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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]:

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

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

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

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 $\Delta = R_\Delta \sin \alpha$

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

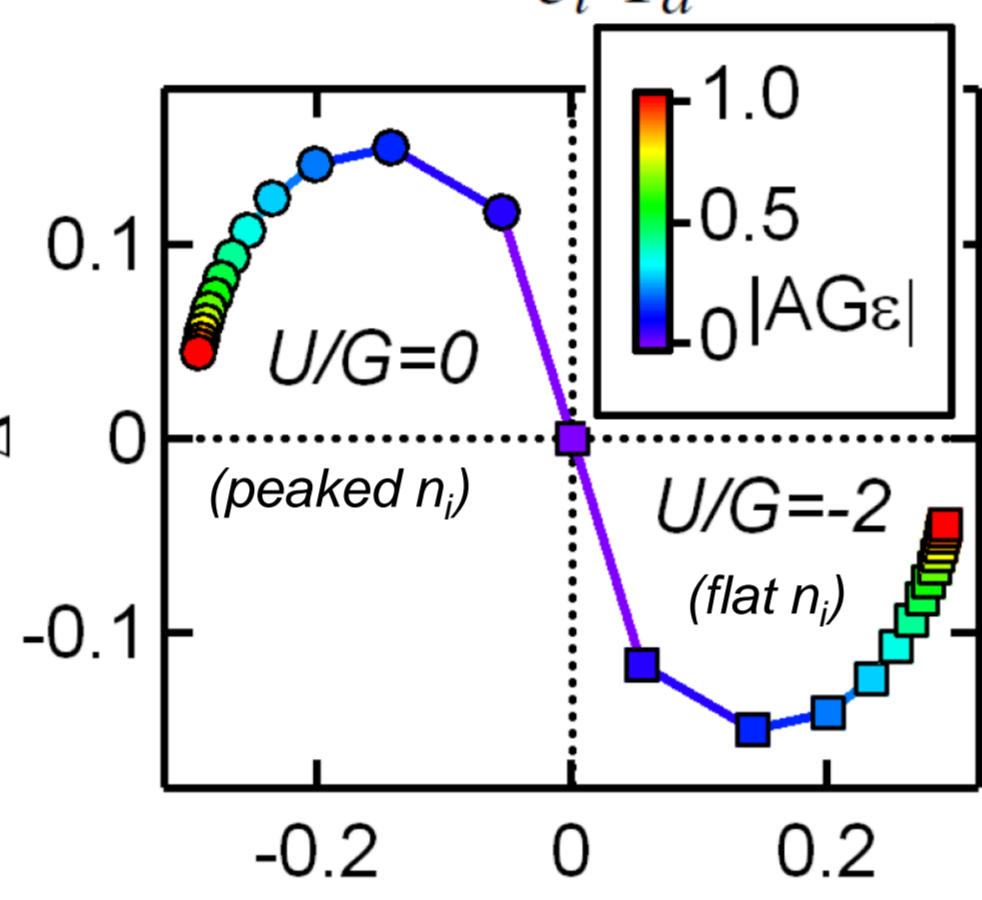
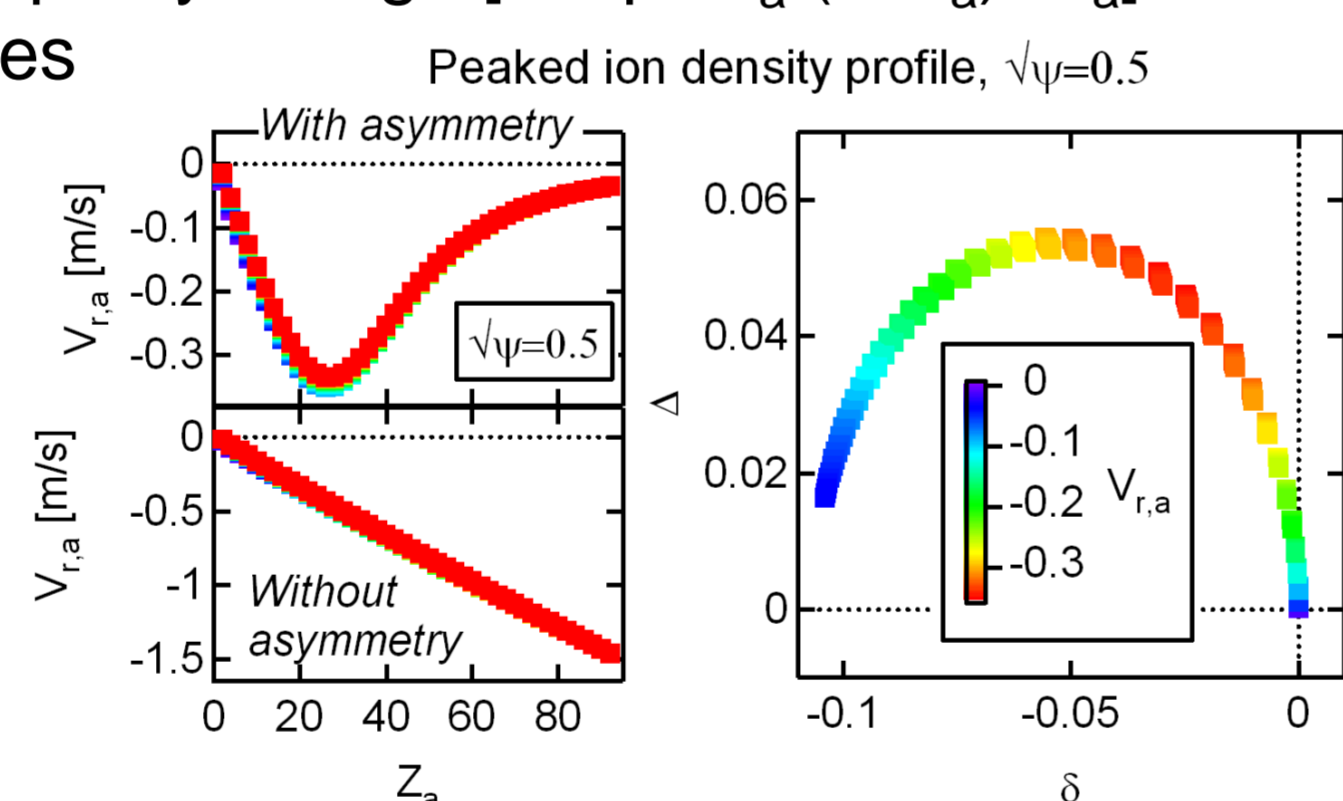


