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Collisional vertical f -asymmetry effect

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P. Maget¹, J. Frank^{1,2}, P. Manas¹, R. Dumont¹, T. Nicolas³, J-F. Artaud¹, C. Bourdelle¹, L. Colas¹, M. Goniche¹, O. Agullo², X. Garbet¹, H. Lütjens³ and the WEST team[#]

¹ CEA, IRFM, F-13108 Saint Paul-lez-Durance, France.

² Aix-Marseille Université, CNRS, PIIM UMR 7345, 13397 Marseille Cedex 20, France.

³ Centre de Physique Théorique, Ecole Polytechnique, CNRS, 91128 Palaiseau, France.

[#] see <http://west.cea.fr/WESTteam>



West

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]:

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

- with $D_{PS}^a \equiv 2q^* m_a \nu_a T_a / (e_a^2 \langle B^2 \rangle)$, $\epsilon = r/R_0$, $C_0^a \sim 1.5$ and $k_T \sim 1.17$ in the banana regime

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

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

Poloidal asymmetry

- The poloidal asymmetry is given by the parallel force balance

$$\delta + \delta_\phi^a - \delta_M = -\mathcal{A} [\Delta \mathcal{G} + \Delta \mathcal{U} - \mathcal{R} \delta_M \epsilon \Delta]$$

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

$$\mathcal{A} = q^2 \nu_a / (\epsilon \Omega_a)$$

$$\mathcal{R} = \frac{1}{2\epsilon} \left(1 - \frac{m_i e_a}{m_a e_i} \right)$$

- With the electrostatic potential modelled as $e(\phi - \langle \phi \rangle) / T_e = \delta_\phi \cos \theta + \Delta_\phi \sin \theta$ and $(\delta_\phi^a, \Delta_\phi^a) = Z_a (T_e/T_a) (\delta_\phi, \Delta_\phi)$

Self-consistent collisional impurity transport model

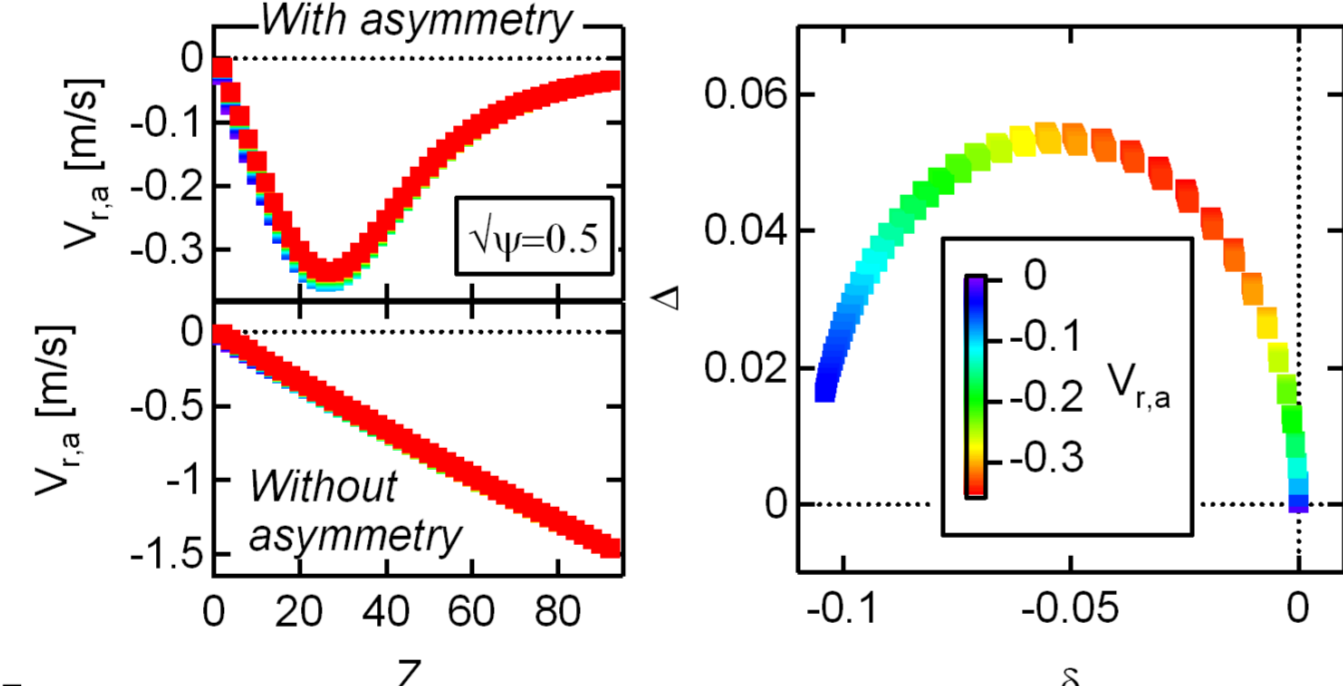
- Implemented in FACIT code (FAst Collisional Impurity Transport)
- Impurity flux & asymmetry are non-linear functions of the impurity gradient
- Collisional friction couples vertical & horizontal asymmetry: tilting w.r.t. the drive

