Impurity transport and its modification by MHD in tokamak plasmas, with application to tungsten in WEST

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IMPURITY TRANSPORT AND ITS MODIFICATION BY MHD IN TOKAMAK PLASMAS, WITH APPLICATION TO TUNGSTEN IN WEST

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Summary

- Neoclassical impurity transport & poloidal asymmetry
  - Can be determined analytically in a self-consistent way
  - Natural asymmetry (no torque) has already a large impact
- A magnetic island suppresses thermal screening above a critical size
  - Verified numerically on a typical WEST plasma equilibrium
- When impurity transport is predominantly turbulent (as on WEST)
  - Poloidal asymmetry remains essentially neoclassical

Neoclassical impurity transport & self-consistent poloidal asymmetry

Neoclassical impurity transport

- With a poloidal distribution parametrized as $n_a/\langle n_a\rangle = 1+\delta\cos\theta+\Delta\sin\theta$ [1]:

$$\langle\Gamma_a\cdot\nabla r\rangle \approx -\langle n_a\rangle D^a_{PS}\left[\left(1+\frac{\delta}{\varepsilon}+\frac{\delta^2+\Delta^2}{4\varepsilon^2}\right)G+\frac{1}{2}\left(\frac{\delta}{\varepsilon}+\frac{\delta^2+\Delta^2}{2\varepsilon^2}\right)U\right]$$

- with $D^a_{PS}\equiv 2q^{*2}m_a\nu_a T_a/(e_a^2\langle B^2\rangle)$, C_0^a~1.5 and k_i~-1,17 in the banana regime

$$G=\partial_r\ln p_a-\frac{e_a}{e_i}\frac{T_i}{T_a}\partial_r\ln p_i+C_0^a\frac{e_a}{e_i}\frac{T_i}{T_a}\partial_r\ln T_i \qquad U\approx-(C_0^a+k_i)\frac{e_a}{e_i}\frac{T_i}{T_a}\partial_r\ln T_i$$

Poloidal asymmetry

- Asymmetry parameters (δ,Δ) verify:

$$\Delta^2+(\delta-C_\delta)^2=R_\Delta^2$$

- with $C_\delta=-\varepsilon/(1+U/G)$, $\varepsilon=r/R$, and $R_\Delta=|C_\delta|$
- Defining $\delta=C_\delta+R_\Delta\cos\alpha$ and $\Delta=R_\Delta\sin\alpha$

$$\cos\alpha=\frac{R_\Delta}{C_\delta}\frac{(AG\varepsilon)^2-R_\Delta^2}{(AG\varepsilon)^2+R_\Delta^2},\qquad \sin\alpha=2R_\Delta\frac{AG\varepsilon}{(AG\varepsilon)^2+R_\Delta^2}$$

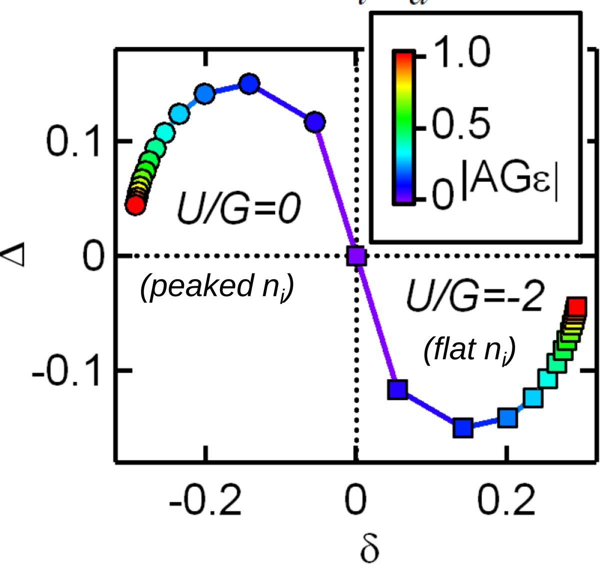


Fig.1 : Self-consistent asymmetry

- This fully determines the self-consistent asymmetry when the ion and electric potential asymmetries can be neglected (the formula can be extended in these cases).
- Characteristics of the asymmetry circle (fig. 1 & 2)
  - The circle is centered at δ<0 for a peaked ion density profile (δ>0 for a flat one)
  - The asymmetry angle α increases with impurity charge [$A=q^2R\nu_a/(\varepsilon^2\Omega_a)$~$Z_a$]
- At saturation ($V_{r,a}$=0), the asymmetry vanishes

