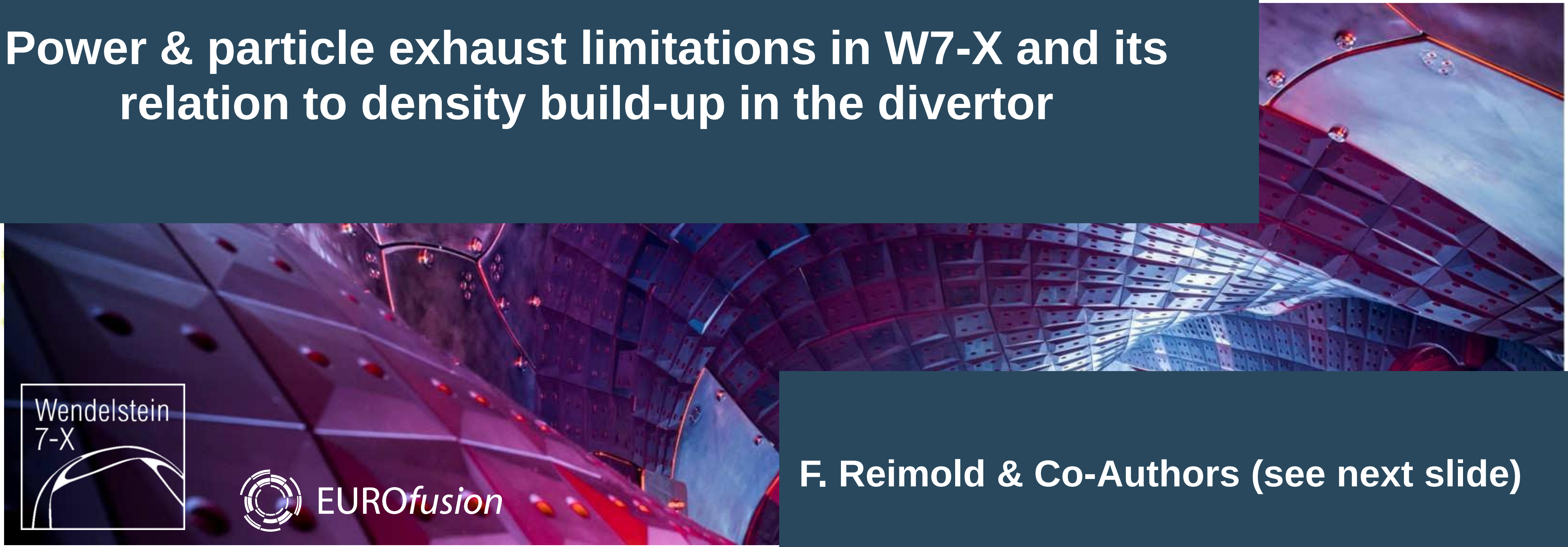
MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

Power & particle exhaust limitations in W7-X and its relation to density build-up in the divertor



F. Reimold & Co-Authors (see next slide)

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Many thanks to the co-authors

V. Winters[1], V. Perseo[1], N. Maaziz[1], F. Henke[1], E. Flom[3], G. Partesotti[1], A. Tsikouras[1], S. Ballinger[1], D. Bold[1], B. Buttenschön[1], R. Davies[1], Y. Feng[1], Y. Gao[1], D. Gradic[1], V. Haak[1], M. Jakubowski[1], R. König[1], A. Kharwandikar[1], C. Killer[1], M. Krychowiak[1], A. Pandey[1], B. Shanahan[1], T. Tork[1], D. Zhang[1], and the W7-X Team[1]

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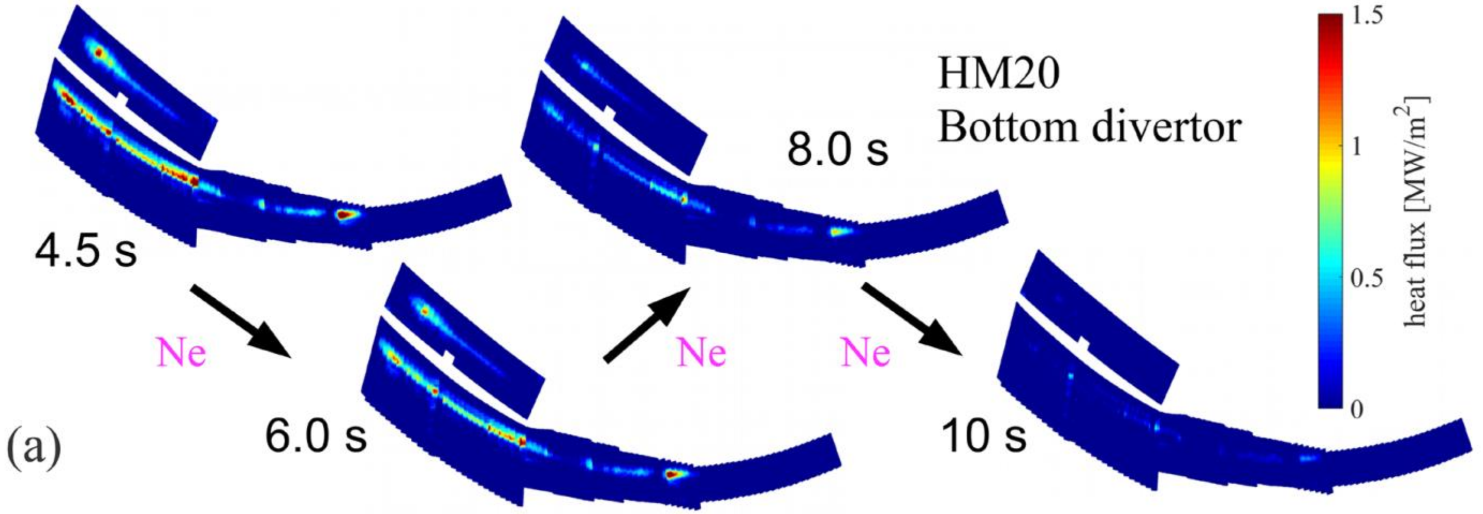
[2] *Department of Physics, Auburn University, Auburn, Alabama, USA*
[3] *Department of Engineering Physics, University of Wisconsin-Madison, Madison, Wisconsin, USA*