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 self-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)

Neoclassical steady-state ($\Gamma^{neo}=0$)

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

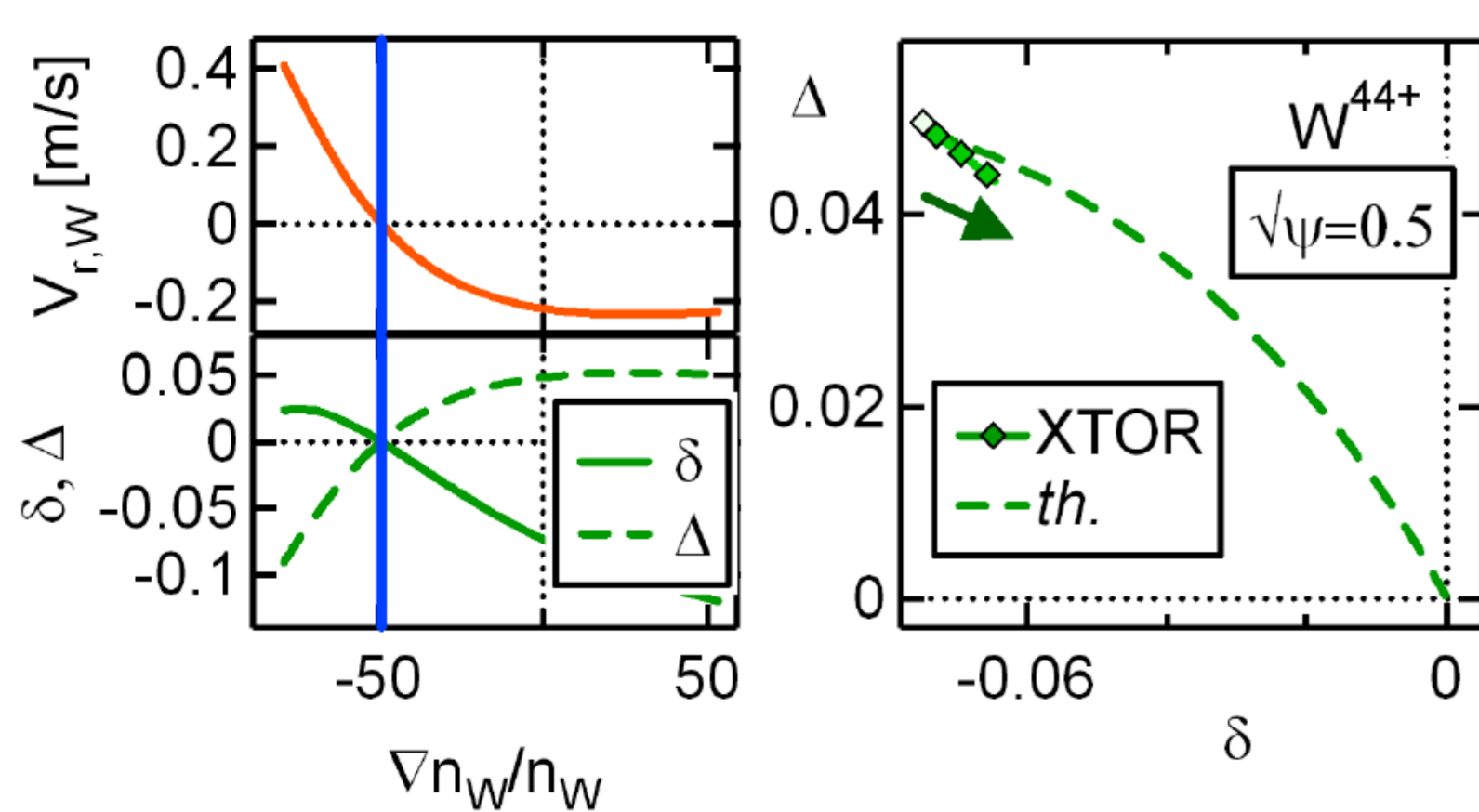


Fig.3 : Left: radial flux (top) and asymmetry (bottom). Right: XTOR simulations & FACIT model

