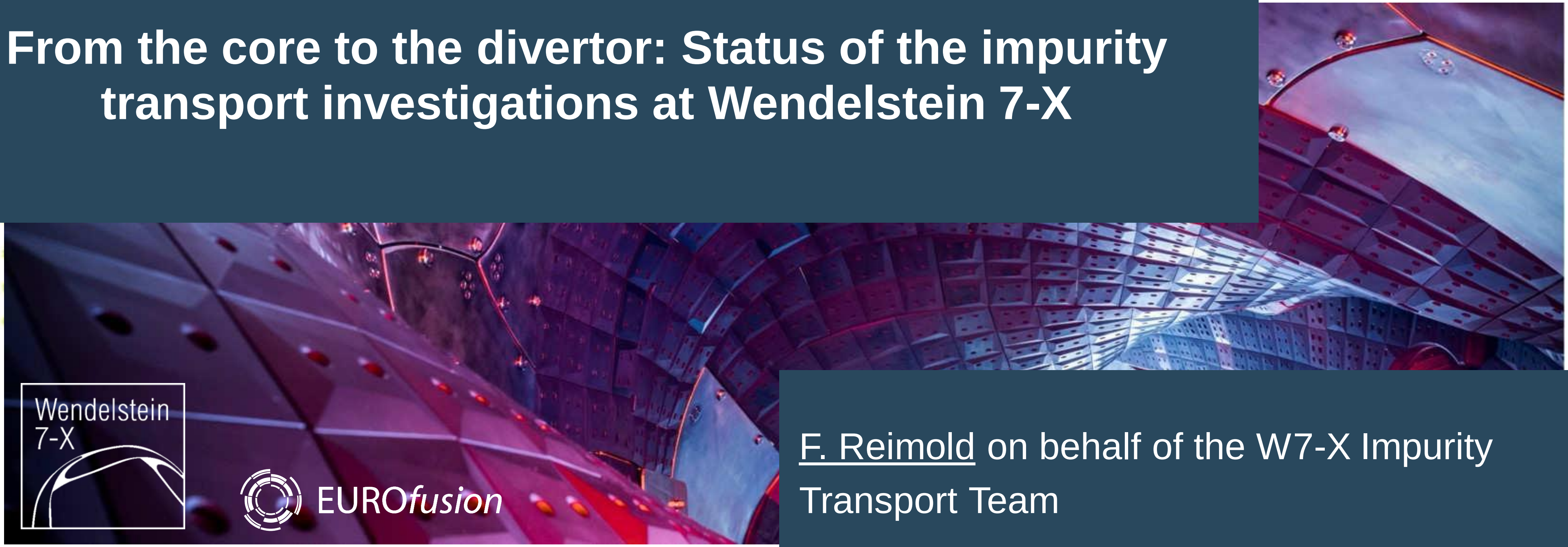
From the core to the divertor: Status of the impurity transport investigations at Wendelstein 7-X



Wendelstein 7-X

EUROfusion

F. Reimold on behalf of the W7-X Impurity Transport Team

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Impurity Transport Team

C.D. Beidler[1], D. Bold[1], C. Brandt[1], R. Bussiahn[1], B. Buttenschön[1], A. Demby[1], R. De Wolf[8], Y. Feng[1], O. Ford[1], T. Fornal[6], J.M. García-Regaña[2], B. Geiger[4], T. Gonda[3], M. Gruca[6], F. Henke[1], M. Kriete[3], I. Ksiazek[6], M. Kubkowska[6], A. Langenberg[1], N. Mazziz[1], K. McCarthy[2], N. Pablant[7], G. Partesotti[1], V. Perseo[1], P. Pöleskei[1], T. Romba[1], D. Medina Roque[2], H. Smith[1], C. Swee[4], N. Tamura[5], A. Tsikouras[1], T. Tork[1], J.L. Velasco[2], Th. Wegner[1], N. Wendler[6], V. Winters[1], D. Zhang[1], A. Zocco[1] and W7-X Team

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[5]National Institute for Fusion Science, Toki, Japan

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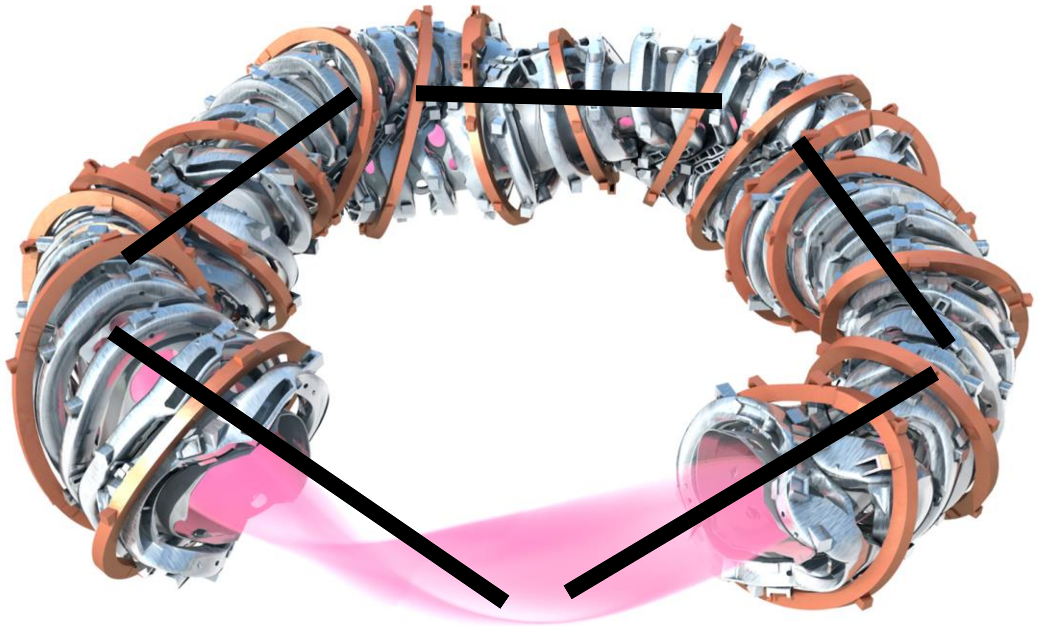
Introducing the W7-X geometry

Full 3D- equilibrium

- 5-fold periodicity (stellarator-symmetry)
- Low shear device with $\iota = \frac{1}{q} \approx 1$
- Low poloidal mode number $4 \leq m \leq 6$

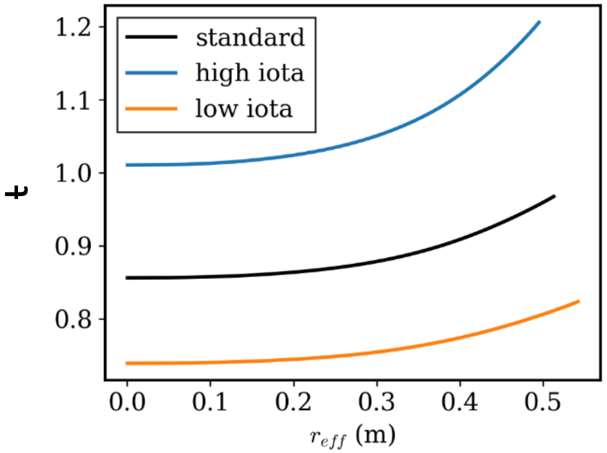


Core topology

- More complex geometry
  - Loss of tor. symmetry & variation of mag. field strength
  - Locally trapped particles
- Options for optimization (turbulence & neoclassics)

Edge topology

- Multiple Islands/X-points
- Upstream vs. Downstream & Main Chamber vs. Divertor
  - Source, shielding, profile monotonicity,…
- More shallow fieldline pitch (θ ~ 0.001 (W7-X) vs 0.1 (tok.))
  - Perpendicular transport much more important



R_{maj} = 5.5 m
r_{min} ≈ 0.5 m
B_{axis} = 2.5-2.6 T

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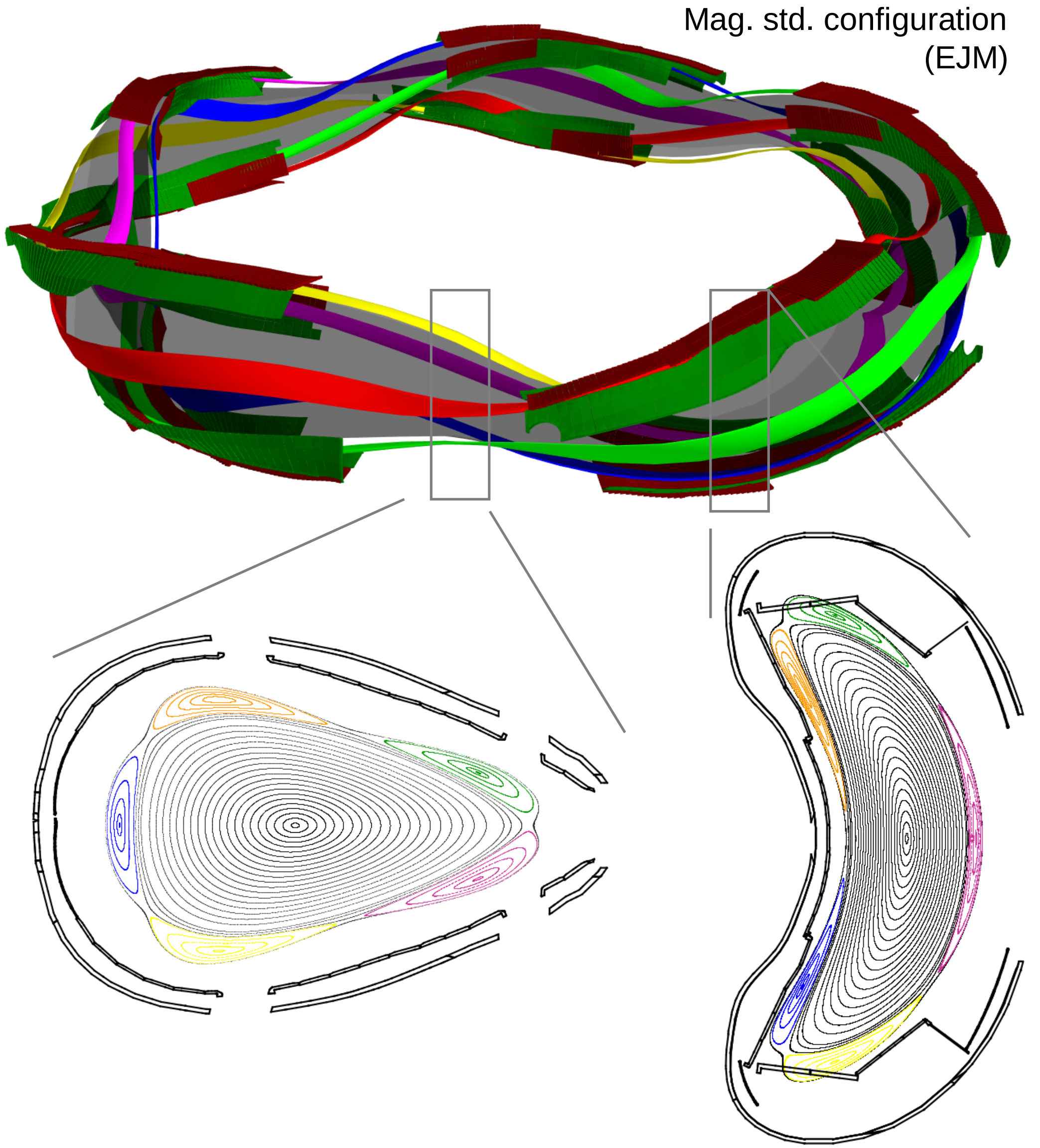

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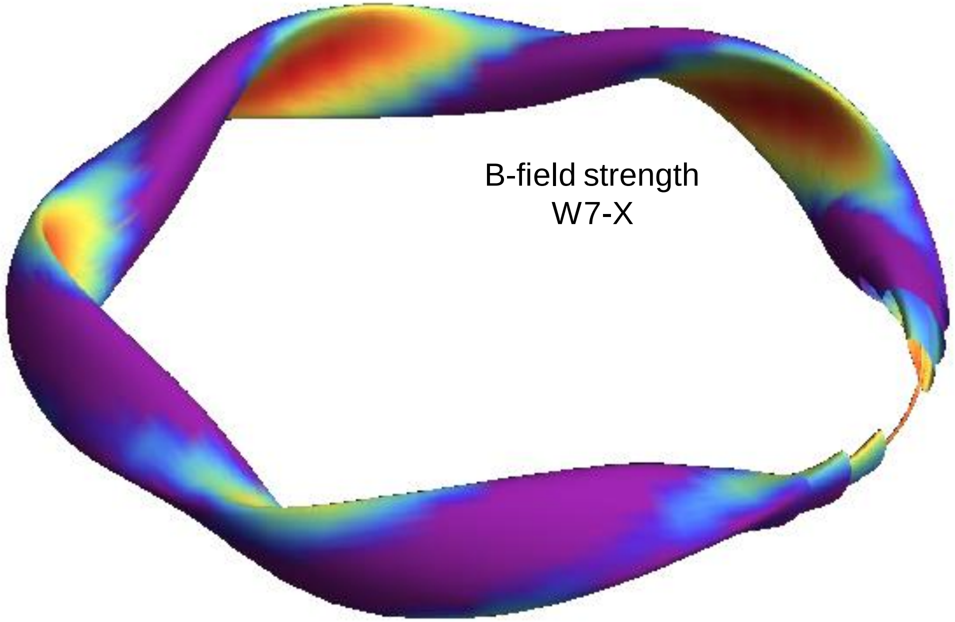

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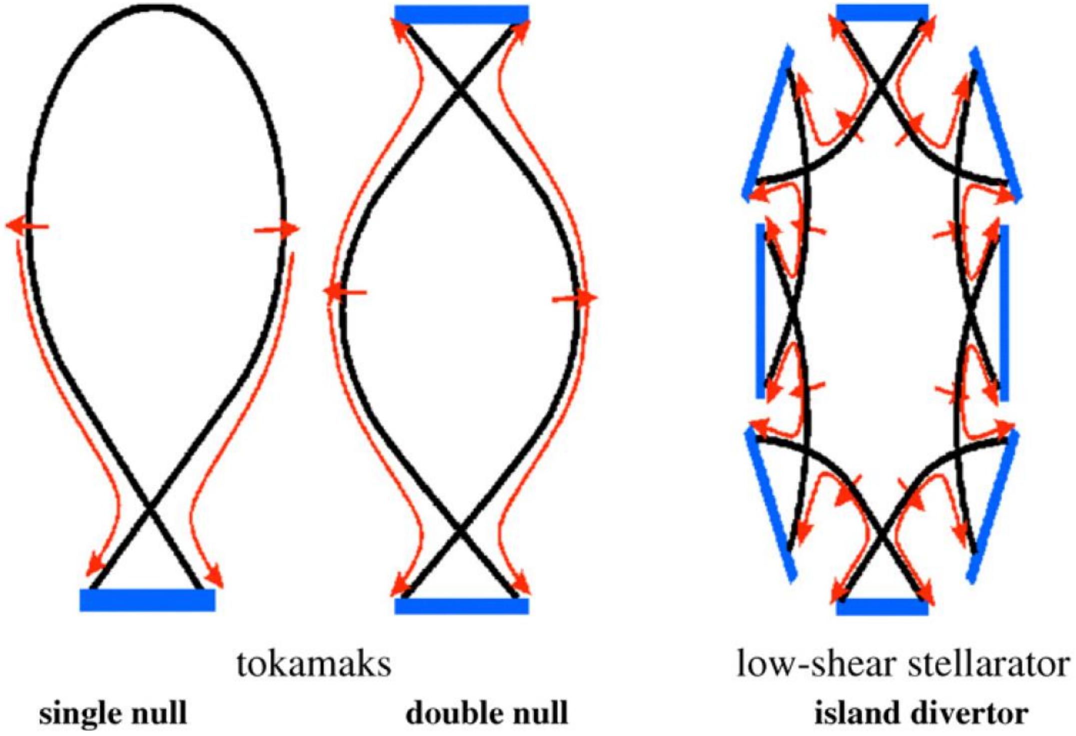

