Neoclassical transport in density pedestals in the presence of impurities

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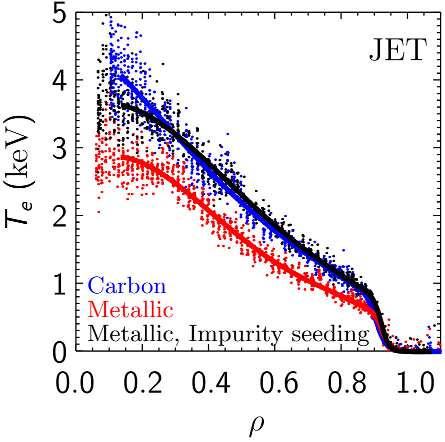
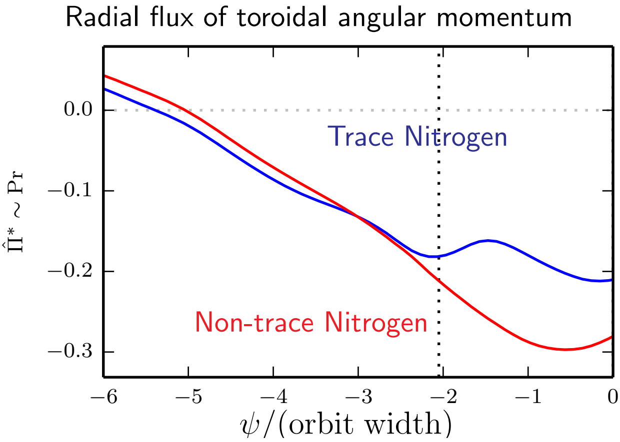
Impurities affecting pedestal performance



[*M. N. A. Beurskens et al. (2013) Nuclear Fusion* **55** *113031*]

- Global energy confinement strongly correlated with pedestal performance
- Carbon to ITER-like wall: Confinement degradation
- Impurity seeding: Performance recovered
- Changes linked to pedestal
- Turbulence suppressed, neoclassical processes could play a role

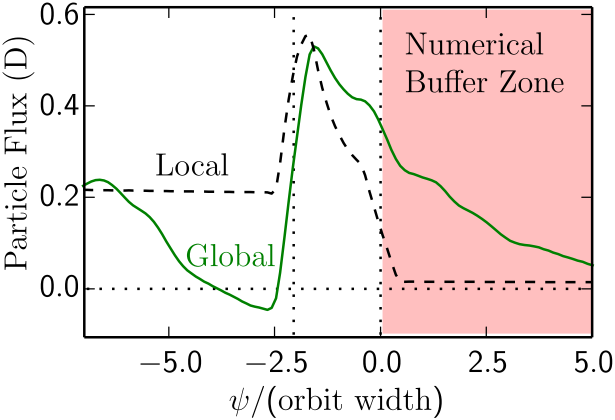
Significant momentum transport due to finite orbit width, affected by non-trace impurities



Radially local vs. global

Local given by local values of plasma parameters and their gradients, ψ is only a parameter

Global couples nearby radii $\implies$ Differential equation in ψ



Radially global δf drift kinetic equation

- Linearize and retain $\vec{v}_d \cdot \nabla g = (\vec{v}_{E0} + \vec{v}_m) \cdot \nabla g$
- $O(1)$ variation of $e\Phi/T$ along ion orbit, and radial coupling
- $g = f - f_M(1 - Ze\Phi_1/T)$, $\Phi_1 = \Phi - \langle \Phi \rangle_{\mathrm{FSA}}$

Global drift-kinetic equation

$$(v_{||}\vec{b} + \vec{v}_d) \cdot \nabla g - C_l[g] = -\vec{v}_d \cdot \nabla f_M + S$$