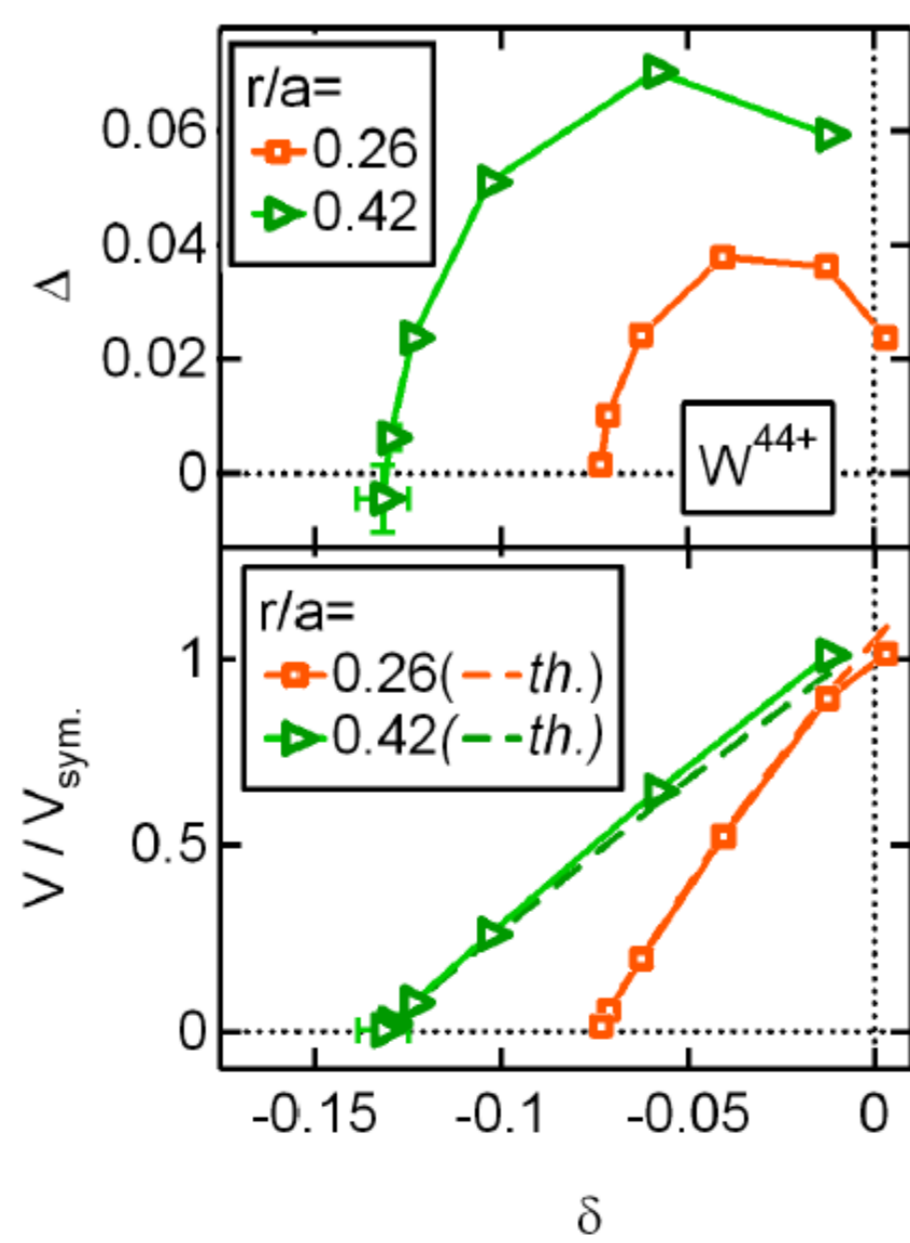


Fig.2 : Asymmetry (top) and ratio of radial flow to theoretical value without asymmetry (bottom): XTOR simulations & FACIT model

References

- [1] Angioni et al *PPCF* **56** 124001 (2014)
 [2] Maget et al, *PPCF* **62** 105001 (2020)
 [3] Lütjens *J. Comp. Phys.* **229** 8130 (2010)
 [4] Maget et al, *PPCF* **62** 025001 (2020)
 [5] Belli et al *PPCF* **50** 095010 (2008)
 [6] Helander *Physics of Plasmas* **5** 3999 (1998)
 [7] Hinton *The Physics of Fluids* **16** 836 (1973)
 [8] Yang *Nuclear Fusion* **60** 086012 (2020)
 [9] Artaud *Nuclear Fusion* **58** 105001 (2018)
 [10] Dumont *NF* **49** 075033 (2009); *NF* **53** 013002 (2012)