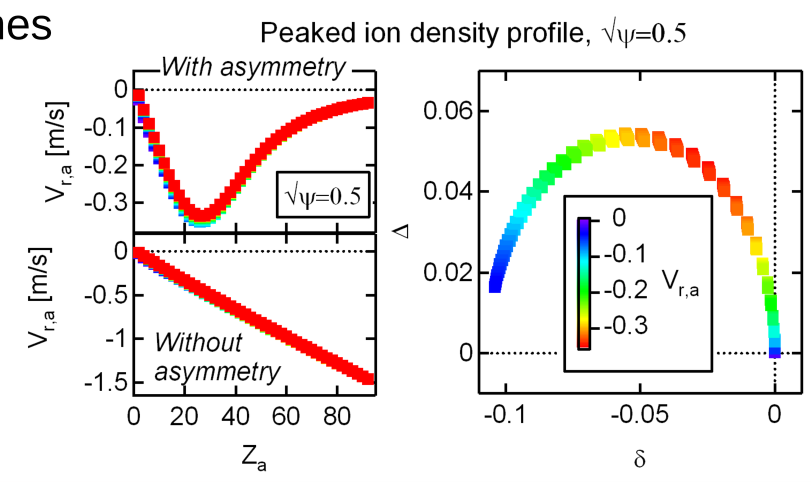


Fig.2 : Radial impurity flow as a function of the impurity charge Z_a with & without self-consistent poloidal asymmetry (left); corresponding asymmetry (right).The impurity profile is flat.

Neoclassical impurity transport: numerical settings

Numerical experiments are performed with the XTOR-2F code [2] including neoclassical physics [3] and two equations per impurity:

$$\partial_t n_a+\nabla\cdot(n_a\mathbf{V}_a) = -\nabla\cdot\Gamma_a^{turb}$$

$$m_a n_a D_t V_{a\parallel} = -\nabla_\parallel p_a+n_a e_a E_\parallel+R_{a\parallel}-(\nabla\cdot\Pi_a)_\parallel$$

with $\dfrac{R_{a\parallel}-(\nabla\cdot\Pi_a)_\parallel}{m_a n_a}=\nu_a\left(V_{i\parallel}-V_{a\parallel}-C_0^a\dfrac{2q_{i\parallel}}{5p_i}\right)+$ ... *(small terms)*

- The impurity-ion collision frequency ν_a is scanned artificially
- We consider a peaked and a flat ion density profile (same pressure) (fig.3a)
- Turbulent diffusion coefficient is set to a very low value (fig.3b)

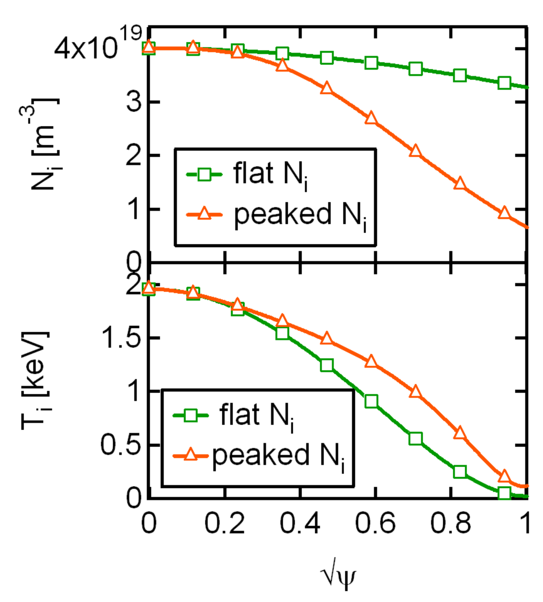


Fig.3a : Ion density and temperature profiles.

