Collisional transport and poloidal asymmetry distribution of impurities in tokamak plasmas, with application to WEST

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Summary

- Heavy impurity transport is a key issue in metallic wall tokamaks
  - Collisional part can be dominant over turbulent one in the core [1]
- Derivation of a fast analytical model for collisional impurity transport
  - Self-consistent Poloidal asymmetry and radial flux
  - Applicable to rotating & ICR Heated plasmas [2]
  - Compared with XTOR [3,4] simulations, and with NEO [5]
- Investigation on a rare case of Tungsten accumulation on WEST
  - ICRH-driven asymmetry could be the main mechanism

Analytical approach for collisional impurity transport

Neoclassical impurity transport

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

$$\langle\Gamma_a^{neo}\cdot\nabla r\rangle \approx -\langle n_a\rangle\frac{D_{PS}^a}{R_0}\left[\left(1+\frac{\delta}{\epsilon}+\frac{\delta^2+\Delta^2}{4\epsilon^2}\right)\mathcal{G}+\frac{1}{2}\left(\frac{\delta}{\epsilon}+\frac{\delta^2+\Delta^2}{2\epsilon^2}\right)\mathcal{U}-\frac{\delta_M}{2\epsilon^2}\left(1-\frac{m_i}{m_a}\frac{e_a}{e_i}\right)\left(1+\frac{\delta}{2\epsilon}\right)\right]$$

- with $D_{PS}^a \equiv 2q^{*2}m_a\nu_a T_a/(e_a^2\langle B^2\rangle)$, ε=r/R$_0$, C_0^a~1.5 and k_i~-1.17 in the banana regime

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

$$\delta_M=2\epsilon(m_a/m_i)(T_i/T_a)M_i^2$$

Poloidal asymmetry

- The poloidal asymmetry is given by the parallel force balance

$$\delta+\delta_\phi^a-\delta_M = -\mathcal{A}\left[\Delta\mathcal{G}+\Delta\mathcal{U}-\mathcal{R}\delta_M\epsilon\Delta\right]$$
$$\Delta+\Delta_\phi^a = \mathcal{A}\left[(2\epsilon+\delta)\mathcal{G}+\delta\mathcal{U}-2\mathcal{R}\delta_M\right]$$

$$\mathcal{A}=q^2\nu_a/(\epsilon\Omega_a) \qquad \mathcal{R}=\frac{1}{2\epsilon}\left(1-\frac{m_i}{m_a}\frac{e_a}{e_i}\right)$$

- With the electrostatic potential modelled as e(ϕ-<ϕ>)/T$_e$ = $\delta_\phi\cos\theta+\Delta_\phi\sin\theta$ and

$$(\delta_\phi^a,\ \Delta_\phi^a)=Z_a(T_e/T_a)(\delta_\phi,\ \Delta_\phi)$$

Self-consistent collisional impurity transport model

- Implemented in FACIT code (FAst Collisional Impurity Transport)
- Impurity flux & asymmetry are non-linear functions of the impurity gradient
- Collisional friction couples vertical & horizontal asymmetry: tilting w.r.t. the drive

The natural case (no rotation, no ϕ asymmetry)

Poloidal asymmetry parameters (δ, Δ) move on a circle as collisionality varies

- Pinch velocity is strongly reduced by poloidal asymmetry at high Z (flat n$_a$) [6] *(fig.1)*