Collisional vertical ϕ - asymmetry effect

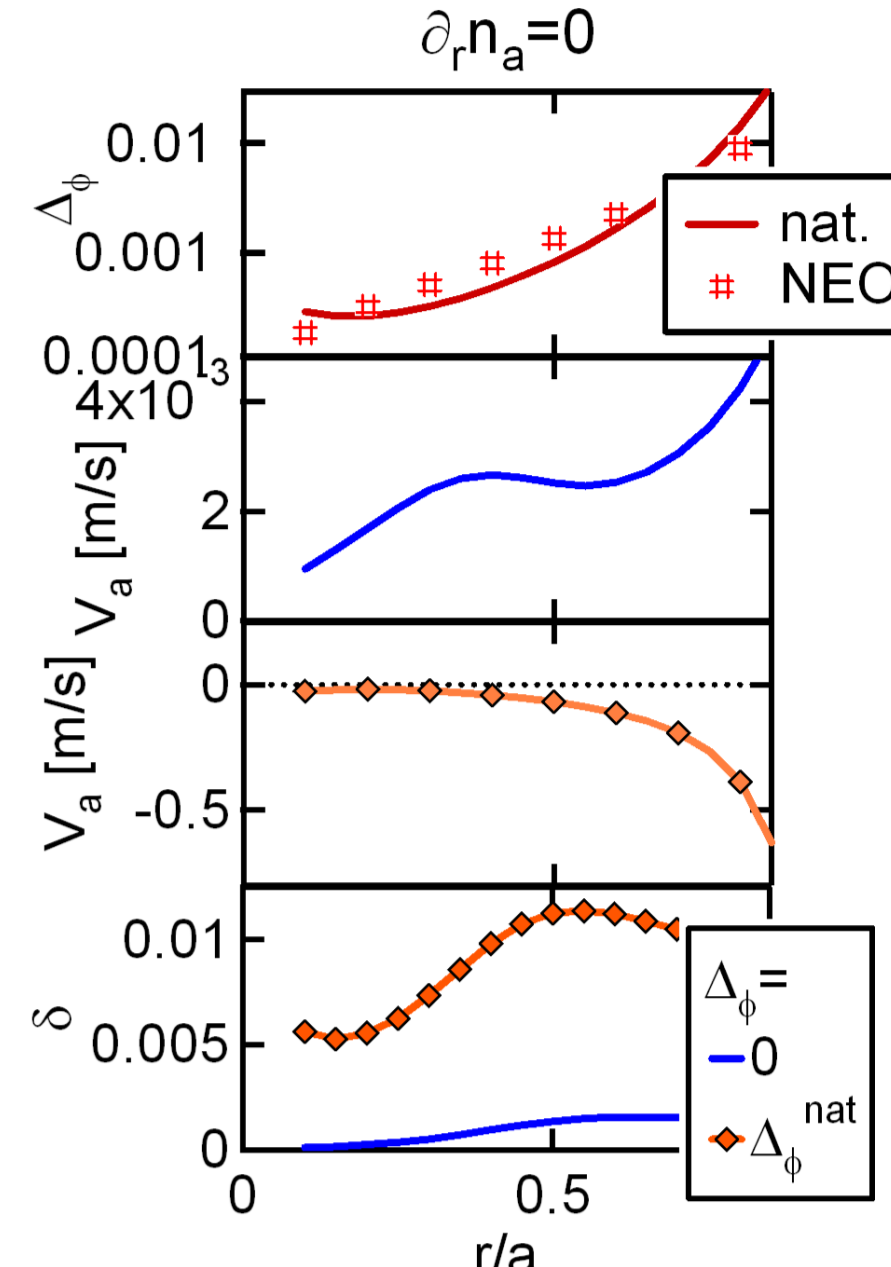
Extension of the natural case to finite ϕ - asymmetry

- Ion-electron collisions drive a vertical ϕ - asymmetry [7]

$$\Delta_\phi^{nat} \approx \frac{C^{nat}}{Z_i + T_e/T_i} \frac{q^2 x \partial_x \ln T_i}{\epsilon^{5/2} \tau_{ii} \Omega_i} \quad \text{with } C^{nat} \approx -0.165$$

- Asymmetry recovered with NEO at 1st 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_ϕ^{nat} .