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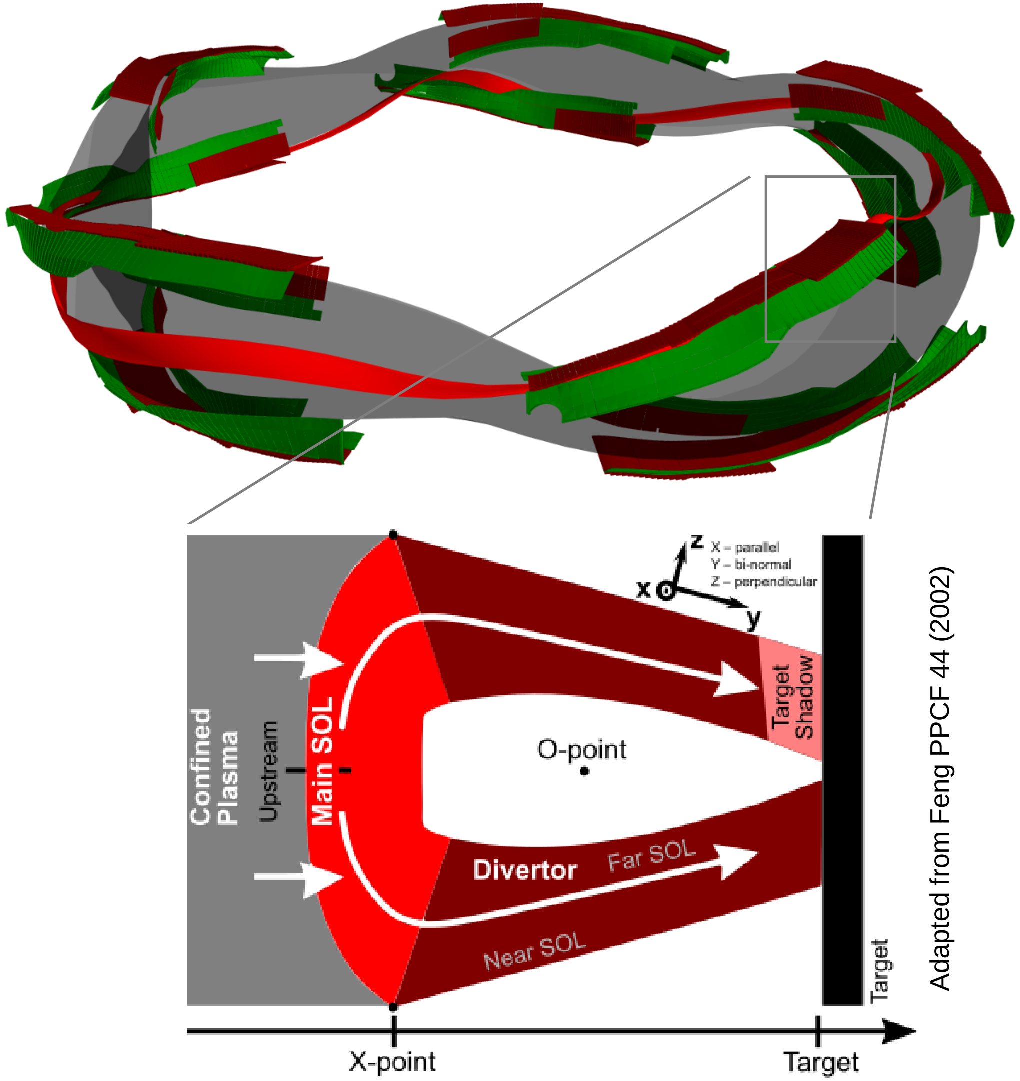


Adapted from Feng PPCF 44 (2002)

Outline

Impurity Transport

Part I: Core Transport

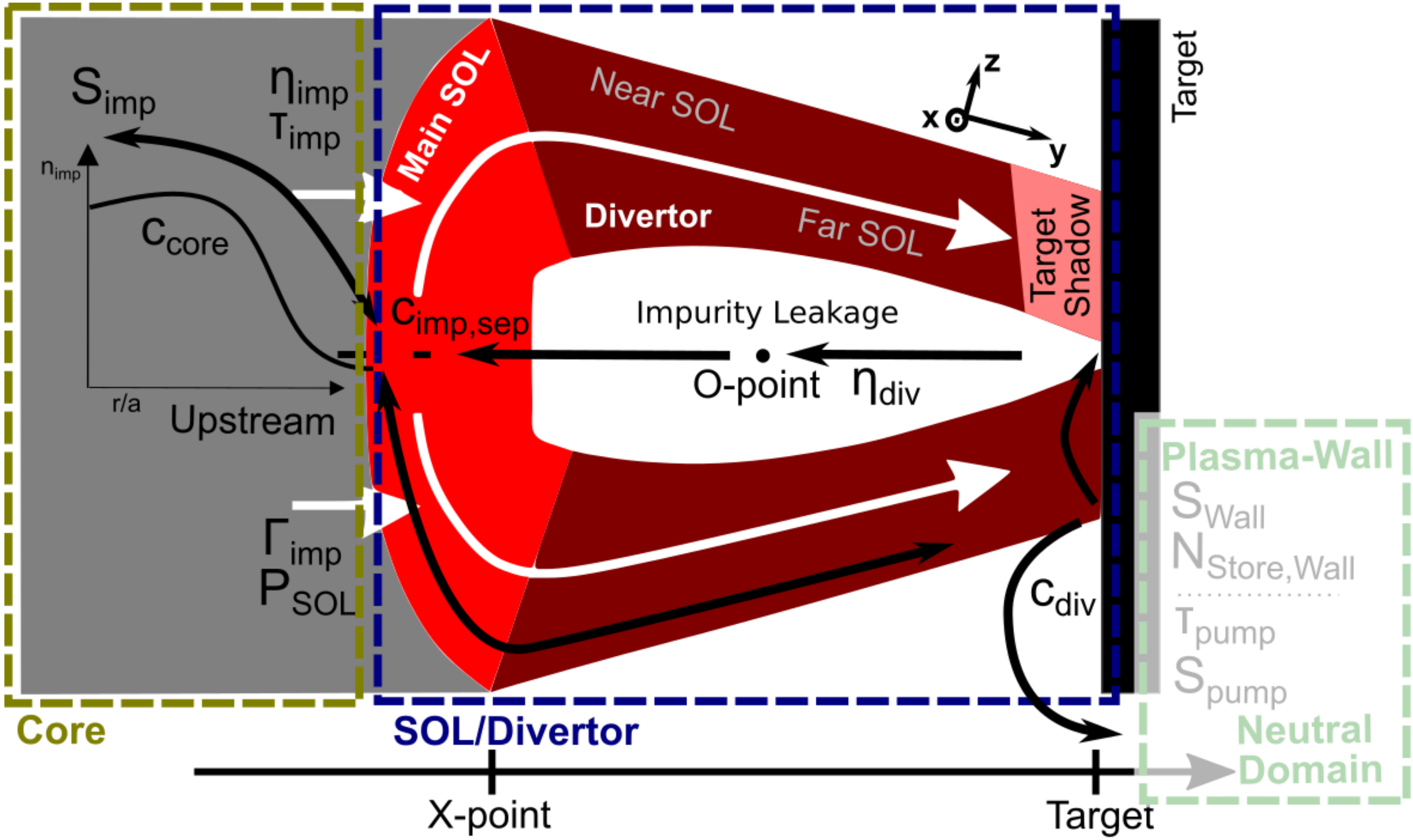
- Neoclassical Transport
- Turbulent Transport
- Some Exp. Highlights

Part II: SOL-Transport

- Parallel Force Balance
- Perpendicular Transport

Part III: Neutrals & PWI

Summary



PART I -

What do we expect from theory for core transport?

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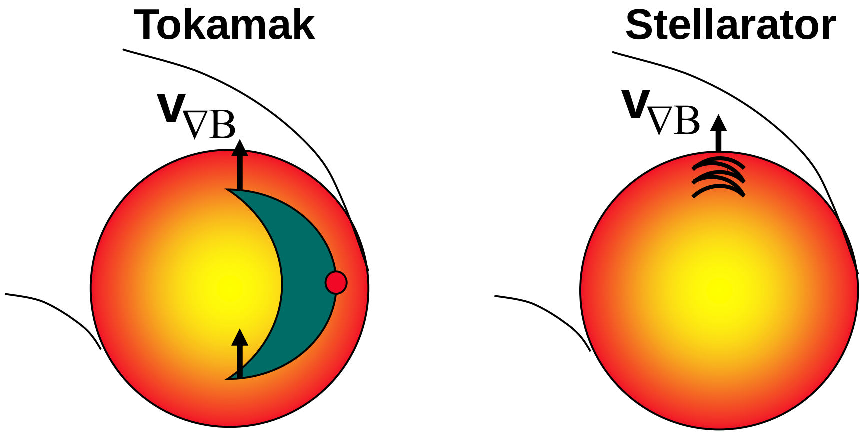
Collisional transport at low collisionality significantly different between stellarators & tokamaks:

- **Particles trapped in local magnetic wells (ε_{eff})**
  - Increased perp. transport via drifts orbit losses
- **E_r establishes to provide ambipolar transport**
  - Drift orbit losses reduced → lower transport
  - Electron ($E_r > 0$) vs. ion root ($E_r < 0$)

Optimization:

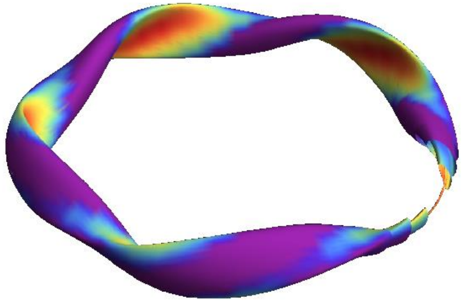
- Reducing ε_{eff}
- Separate optimization of ion/electron fluxes

Note: In optimized stellarators classical transport can become important



Radial drift averages over a banana orbit

Radial drift doesn‘t average to zero due to local mirrors



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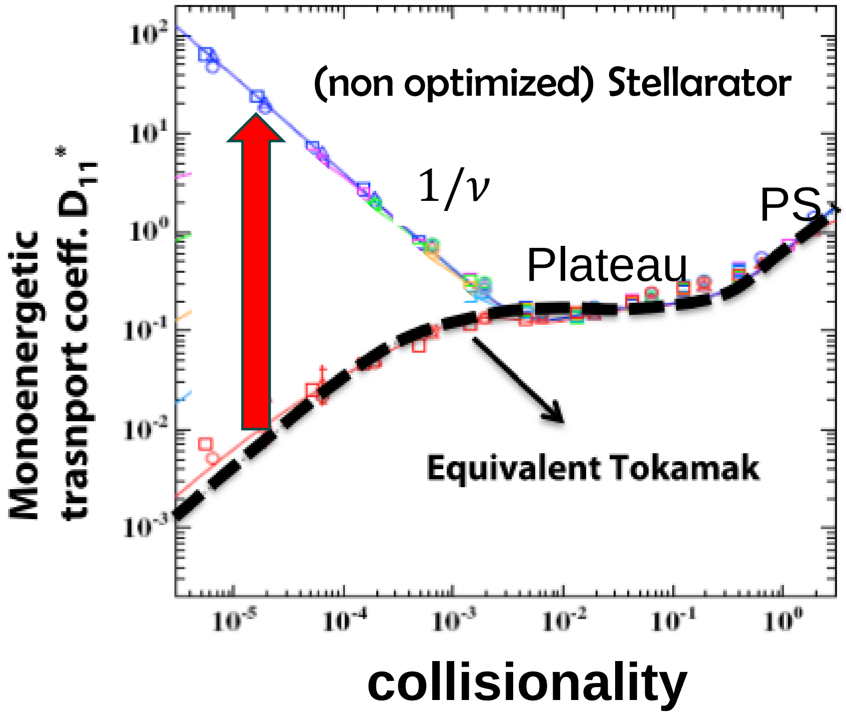

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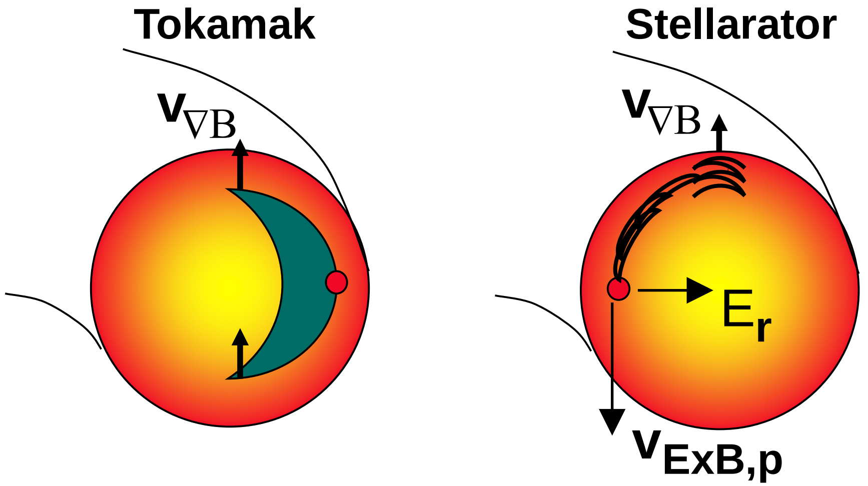

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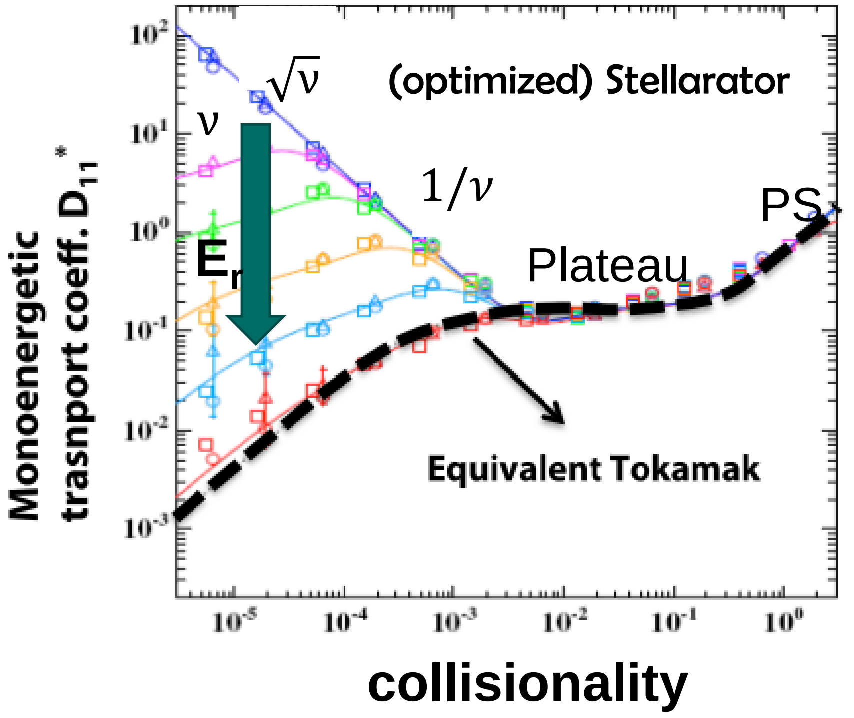

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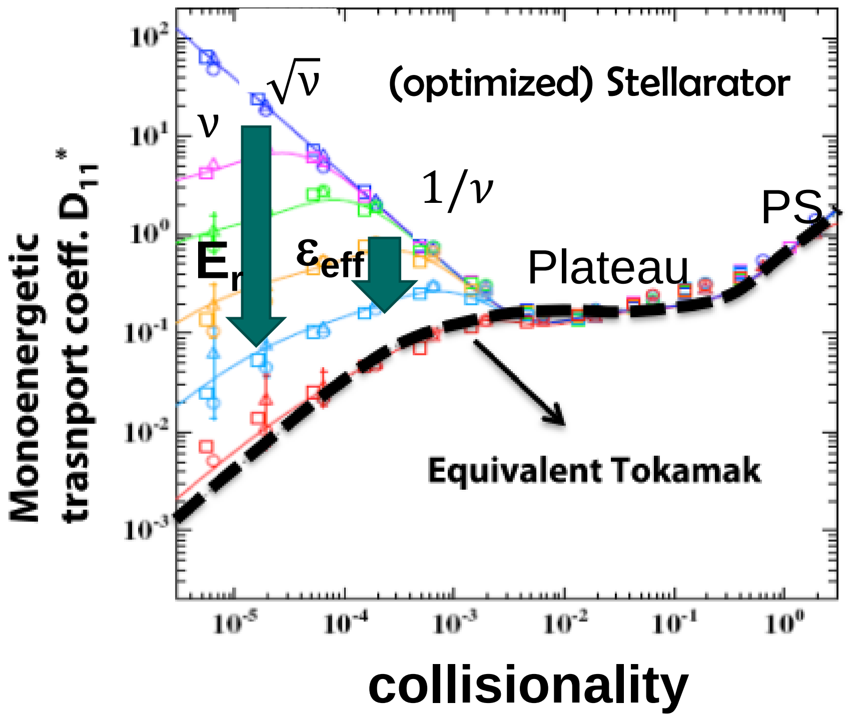

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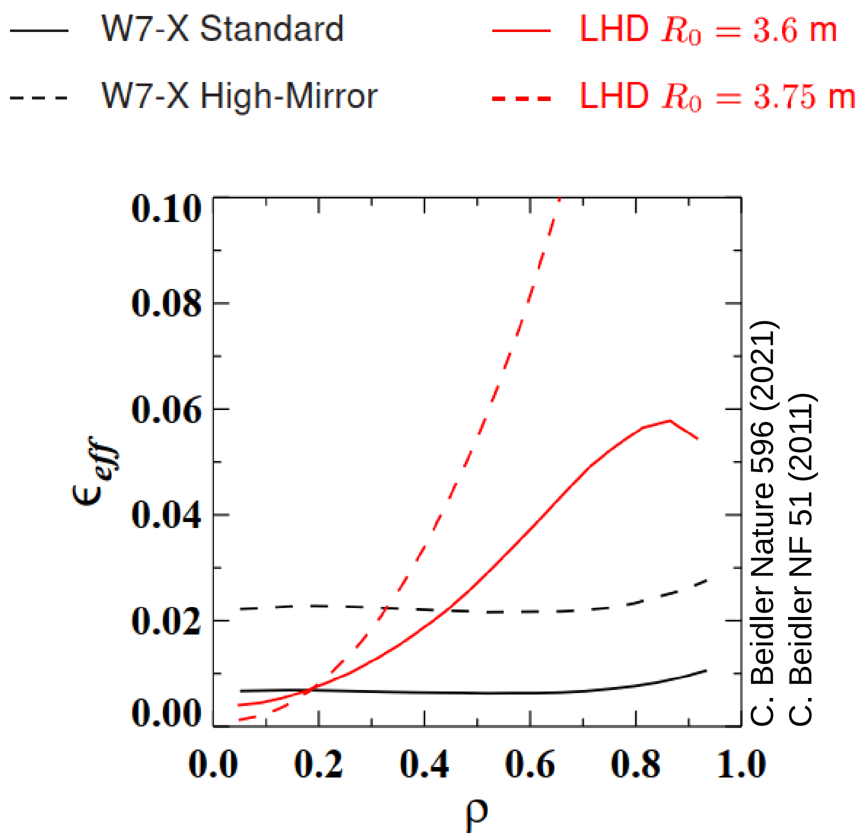

