Interplay between neoclassical and turbulent transport on Tore Supra

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[4]CPhT Ecole Polytechnique

Motivation and outline

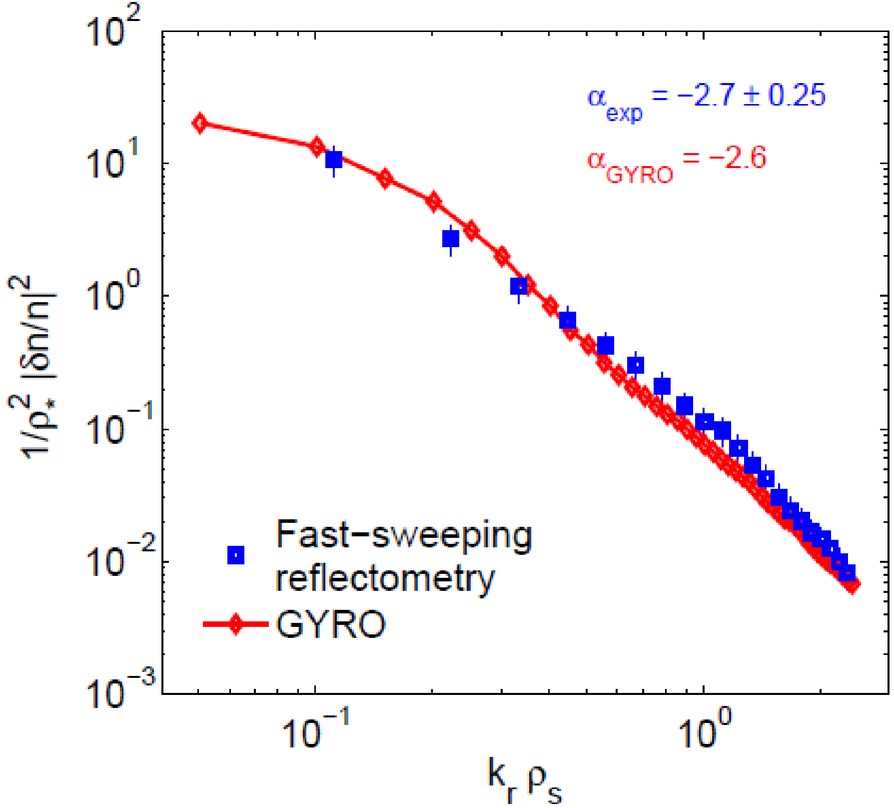
- Usual statement : perpendicular transport is turbulent, parallel dynamics is collisional – in practice, a competition.
- When axisymmetry is lost, competition between turbulence and collisional processes is exacerbated.

Outline

- Large scale flows : competition between turbulence Reynolds stress and viscous damping
- Particle transport : competition between Ware and turbulent pinch velocities – Perp. diffusion is enhanced in presence of helical perturbations.

Turbulence diagnostics and codes on Tore Supra

- 2 Doppler and 2 fast sweeping reflectometers: profile of turbulence intensity, frequency and wavenumber spectra
- Numerical tools: global (GYSELA) local (GYRO, GENE) gyrokinetic codes, integrated modelling (CRONOS)



Casati 09

Large scale flows : interplay between turbulence generation and collisional damping

- Tore Supra: large (7%) magnetic field ripple
- Leads to magnetic braking in toroidal direction – controls radial electric field.
- Competes with turbulence Reynolds stress

Flow dynamics

- Radial force balance equation

$$E_r + V_\theta B_\varphi - V_\varphi B_\theta - \frac{\nabla_r p}{ne} = 0$$

- Reynolds stress + collisional viscous damping (w/o MHD , fast ion losses) Diamond 05

$$\partial_t \langle \mathbf{V} \rangle = -\nabla \cdot \langle \tilde{\mathbf{V}} \tilde{\mathbf{V}} \rangle - \nu_{neo} \left(\langle \mathbf{V} \rangle - \mathbf{V}_{neo} \right)$$

Reynolds stress Π

Viscous damping

→ determine V_θ , V_φ , et E_r

Rotation measurements

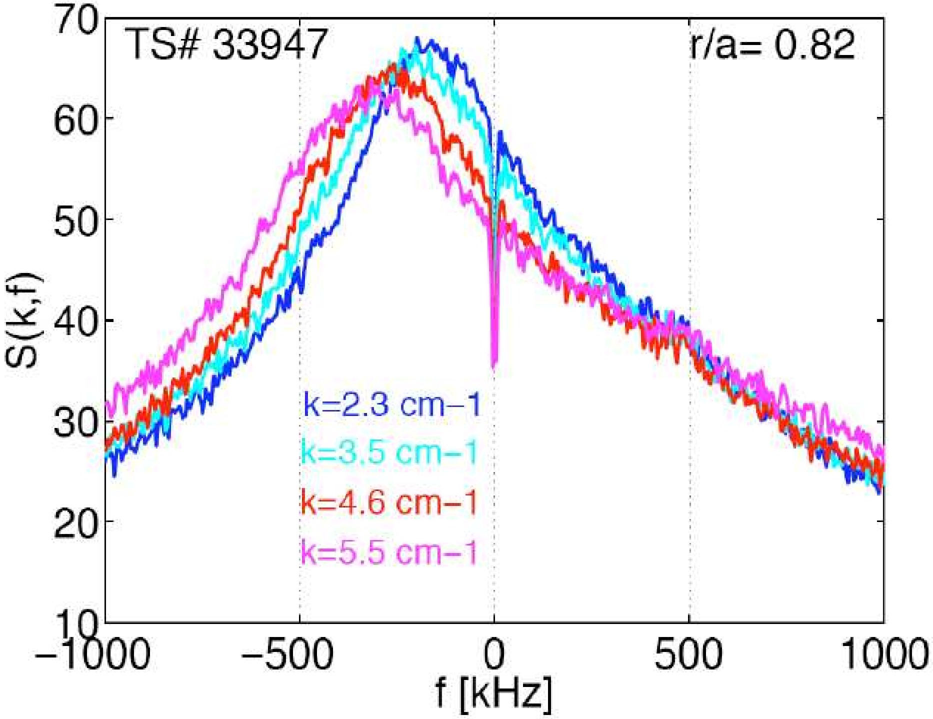
- Scan in ripple : plasma size
- Doppler reflectometry

$$V_{lab} = -\frac{E_r}{B} + V_{ph}$$

Assumption : $V_{ph} \ll -E_r/B$ - supported by simulations$\rightarrow$ direct measurement of E_r