Allows Ion orbit-width scale n, Φ, T_e variations

Assumes Electrostatic ion confinement & weak T_i variations

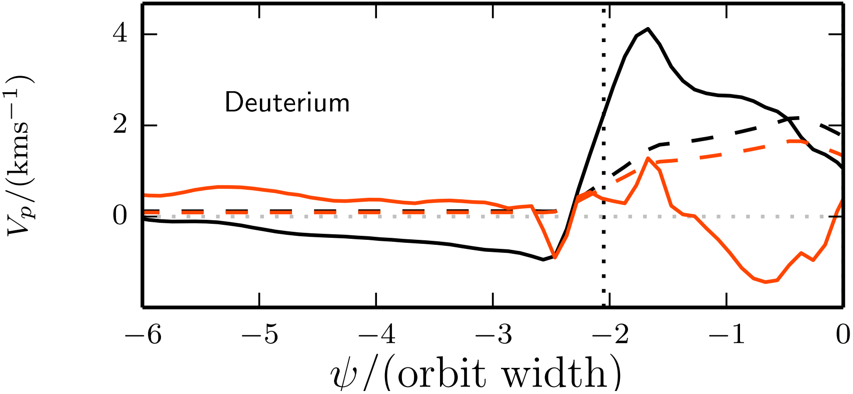
Solved with the PERFECT code

[*M. Landreman et al. (2012) PPCF* **54** *115006*]

[*M. Landreman et al. (2014) PPCF* **56** *045005*]

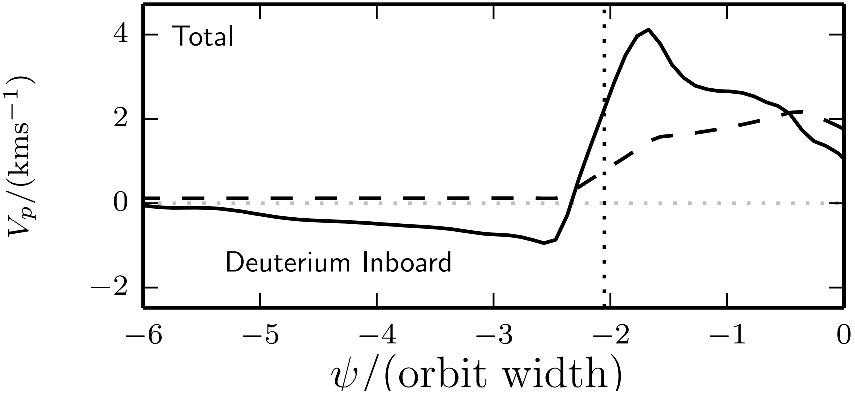
Poloidal flows modified by global effects

- Inboard-outboard asymmetry in global simulations.
- Significant effect several orbit widths away from pedestal.



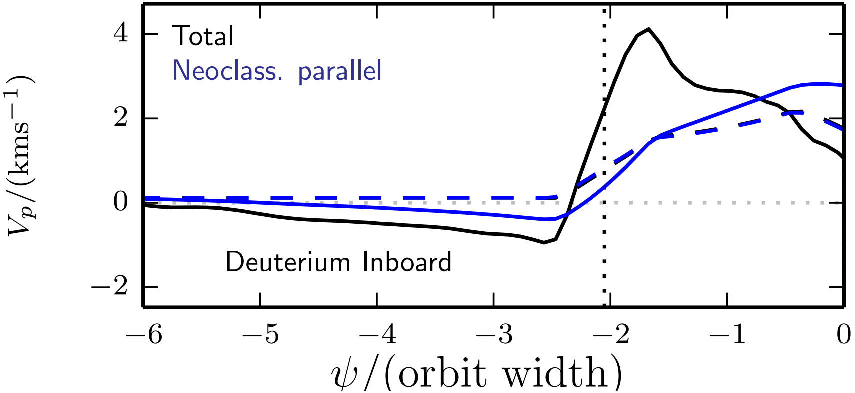
Inboard Outboard Solid: global Dashed: local