Fig.1 : Self-consistent asymmetry

- 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 $\delta < 0$ for a peaked ion density profile ($\delta > 0$ for a flat one)
 - The asymmetry angle α increases with impurity charge [$A = q^2 R \nu_a / (\varepsilon^2 \Omega_a) \sim Z_a$]
- 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:

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

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

with $\frac{R_{a||} - (\nabla \cdot \Pi_a)_{||}}{m_a n_a} = \nu_a \left(V_{i||} - V_{a||} - C_0^a \frac{2q_i}{5p_i} \right) + \dots$ (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.

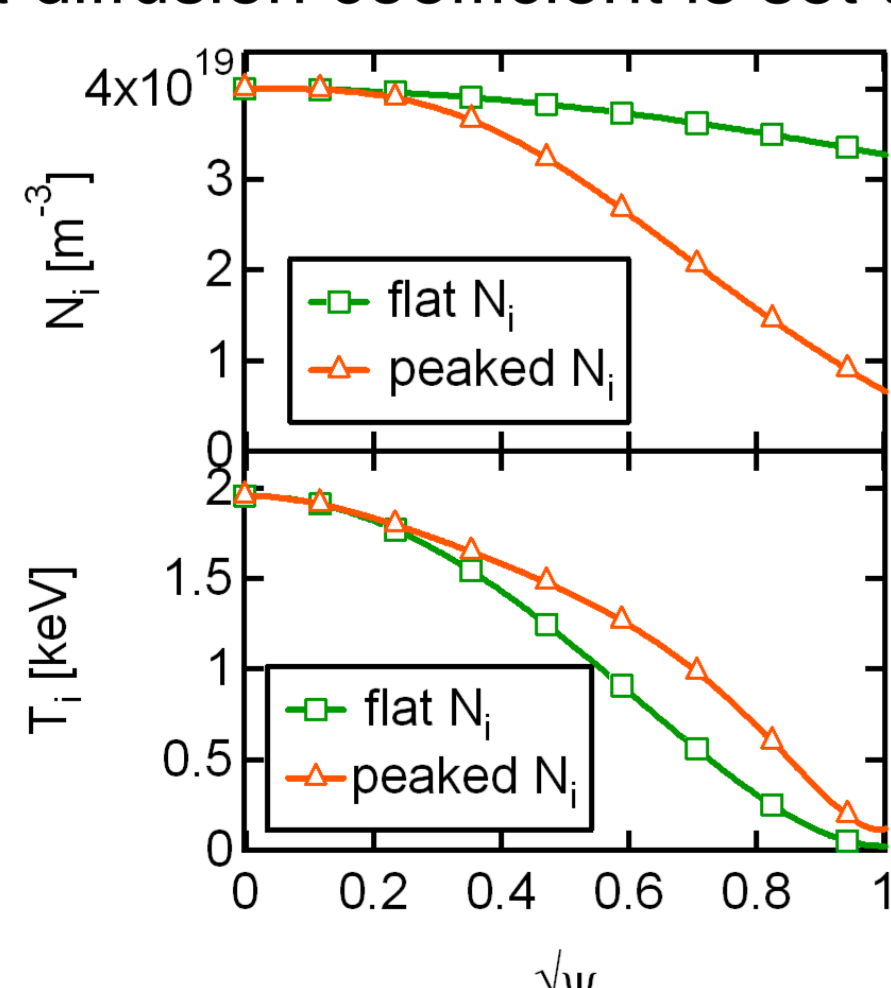
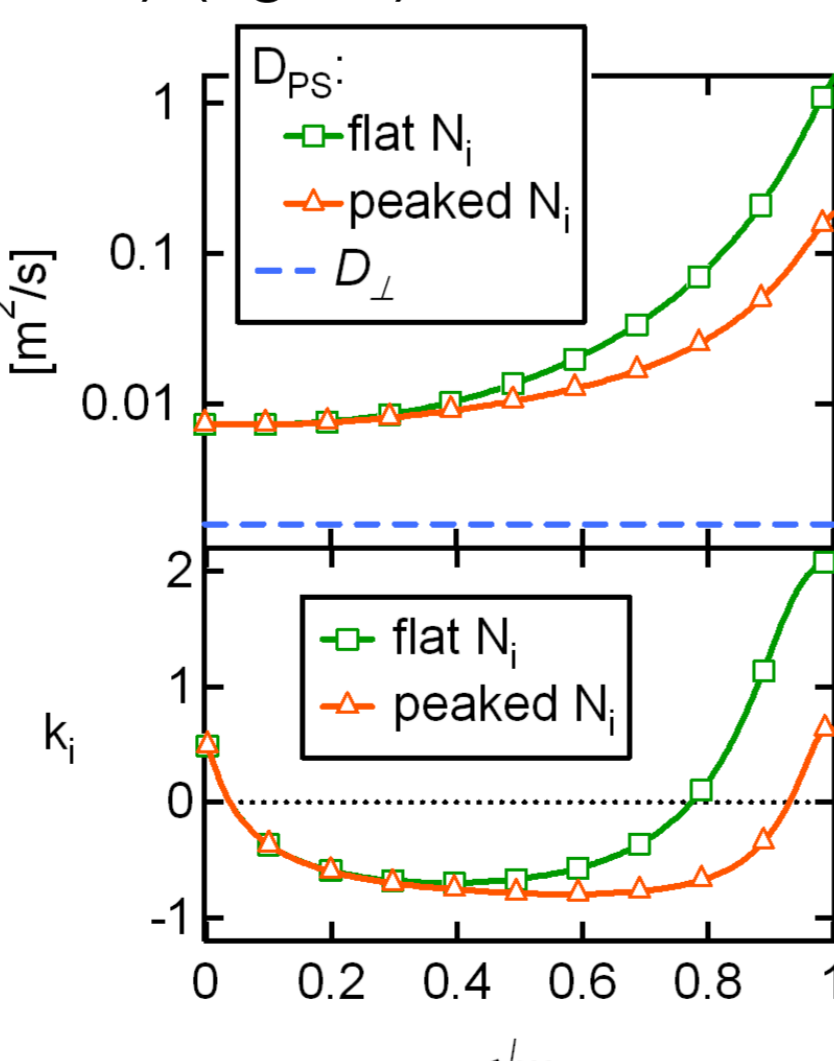


Fig.3b: Pfirsch-Schlüter diffusion coefficient & k_i parameter.



References

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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)