Short summary of detachment observations

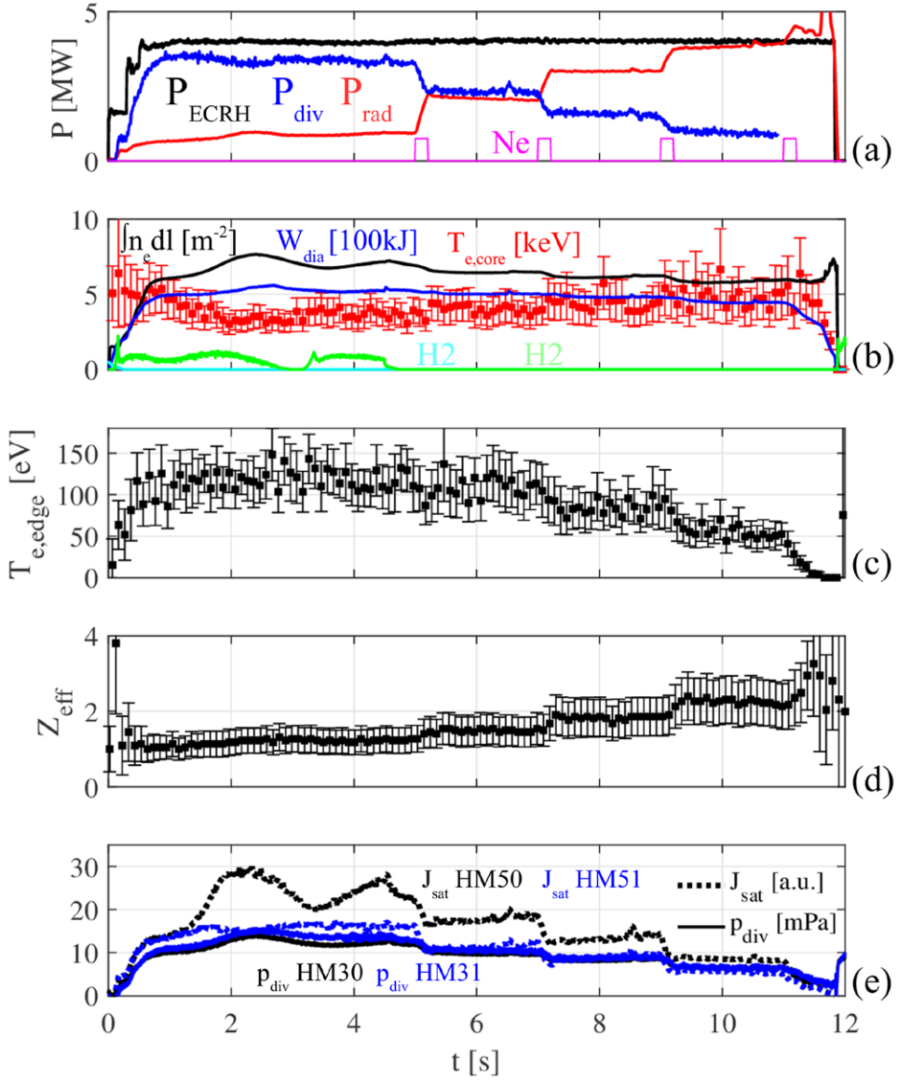
Steady-State, complete detachment in W7-X achieved

Detachment readily achieved

- Density ramps (intrinsic C) or impurity seeding
- Detachment is stable (except DBM)
- Detachment is complete across target



Effenberg NF 59 (2019)



Zhang PRL (2019)
Schmitz NF 61 (2021)
Jakubowski NF 61 (2021)

More on radiation & detachment:
V. Winters (Talk)
G. Partesotti (Poster)
Y. Feng (Poster)

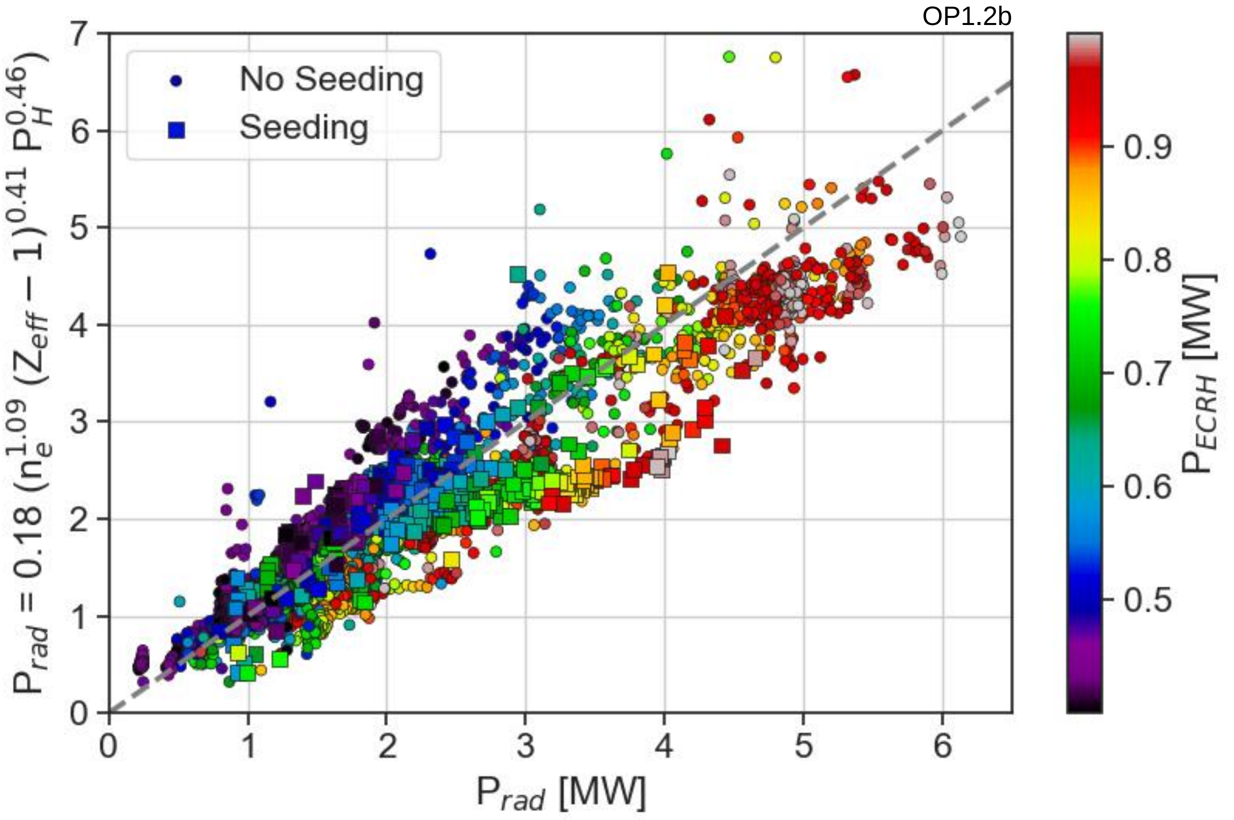
Are there known limits to detachment in W7-X?