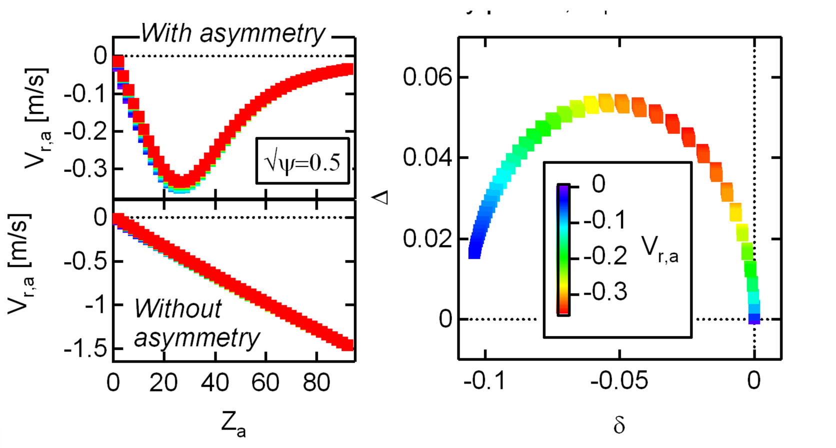

Fig.1 : Radial impurity flow as a function of the impurity charge Z_a with & without selft-consistent poloidal asymmetry (left); corresponding asymmetry (right). The impurity profile is flat.

Numerical experiments with XTOR-2F code [2]

- Neoclassical physics [4]
- Impurity conservation and momentum equations
- The collisionality (ν_a) is scanned artificially
- The circle in the (δ, Δ) plane is recovered …
- … as well as the reduction of the pinch velocity *(fig. 2)*

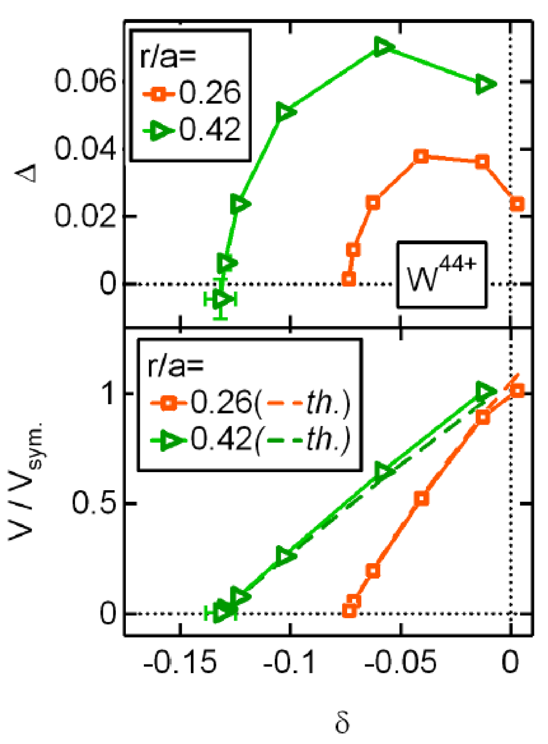

Fig.2 : Asymmetry (top) and ratio of radial flow to theoretical value without asymmetry (bottom): XTOR simulations & FACIT model

Neoclassical steady-state (Γ^{neo}=0)

- Poloidal asymmetry cancels *(fig. 3)*
- XTOR simulation follow same initial trajectory in (δ, Δ)

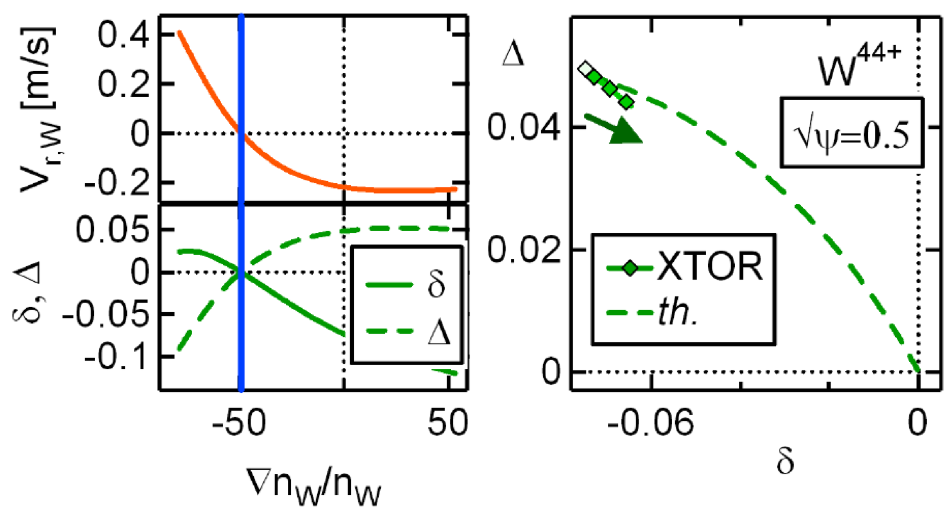

Fig.3 : Left: radial flux (top) and asymmetry (bottom). Right : XTOR simulations & FACIT model