- CXRS: measurements of V_φ

Hennequin 09



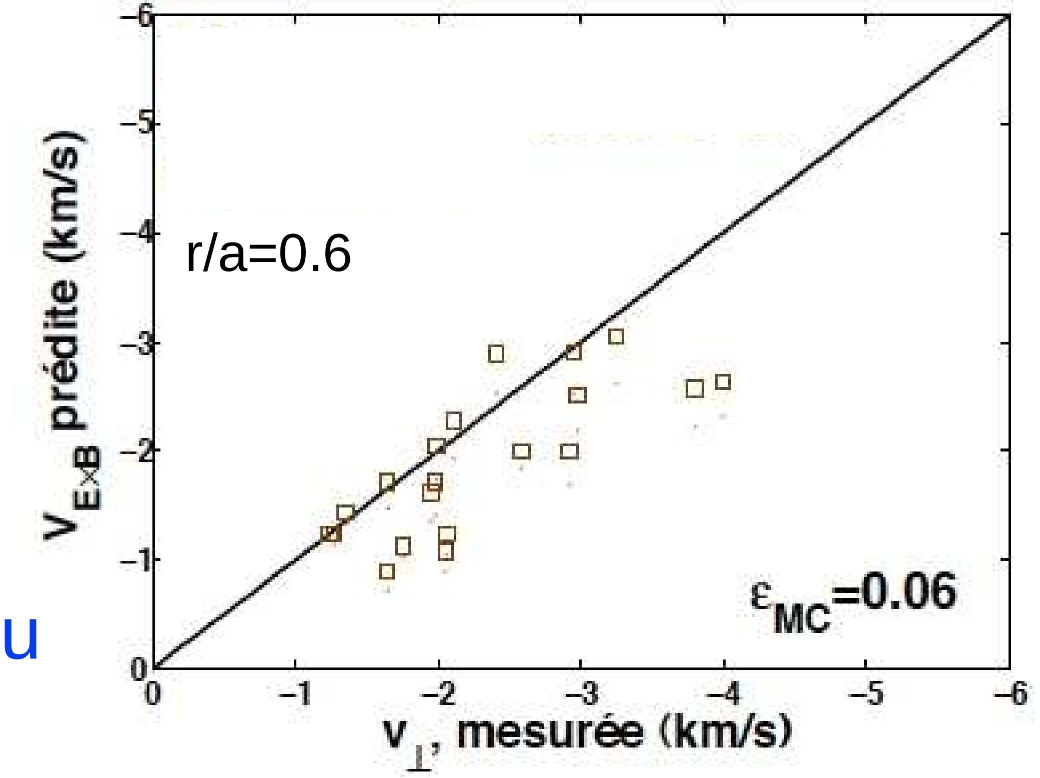
Radial electric field

- Radial electric field is negative : controlled by thermal ripple losses

$$E_r = \frac{T_i}{e}\left(\frac{dn_i}{n_i dr} + k_{rip}\frac{dT_i}{T_i dr}\right)$$

- Local trapping $k_{rip}=3.37$ Connor 73 . Ripple-plateau $k_{rip}=1.5$ Boozer 80, Kovrizhnykh 99

Trier 08

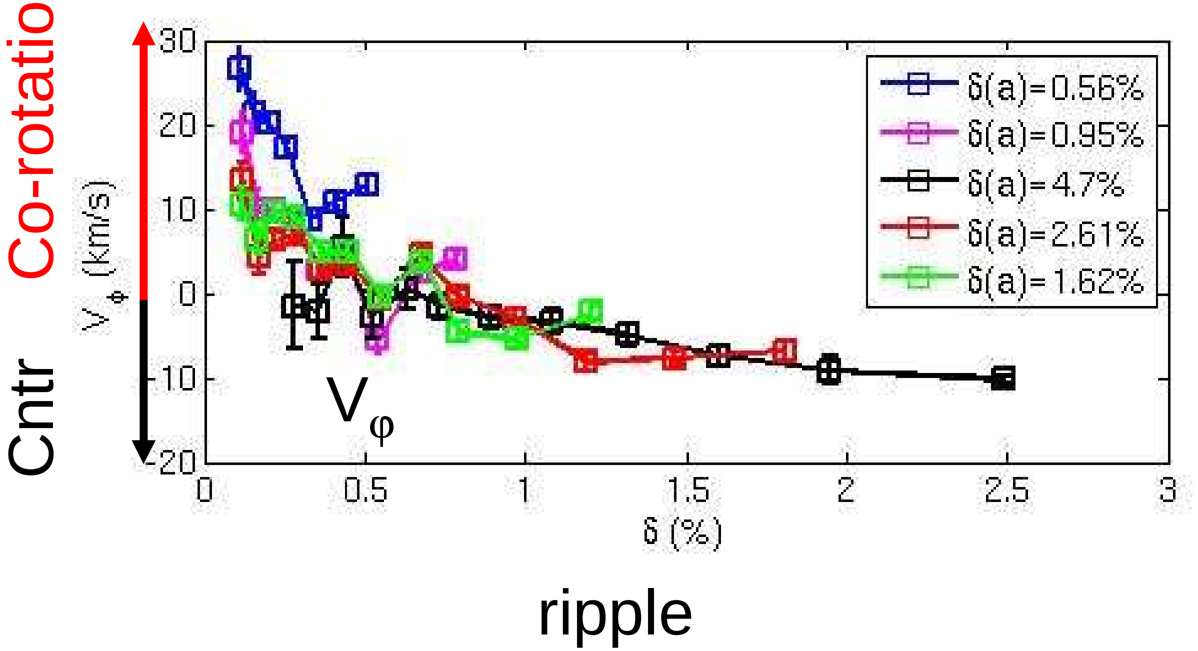


Intrinsic toroidal rotation

Fenzi 10

- Counter-rotation in Ohmic plasmas for large ripple

- Co-rotation with smaller ripple.