Power exhaust limit in W7-X

Regression analysis of radiation data

- Consistent scaling with line-integrated density with intrinsic and seeding

$$P_{rad}[MW] = 0.18\ \ n_{e,int}^{1.09}\ [10^{19}m^{-3}]\left(Z_{eff}-1\right)^{0.41}\ P_{Heat}^{0.46}[MW]$$



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Extrapolate detachment with radiation scaling

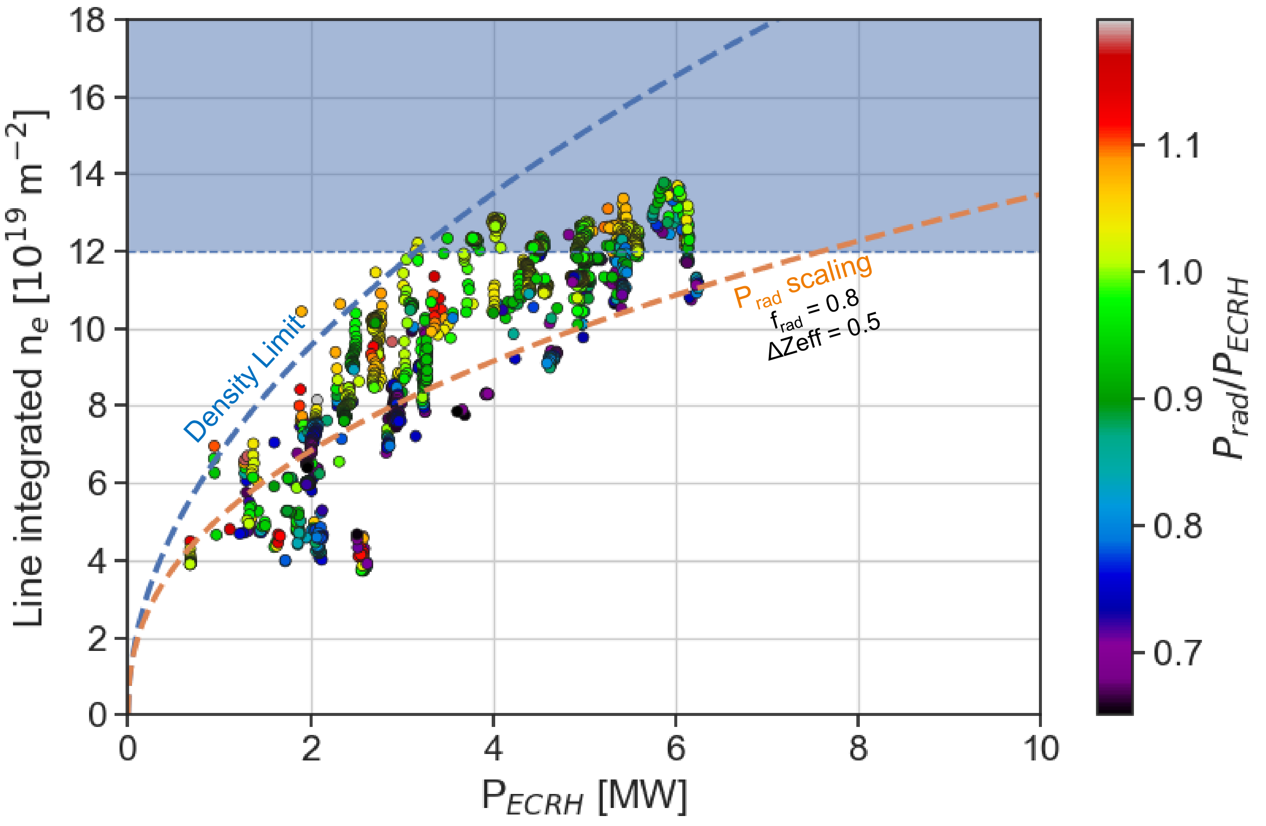
- Detachment qualifier: $f_{rad} > 0.8$
- Intrinisic impurities / low seeding: $\Delta Z_{eff} = 0.5$
- Detachment limitations with ECRH:

X2-Heating $(n_c = 1.2 - 1.4x10^{20}m^{-3})$

→ $P_{lim,det} = 10\ MW$

O2-Heating $(n_c = 1.8x10^{20}m^{-3})$

→ $P_{lim,det} = 20\ MW$



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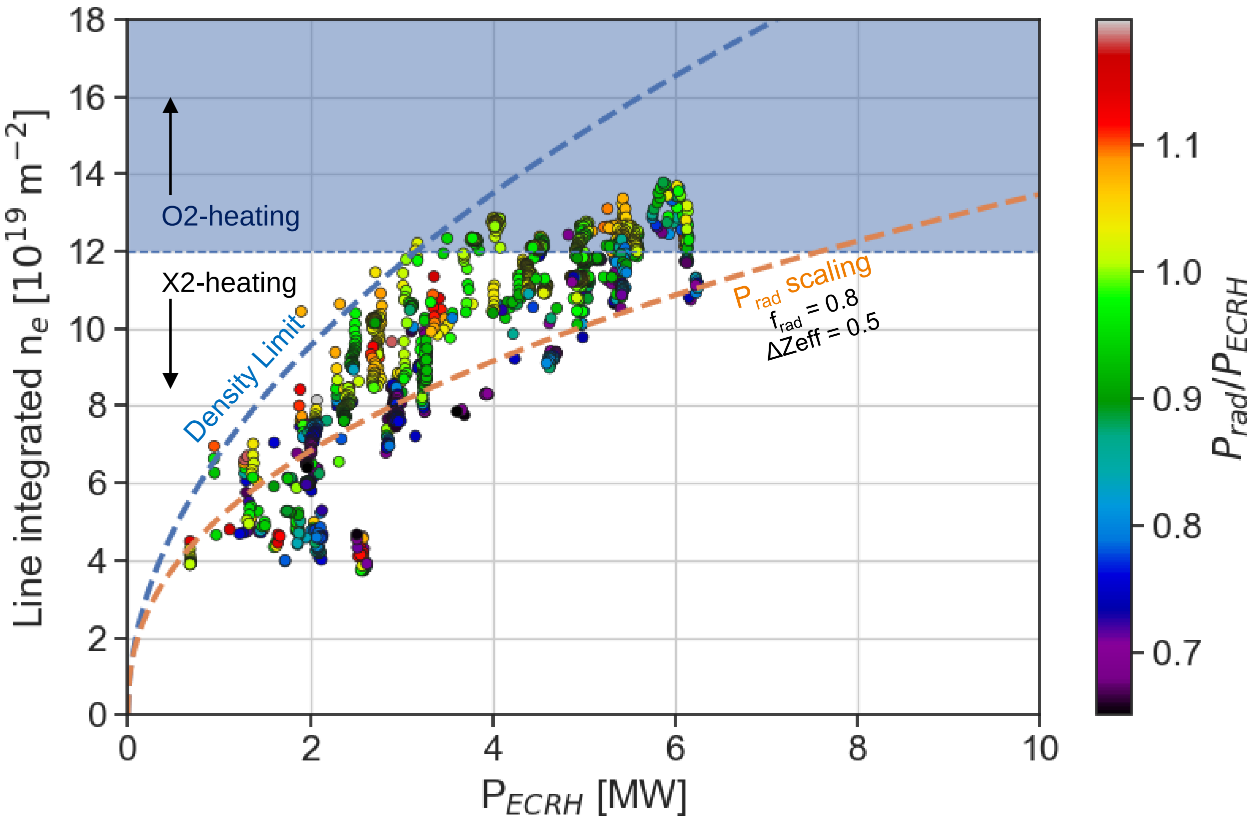


Power exhaust limit in W7-X

Can we cure this with impurity seeding?