C. Beidler Nature 596 (2021)

C. Beidler NF 51 (2011)

$$D_{11}^{e} \propto \left(\frac{4}{3\pi}\right)^{2} \frac{\left(2\epsilon_{eff}\right)^{3/2}}{\nu^{*}}$$

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$$\Gamma_Z = -n_Z\, {L_{11}}^Z \left(\underbrace{\frac{d\ \ln n_Z}{dr}}_{\text{diffusion}} - \underbrace{Z\frac{E_r}{T_Z} + \delta_{12}^Z \frac{d\ln T_Z}{dr}}_{\text{convection}} \right)$$

Ion root: $D_i \gg D_e$
$\rightarrow \Gamma_i(E_r) = 0$

$$\frac{d\ \ln n_i}{dr} - \frac{E_r}{T_i} + \delta_{12}^i \frac{d\ln T_i}{dr} = 0$$

$$\downarrow$$

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$T_Z = T_i, Z_i = 1$

$D_{11}^Z = D_{11}^Z(E_r)$

Regime	δ_{12}	
Banana regime	-1/2	Screening
$1/\nu$ – regime	+7/2	
$\sqrt{\nu}$ – regime	+5/4	
ν – regime	+1/2	
Plateau	+3/2	
Pfirsch-Schlüter	-1/2	Screening

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$$\Downarrow$$

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Beidler NF (in preparation)
Velasco PPCF 60 (2018)
Helander PRL 118 (2017)

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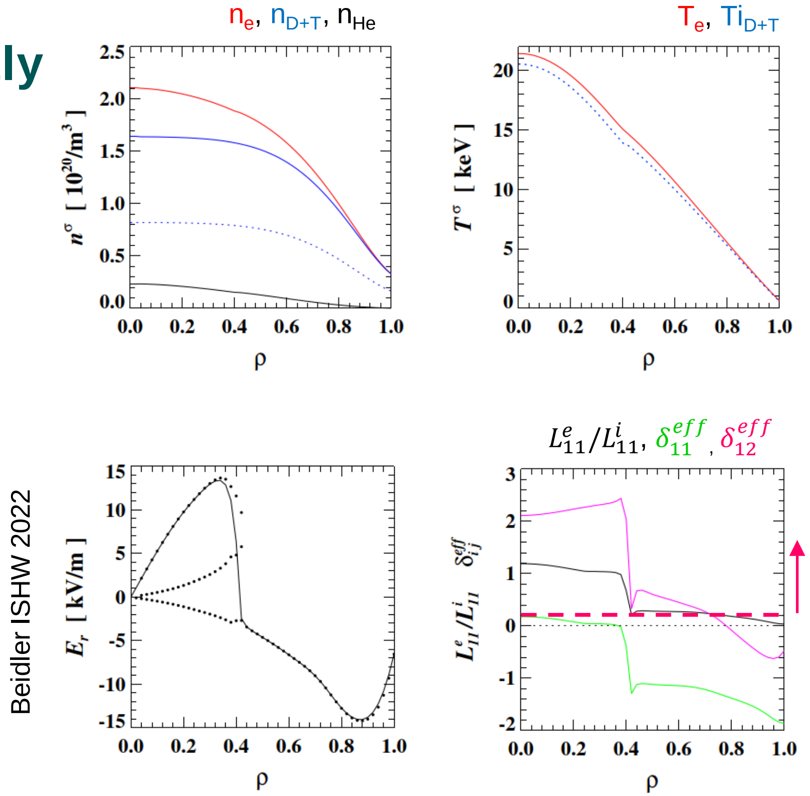

Temperature screeining

Hydra-NP04
20190108
Pol. force balance solved

$B_0 = 4.4T$, $< \beta i >= 5.43\%$,
$\tau_E = 2.03s = 1.61\ \tau_E^{ISS04}$,
$P_\alpha = 680$ MW, $P_{brems} = 92$MW

$$\Gamma_z = -n_z L^Z_{11}\left(\frac{d\ln n_Z}{dr} + \delta^{eff}_{11}\frac{d\ln n_i}{dr} - \delta^{eff}_{12}\frac{d\ln T_i}{dr}\right)$$

Condition for temperature screening:

$$\delta^{eff}_{12} = \frac{\delta^Z_{12} - Z\delta^i_{12} + L^e_{11}/L^i_{11}(\delta^Z_{12} + Z\delta^e_{12})}{1 + L^e_{11}/L^i_{11}} > 0 \quad \rightarrow \quad \frac{L^e_{11}}{L^i_{11}} > \frac{Z\delta^i_{12} - \delta^Z_{12}}{Z\delta^e_{12} + \delta^Z_{12}}$$

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Turbulent transport from electrostatic microinstabilities (low β):

- ITG
- TEM
- “KBM” (at high β, sub-dominant contributions?)

P. Xanthopulos PRL 125 (2020), J.M. Garcia-Regana NF 61 (2021) , J. Alcuson PPCF 62 (2020), M.N. Beurskens NF 61 (2021), G. Weir NF 61 (2021), Plunk PRL 122 (2019) , J. Proll JP 88 (2022), A. Krämer-Flecken (TTF ’23)

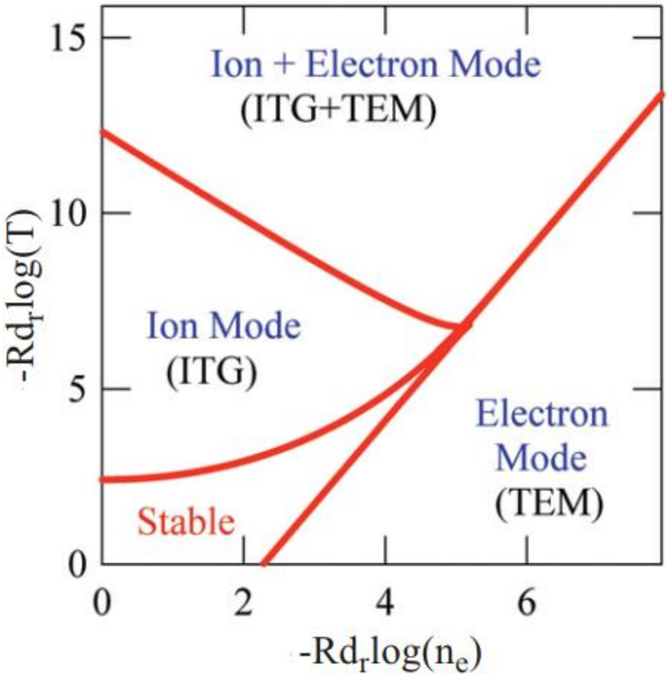
K. Aleynikov JPP 88 (2022)
P. Mulholland PRL (accepted)

Prediction from turbulence modeling

- Strong diffusion, low Z-dependence & low v/D

  → low τ_{imp} & flat n_{imp}-profiles
- Impact of impurities on turbulence in W7-X

See Poster Session today
J. Proll
See Poster Session Wednesday
A. Krämer-Flecken



Garbet et al, PPCF 2004

Limited amount of modeling for impurity transport: Stella, Gene3D, Euterpe

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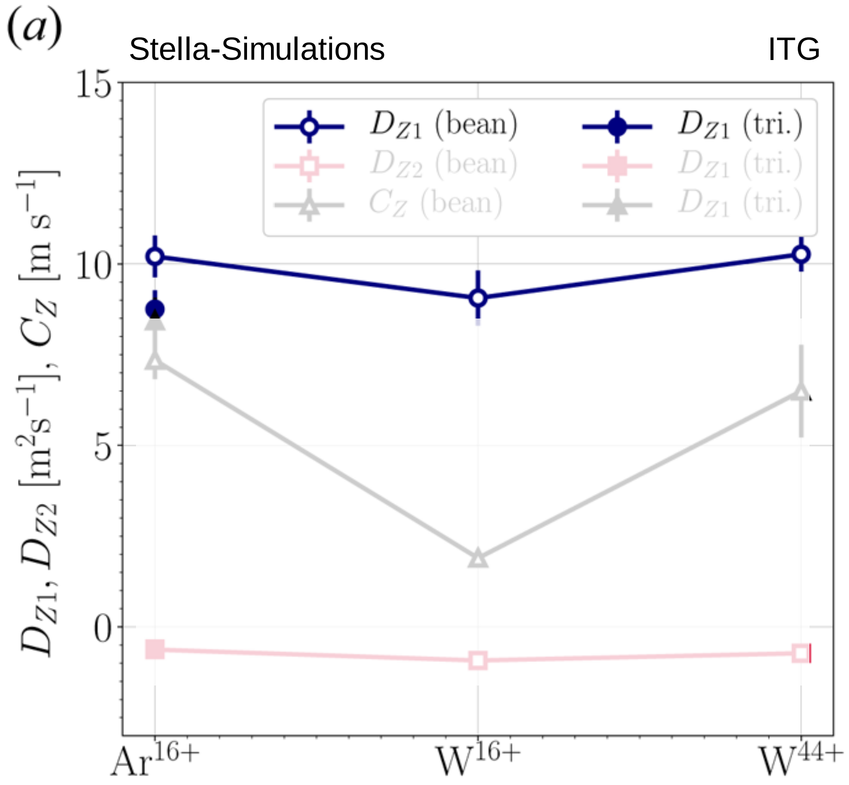

Stella-Simulations

ITG

J.M. Garcia-Regana JPP 87 (2021)

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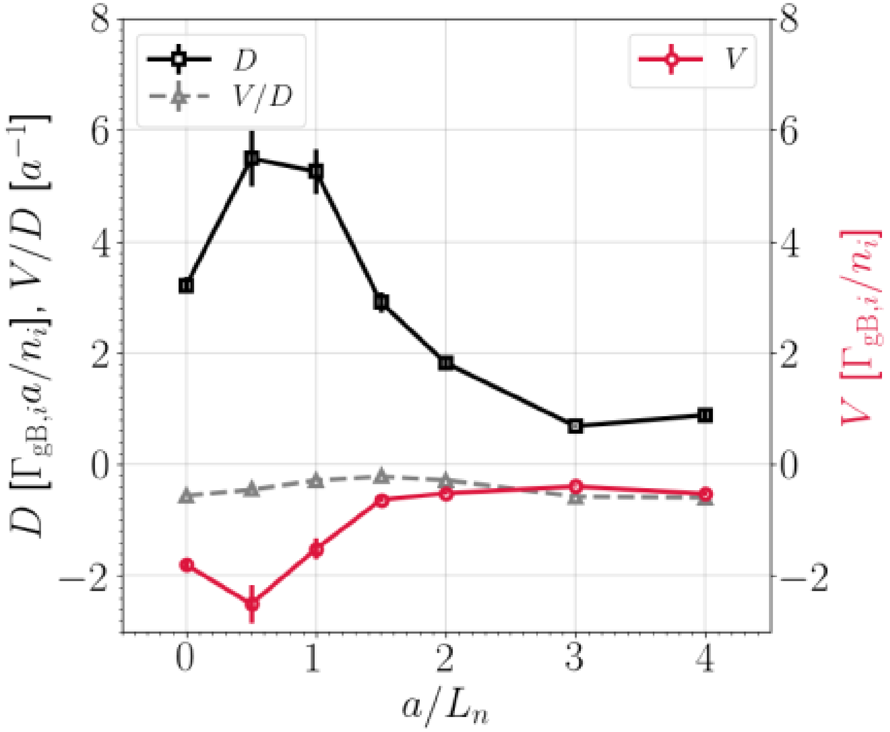

J.M. Garcia-Regana EPS (2022)

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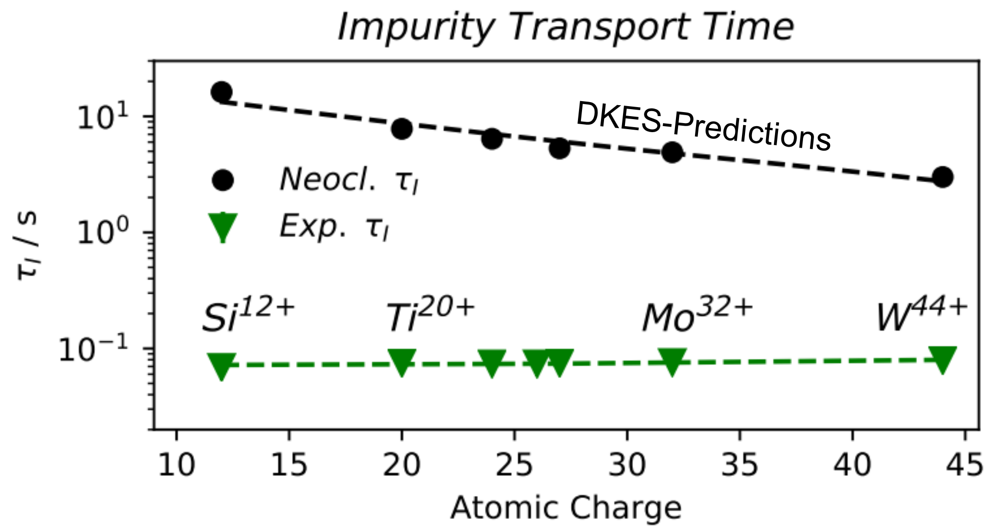

A. Langenberg POP 27 (2020)

Limited amount of modeling for impurity transport: Stella, Gene3D, Euterpe

- τ_{exp} ~ O(100 ms) vs. $\tau_{neoclassic}$ ~ O(1-10s)
- No Z-dependence

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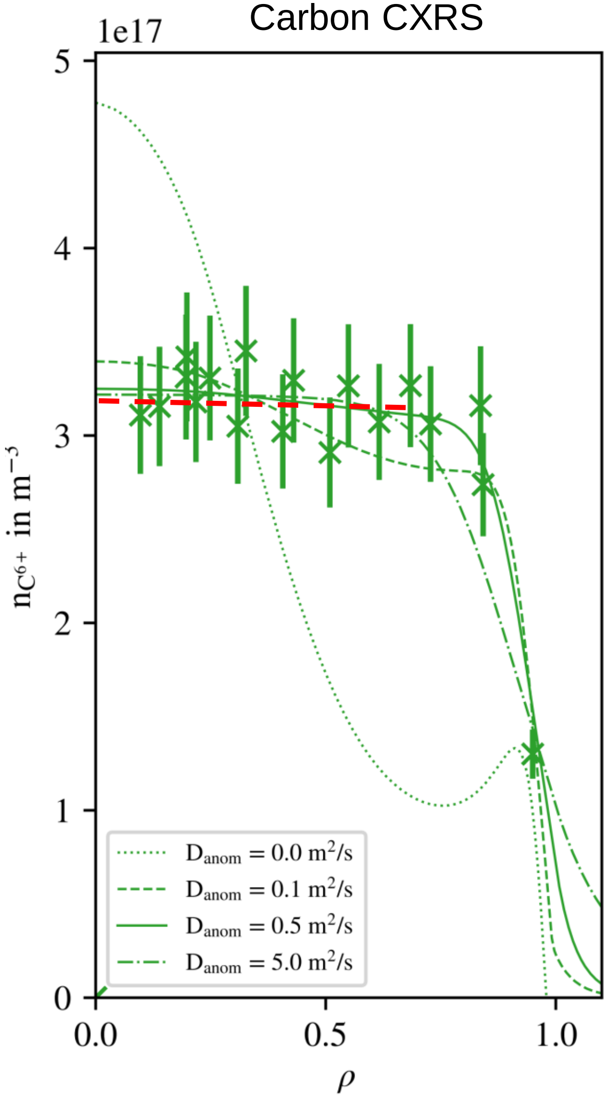
Carbon CXRS



T. Romba PPCF 65 (2022)

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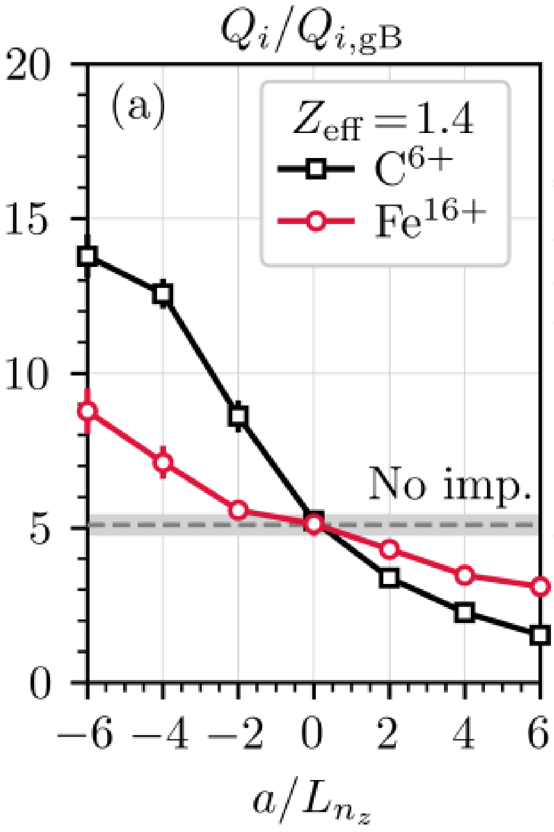