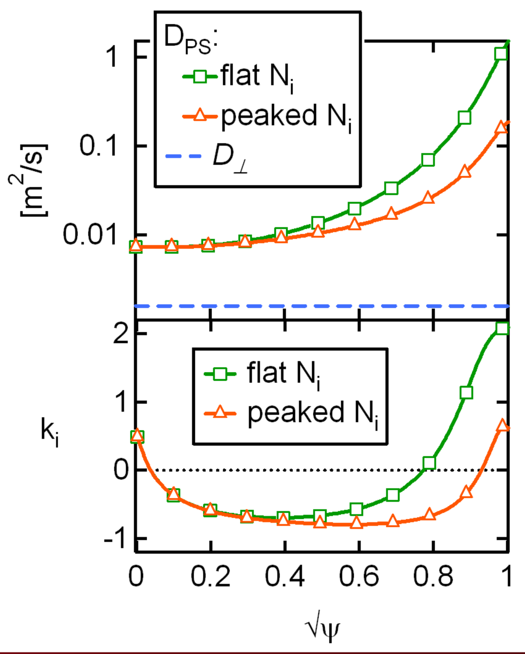


Fig.3b: Pfirsch-Schlüter diffusion coefficient & k_i parameter.

Neoclassical impurity transport: validation

Impurity flow & poloidal asymmetry during the (artificial) collisionality scan

- Impurity : Tungsten W^{44+}, flat initial profile, and decreasing collisionality (fig.4)

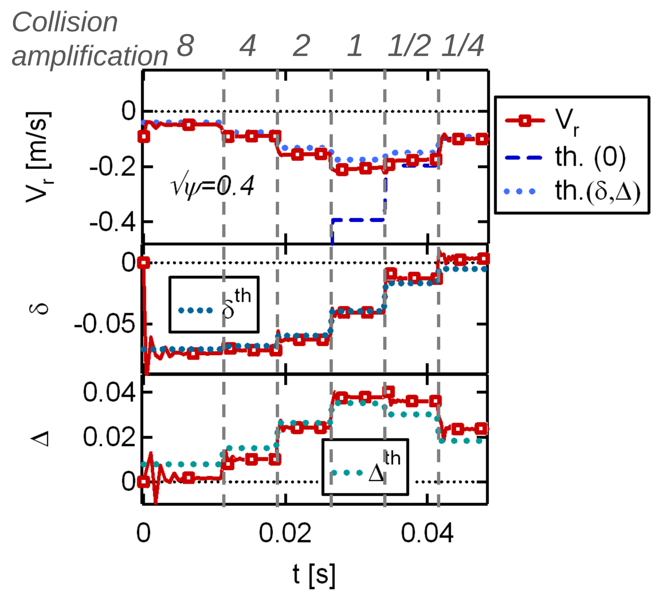


Fig.4 : Radial flow, δ and Δ during the collisionality scan with factor 8, 4, 2, 1, 0.5, 0.25 (peaked ion density profile).