Poloidal flow components



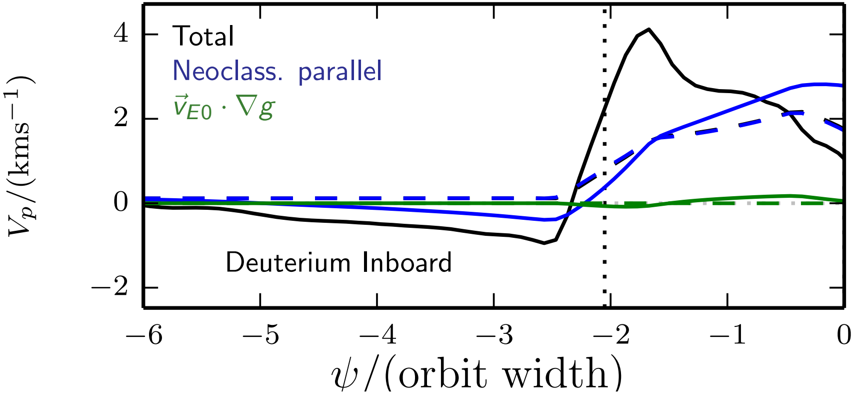
Solid: global   Dashed: local

Poloidal flow components



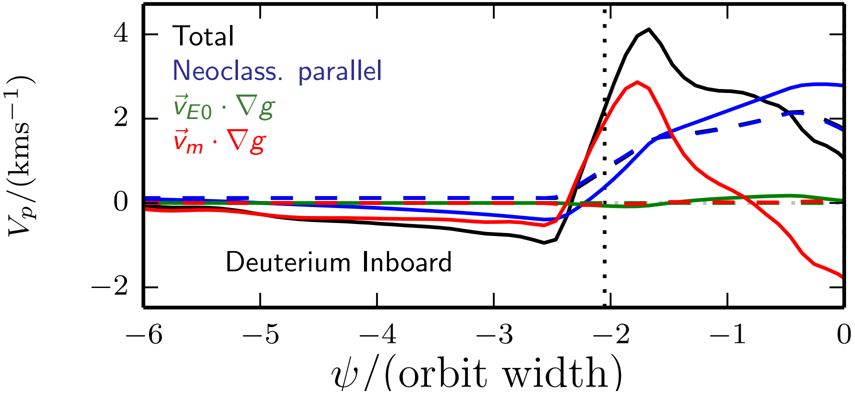
Solid: global Dashed: local

Poloidal flow components



Solid: global   Dashed: local

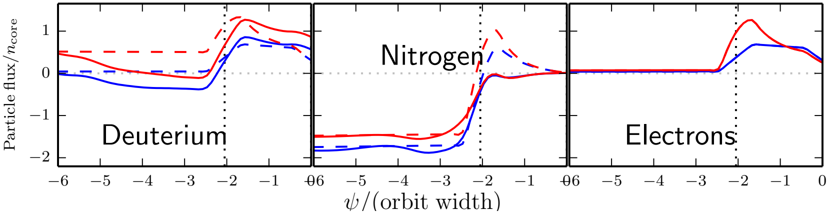
Poloidal flow components



Solid: global Dashed: local

Particle transport

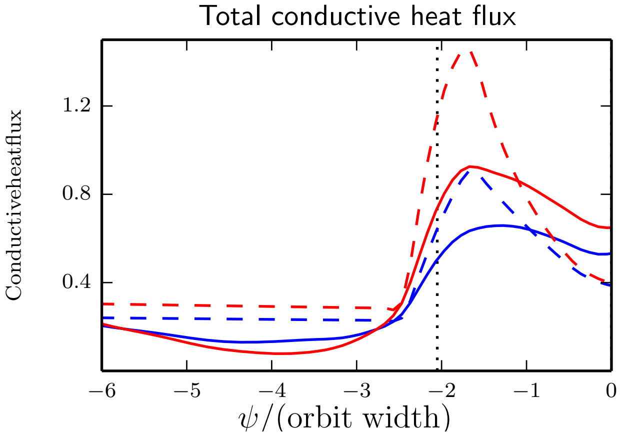
Particle fluxes (normalized by species density in the core)



$Z_{eff} = 1.017$ $Z_{eff} = 2.33$ Solid: global Dashed: local

- Fluxes deviate from local several orbit widths into core
- Γ_e can be substantial in the pedestal
- Particle transport is not intrinsically ambipolar
- Ion and non-trace impurity fluxes in the same direction