J.M. Garcia-Regana NF (submitted)

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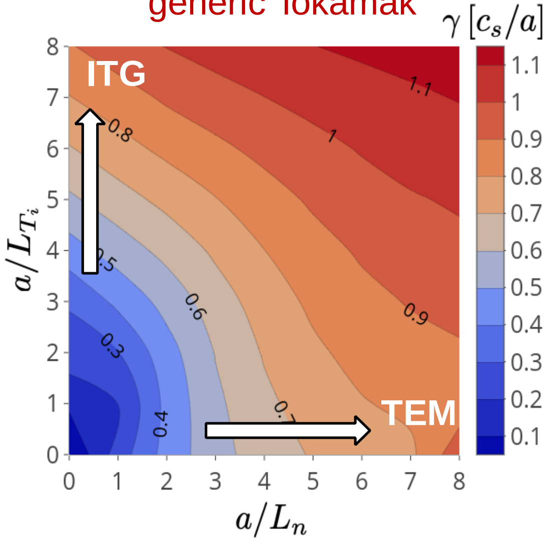
G. Roberg-Clark PRR 4 (2022), PRR 5 (2023)
J. L. Velasco arXiv:2306.17506v1 (2023)
A. Goodman arXiv:2211.09829 (2023)

Regimes with reduced turbulent transport

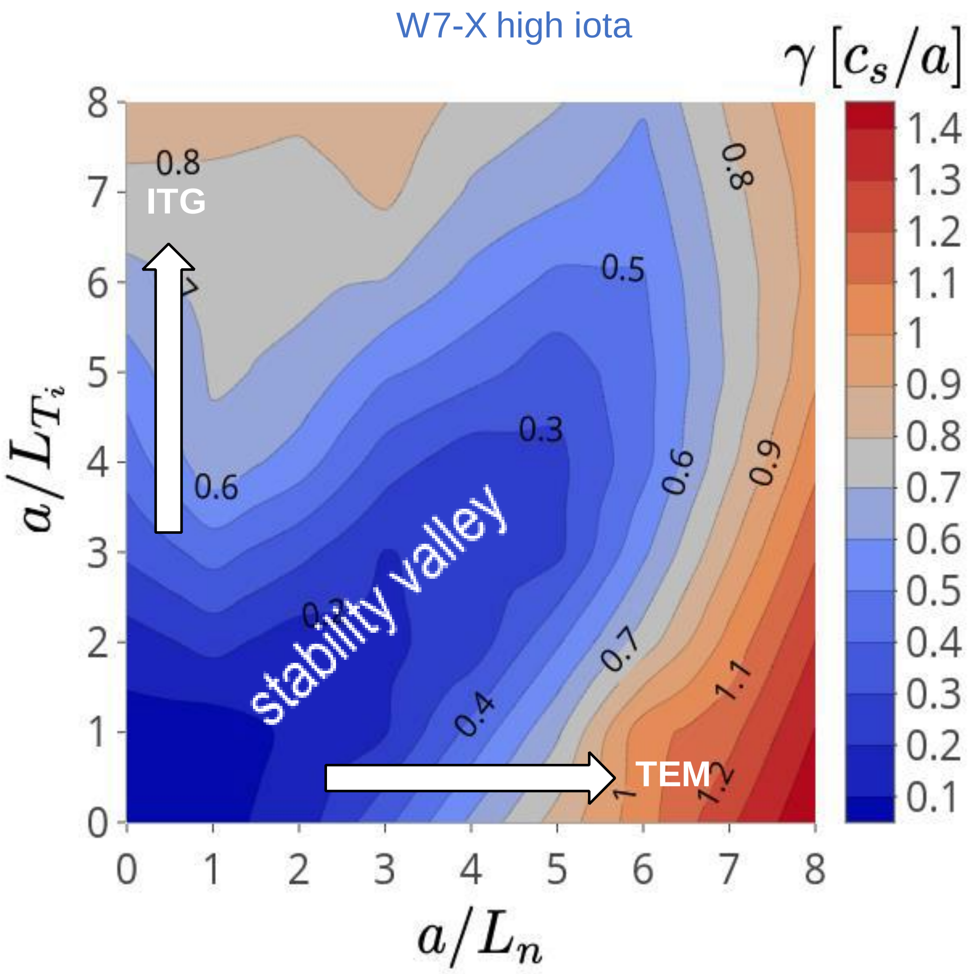
Significant variation of impurity transport observed under specific conditions

- Profile effects drive turbulence stabilization
- Consistent with ITG-type turbulence:
  - T_e/T_i
  - Density gradient

generic Tokamak



W7-X high iota



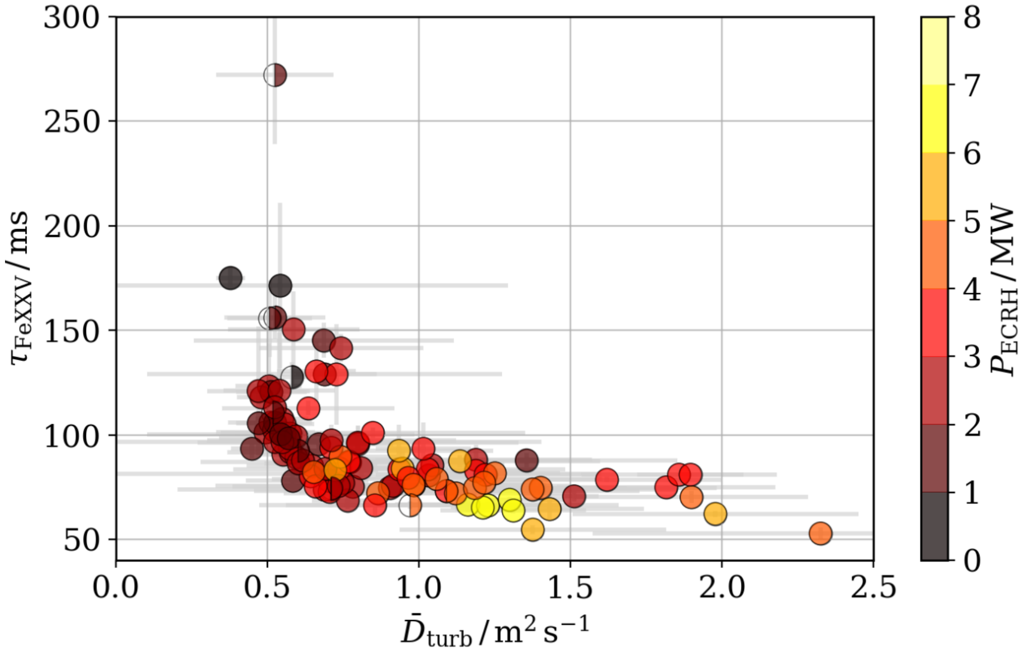
J. Alcuson PPCF 62 (2020)

H. Thienpondt ISHW (2022)

Regimes with reduced turbulent transport

Reduced turbulence impacts impurity transport and is consistently correlated to profile effects:

- **Low power & low density scenarios**
  - Impurity accumulation for low edge densities
    - Wall conditioning & gas puff
- **Pure NBI-heating**
  - Decoupled turbulent impurity transport
  - Radial evolution of transport suppression
  - Complete suppression of turbulent impurity transport
    → purely (neo-)classical
  - ECRH ‘flushing’ observed



T. Wegner JPP 89 (2023)

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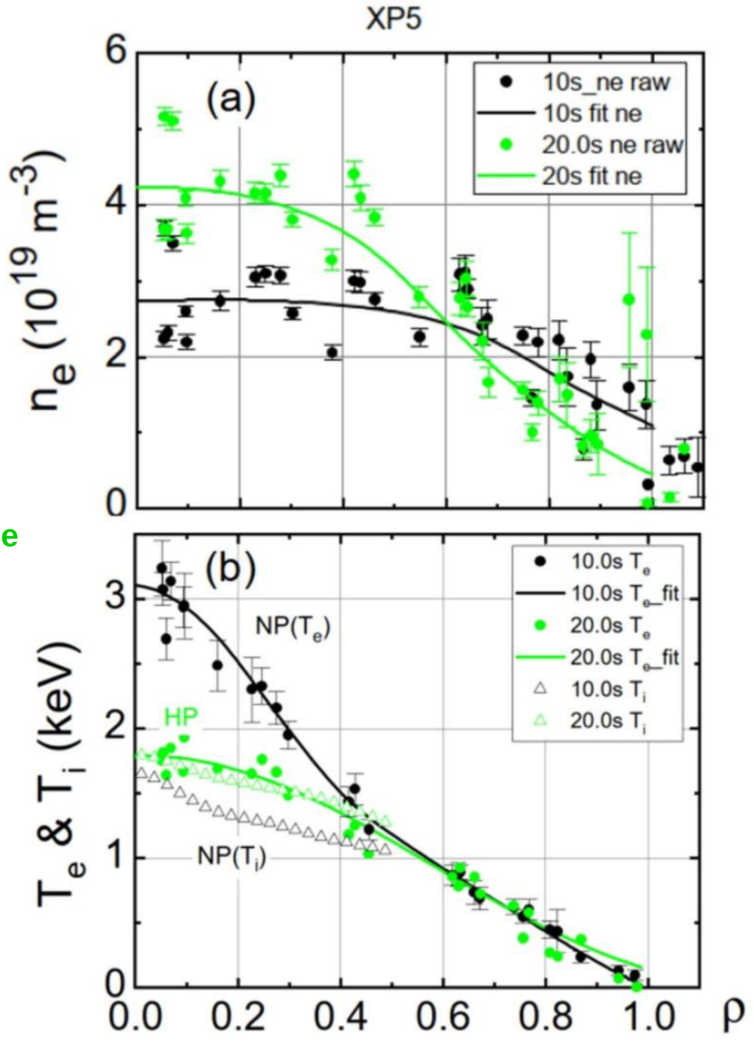
Reference

Red. turbulence



D. Zhang PPCF 65 (2023)

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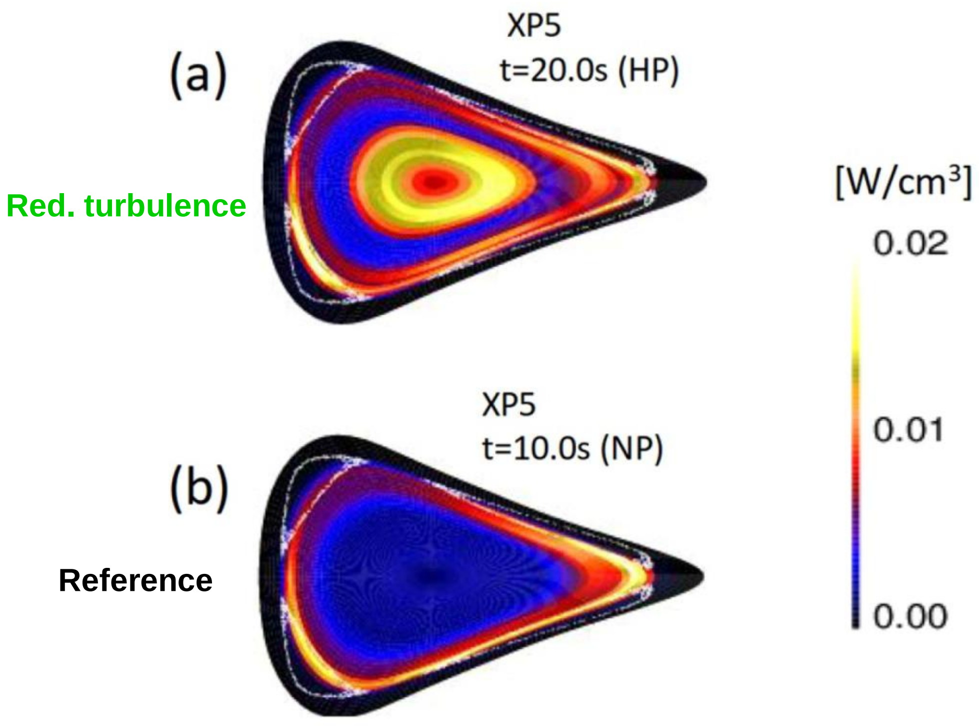

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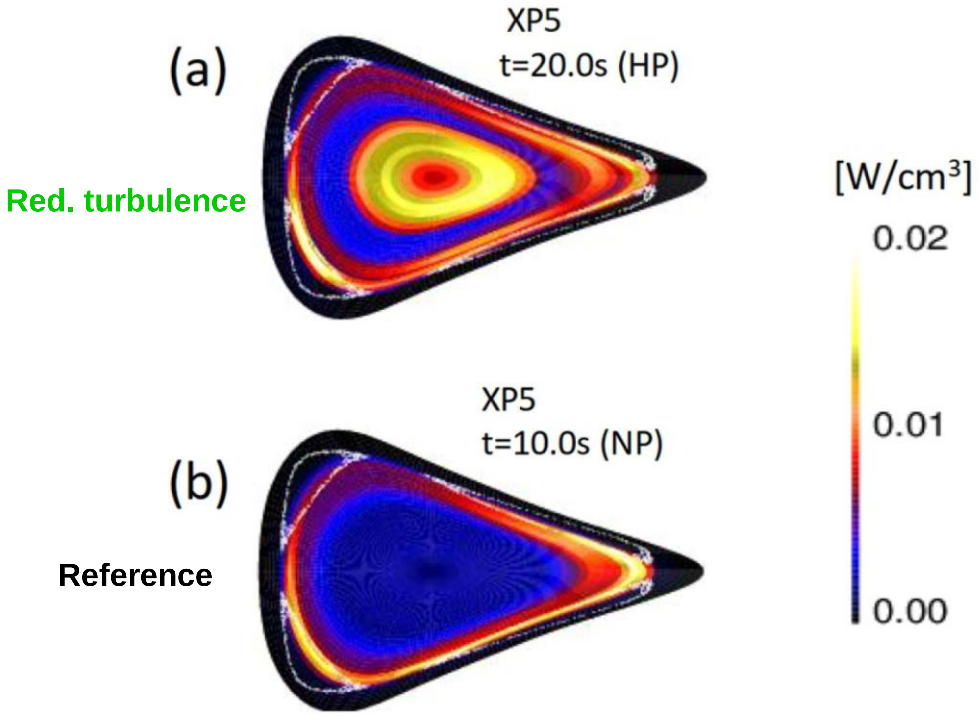
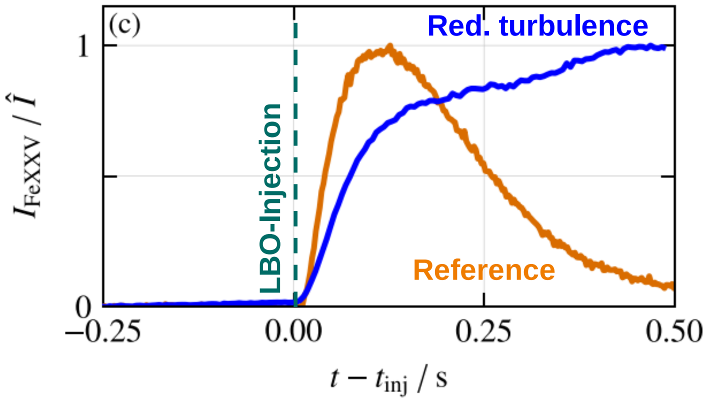


D. Zhang PPCF 65 (2023)

J. Alcuson NF 63 (2023)



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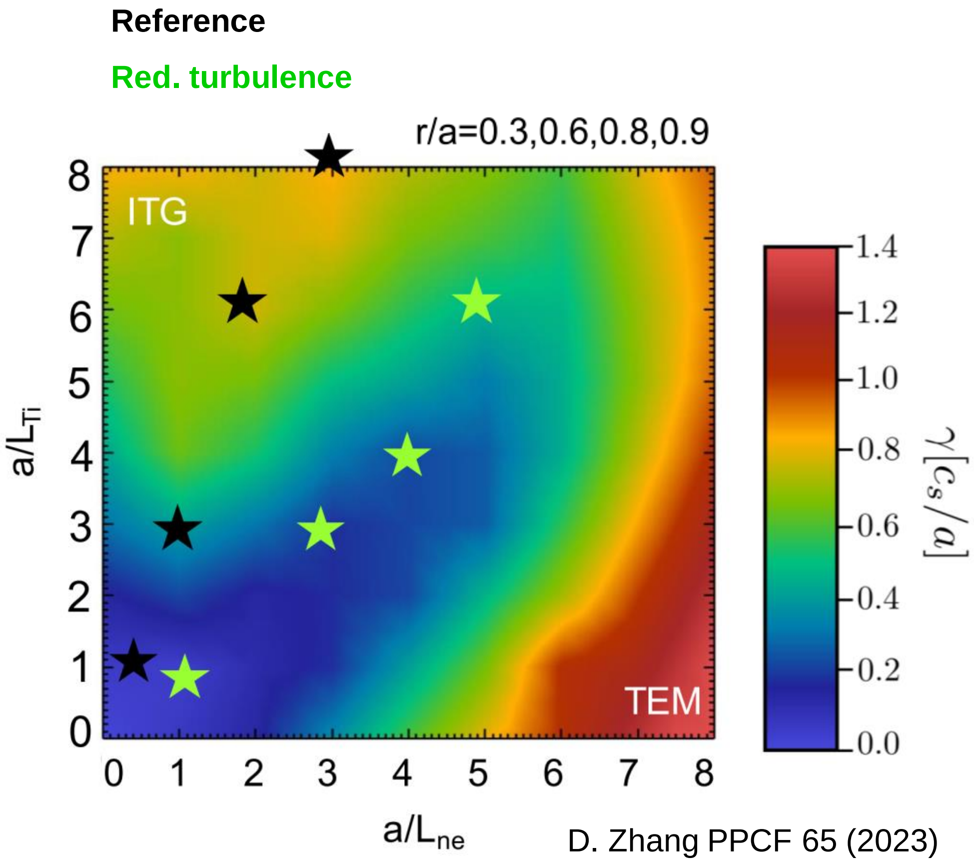