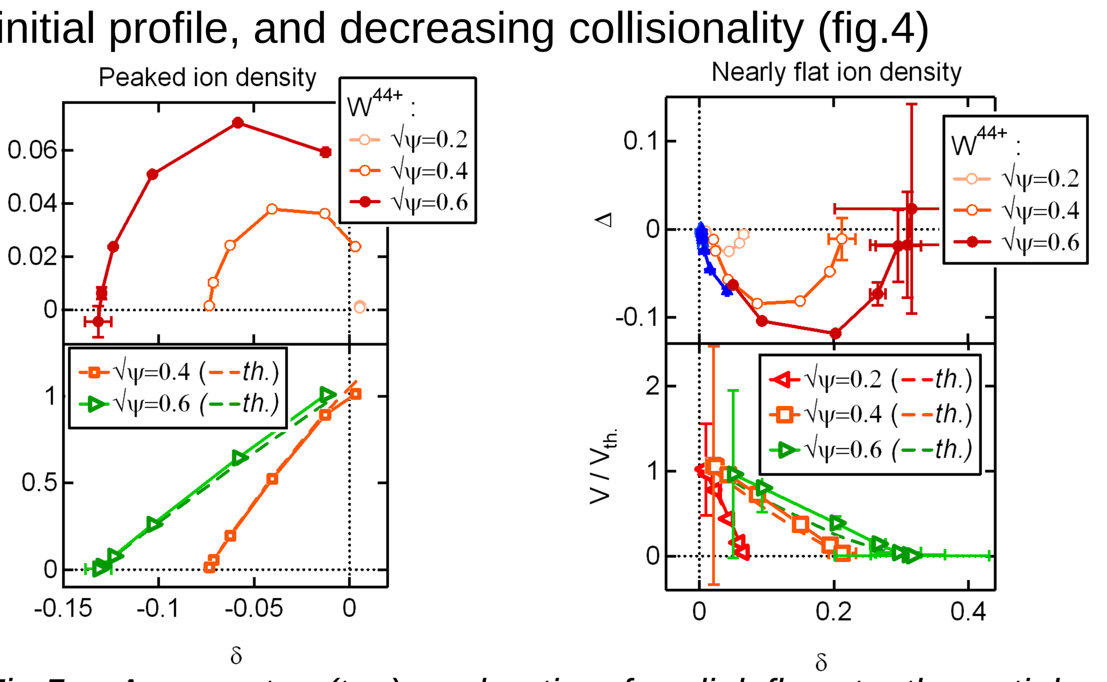


Fig.5 : Asymmetry (top) and ratio of radial flow to theoretical value without asymmetry (bottom), for the peaked and flat ion density profiles, and several radial positions.

Radial flow & poloidal asymmetry vs theoretical model

- The asymmetry circle is reproduced (fig. 5)
- The radial flow & poloidal asymmetry profiles are well predicted (fig.6).
- Radial W^{44+} flow is damped for both the peaked & flat ion density profiles (fig.5 & 6)

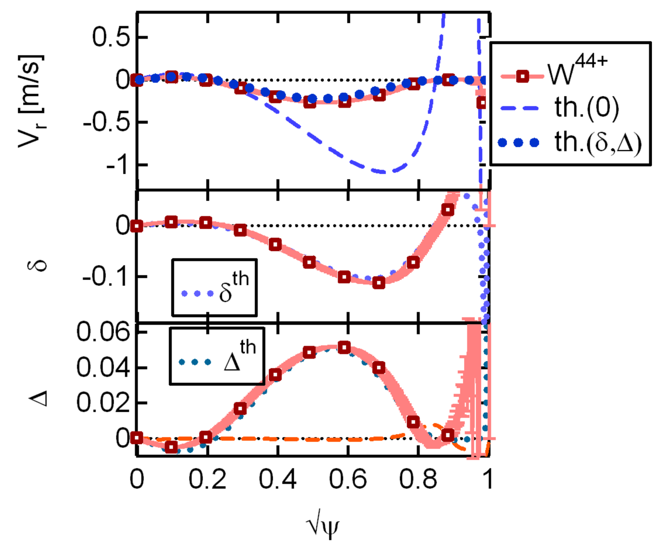


Fig.6 : Radial flow, δ and Δ profiles for the real collisionality (peaked ion density profile). Comparison of simulation results with theory with (th(δ,Δ)) and without (th(0)) poloidal asymmetry.

Neoclassical impurity transport in presence of a (2,1) island on WEST

Magnetic islands remove the outward thermal screening term

- This mechanism could accelerate plasma contamination [4]
- A (2,1) island is inserted in a WEST equilibrium and decays to W_{sat}~4% (fig.7)
- Locally, the radial flow of W^{28+} approaches its theoretical value without thermal screening (fig.8).