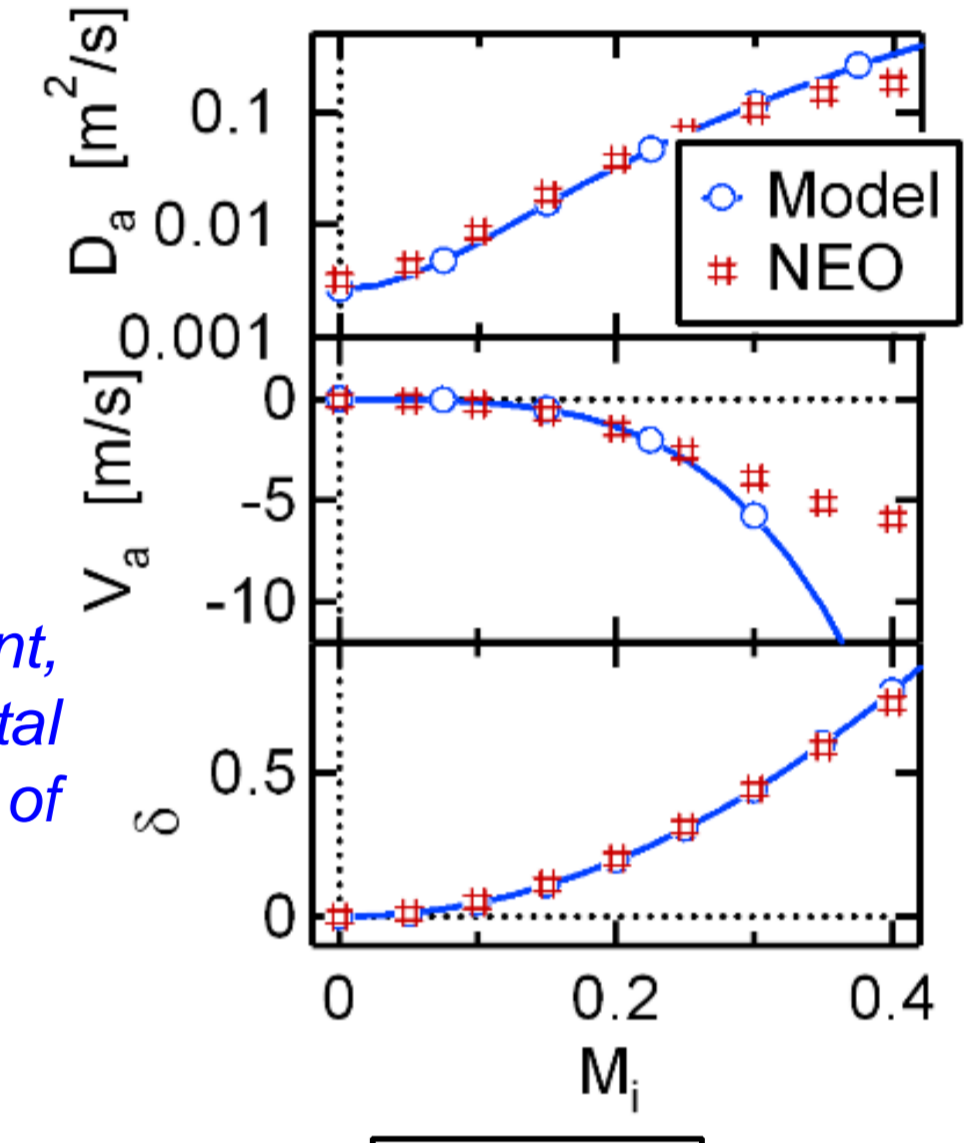


Toroidal rotation and ICRH effect

Toroidal rotation

- Neoclassical diffusion coefficient, pinch velocity and horizontal asymmetry at $\Gamma^{neo}=0$ 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

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

- Neoclassical diffusion coefficient, pinch velocity and horizontal asymmetry at $\Gamma^{neo}=0$ 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