- To some extent possible
- BUT, at the expanse of increased Zeff

W7-X is a carbon machine, i.e. significant intrinsic impurities are already present

Focus on: P_{Heat} = 2-5 MW & $n_{e,int} > 3x10^{19}$ m^{-3}

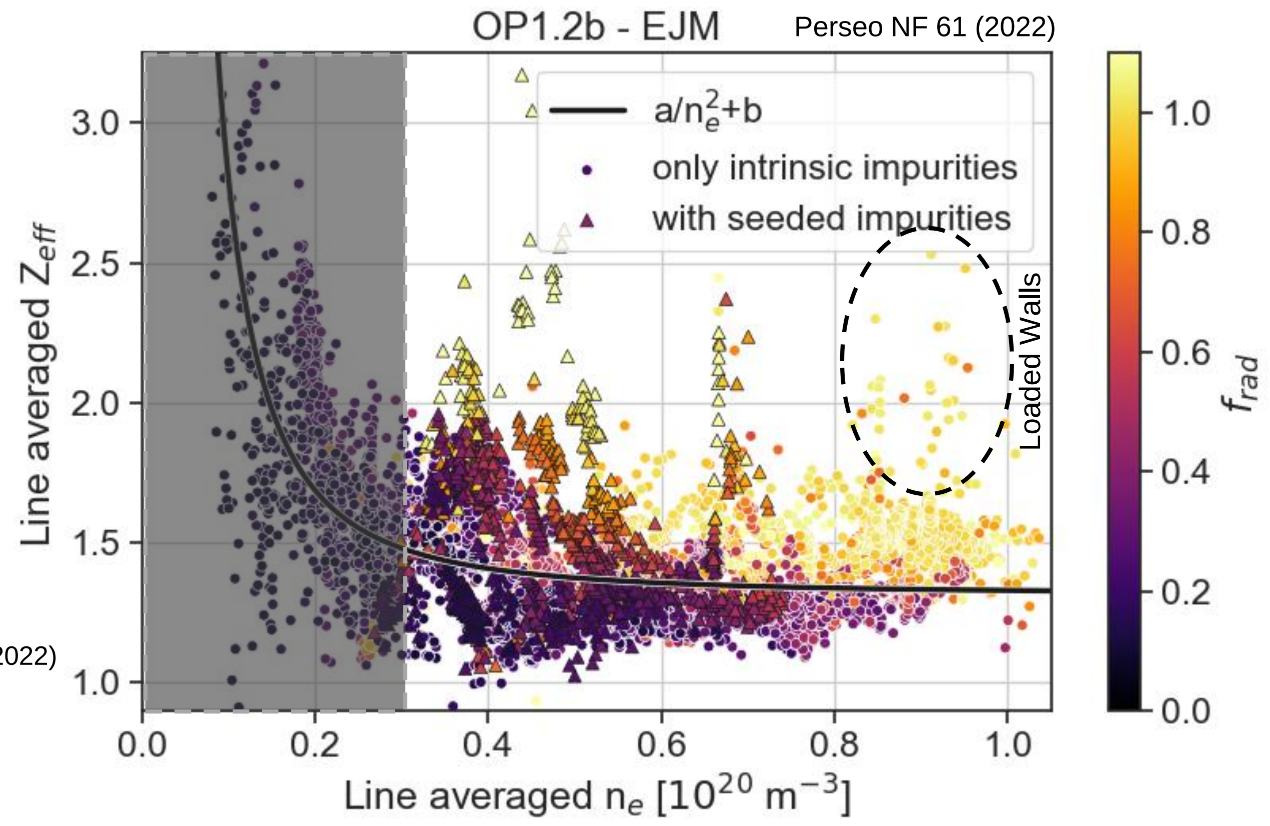
- Impurity concentration (spectroscopy & CXRS)
  - Z_{eff} = 1.1 - 1.7
  - $c_{C,core}$ = 0.5-1.5%
- Predicted enrichment (EMC3-Eirene)
  - η_{imp} = 4-6

Perseo NF 61 (2022)
F. Reimold PSI 2020
F. Henke PSI 2022
T. Romba PPCF 65 (2022)

→ Estimate $c_{C,div}$ = 4-6% (consistent with $Y_{sput,chem}$)

Roth JNM (1999)

Perseo NF 61 (2022)



Note: Direct divertor concentration measurements under development

Divertor Spectroscopy
F. Henke (Poster)

Power exhaust limit in W7-X

Extrapolating to nominal operational heating power of W7-X (10-20 MW) with C-impurities

Use EMC3-Modeling:

$D = 0.5\ m^2/s$, $X = 1.5\ m^2/s$

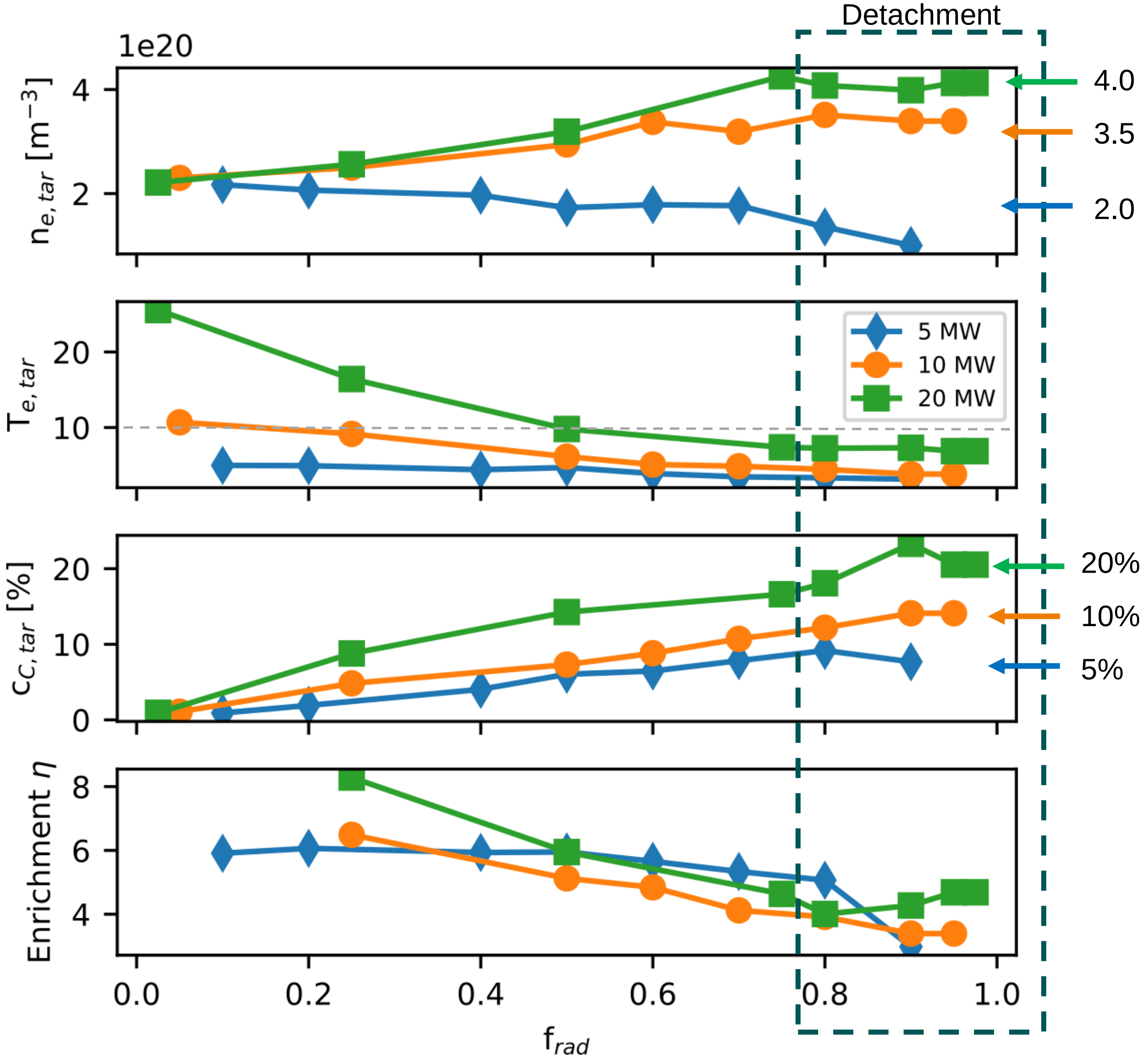
$n_{e,sep} = 3.0x10^{19}\ m^{-3}$

– Strong increase in c_C required to radiate sufficiently ($f_{rad} > 0.8$)

– Divertor impurity concentration:
  $c_{C,div,det}$= 10-20%

– Separatrix impurity concentration:
  $c_{C,sep,det}$ up to 4-5% (Z_{eff} = 2)

More investigations required:
- Impurity species (Ne, Ar,…)
- Transport coefficients (similar trend for reduction by x3)



Particle exhaust limits in W7-X

Neutral pressure sufficient for particle control

- Steady-state detached, high-density plasmas
- Wall important for low to medium densities (not shown here)
- Neutral compression retained up to $f_{rad} < 0.8$ (as in closed divertor tokamaks)

Feng NF 61 (2021)
Kremeyer IAEA (2023)
Schmitz NF 61 (2021)
Jakubowski NF 61 (2021)

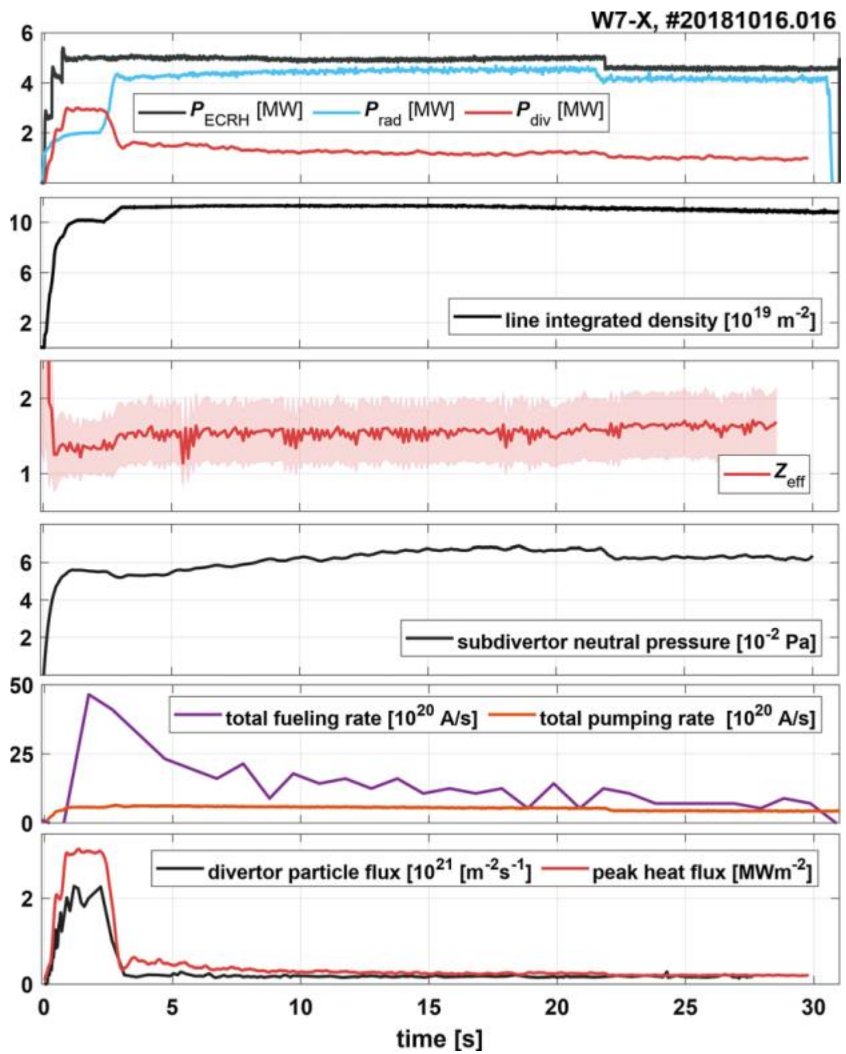
Limited neutral pressure & scaling

- Neutral pressure scaling:

$$p_{0,div}[Pa] \propto n_{e,int}^{1.0}[1E19]P_{Heat}^{0.5}[MW]\,(I_{CC}[kA]+2)^{0.5}f_{rad}^{0.1}$$

→ But low levels of absolute pressure:

$$p_{0,div} < 0.1 - 0.15\ Pa$$



Jakubowski NF 61 (2021)

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- Neutral pressure scaling:

$$p_{0,div}[Pa] \propto \ n_{e,int}^{1.47}[1E19]P_{Heat}^{0.3}[MW]\ (I_{CC}[kA]+1.5)^{0.3}$$