D. Zhang PPCF 65 (2023)

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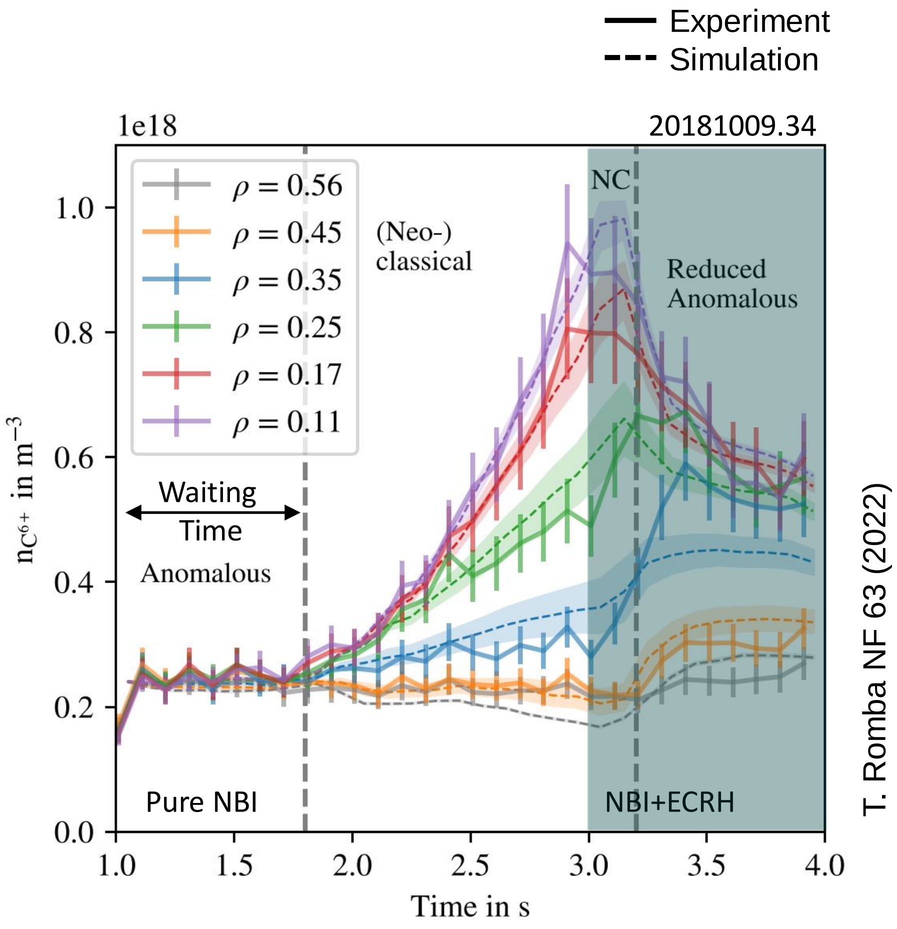
See Poster Session today T. Romba

Other suppressed conditions:

- On/Off-axis ECRH heating
- Pellet & TESPEL fueling
- Boron dropper
- Massive LBO & TESPEL

See invited talk by A. Bortolon



T. Romba NF 63 (2022)

PART II -

What do we expect from theory for SOL transport?

‚Standard‘ divertor flow structure

- Parallel impurity transport:

$$\nabla\left(n\boldsymbol{v} - \boldsymbol{D}\frac{\partial n}{\partial r}\right) = S \quad \rightarrow \quad \frac{d}{dx} n v_{\parallel} = S$$

with $x = l_{\parallel}$

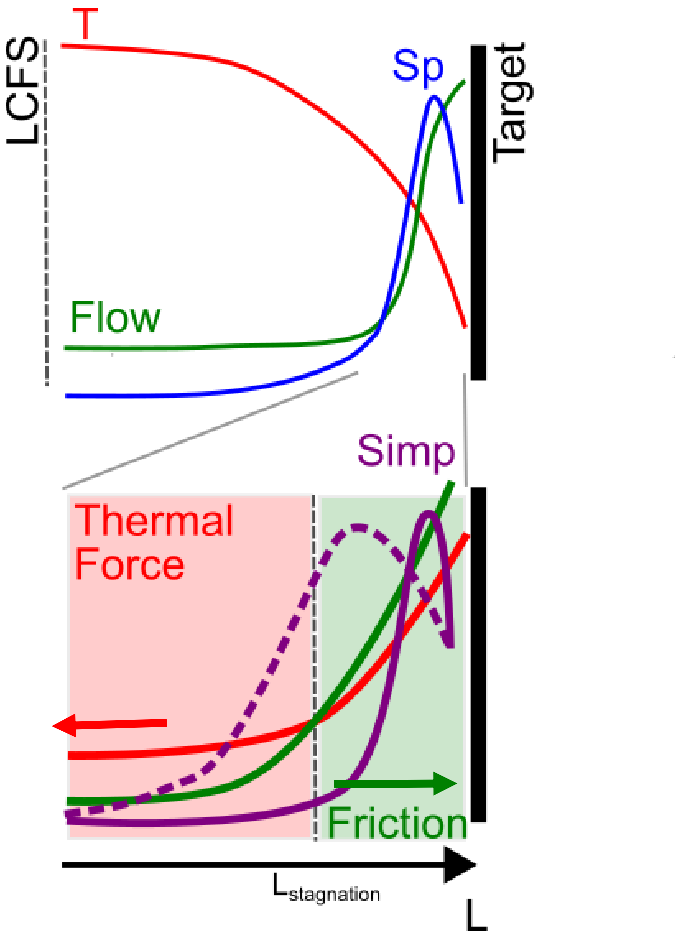
- Impurity velocity set by parallel force balance:

$$v_{Z,\parallel} = \boxed{v_{i,\parallel}} + \boxed{\frac{\tau_s}{m_Z} 2.6 Z^2 \frac{\partial T_i}{\partial x}}$$

friction thermo-force

Senichenkov PPCF 61 (2019) 045013
Hitzler PPCF 62 (2020)
Feng PPCF 53 (2011) 024009
Feng NF 49 (2009) 095002

→ Ionization location of impurity neutrals important



Feng et al, PPCF 53 (2011)
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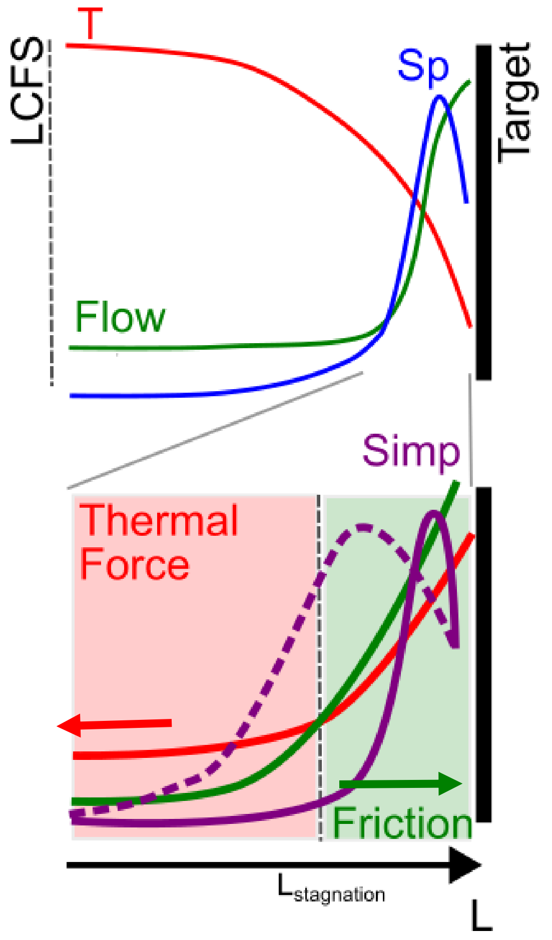


Adding perpendicular diffusion to SOL-transport

In W7-X: Low pitch angle (Θ ~ 0.001 vs 0.1) – long L_c

- Parallel convection less important
- Perpendicular transport much more important

1D force balance analysis along single flux tube

- Divertor retention by parallel dynamics (friction-dominated)

$$v_{Z,\|} = \boxed{v_{i,\|}} + \boxed{\frac{\tau_s}{m_Z} 2.6 Z^2 \frac{\partial T_i}{\partial x}}$$

friction thermo-force

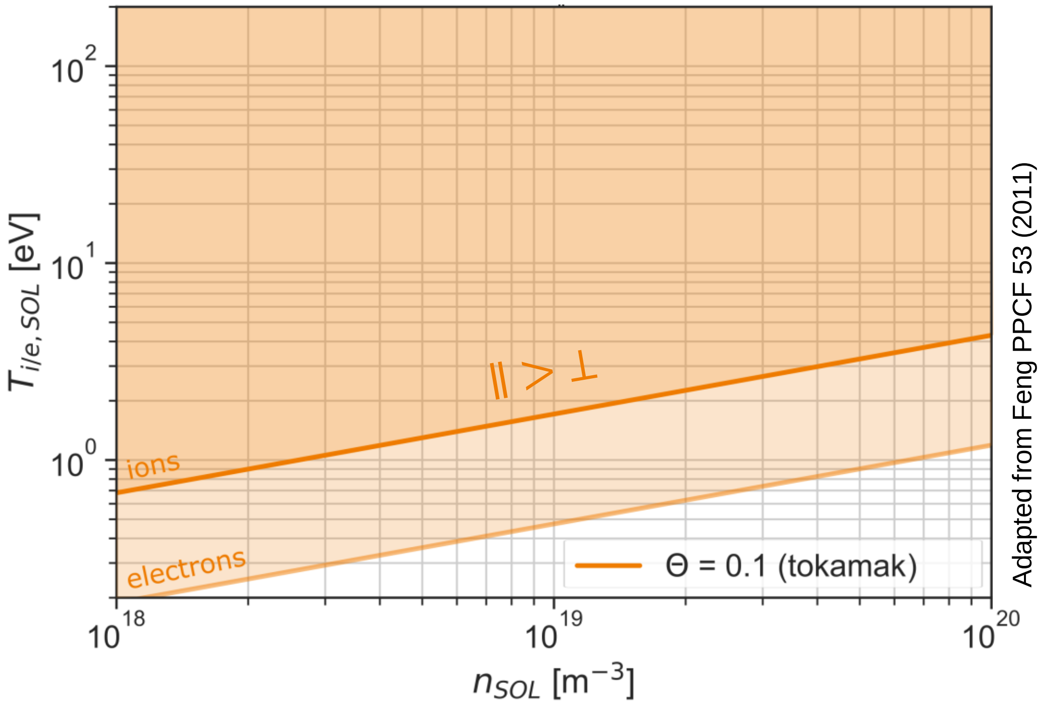
Add bi-normal diffusion for source-free 1.5D model

- Retention limited by perpendicular (bi-normal) diffusion

$$\frac{d}{dy}\left(\boxed{\Theta v_{z\|} n_I} - \boxed{D \frac{dn_I}{dy}}\right) = 0$$

parallel bi-normal

Θ – fieldline pitch



Adapted from Feng PPCF 53 (2011)

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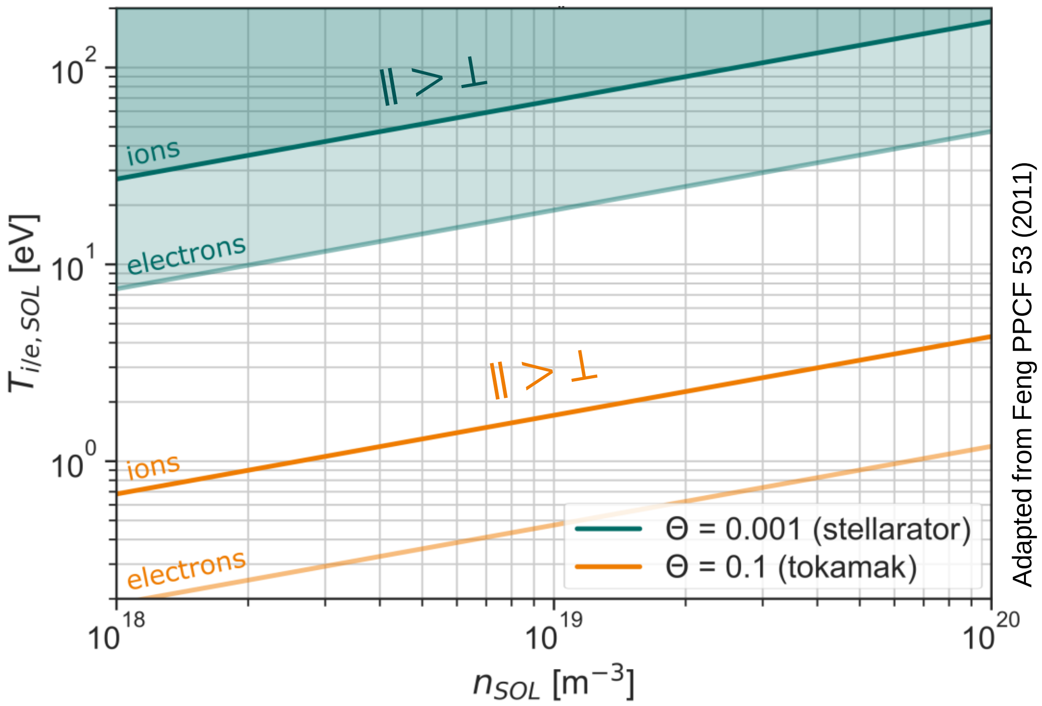

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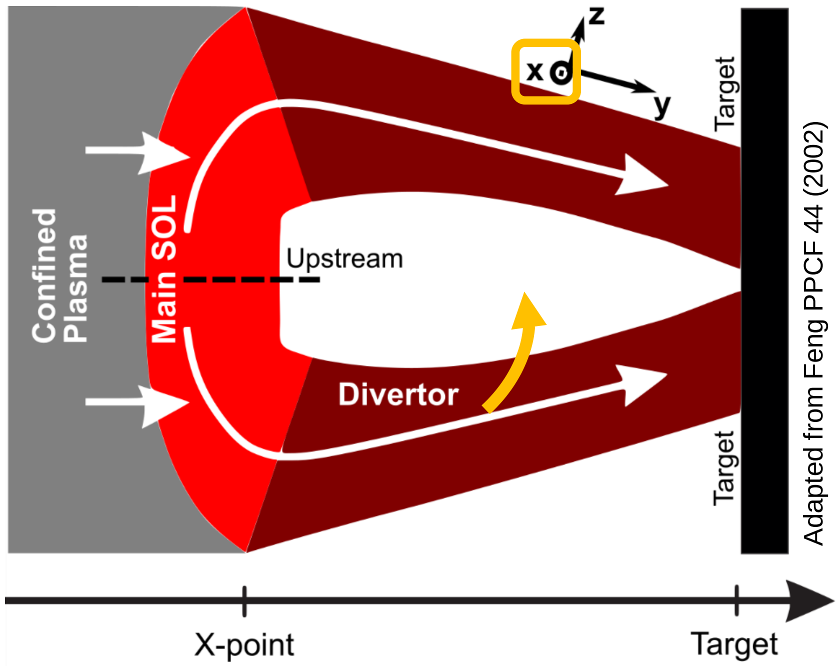

X – parallel
Y – diamagnetic
Z – perpendicular

Feng PPCF 44 (2002)

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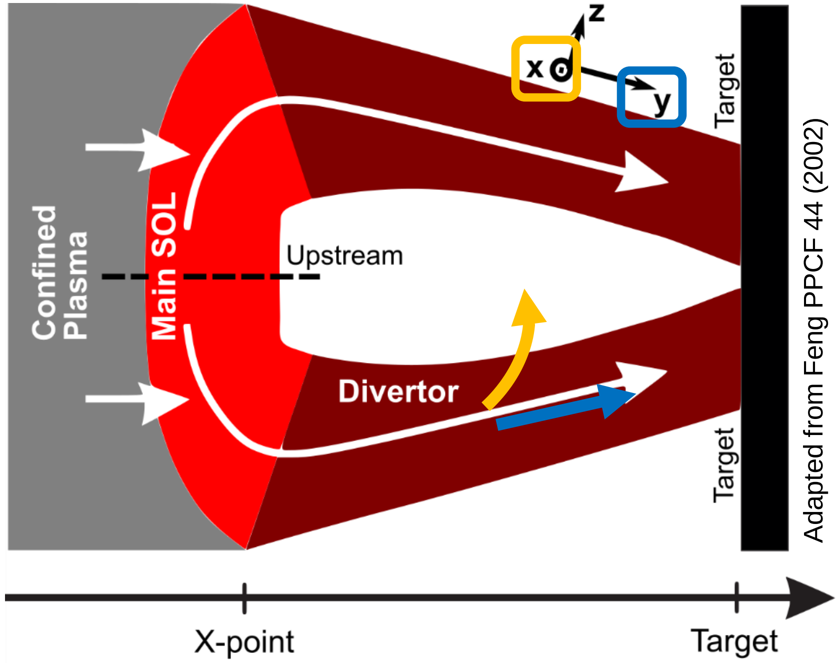

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What does this mean for W7-X?