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

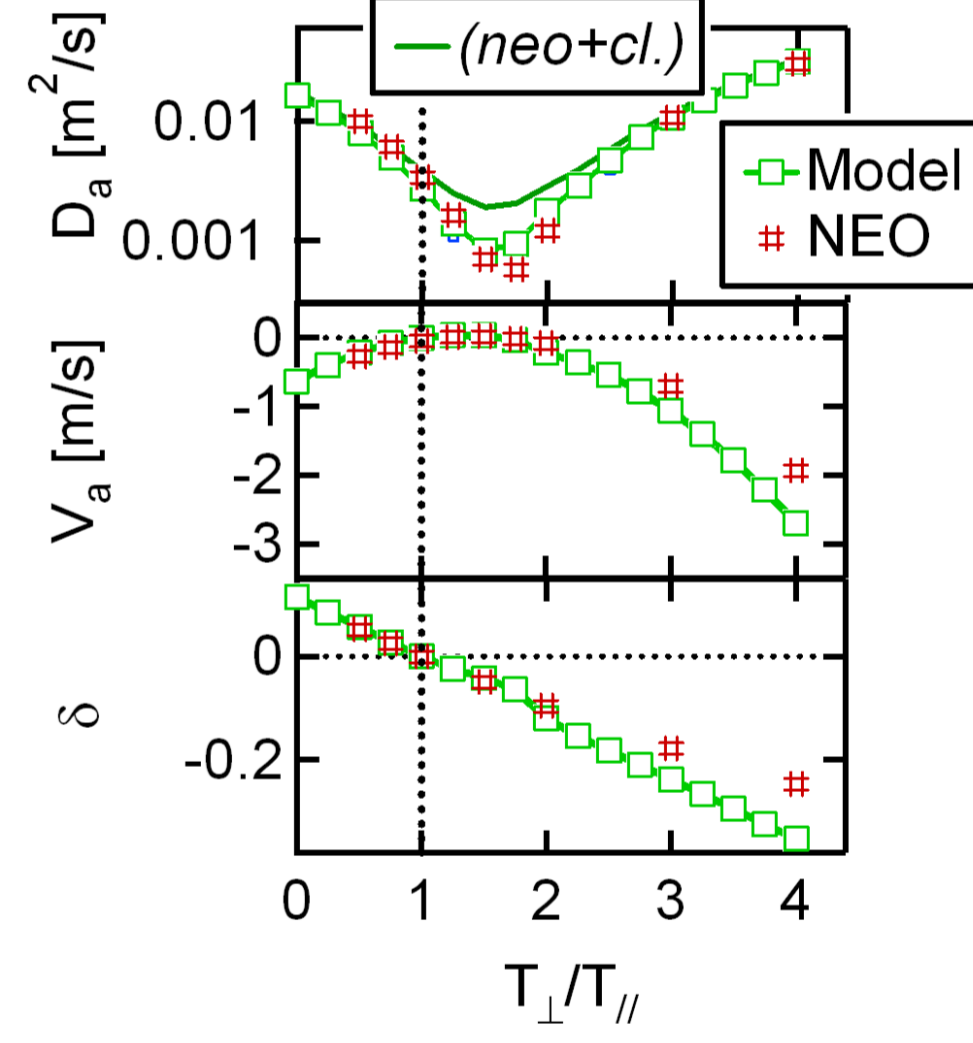


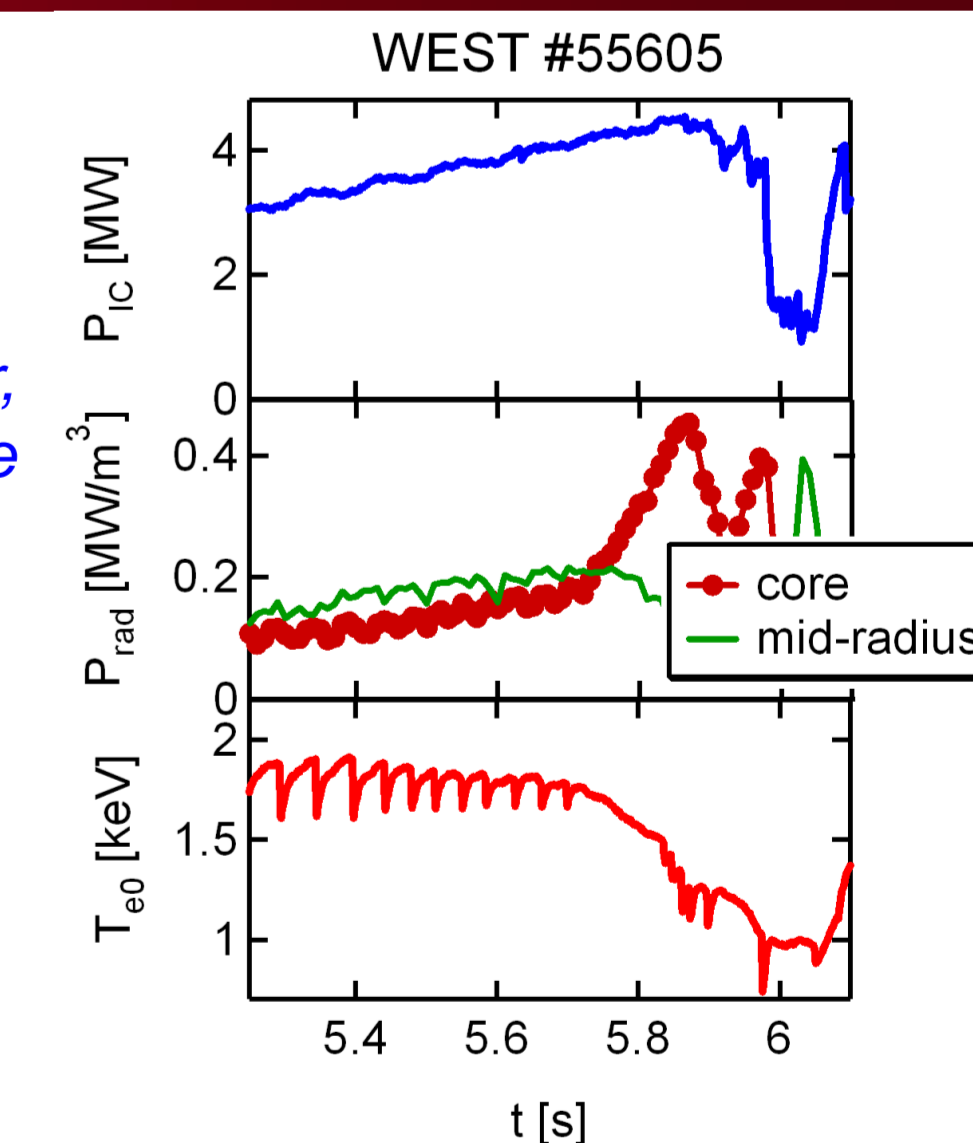
Fig.6 : Diffusion coefficient, pinch velocity and horizontal asymmetry as a function of T_\perp/T_\parallel .