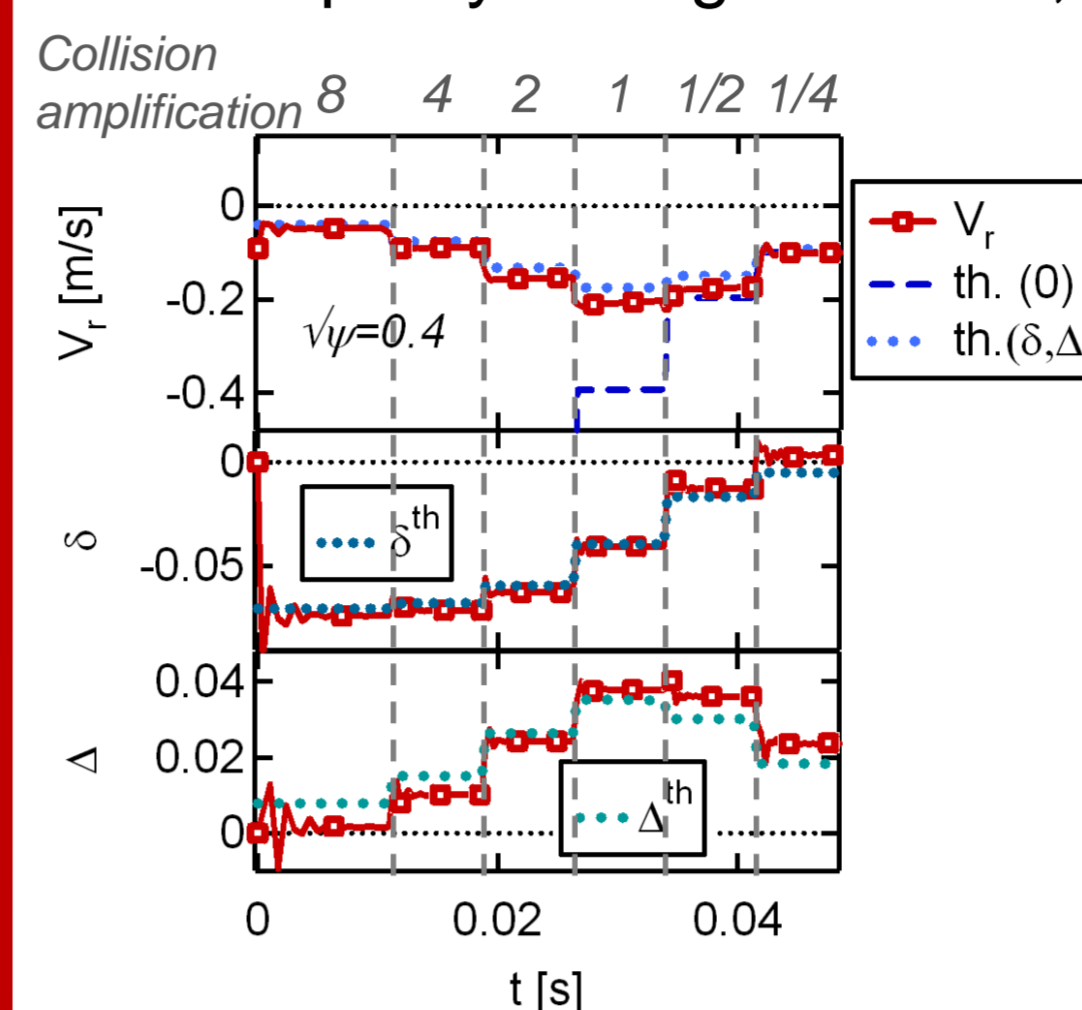


Fig.4 : Radial flow, δ and Δ during the collisionality scan with factor 8, 4, 2, 1, 0.5, 0.25 (peaked ion density profile).