W7-X operates mostly in friction force dominated regime

Feng et al, PPCF **53** (2011)
Feng et al, NF **49** (2009)

- Sources are target localized
  - C-sputtering or seeding
  - Impurity radiation close to the targets
- Clear & strong target-directed counter-streaming flows
- Early transition to friction-dominated regime (~2 x 10^{19} m^{-3})

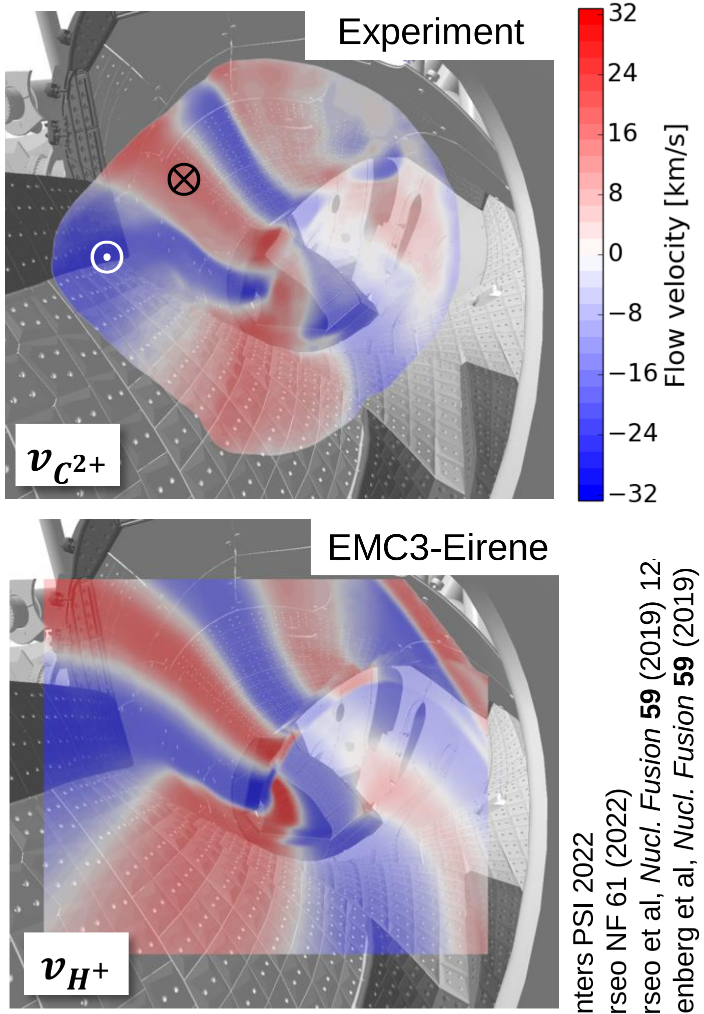
Indications of good retention

- Low to medium impurity core content (0.1-2 %) & $Z_{eff} \approx 1.5$
- Indications of high enrichment factors (preliminary)
  - $c_{imp,div}$ measured spectroscopically by line-ratios
  - Extended to other impurities & verified

R. Wang PSI 2020
V. Winters PSI 2022
F. Reimold PSI 2020

F. Reimold PSI 2020
F. Henke PSI 2022
T. Romba PPCF 65 (2022)

C-III emission weighted flow velocities



Winters PSI 2022
Perseo NF 61 (2022)
Perseo et al, *Nucl. Fusion* **59** (2019) 12
Effenberg et al, *Nucl. Fusion* **59** (2019)

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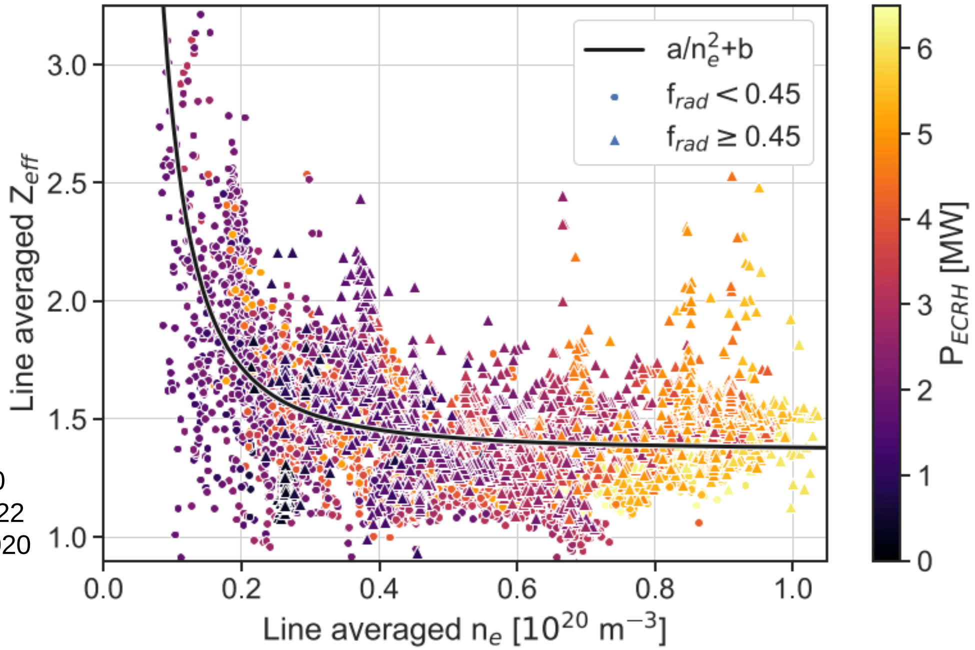

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  - Very localized, contained thermal force regions
  - Extended retention improvement beyond transition
- Retention dependent on species & energy as expected
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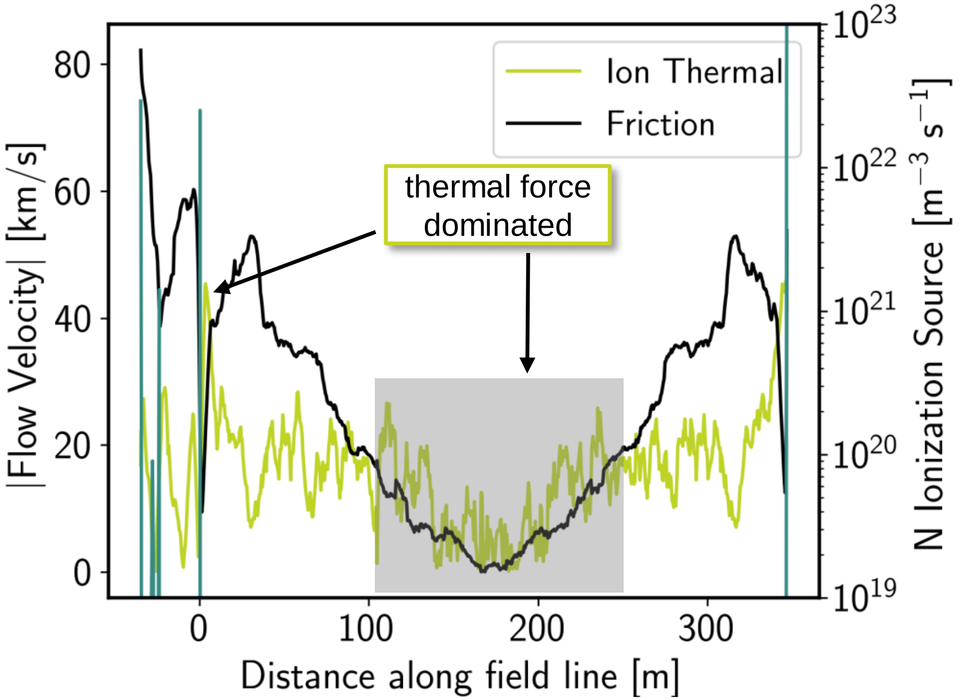
  - No direct penetration to thermal force dominated regions

BUT: *Even stronger* role of perpendicular transport

- Main ion flow stagnation region across O-point
  - Accumulation of impurities in O-point region
  - Long residence times → leakage via perp. diffusion
- Lower retention for O-point located seeding



V. Winters PSI 2022
V. Winters (submitted)

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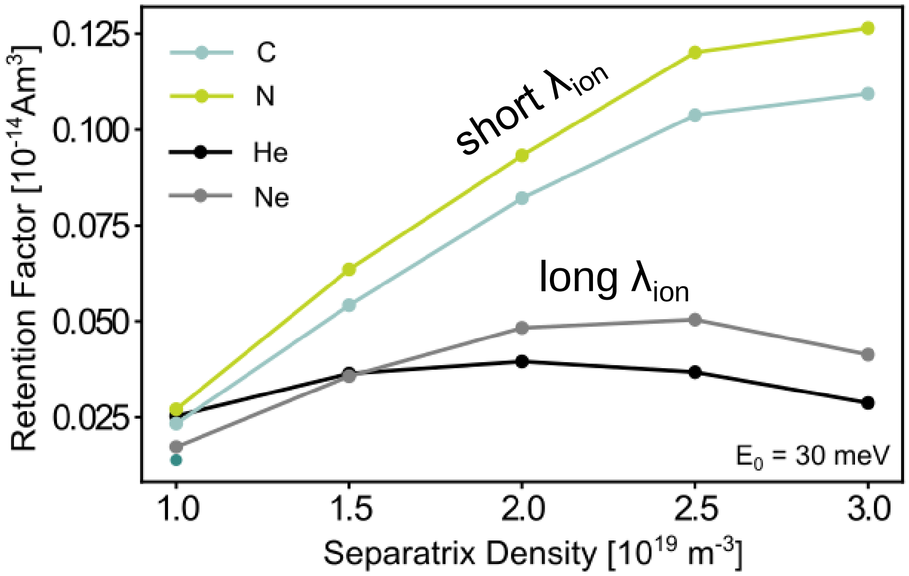

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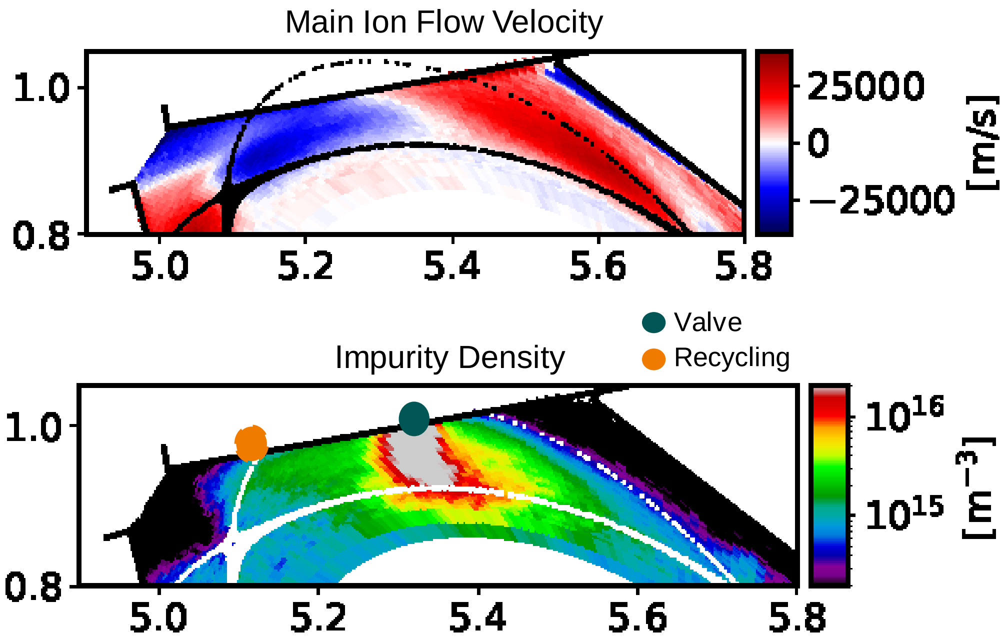

Courtesy of V.Winters

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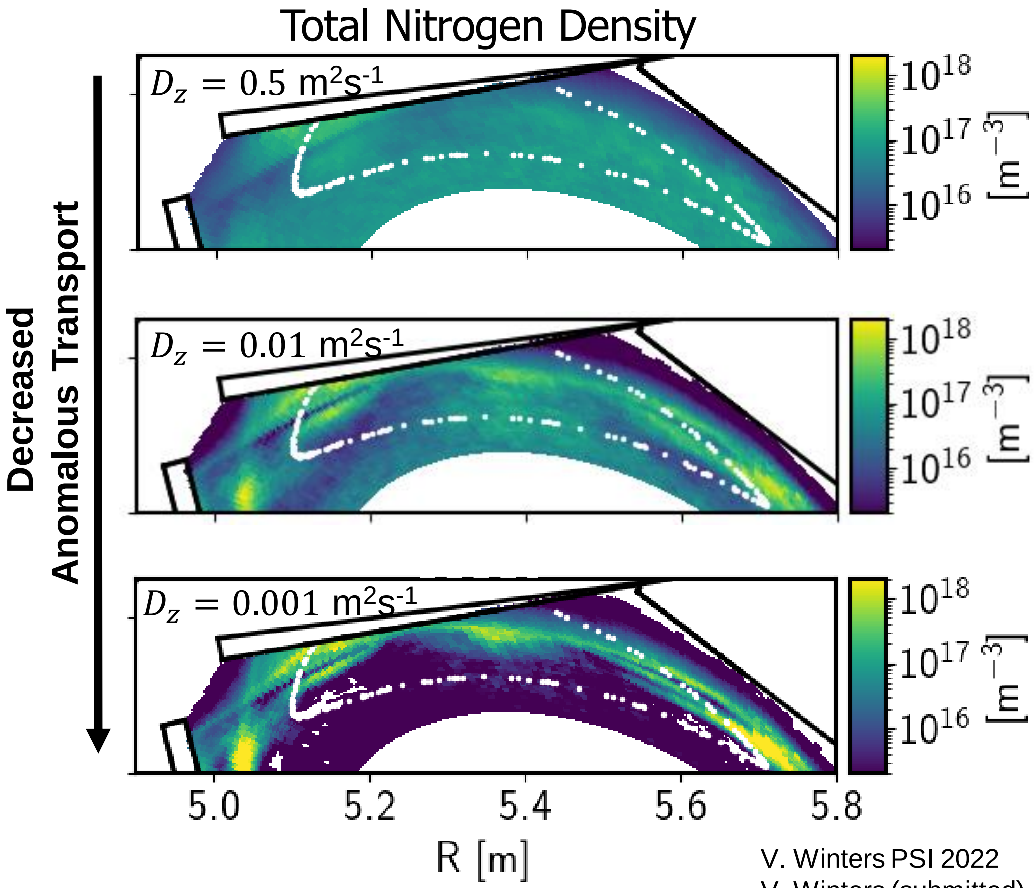

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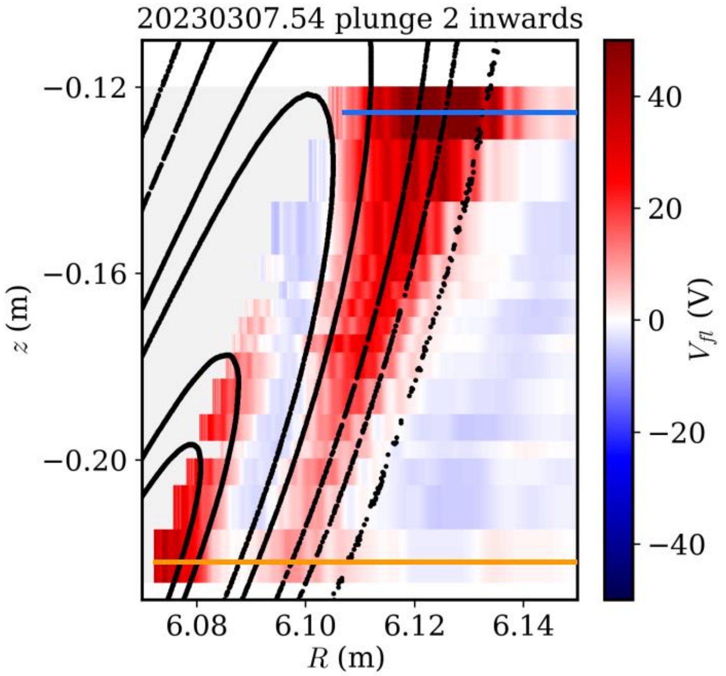

D. M. Kriete NF 63 (2023)
D. Cipciar EPS 2023
C. Killer EPS 2023
S. Ballinger EPS 2023
A. v. Stechow EPS 2023

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Missing Physics R. De Wolf PET 2023