- Consistent with competition between ripple friction and turbulent Reynolds stress Ku 10, Wang 10, Kwon 10, …

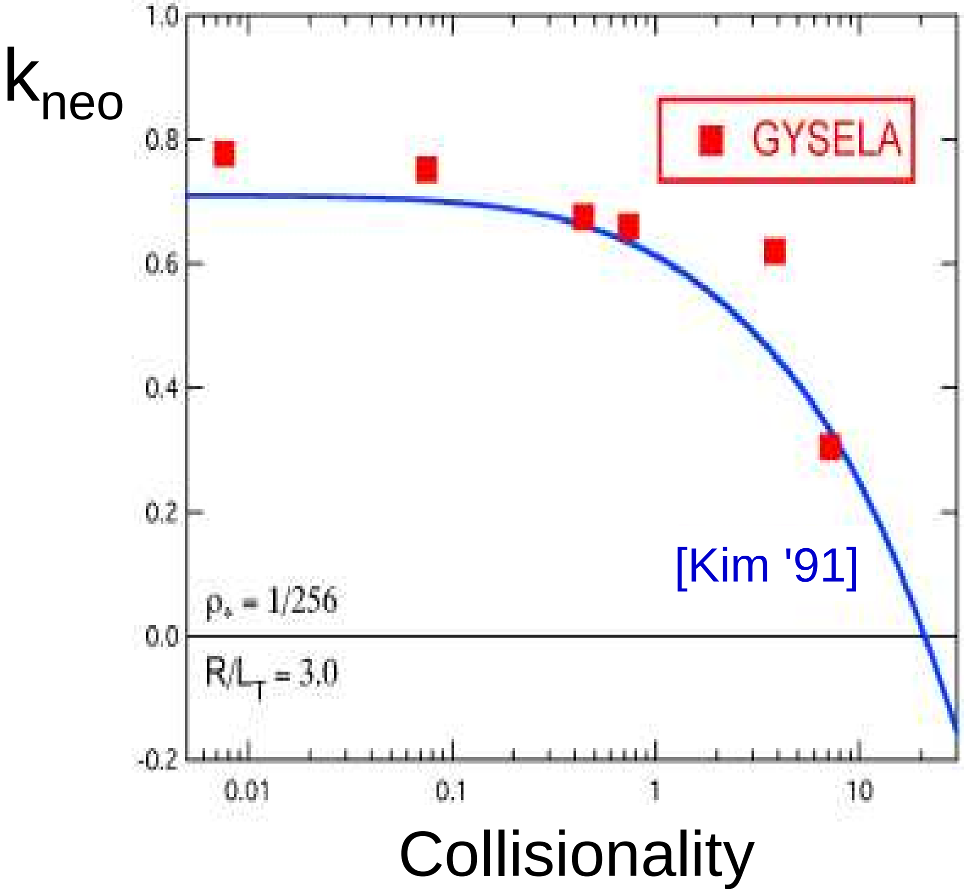
$$V_\varphi = V_{neo} - \frac{\nabla \cdot \Pi}{\nu_{neo}}$$

Neoclassical viscous damping

- Strong collisional friction at the passing/trapped boundary
- Poloidal flow scales with ∇T:

$$V_\theta = k_{neo}\frac{\nabla_r T_i}{eB}$$

Dif-Pradalier 08

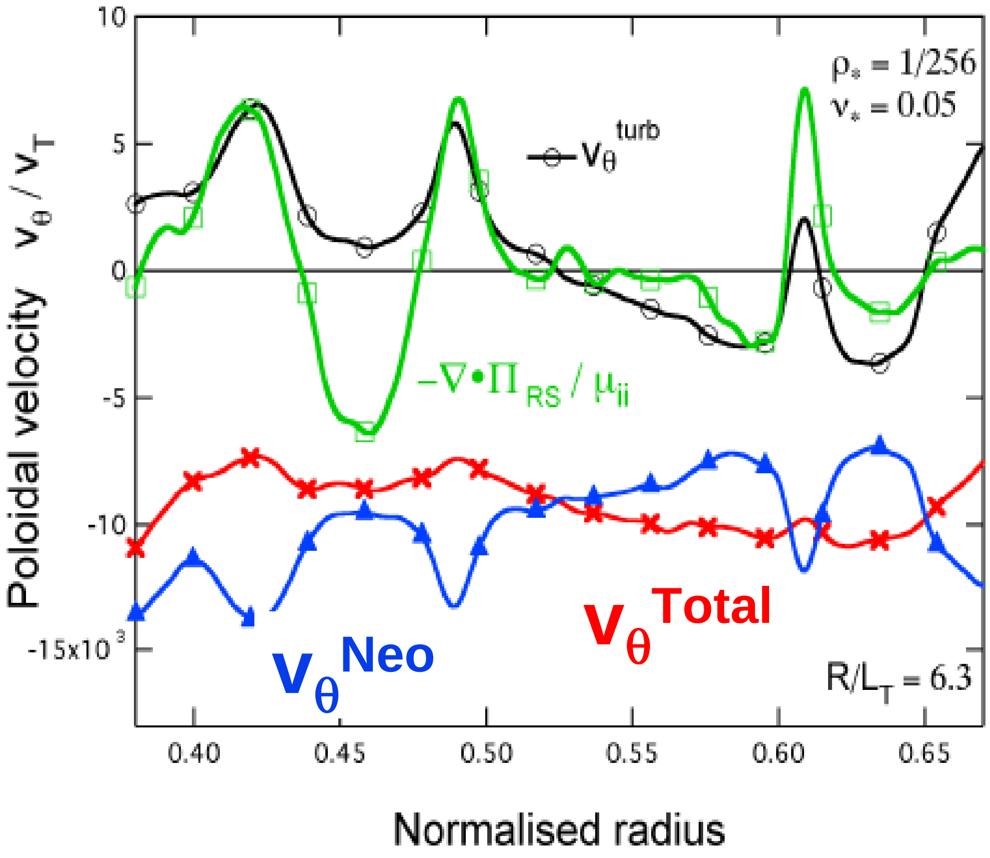


Poloidal rotation agrees with neoclassical theory in global simulations

Dif-Pradalier 09

- Consistent with poloidal viscous damping
- However: large corrugations due to turbulent Reynolds stress.

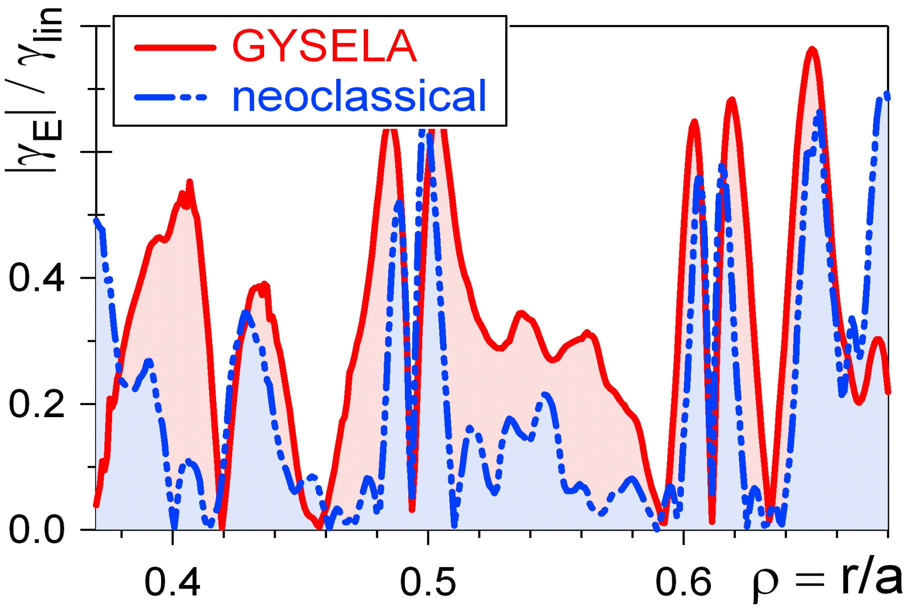
$$V_\theta = V_{neo} - \frac{\nabla \cdot \Pi}{\nu_{neo}}$$



Reynolds stress important for shear flow

- $V_\theta \approx V_{neo}$, but velocity shear is different
- ExB shear $\gamma_E = \frac{d}{dr}\left(\frac{E_r}{B}\right)$ not the same with or w/o turbulence

Sarazin 10



Is the poloidal rotation neoclassical on Tore Supra?

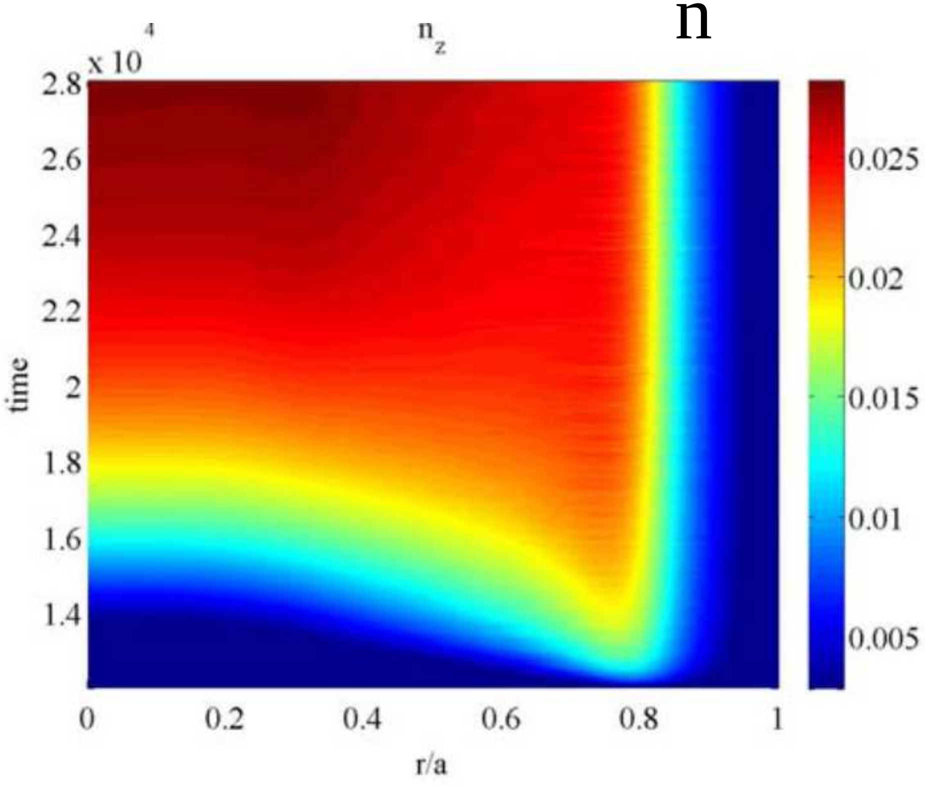
- Doppler reflectometry → E_r **always** agrees with $\Gamma_{ripple}=0$ in the core
- CXRS → V_φ **changes** from cntr to co-rotation when ripple becomes weaker
- Radial force balance equation → $\mathbf{V_\theta \neq V_{neo}}$ at low ripple
- Not impossible (e.g. JET Crombé 06, DIII-D Kim 94 TFTR transient Bell 98) but surprising : turbulence simulations find $\mathbf{V_\theta \approx V_{neo}}$ + turbulence corrugations

