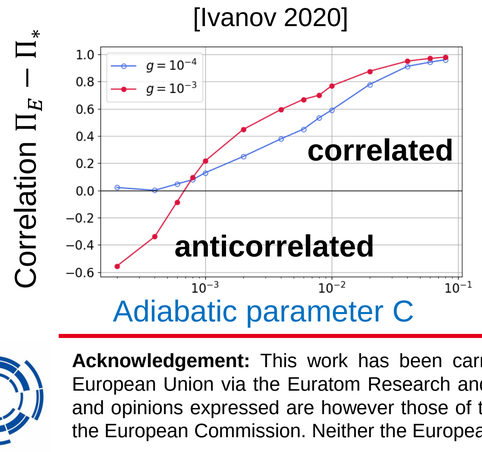
Turbulent flux $\Gamma_{ES} = \langle n\ v_{Ex}\rangle$



5. Electric and diamagnetic Reynolds stresses anticorrelated in interchange dominated plasmas

Scan of the adiabatic parameter **C** for 2 values of magnetic curvature **g**

[Ivanov 2020]



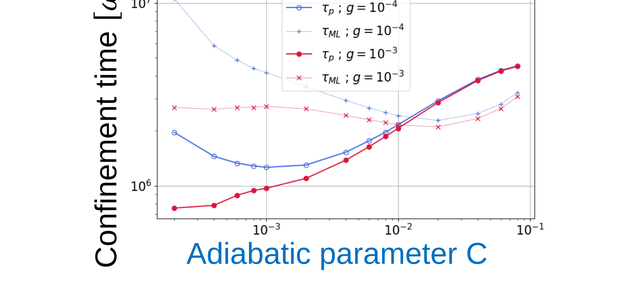
Quasilinear estimation:

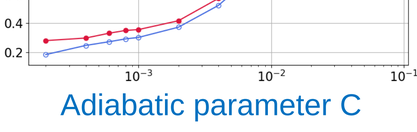
$$\Pi_* = \Re\left(\frac{\tau N_k}{\phi_k}\right)\Pi_E + \Im\left(\frac{\tau N_k}{\phi_k}\right)\Re(k\phi_k\partial_x\phi_k^*)$$

- ❖ **Correlation** between RS at high C
- ❖ Asymptotic limits consistent with quasilinear estimation
- ❖ Diamagnetic RS Π_* **dominates** except at very high g and low C (interchange dominated cases)

6. Turbulent energy gets stored in flows at high C

Energy channels calculated from energy conservation theorem
- Flows energy: $E_{V_{eq}}$
- Turbulence energy: E_{turb}





- ❖ **Energy gets stored** in flows at high C
- ❖ Large mean shear values $|\partial_x V_{eq}|$
- ❖ Modulation of ZF source: $\Pi_{tot} = \Pi_E + \Pi_*$

❖ $C = \frac{\omega_{ce}}{\nu_{ei}} \propto \frac{1}{N_{eq}} \Rightarrow$ Strong reduction of ZFs energy at large density
Consistent with [Hajjar 2018]

7. Zonal flows mitigate turbulent transport

Confinement time of particles τ_p compared to mixing length estimate τ_{ML}
- τ_p computed from profile & source
- $\tau_{ML} = \frac{L_x^2 k_1^2}{\gamma_{lin}}$ computed from **linear growth rate** at saturation with **no flows**

- ❖ Confinement time increases with C
- ❖ After normalization: effect of flows on confinement is retrieved

Conclusion

Turbulence-ZF interaction

- ❖ Reduced 1-dimensional model:
  - Self-consistent flux-driven non-linear model for edge turbulence
  - Flexible tool, coupling of interchange and drift waves instabilities
- ❖ Structuration of flows at high g & evidence of avalanche transport
- ❖ Increasing C reduces cross-phase & creates flows ⇒ improved confinement
- ❖ Flows essential to mitigate turbulent transport

Perspectives

- ❖ Neoclassical effects: relaxation towards force balance equilibrium
- ❖ Study formation of edge transport barrier (adding scrape-off layer physics)
- ❖ Experimental measurement: Doppler backscattering reflectometry & Langmuir probes

References

[1] Lin Z et al, Science, 1998
[2] P.H. Diamond et al., Plasma Phys. Control. Fusion, 2005
[3] G. Dif-Pradalier et al., Phys. Rev. E 2010
[4] P. Beyer HDR thesis, 2004
[5] N. Fedorczak et al, Plasma Phys. Control. Fusion, 2013
[6] A. Hasegawa, M. Wakatani, Phys. Rev. Lett., 1983
[7] Y. Sarazin et al, Phys. of Plasmas, 1998
[8] Y. Sarazin et al., Plasma Phys. Control. Fusion, 2021
[9] P. Ivanov et al, J. Plasma Phys, 2020
[10] R.J. Hajjar et al, Phys. of Plasmas, 2018

Acknowledgement: This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 – EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

TTF Nancy 2023

olivier.panico@cea.fr