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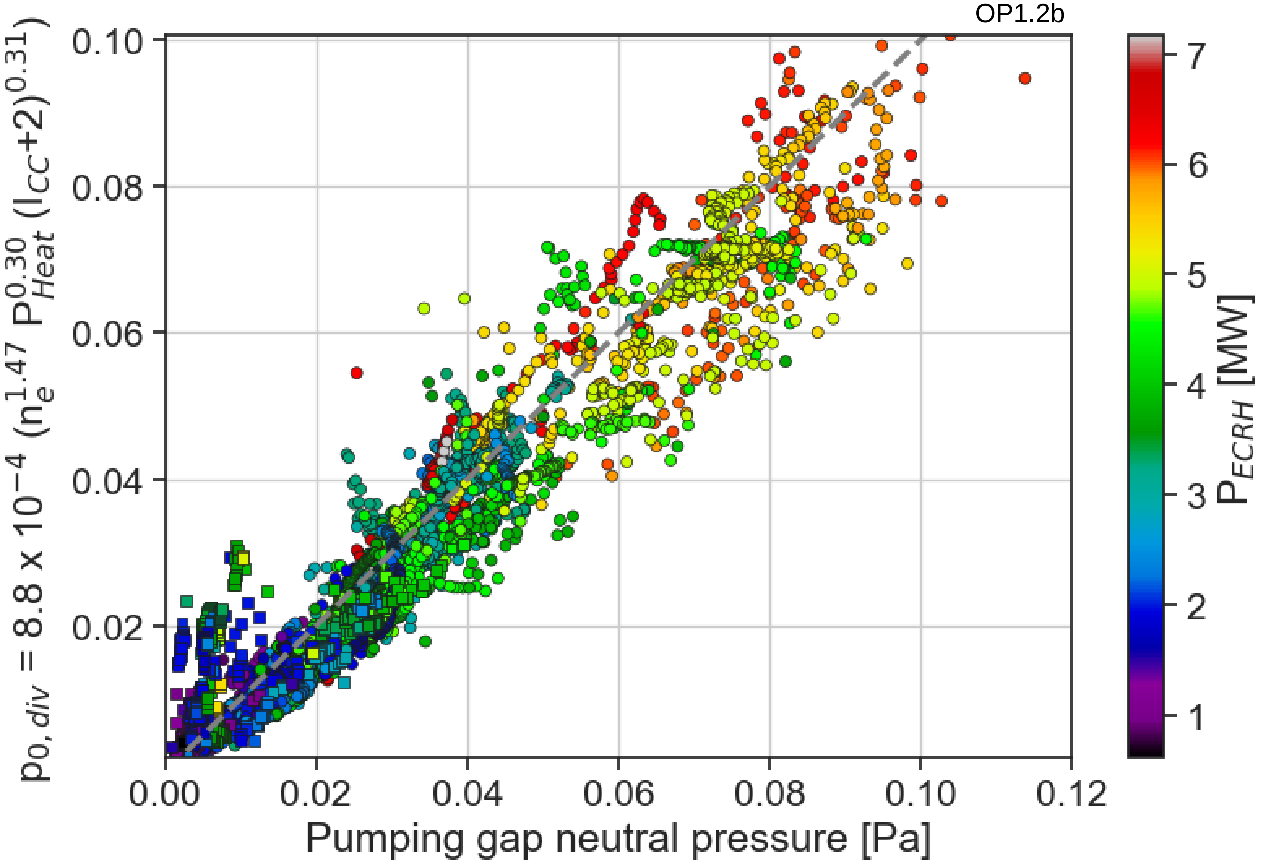


Where do we think the limit comes from?

Limited density build-up in the divertor

Divertor densities measured by Stark broadening of H_δ

- Increased downstream density: $n_{tar} > n_{up}$
  - → Step forward with respect to W7-AS (except HDH)
- No tokamak-like high-recycling in W7-X: $n_{tar} \ll n_{up}^3$

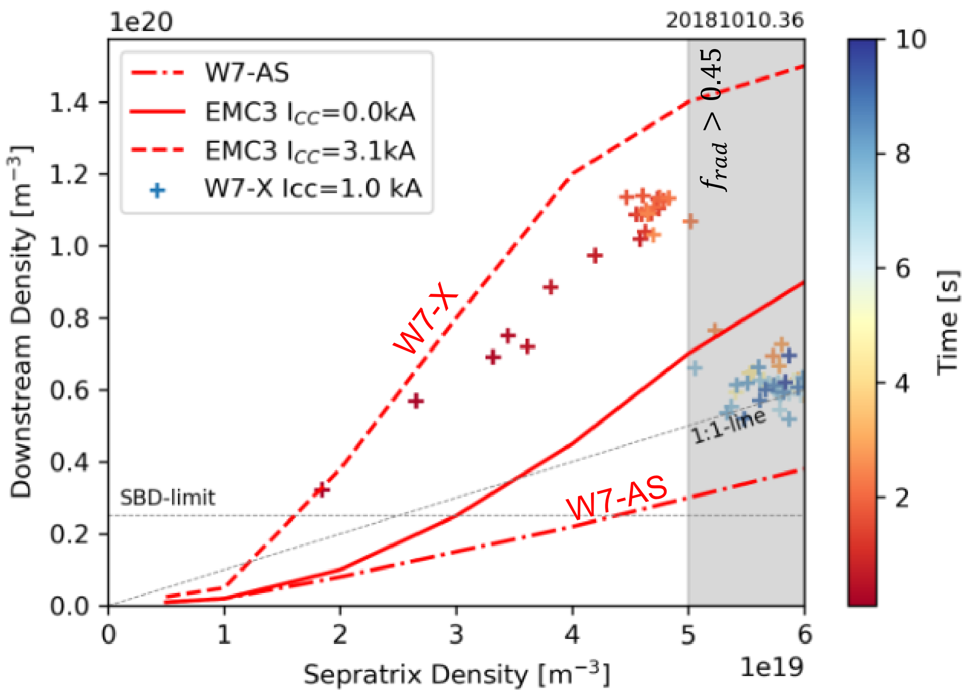
Comparison to modeling predictions (EMC3-Eirene)

- Density evolution & magnitude seems consistent
- BUT: Density scaling & distribution is different
  - → no strong effect of island size (fieldline pitch)

Database scaling approach

$$n_{Stark}[10^{19}m^{-3}] \propto \; n_{e,int}^{0.43}[10^{19}m^{-3}](I_{CC}[kA]+1.5)^{-0.07}P_{Heat}^{0.17}[MW]$$

Power starvation detachment



Reimold IAEA (2023)

Feng PPCF 53 (2011)