Particle and impurity transport in the plasma core (q<1)

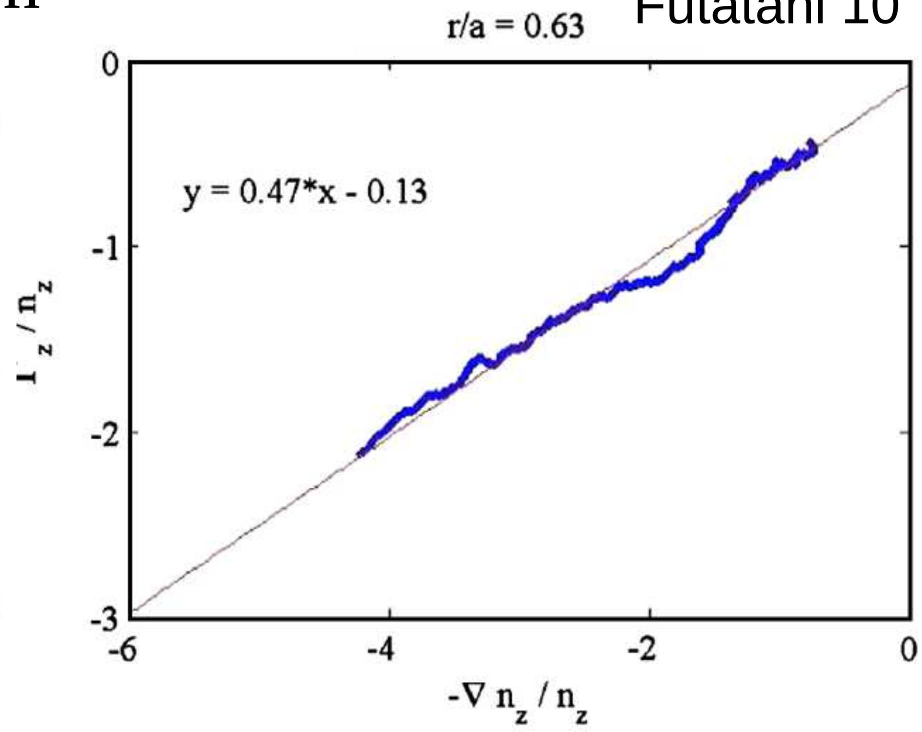
- Usual form of particle transport $\Gamma=-D\nabla n+Vn$
- Usually $D,V \gg D_{neo},V_{neo}$
- Not always true in the core, where values get closer to neoclassical (“neoclassical” here means axisymmetric value)