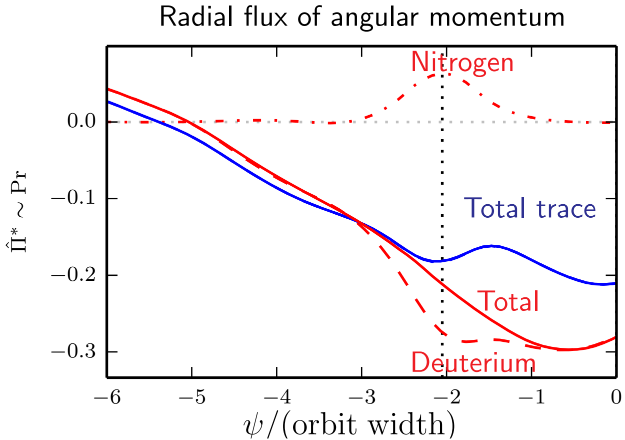
Conductive heat transport



$Z_{\text{eff}} = 1.017$ $Z_{\text{eff}} = 2.33$ Solid: global Dashed: local

- Radial coupling reduces heat flux at the pedestal top.

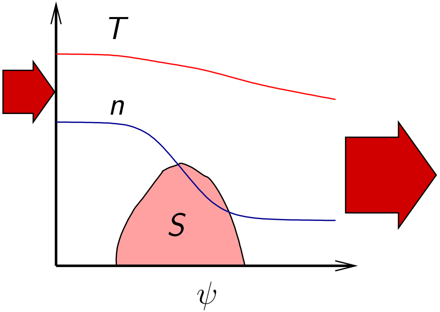
Momentum transport



$Z_{\text{eff}} = 1.017$ $Z_{\text{eff}} = 2.33$ $\hat{\Pi}^* = \Pi/q_{\text{D}}\,(d_\psi T_{\text{D}})/(R m_{\text{D}} V_{\text{torD}} d_\psi n_{\text{D}})$

- Ion momentum flux significantly increased by impurities
- Robustness tested for impurity profiles pushing orderings

Momentum transport and pedestal performance



Increased impurity content

$\Longrightarrow$ Increased neoclassical momentum transport

$\Longrightarrow$ Sources increase

$\Longrightarrow$ (Speculation) Increased turbulent momentum transport

$\Longleftrightarrow$ Steeper pedestal

Conclusions

- Modeling neoclassical transport in density pedestals with non-trace impurities.
- Poloidal flows affected by sharp radial variation of transport.
- Ion and non-trace impurity fluxes in the same direction.
- Global effects several orbit widths away from pedestal.
- Sizable momentum transport, increased by impurities.

Modeling I. Pusztai et al. (2016) PPCF **58** 085001

Prandtl nr. S. Buller et al. (2016) EPS conference O4.118

PERFECT M. Landreman et al. (2012) PPCF **54** 115006

PERFECT M. Landreman et al. (2014) PPCF **56** 045005

Extra slides

PERFECT inputs

Profile considerations:

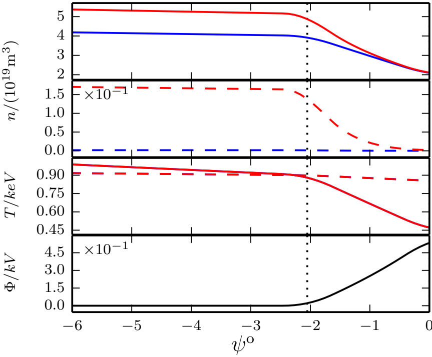
- Preferably close to experiments
- $\begin{cases} \rho_p \nabla \ln T \ll 1 \\ \rho_p \nabla \ln \eta \ll 1 \end{cases}$, $\begin{cases} \eta = n e^{Ze\Phi/T} \\ \rho_p = \frac{m v_T}{Z e B_p} \end{cases}$

$\Longrightarrow$ $V_{\text{dia}} + V_{E\times B} \sim \delta v_T$ (Low flows).

- Local boundary conditions
- Modest variation of ion heat flux

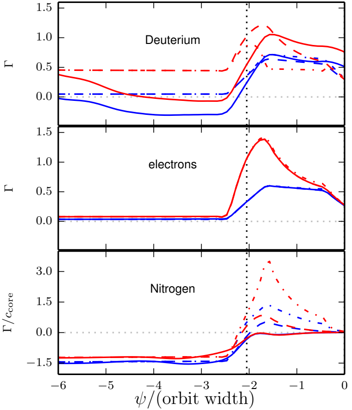
Local Miller magnetic geometry:

$q = 3.5$, $\epsilon = 0.263$,
$\kappa = 1.58$, $s_\kappa = 0.479$,
$\delta = 0.24$, $s_\delta = 0.845$,
$dR_0/dr = -0.14$.