Note: Strong variation in different density measurements

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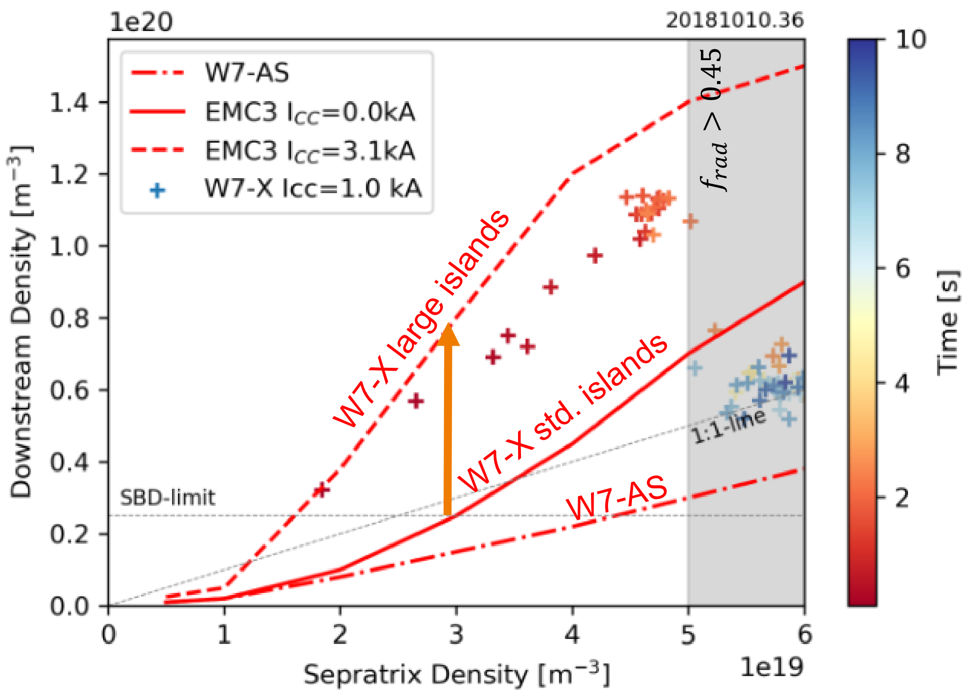

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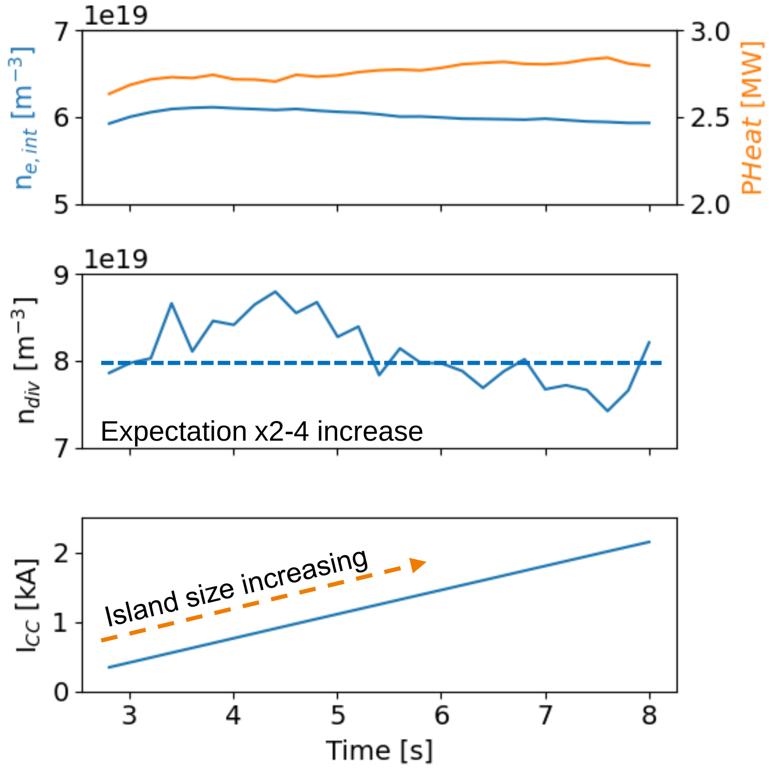

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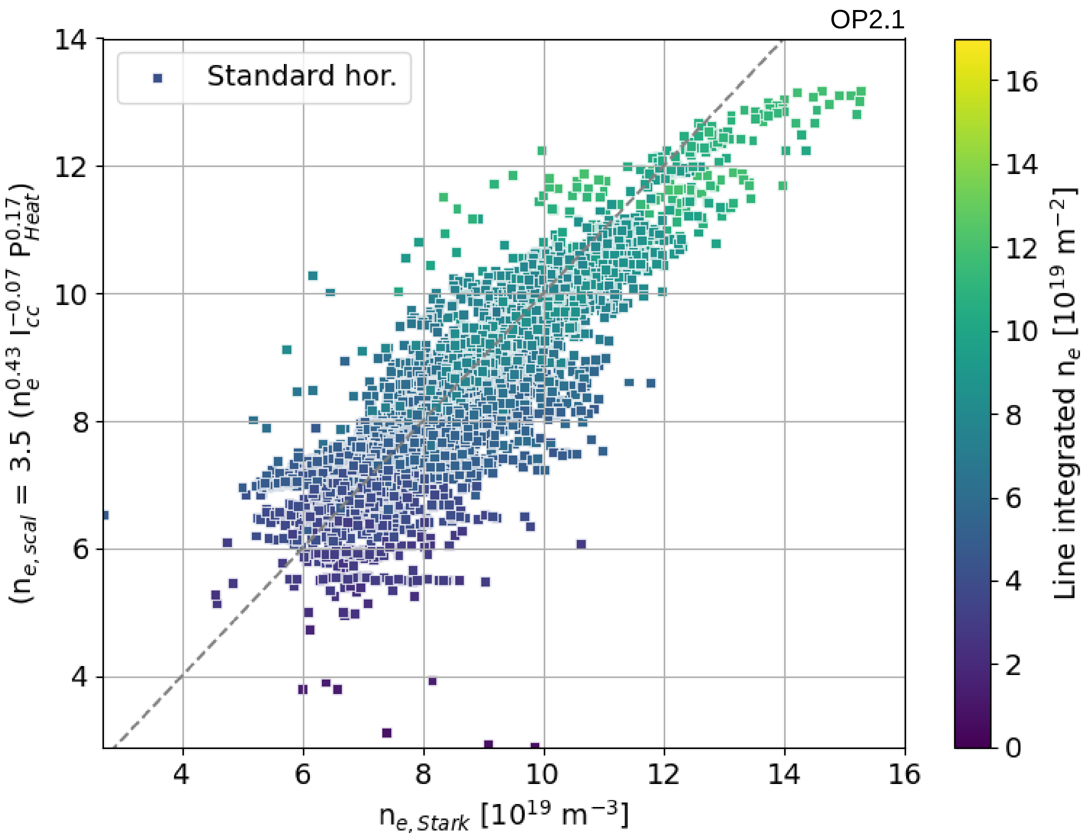
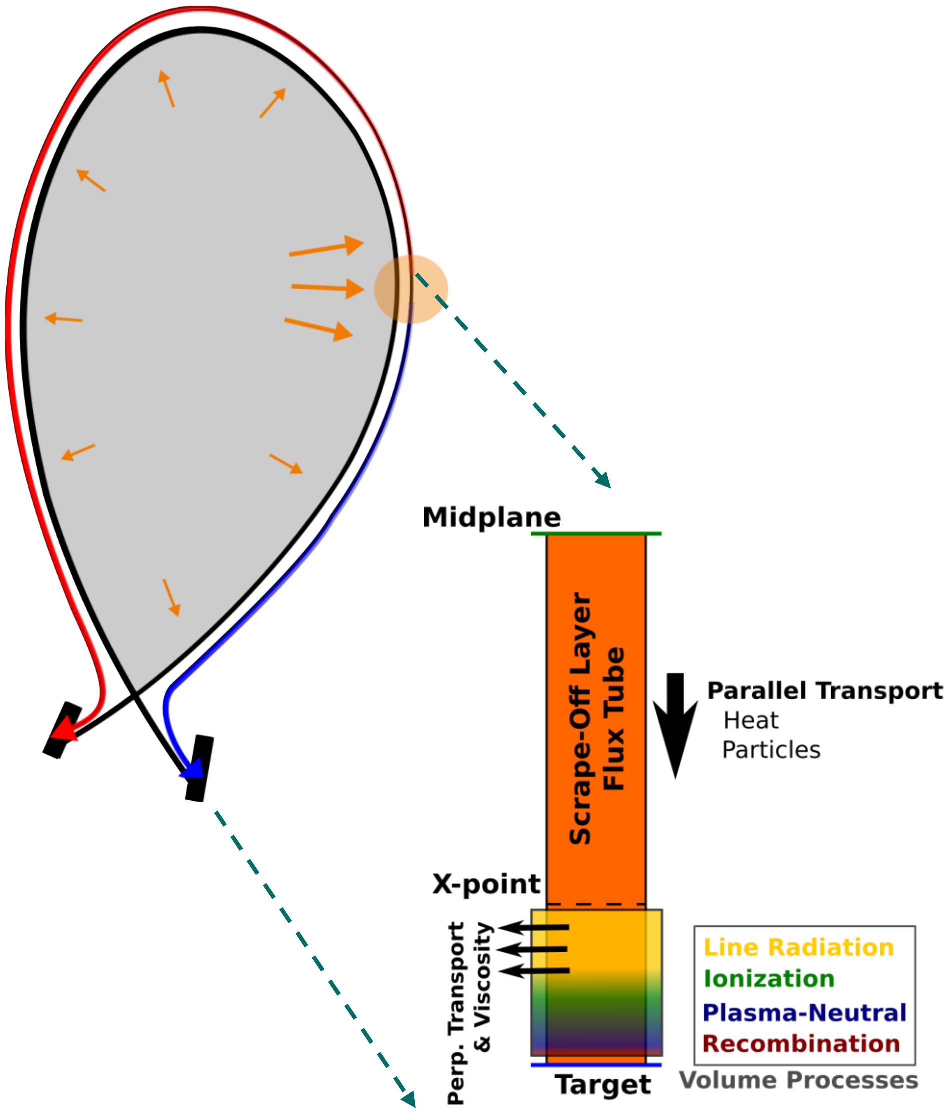