Collisional vertical ϕ - asymmetry effect

Extension of the natural case to finite ϕ - asymmetry

- Ion-electron collisions drive a vertical ϕ - asymmetry [7]
- $$\Delta_\phi^{nat}\approx\frac{C^{nat}}{Z_i+T_e/T_i}\frac{q^2x\,\partial_x\ln T_i}{\epsilon^{5/2}\;\tau_{ii}\Omega_i}$$ with $C^{nat}\approx-0.165$
- Asymmetry recovered with NEO at 1[rst] order : not used for computing impurity flux
- But in fact, it strongly impact impurity flux & poloidal asymmetry in the absence of other drives (no rotation & no ICRH) *(fig.4)*
- Only effective at low T$_i$

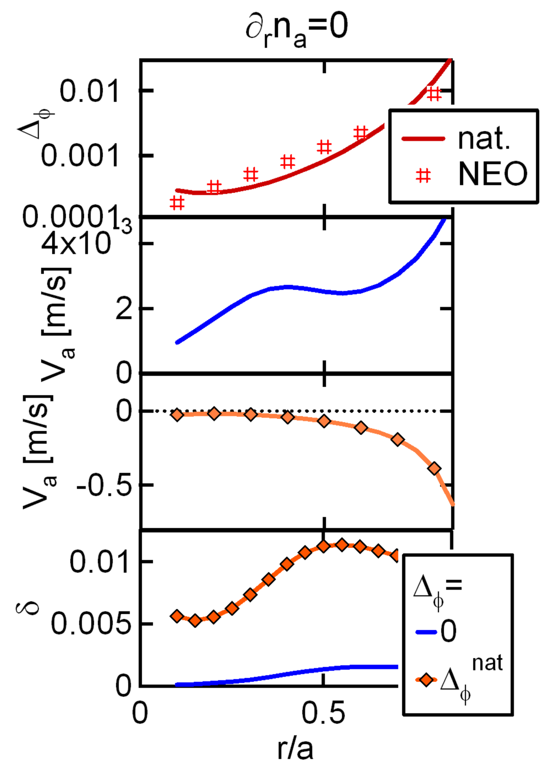

Fig.4 : Natural vertical electrostatic potential asymmetry profile, pinch velocity and horizontal asymmetry with and without Δ^{nat}, .

Toroidal rotation and ICRH effect

Toroidal rotation

- Neoclassical diffusion coefficient, pinch velocity and horizontal asymmetry at Γ^{neo}=0 in good agreement with NEO for M$_i$<0.3 *(fig. 5)*
- Pinch velocity overestimated above M$_i$<0.3
- Low Field Side localization due to centrifugal force

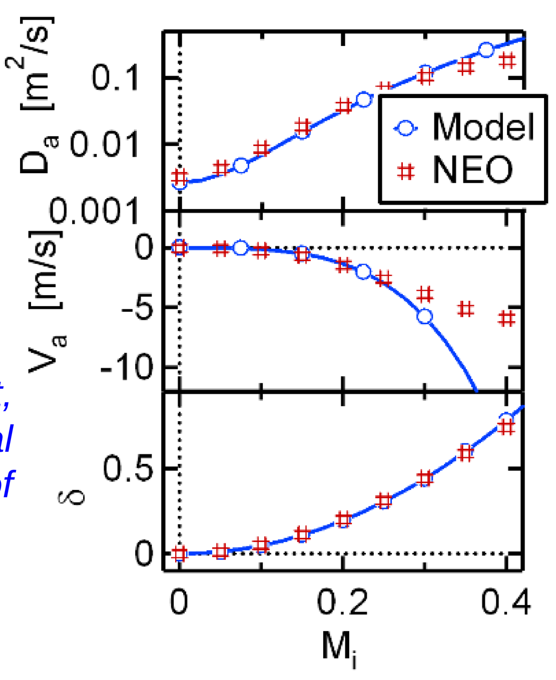

Fig.5 : Diffusion coefficient, pinch velocity and horizontal asymmetry as a function of the ion Mach number.