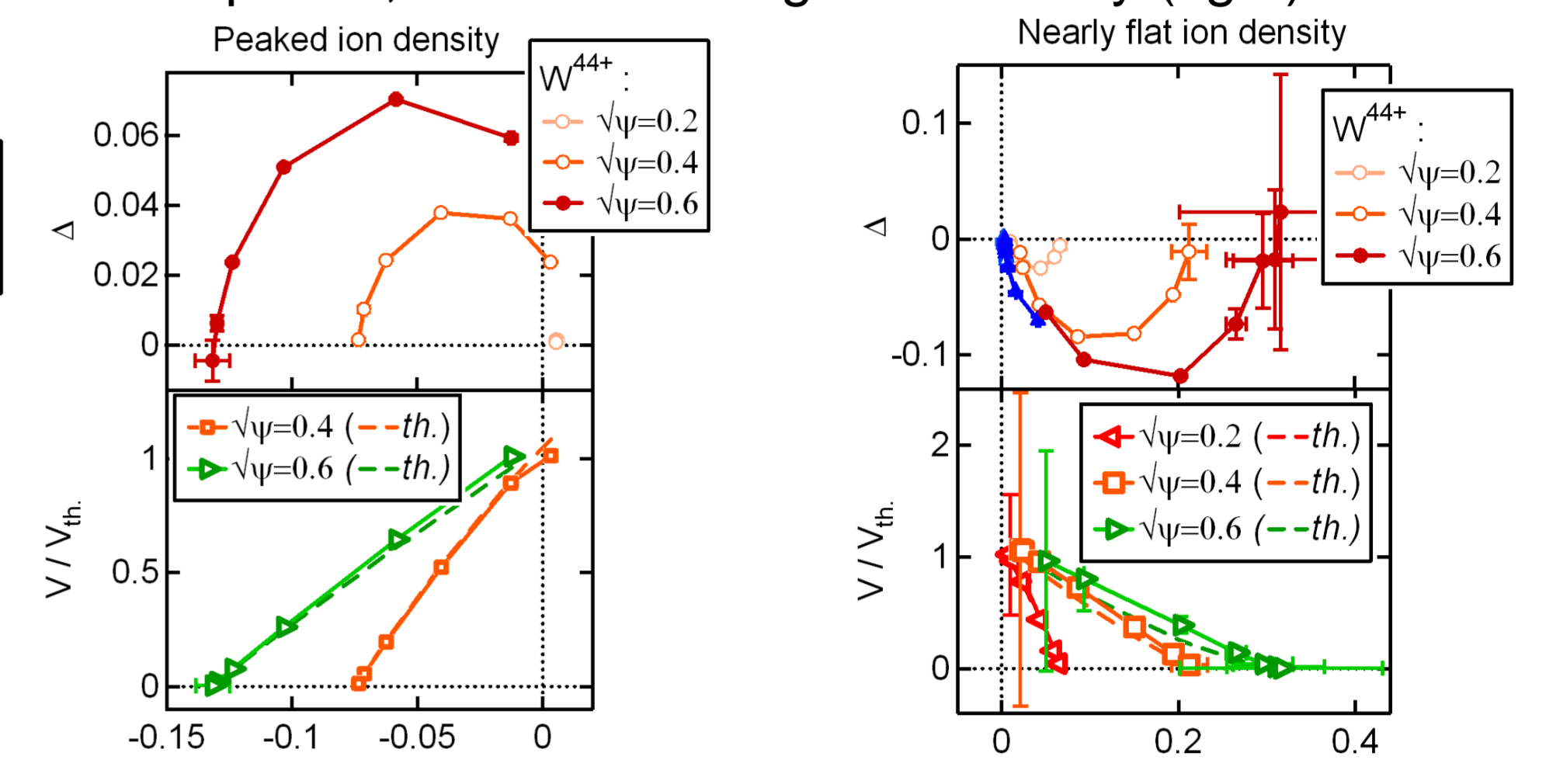
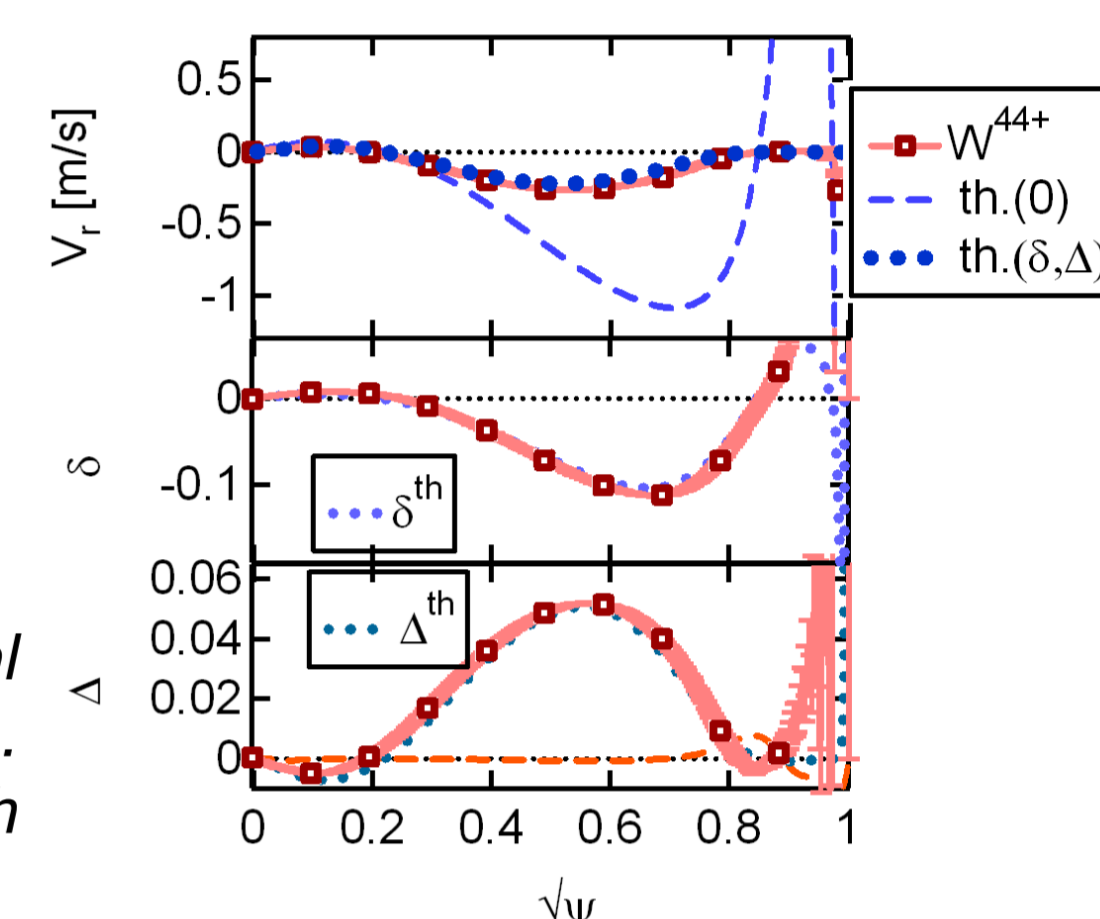


Fig.5 : Asymmetry (top) and ratio of radial flow to theoretical value without asymmetry (bottom), for the peaked and flat ion density profiles, and several radial positions.