Modelling of transient confirm the diffusion/convection model

$$\frac{\Gamma}{n} = -D\frac{\nabla n}{n} + V$$



Futatani 10

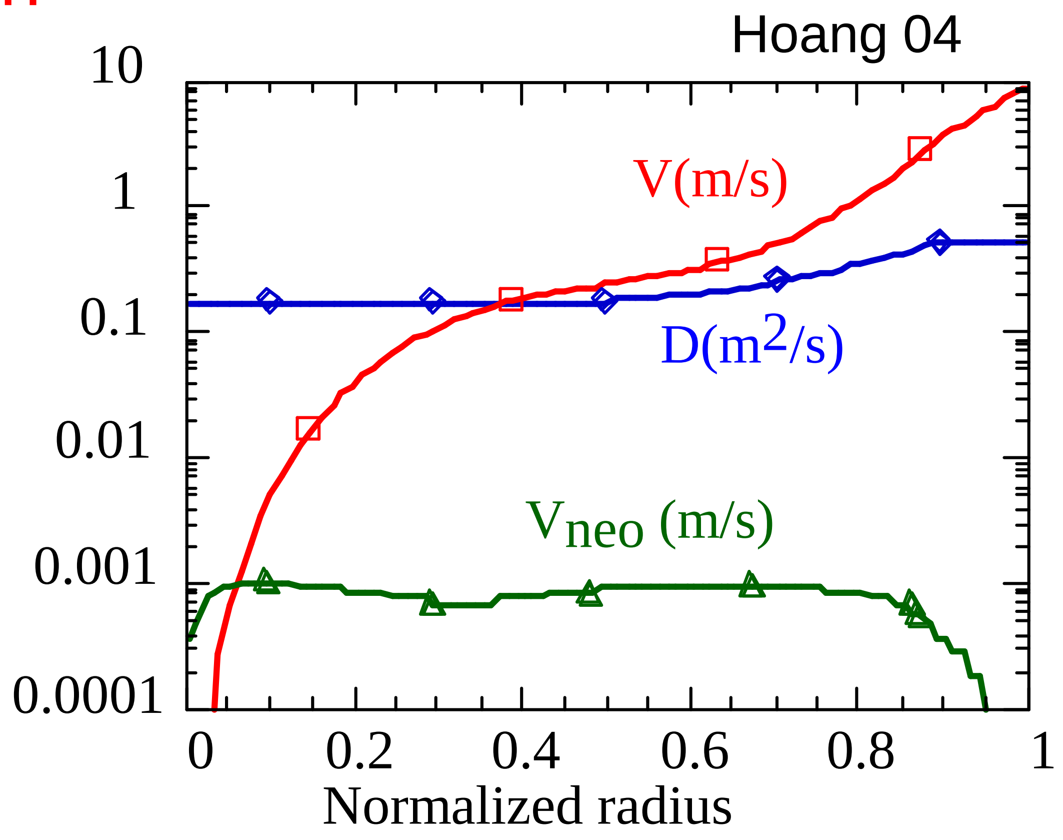


Particle pinch is usually turbulent on Tore Supra

- Long pulses (6mn) with LHCD → E_{ind} ≈0 → Ware pinch=0

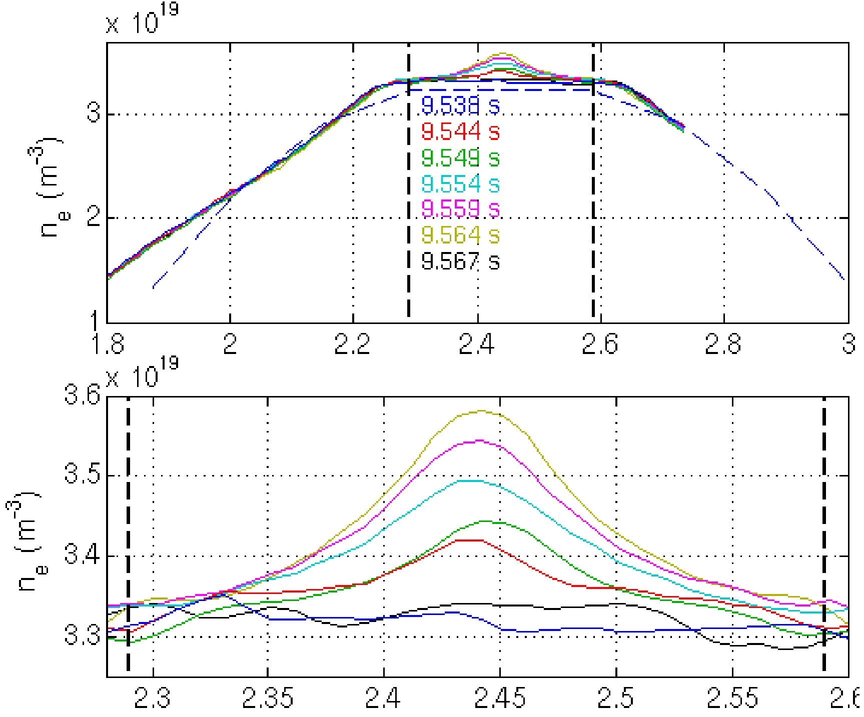
- Ionization source localised in the edge, pinch due to waves is small.