The radial flow can be fitted by a tanh by introducing the characteristic transport width W_χ [5] (fig.9).

$$V_{r,W}=V^0_{r,W}+V^{isl}_{r,W}\times\left[1+\tanh 3\left(W-1.8W_\chi\right)/W_\chi\right]$$

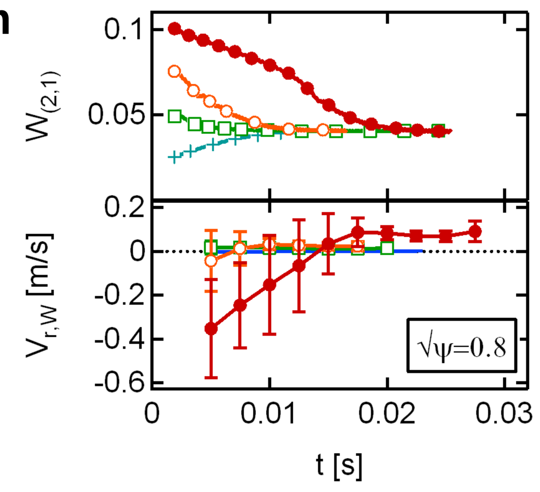
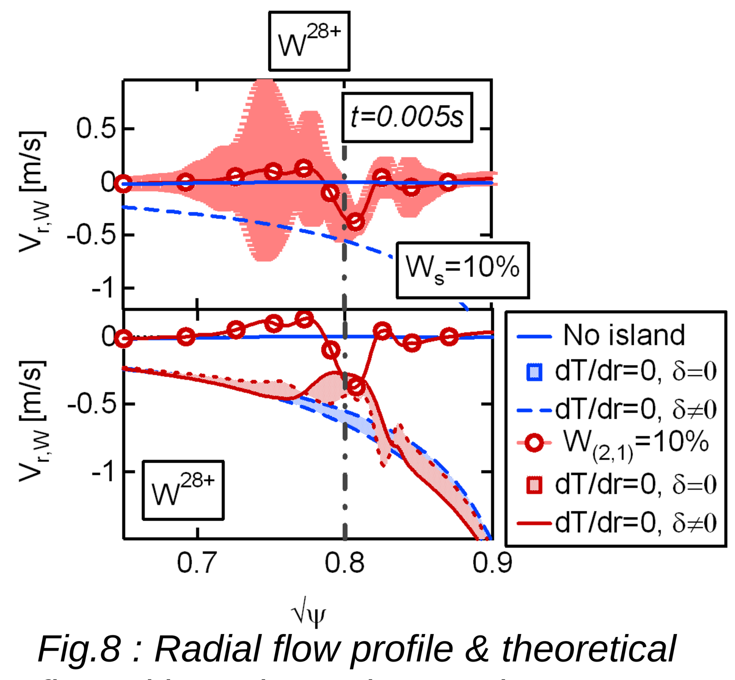


Fig.7 : Island size (W=w/a) & radial flow at the island position for # seeds.