ICRH

- Minority temperature anisotropy : horizontal ϕ-asymmetry

$$\delta_\phi=\frac{\epsilon}{1+Z_iT_e/T_i}\left[f_H\left(\frac{T_\perp}{T_\parallel}-1\right)+m_i\frac{(R_0\Omega)^2}{T_i}\right]$$

- Neoclassical diffusion coefficient, pinch velocity and horizontal asymmetry at Γ^{neo}=0 agrees with NEO *(fig.6)*
- High Field Side localization due to electrostatic force
- Transition from expulsion to accumulation above a critical temperature anisotropy
- Neoclassical diffusion vanishes at the transition: classical diffusion dominant
- Favorable domain $T_\perp/T_\parallel<(T_\perp/T_\parallel)^{crit}$ expands with M$_i$ as

$$\left[f_H\left(\frac{T_\perp}{T_\parallel}-1\right)\right]^{crit}\approx 2\frac{Z_i+T_i/T_e}{Z_a}+2M_i^2\left[\frac{m_a}{m_i}\frac{Z_i+T_i/T_e}{Z_a}-1\right]$$

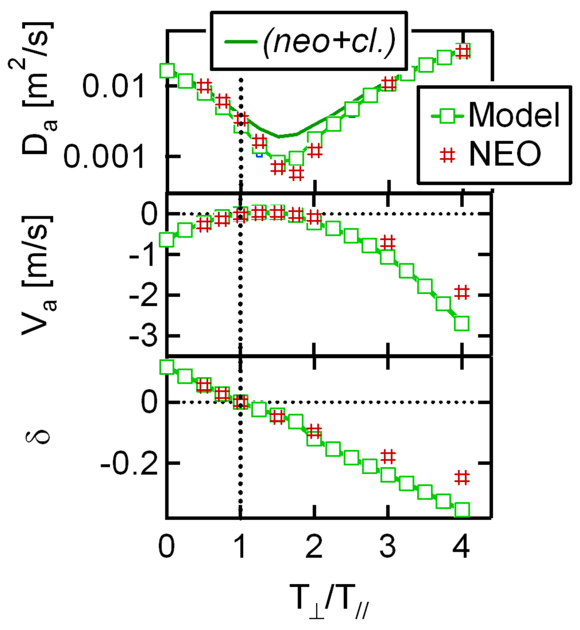

Fig.6 : Diffusion coefficient, pinch velocity and horizontal asymmetry as a function of $T_\perp/T_{||}$.

Tungsten peaking & ICRH operation: a WEST case

Rare cases of Tungsten accumulation on WEST

- Low torque plasma: turbulent transport dominates [8]
- Accumulation observed in some ICRH pulses *(fig.7)*

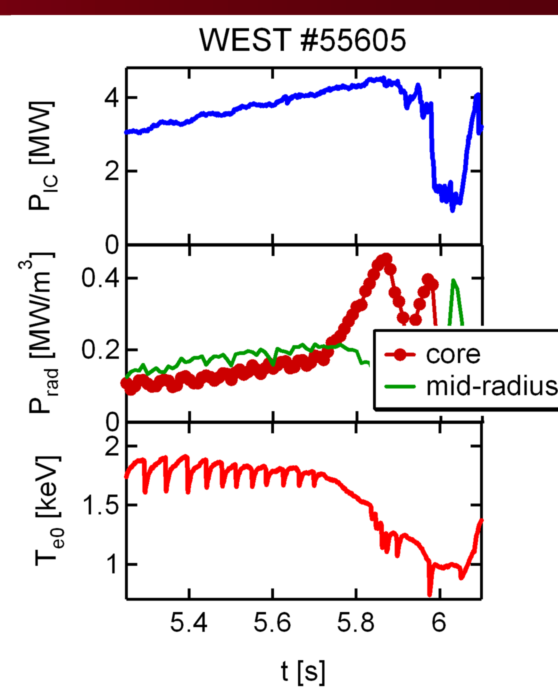

Fig.7 : ICRH power, radiative power and core electron temperature.