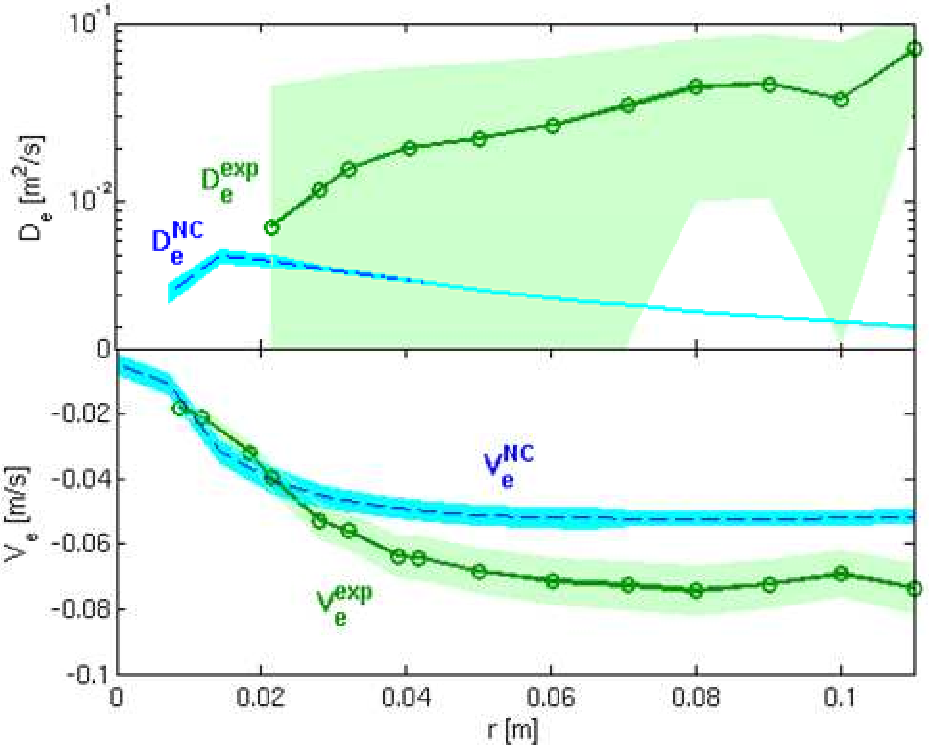
→ V (electrons) is turbulent



Transport during sawtoothing ohmic plasmas

Guirlet 08

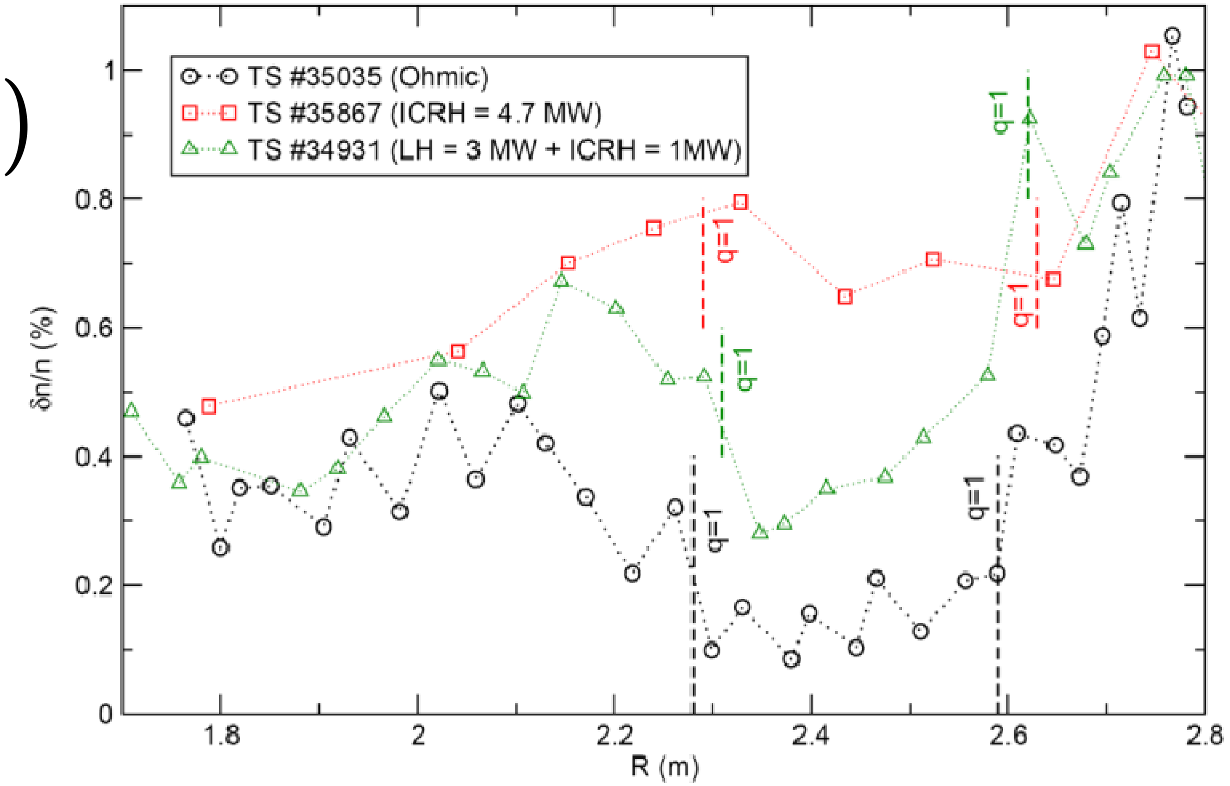




- Pinch velocity close to Ware value, diffusion is not neoclassical

Fluctuation level is low inside $q=1 \rightarrow D_{turb}$ is small

$$\frac{\delta n}{n}(\%)$$



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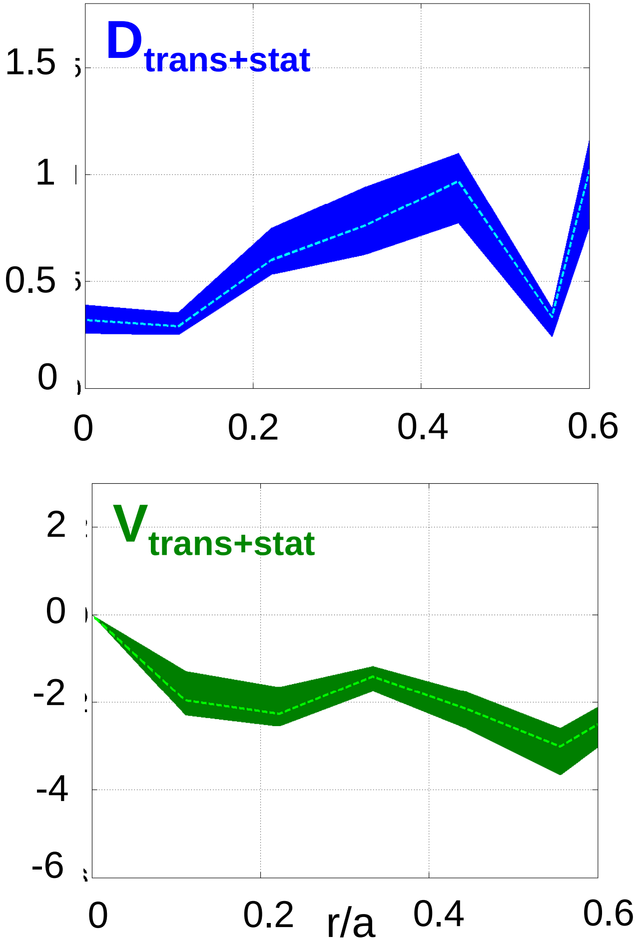
What about impurities?

- Supersonic gas injection or laser blow-off.
- Both transient and steady profiles are used to assess fluxes Γ=-D∇n+Vn
- Allows to reduce error bars on D and V by a large factor.

Guirlet 08



Impurities are neoclassical in the core, electrons are not

- V_{nickel} and D_{nickel} are neoclassical
- How is it possible to get

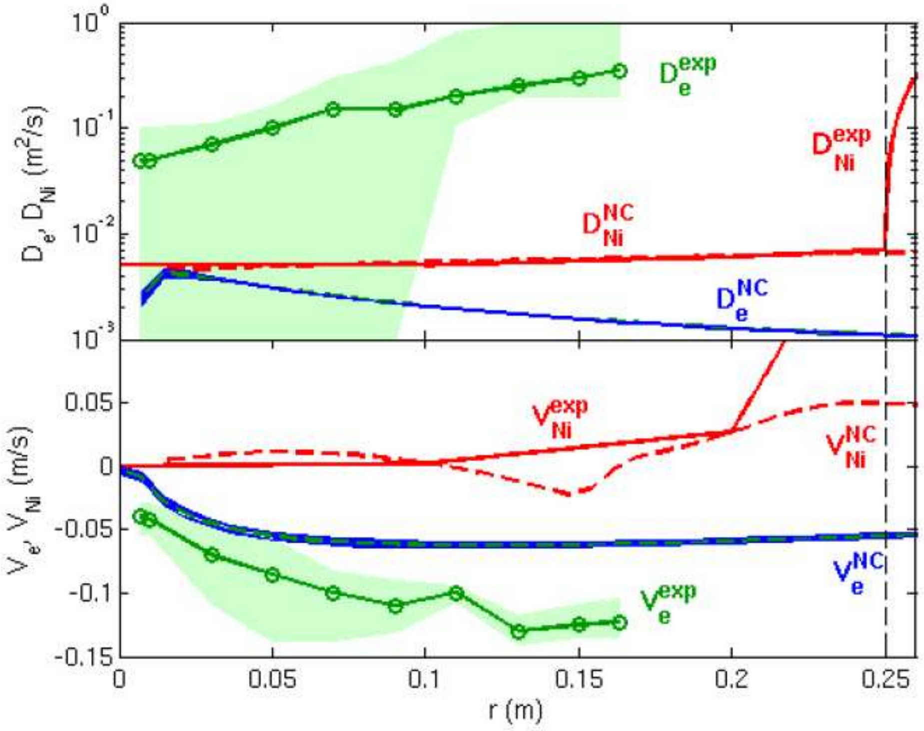
$D_e >> D_{Ni} \approx D_{Ni,neo} >> D_{e,neo}$

- Simplest theory

$$D_{turb} \approx \left\langle \left|\tilde{v}_E\right|^2 \right\rangle \tau_c$$

$\tau_{c,Ni} << \tau_{c,e}$???