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 $(th(\delta, \Delta))$ 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 $W_{sat} \sim 4\%$ (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).

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

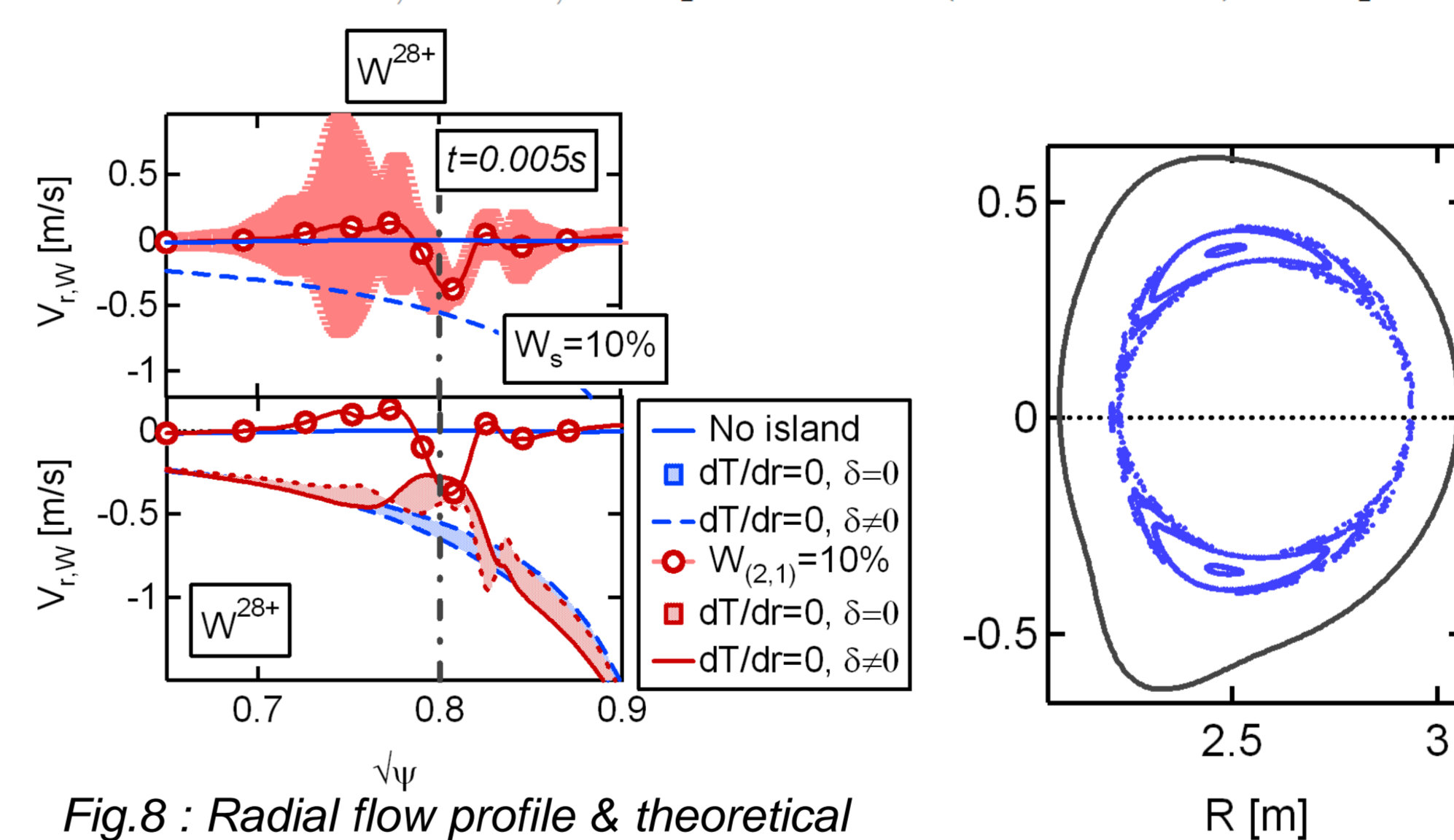