- Drifts (Θ ~ 0.001) → EMC3-development
- Divertor Geometry (Closure)

Summary & Conclusion

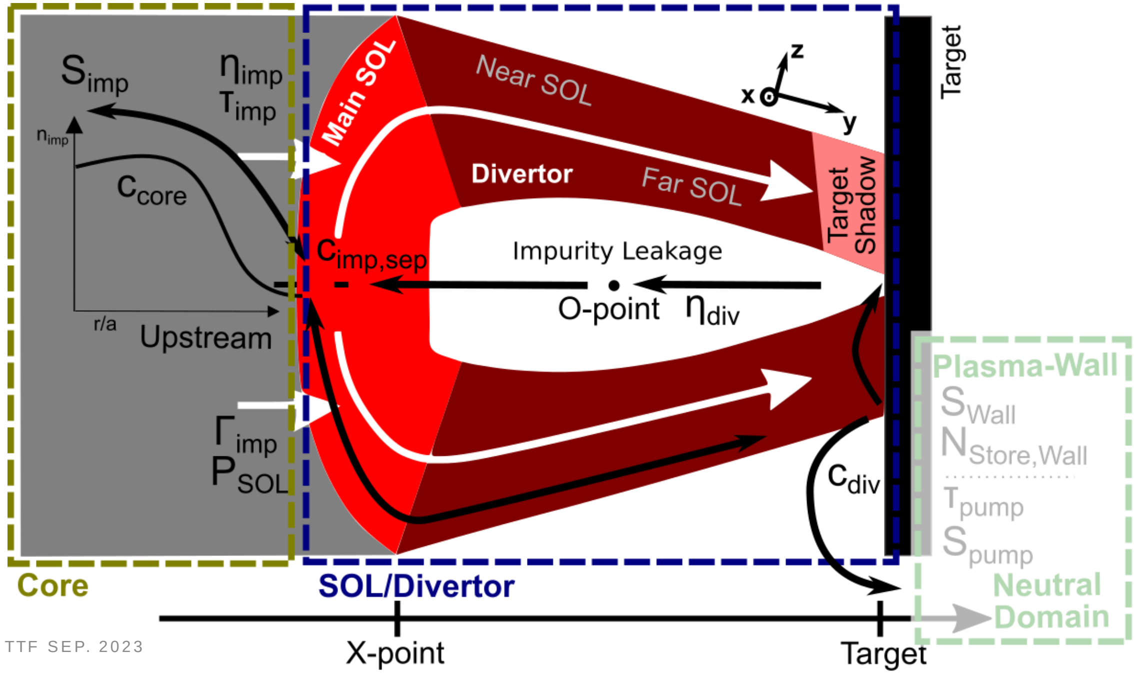
Core Impurity Transport

- Core transport is mostly benign:
  - Neoclassical transport can be optimized
  - Turbulence is dominant in „standard“ operation conditions
- Reduced turb. impurity transport scenarios

  (suppression & decoupling of impurity transport)
- Impact of impurities on turbulence predicted

SOL transport

- Parallel force balance (friction vs. thermal force)
  - Not “relevant” for W7-X conditions: Friction dominated
- Perpendicular transport
  - Diffusive leakage across O-point (main ion flow stagnation)
  - Level of perp. transport dominates retention
- Drift assessment will be important (!) - pending



Turbulence reduced scenarios for core transport

NBI-heating changes kinetic profiles

- Density peaking & T_i-increase
- Changes due to fueling & transport

Delayed onset of impurity accumulation

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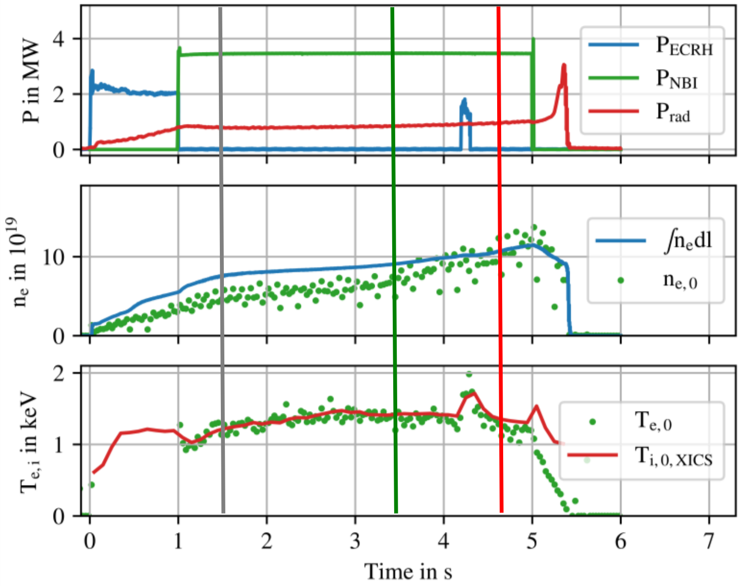
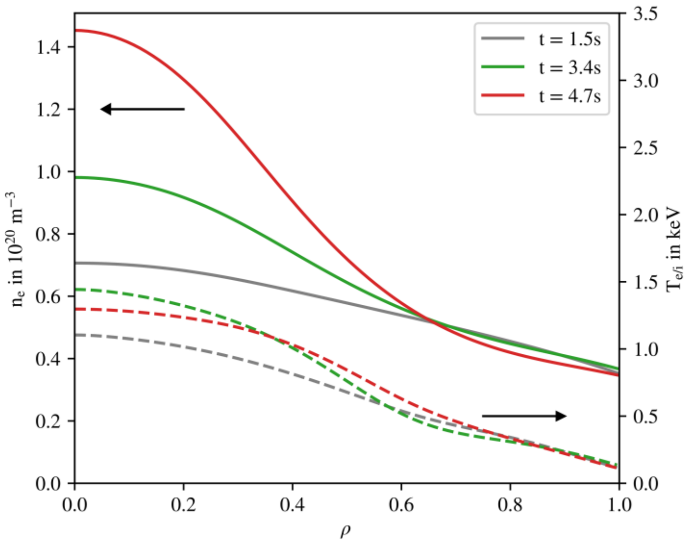
  → purely (neo-)classical

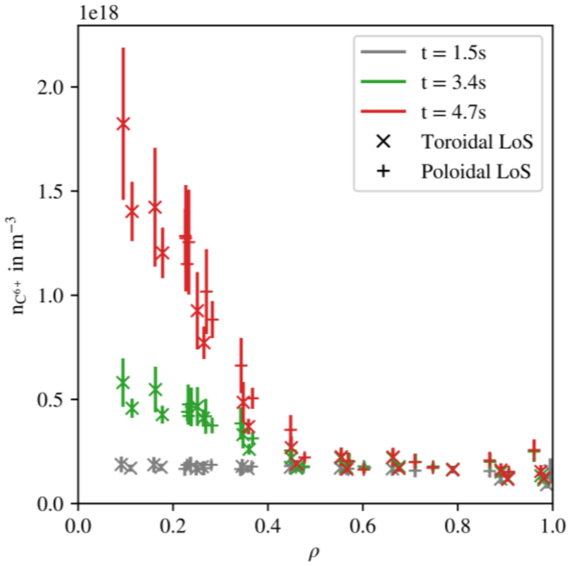
Impurity "flushing" with ECRH

→ Modeling efforts on-going (Stella & Gene)



T. Romba NF 63 (2022)





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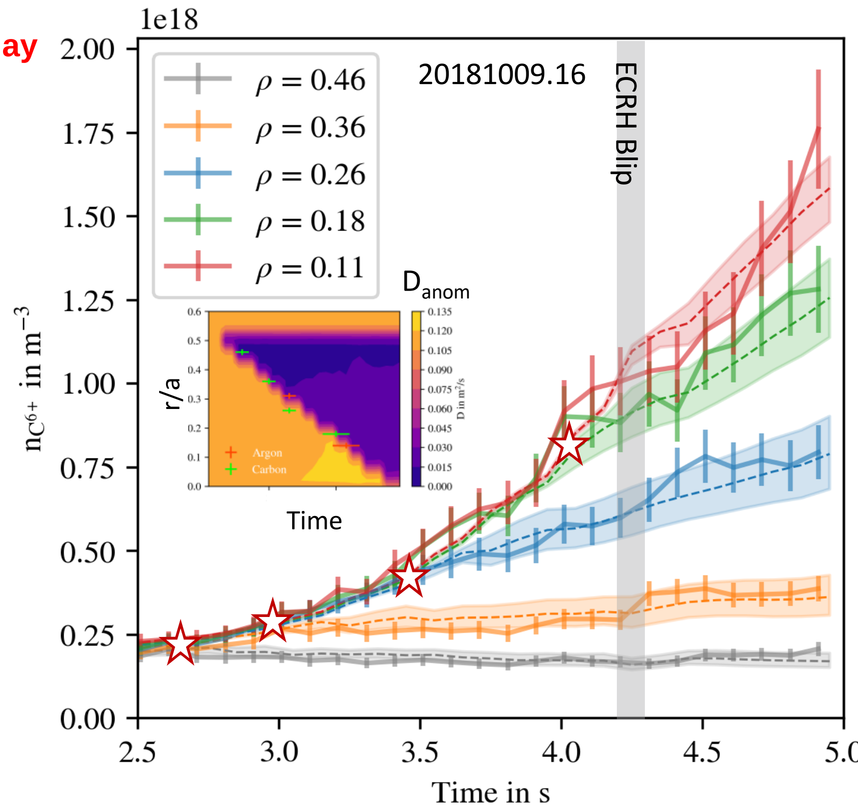
See Poster Session today
T. Romba



T. Romba NF 63 (2022)

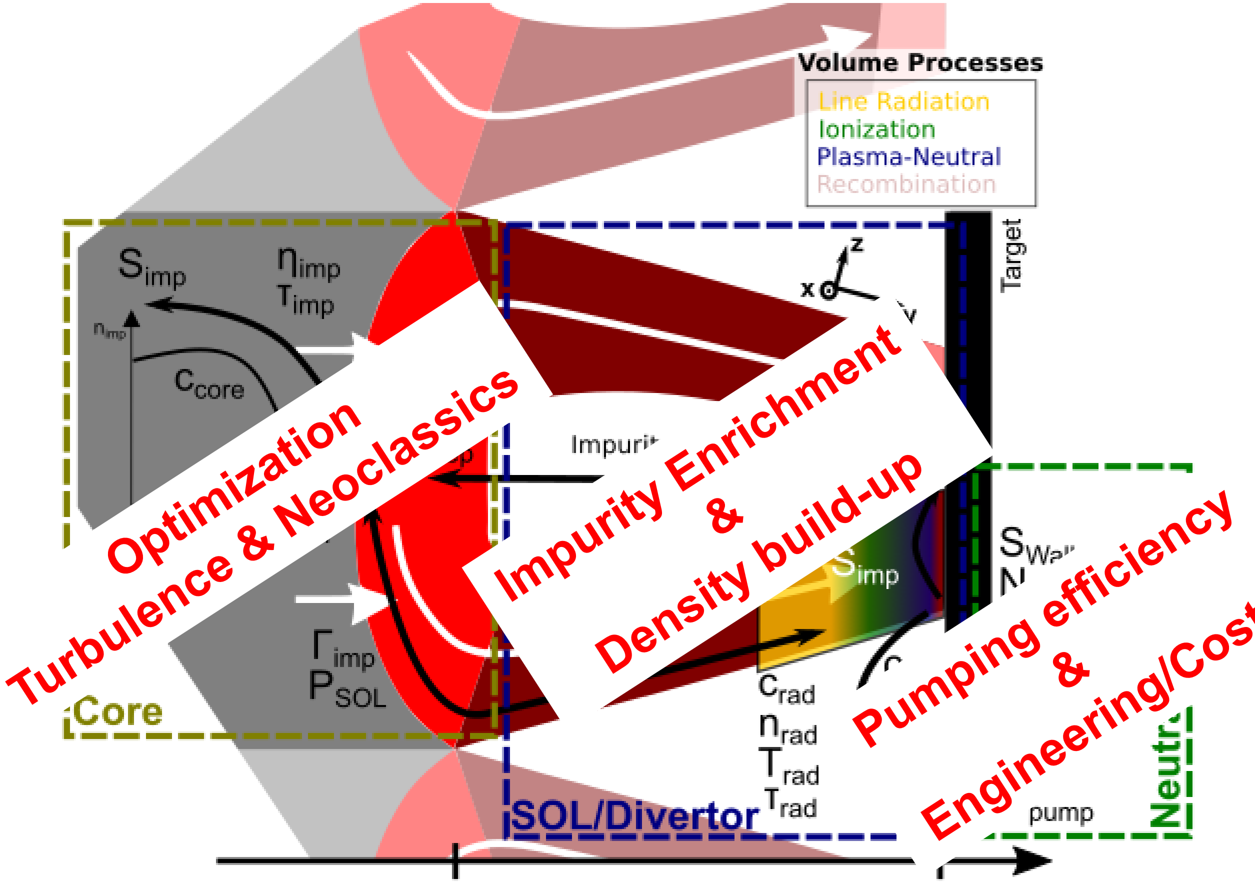
Reactor Perspective

Upper limits on impurity content

- Lawson criterion
- Operational limits
    - density limit
    - confinement degradation
    - (radiation) stability

Lower limits on impurity content

- Power exhaust
    - Detachment threshold & radiation limits
- Particle exhaust = He-removal
    - Particle through-put



Optimization
Turbulence & Neoclassics

Impurity Enrichment
&
Density build-up

Pumping efficiency
&
Engineering/Cost

Fusion Performance

Power Exhaust & Recycling

Particle Exhaust

What do we expect from theory for core transport?

Collisional transport at low collisionality significantly different between stellarators & tokamaks:

- **Particles trapped in local magnetic wells (ε_{eff})**
  - Increased perp. transport via drifts orbit losses
- **E_r establishes to provide ambipolar transport**
  - Drift orbit losses reduced → lower transport
  - Electron ($E_r > 0$) vs. ion root ($E_r < 0$)

Optimization:

- Reducing ε_{eff}
- Separate optimization of ion/electron fluxes

Note: In optimized stellarators classical transport can become important

Take electron & ion transport separately:

$$\Gamma_Z = -n_Z L_{11}^Z \boxed{\Big(\frac{d\ln n_Z}{dr}} + \boxed{\delta_{11}^{eff}\frac{d\ln n_i}{dr} - \delta_{12}^{eff}\frac{d\ln T_i}{dr}\Big)}$$

→ *Condition for temperature screening:*

$$\delta_{12}^{eff} = \frac{\delta_{12}^Z - Z\delta_{12}^i + L_{11}^e/L_{11}^i(\delta_{12}^Z + Z\delta_{12}^e)}{1 + L_{11}^e/L_{11}^i} > 0$$

for $L_{11}^e > 0$

$$\rightarrow \frac{L_{11}^e}{L_{11}^i} > \frac{Z\delta_{12}^i - \delta_{12}^Z}{Z\delta_{12}^e + \delta_{12}^Z}$$

Regime	δ_{12}	
Banana regime	-1/2	Screening
$1/\nu$ – regime	+7/2	
$\sqrt{\nu}$ – regime	+5/4	
ν – regime	+1/2	
Plateau	+3/2	
Pfirsch-Schlüter	-1/2	Screening

Beidler NF (in preparation)
Velasco PPCF 60 (2018)
Helander PRL 118 (2017)

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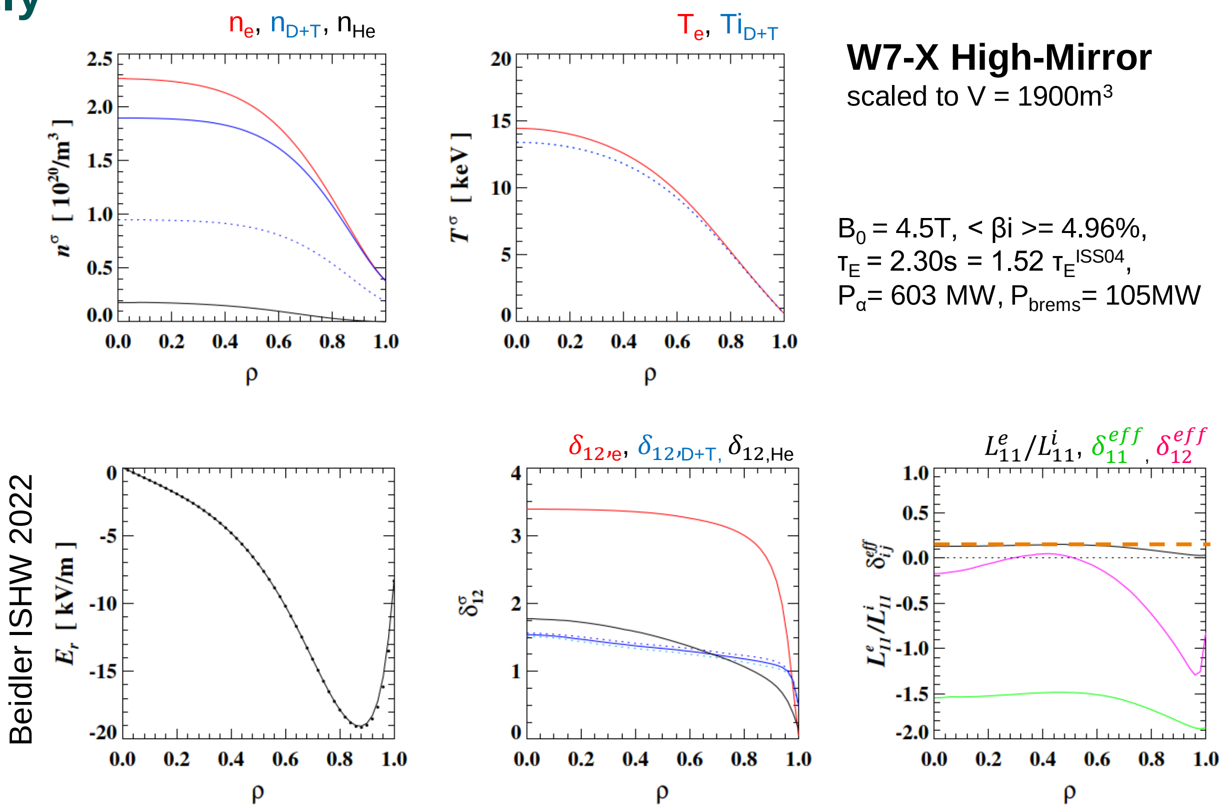
Optimization:

- Reducing ε_{eff}
- Separate optimization of ion/electron fluxes

Note: In optimized stellarators classical transport can become important



Beidler ISHW 2022

W7-X High-Mirror
scaled to V = 1900m³

B_0 = 4.5T, $<\beta i>$ = 4.96%,
τ_E = 2.30s = 1.52 τ_E^{ISS04},
P_α = 603 MW, P_{brems} = 105MW

$$\Gamma_z = -n_z L_{11}^Z \left(\frac{d\ln n_Z}{dr} + \delta_{11}^{eff} \frac{d\ln n_i}{dr} - \delta_{12}^{eff} \frac{d\ln T_i}{dr} \right)$$

L_{11}^e/L_{11}^i small → low He-removal

What do we expect from theory for core transport?