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 & $T_i \propto \sqrt{n_e T_e}$
- Minority temperature anisotropy : EVE/AQL [10] (fig. 8)
- Minority temperature screening effect not considered
- Toroidal rotation not measured but (4,1) MHD mode accelerates linearly with ICRH power (fig.9)
- Rotation: $V_\phi = V_0 + (V/P) \times P_{IC}$ with $(V/P) \sim 3 \text{ km/s/MW}$
- Tungsten peaking from FACIT consistent with ICRH drive at low rotation ($V_\phi \sim 0$) (fig.10)

WEST #55605 - Mirnov coil

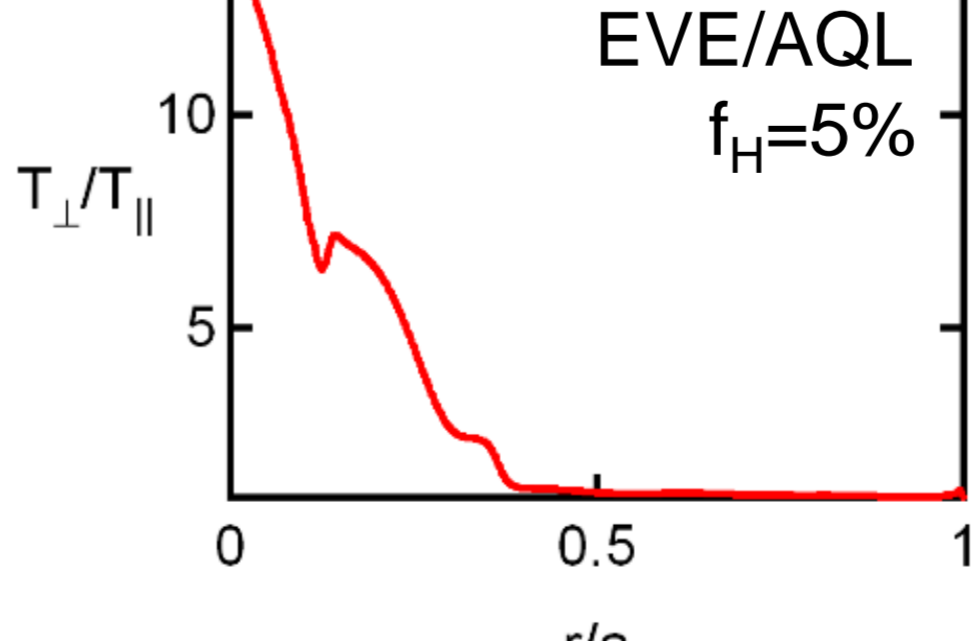


Fig.8 : H temperature anisotropy from EVE/AQL

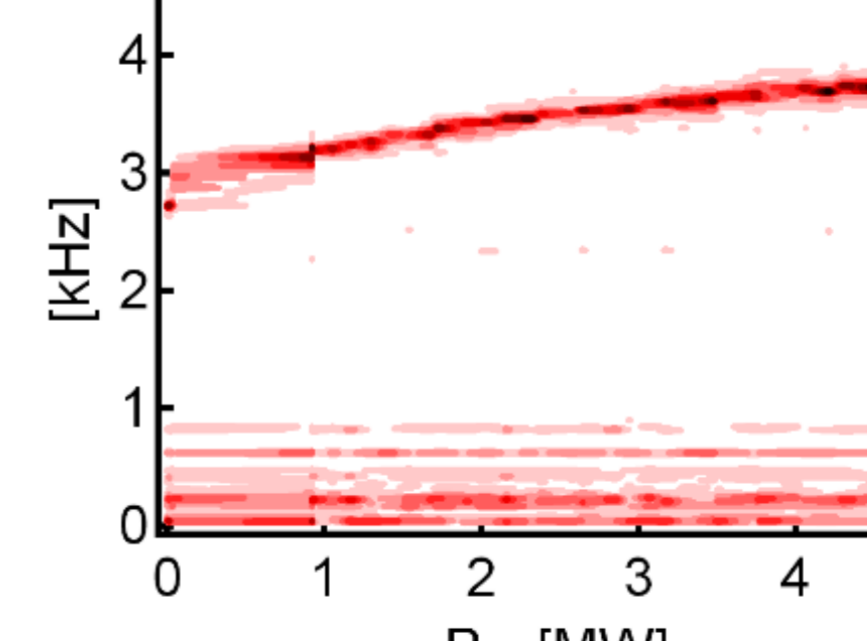


Fig.9 : MHD mode rotation as a function of P_{IC} .

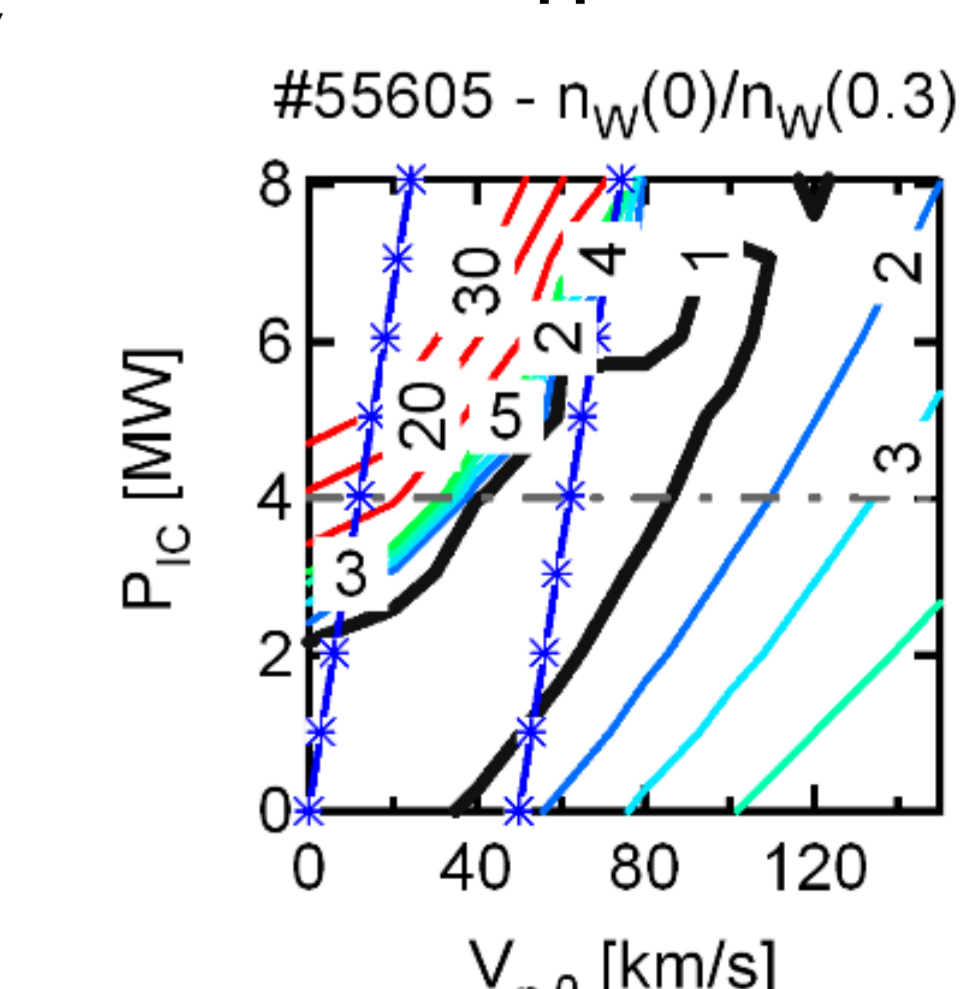


Fig.10 : Tungsten peaking in (P_{IC}, V_ϕ) map. Trajectories for $V_\phi=0$ and 50 km/s

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