Fig.8 : Radial flow profile & theoretical flow without thermal screening

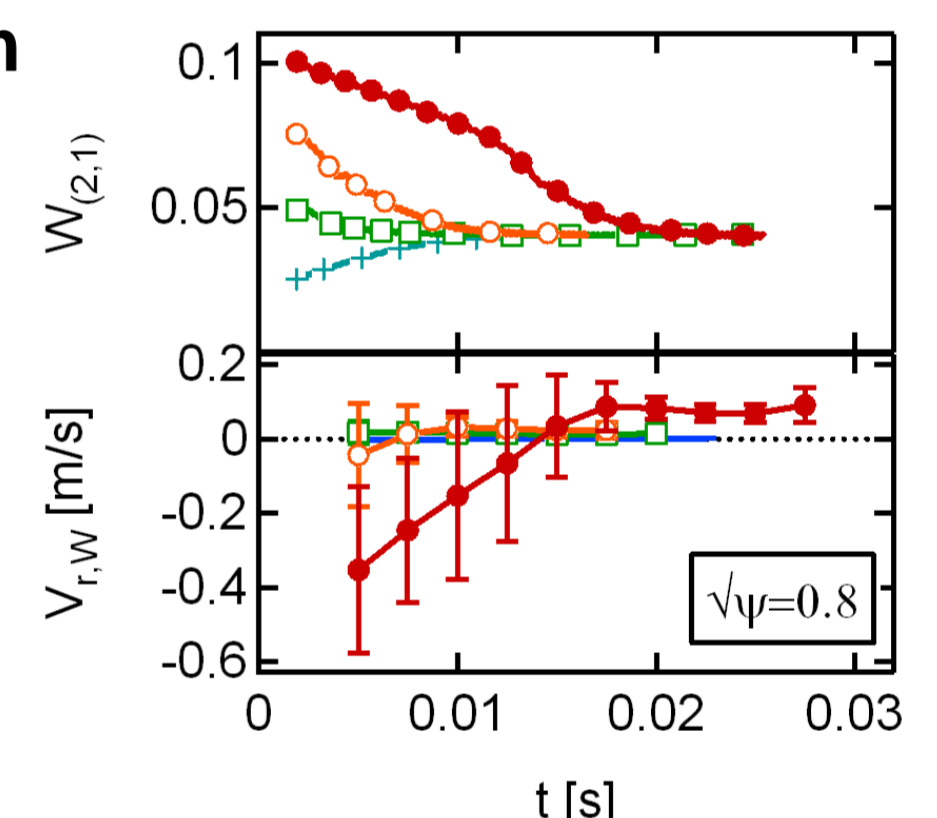


Fig.7 : Island size ($W=w/a$) & radial flow at the island position for # seeds.

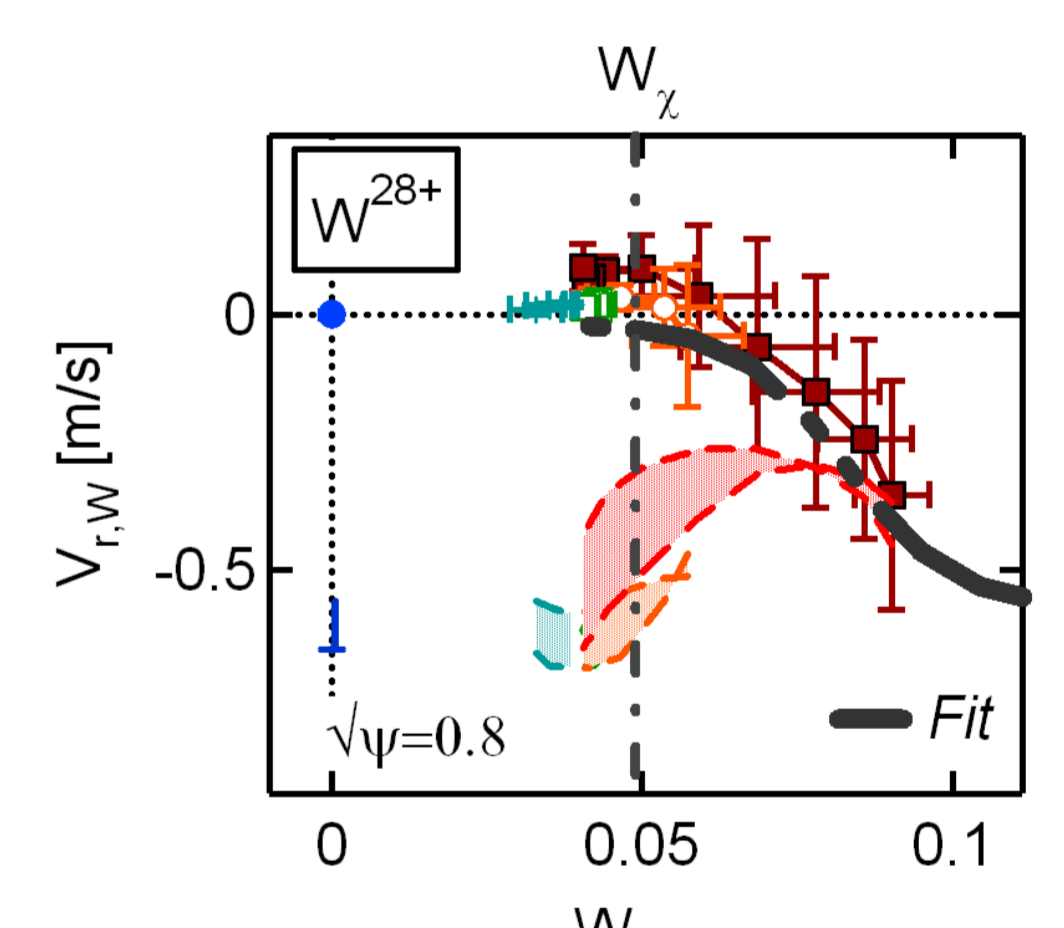


Fig.9 : Radial flow as a function of (2,1) island size.