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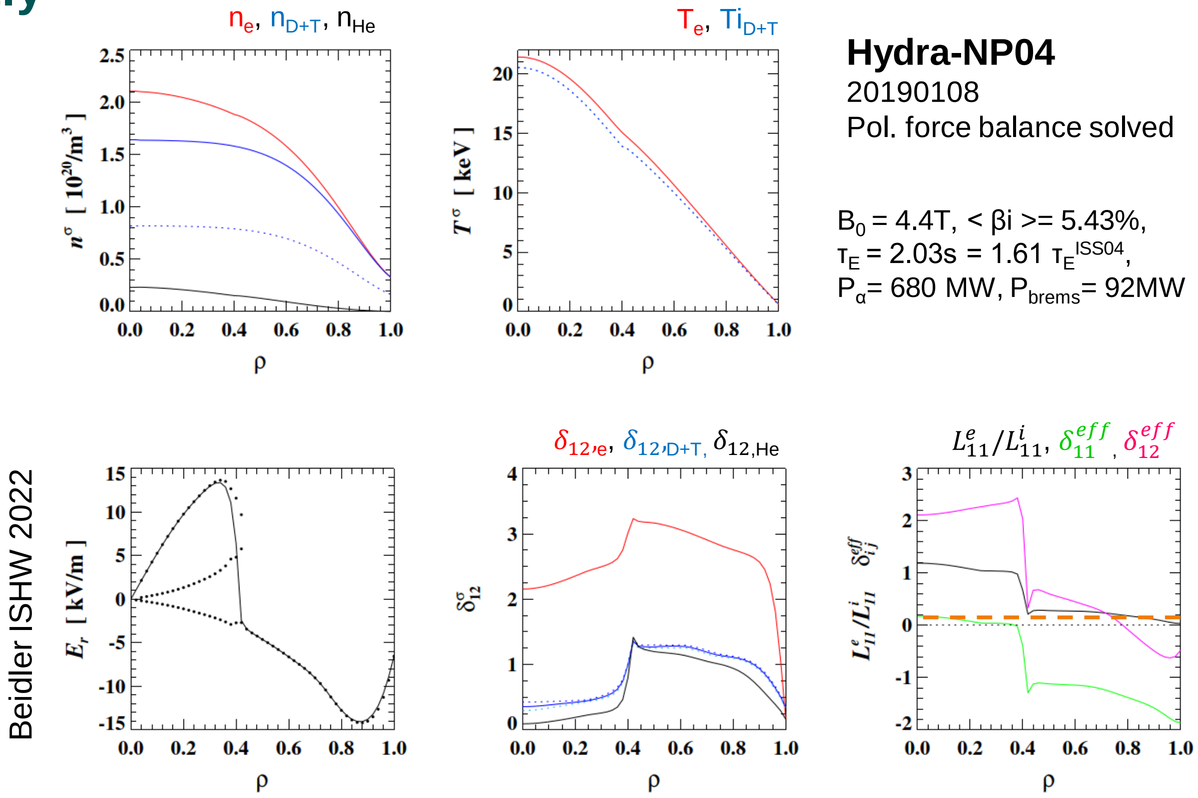

Hydra-NP04
20190108
Pol. force balance solved

$B_0 = 4.4$T, $<\beta i> = 5.43\%$,
$\tau_E = 2.03$s $= 1.61\ \tau_E^{ISS04}$,
$P_\alpha = 680$ MW, $P_{brems} = 92$MW

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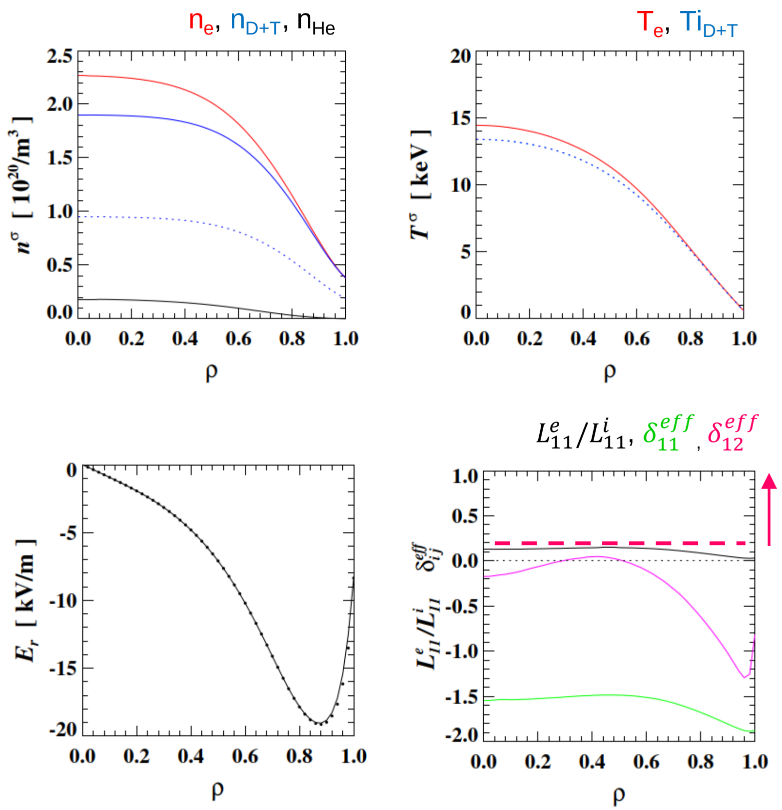

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↑ Temperature screeining

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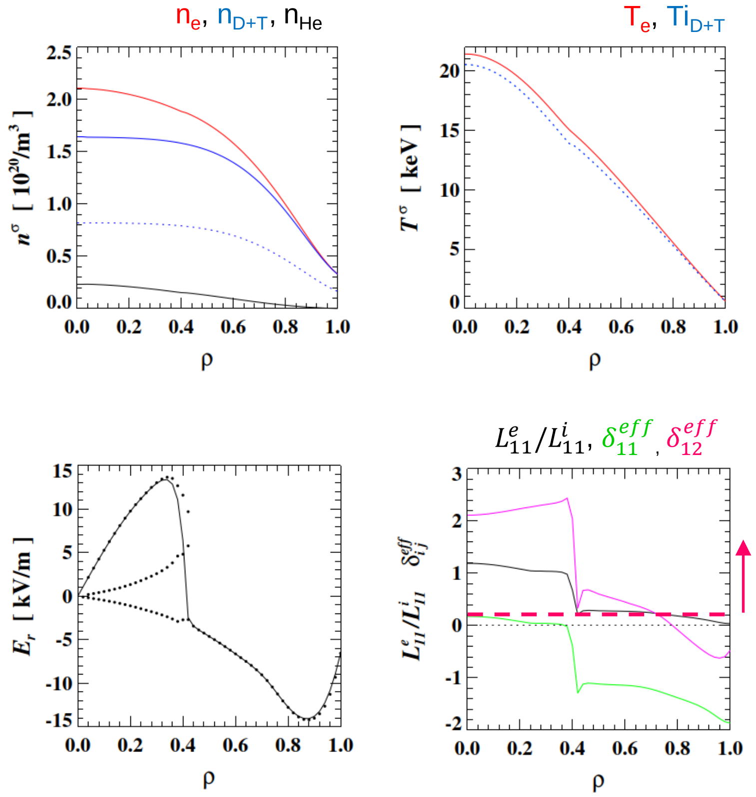

Temperature screening

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20190108
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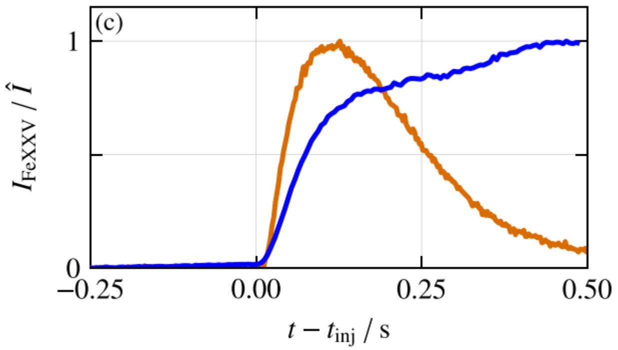
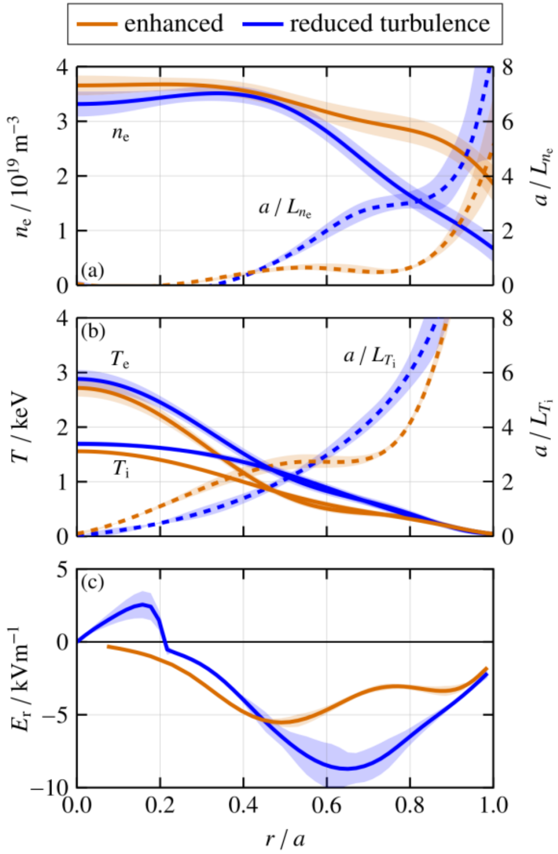
Regimes with reduced turbulent transport

Reduced turbulence impacts impurity transport and is consistently correlated to profile effects:

- **Low power & low density scenarios**
  - Impurity accumulation for low edge densities
    - Wall conditioning & gas puff

- **Pure NBI-heating**
  - Decoupled turbulent impurity transport
  - Radial evolution of transport suppression
  - Complete suppression of turbulent impurity transport → purely (neo-)classical
  - ECRH ‘flushing’ observed





J. Alcuson NF 63 (2023)

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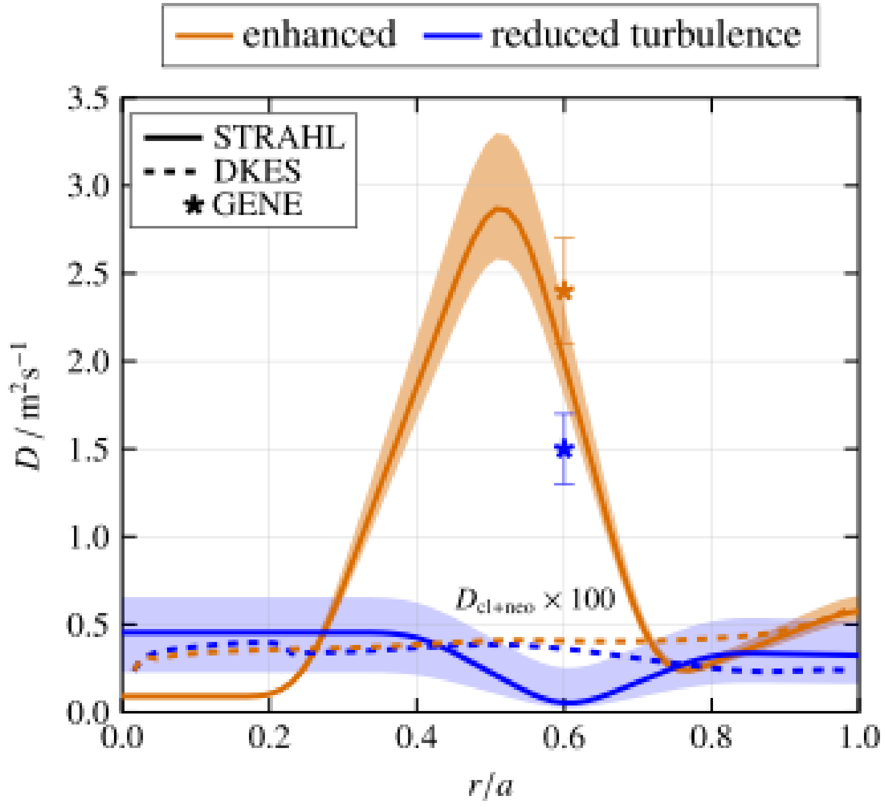

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‚Standard' divertor flow structure

- Parallel impurity transport:

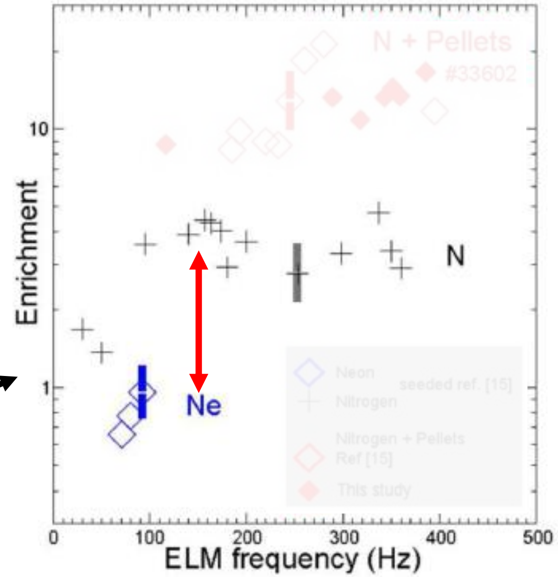
$$\nabla\left(n\boldsymbol{v} - \boldsymbol{D}\frac{\partial n}{\partial r}\right) = S \quad \rightarrow \quad \frac{d}{dx} n v_{\parallel} = S \quad \text{with } x = l_{\parallel}$$

- Impurity velocity set by parallel force balance:

$$v_{Z,\parallel} = \boxed{v_{i,\parallel}} + \boxed{\frac{\tau_s}{m_Z} 2.6 Z^2 \frac{\partial T_i}{\partial x}}$$

friction thermo-force

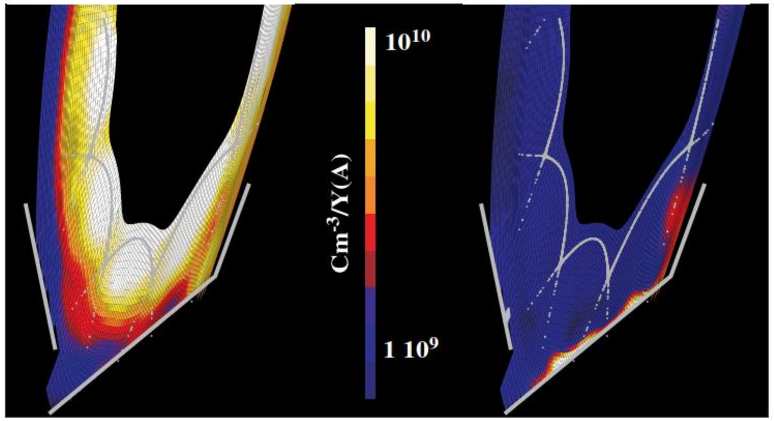
→ Ionization location of impurity neutrals important



Kallenbach PSI 2018

Normalized Carbon density

Thermo-force dominated **low density** Friction-force dominated **high density**



Feng NF 46 (2006)

Feng et al, PPCF 53 (2011)
Feng et al, NF 49 (2009)
Kobayashi NF 53 (2013)
Dai NF 56 (2016)

Different control knobs:

- Impurity species
- Divertor conditions