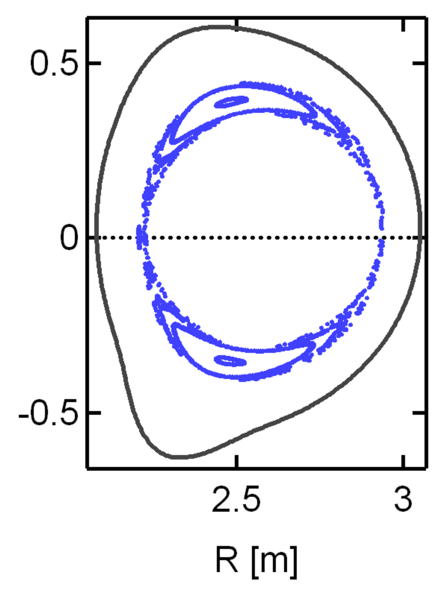


Fig.8 : Radial flow profile & theoretical flow without thermal screening

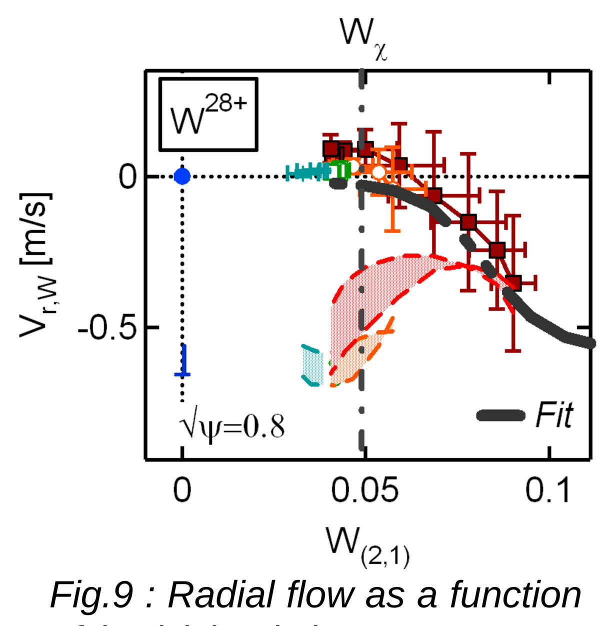


Fig.9 : Radial flow as a function of (2,1) island size.

Turbulent impurity transport on WEST

The Tungsten transport is in fact dominated by turbulence on WEST [6,7]

- An ad-hoc model is implemented in XTOR with $D_\perp$=8m²/s, D_{thd}=0.8m²/s, V_{cur}=-6.7m/s:

$$\Gamma_a^{turb}=-D_\perp^a\nabla n_a+n_a\mathbf{V}_p^a$$

$$\mathbf{V}_p^a=D_{thd}^a\nabla\ln T_a+\mathbf{V}^a_{cur}$$

- The Tungsten profile remains flat as observed experimentally [7]
- Poloidal asymmetry remains close to its neoclassical value (fig.10).

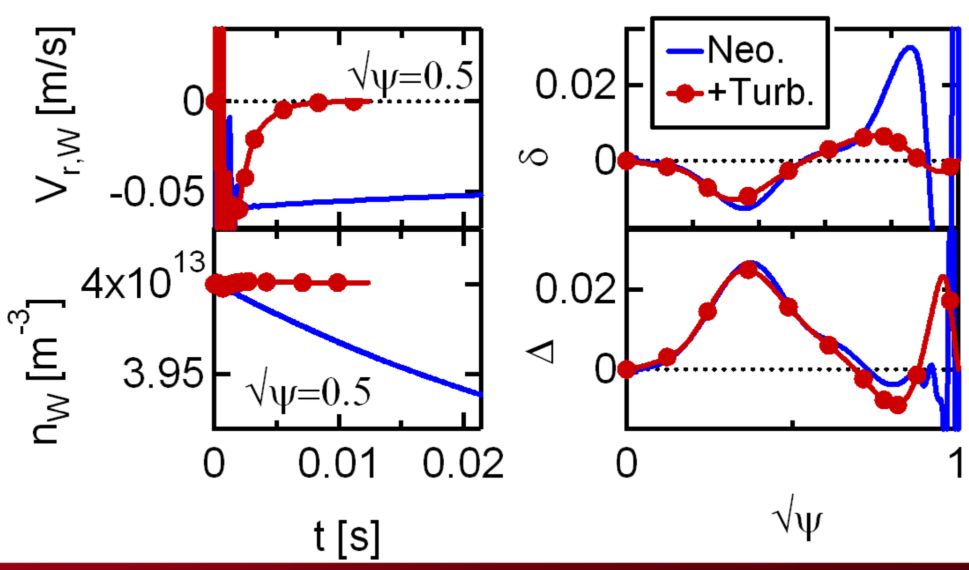


Fig.10 : Radial flow & W^{28+} density at √ψ=0.5 (left); asymmetry profiles with and without turbulence (right).

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