Turbulent impurity transport on WEST

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

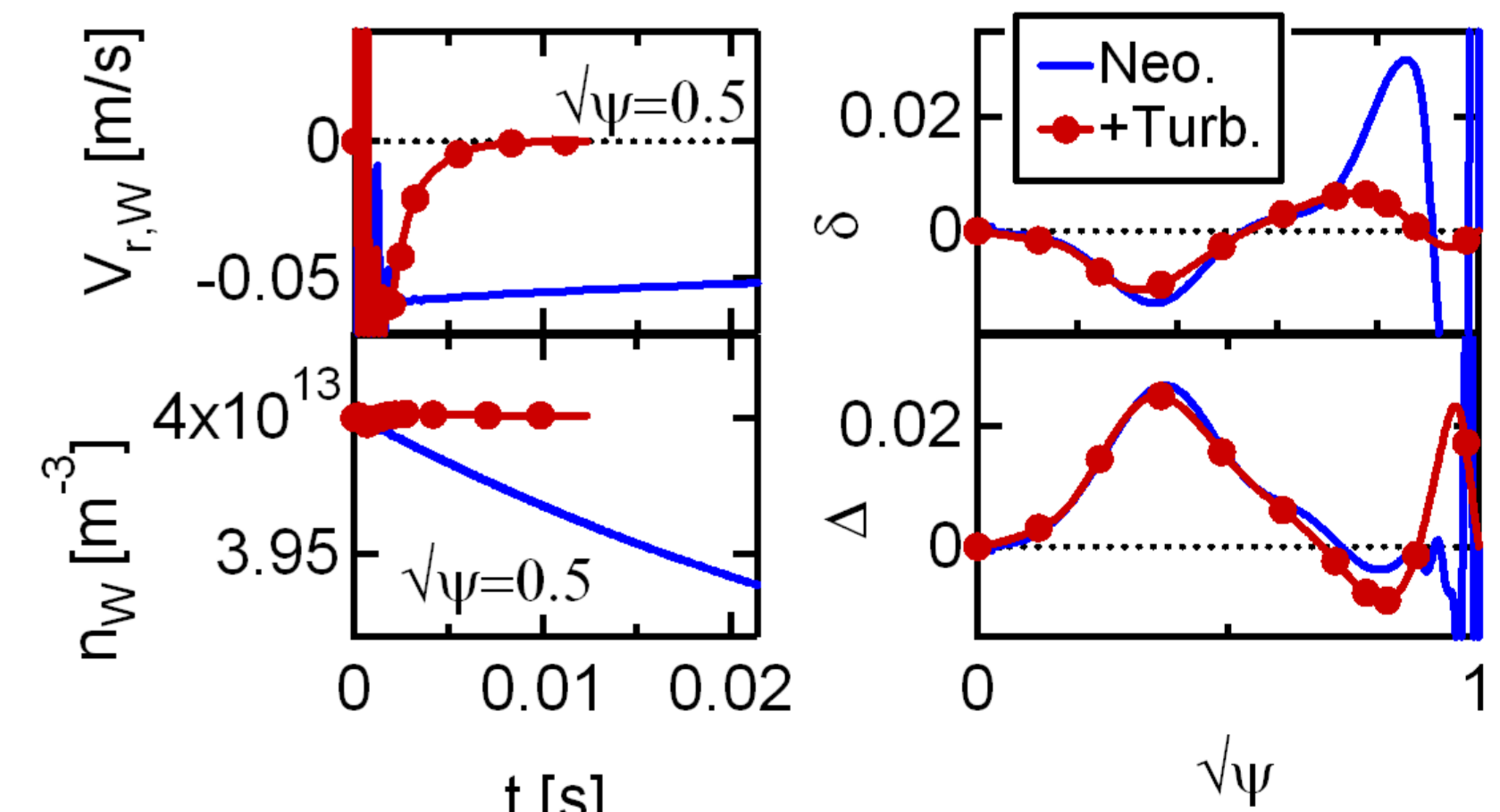
- An ad-hoc model is implemented in XTOR with $D_{\perp} = 8m^2/s$, $D_{thd} = 0.8m^2/s$, $V_{cur} = -6.7m/s$:

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

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

- 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 $\nu_{\psi} = 0.5$ (left); asymmetry profiles with and without turbulence (right).



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