Guirlet 10



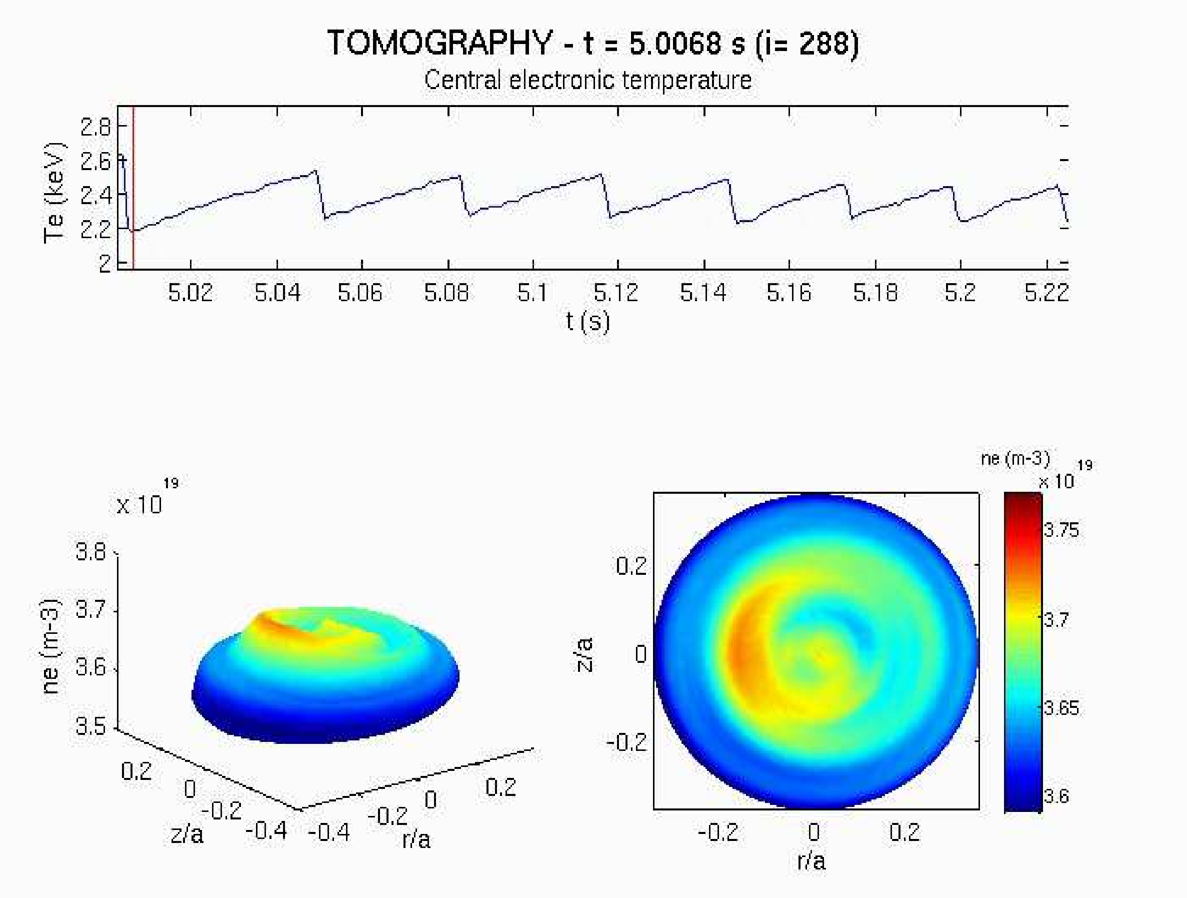
D and V for electrons and Nickel vs neoclassical

Is the internal kink mode responsible for high D_e?

- m=1,n=1 activity part of the time
- Estimation of magnetic field amplitude

$$\delta \approx \frac{\delta B_{//}}{B} \approx \beta \frac{\xi}{L_p}$$

$\approx$a few 10^{-3}



Sabot 10

Orders of magnitude

- Ellectrons: banana-drift regime

$$D_{e,BD} \approx 6.6 \frac{\delta^2}{\sqrt{\varepsilon}} \frac{v_{D,e}^2}{\nu_e} \approx 2.10^{-2} m^2 s^{-1} \leq D_{e,exp}$$

- Nickel: ripple-plateau regime

$$D_{Ni,RP} \approx \frac{\delta^2}{\varepsilon^2} \frac{1}{1-q} \frac{R v_{DZ}^2}{v_{TZ}} \approx 10^{-3} m^2 s^{-1} << D_{Ni,exp}$$

- In summary:

- Collisional electron transport is enhanced–still off by a factor 3-5

- Ni neoclassical transport is unchanged

Conclusions

- GK simulations show that $V_\theta \approx V_{neo}$ but radial corrugations due to turbulence are not negligible.
- E_r and V_φ agree with neoclassical theory in ohmic plasmas, with strong ripple. Situation at low ripple is unclear: looks like V_θ departs from V_{neo}.
- Some evidence that in the core, collisional transport due to n=1,m=1 helical perturbation can matter