Particle fluxes

Trace Non-trace
Solid: global
Dashdot: ExB, no radial coupling
Dashed: Local



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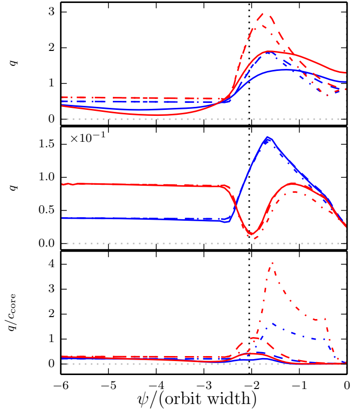

Momentum fluxes

Trace Non-trace
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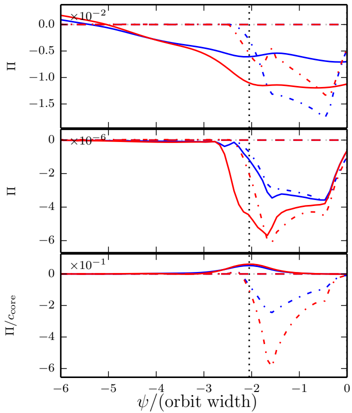
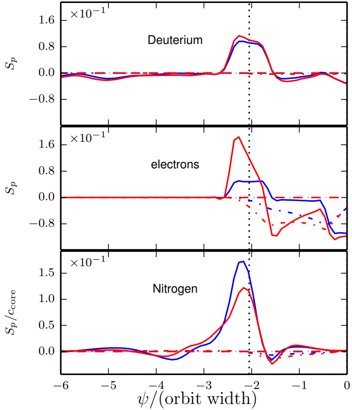


Particle sources

Trace Non-trace
Solid: global
Dashdot: ExB, no radial coupling
Dashed: Local



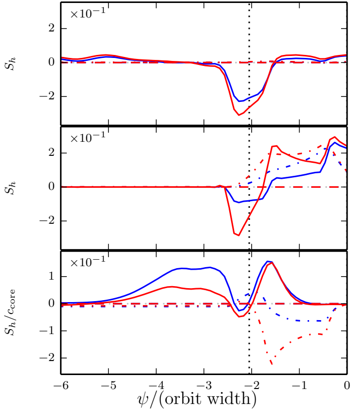
Heat sources

Trace Non-trace

Solid: global

Dashdot: ExB, no radial coupling

Dashed: Local



Equation in PERFECT: Global DKE with Sources

Additional constraints:

$$\left\langle \int \mathrm{d}^3 v g \right\rangle_\psi = 0 \qquad \left\langle \int \mathrm{d}^3 v v^2 g \right\rangle_\psi = 0,$$

Solve for ψ-dependence of particle and heat sources:

$$S = \left(x^2 - \frac{5}{2}\right) e^{-x^2} \Theta(\theta) S_p(\psi) + \left(x^2 - \frac{3}{2}\right) e^{-x^2} \Theta(\theta) S_h(\psi)$$

System of equations solved in simulations:

$$(v_{\|}\vec{b} + \vec{v}_d) \cdot \nabla g - C_l[g] - S = -\vec{v}_d \cdot \nabla f_M$$

$$\left\langle \int \mathrm{d}^3 v g \right\rangle_{FSA} = 0$$

$$\left\langle \int \mathrm{d}^3 v v^2 g \right\rangle_{FSA} = 0.$$

Poloidal flows

$$V_p = \frac{B_P}{nB}\int d^3v v_\| g + \frac{T}{mB\Omega} I B_p \left[\frac{p'}{p} + \frac{Ze\Phi_0'}{T}\right]$$
$$+ \frac{c}{nB^2} I B_p \Phi_0' \int d^3v g + \frac{1}{2nB\Omega} I B_p \frac{\partial}{\partial\psi}\int d^3v v_\perp^2 g.$$

Density perturbation

Solid frame: global
Dashed frame: Local
Above: non-adiabatic $\delta n/n$
Below: total $\delta n/n$