Modeling of Tungsten peaking

- Interpretative Integrated modeling with METIS [9]
- Ion temperature deduced neutron flux & $T_i\propto\sqrt{n_eT_e}$
- Minority temperature anisotropy : EVE/AQL [10] *(fig. 8)*
- Minority temperature screening effect not considered
- Toroidal rotation not measured but (1,1) MHD mode accelerates linearly with ICRH power *(fig.9)*
- Rotation: $V_\varphi=V_0+(V/P)\times P_{IC}$ with *(V/P)~3km/s/MW*
- Tungsten peaking from FACIT consistent with ICRH drive at low rotation *(V_0~0) (fig.10)*

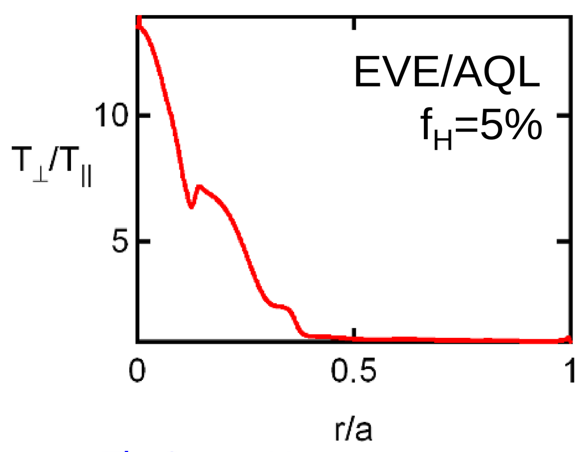

Fig.8 : H temperature anisotropy from EVE/AQL

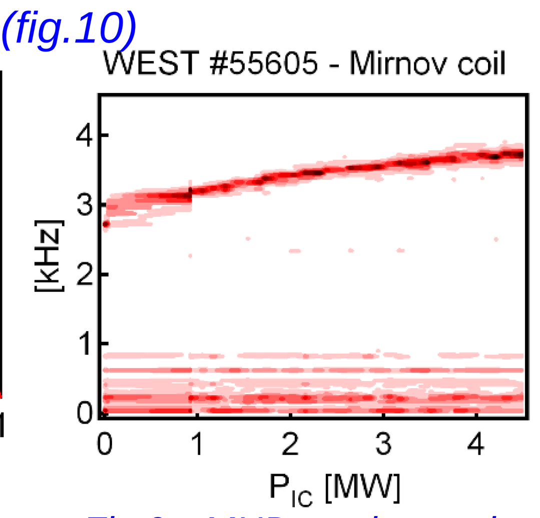

Fig.9 : MHD mode rotation as a function of P$_{IC}$.

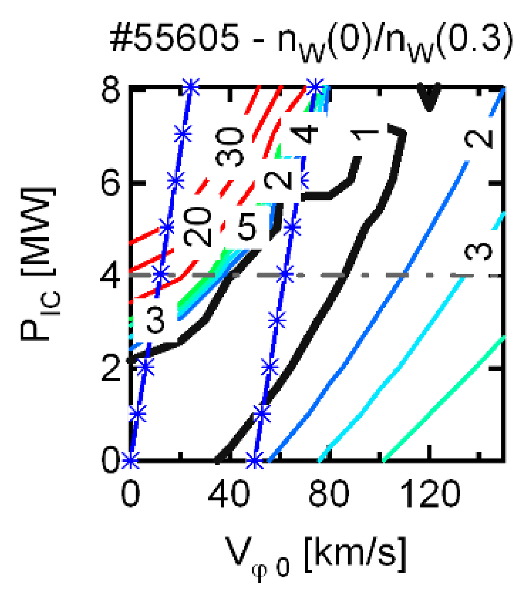

Fig.10 : Tungsten peaking in (P$_{IC}$, V$_\varphi$) map. Trajectories for V$_0$=0 and 50 km/s

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