Divertor Spectroscopy
F. Henke (Poster)

Can we understand this?

Scrape-Off Layer transport: The geometry simplified

Image courtesy of V. Perseo



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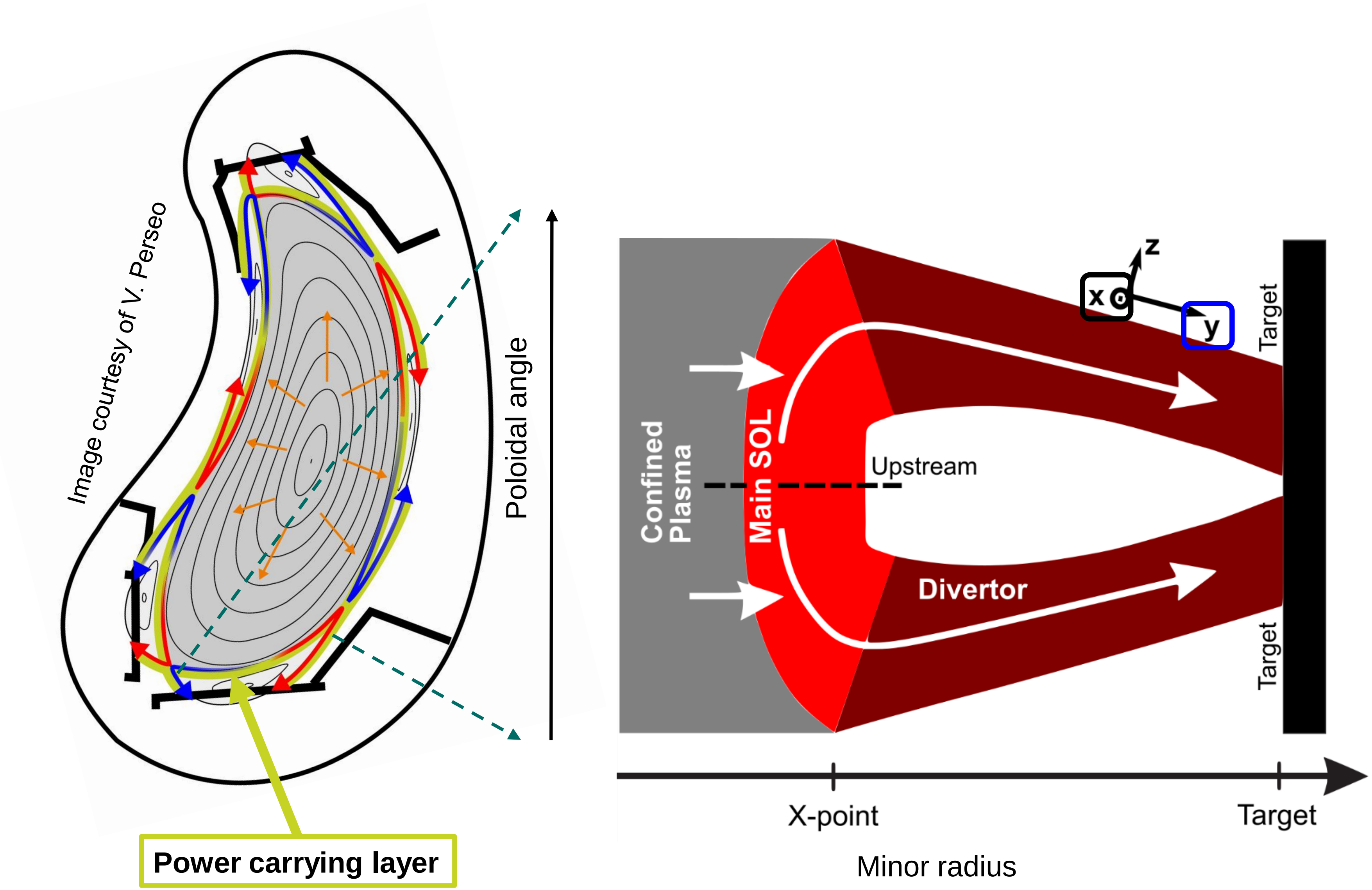

Transport directions

X – **Parallel**

Y – **Bi-normal**

Z – Fluxsurf. perp.

Extended Stellarator Two-Point Model

Transport directions
X – **Parallel**
Y – **Bi-normal**
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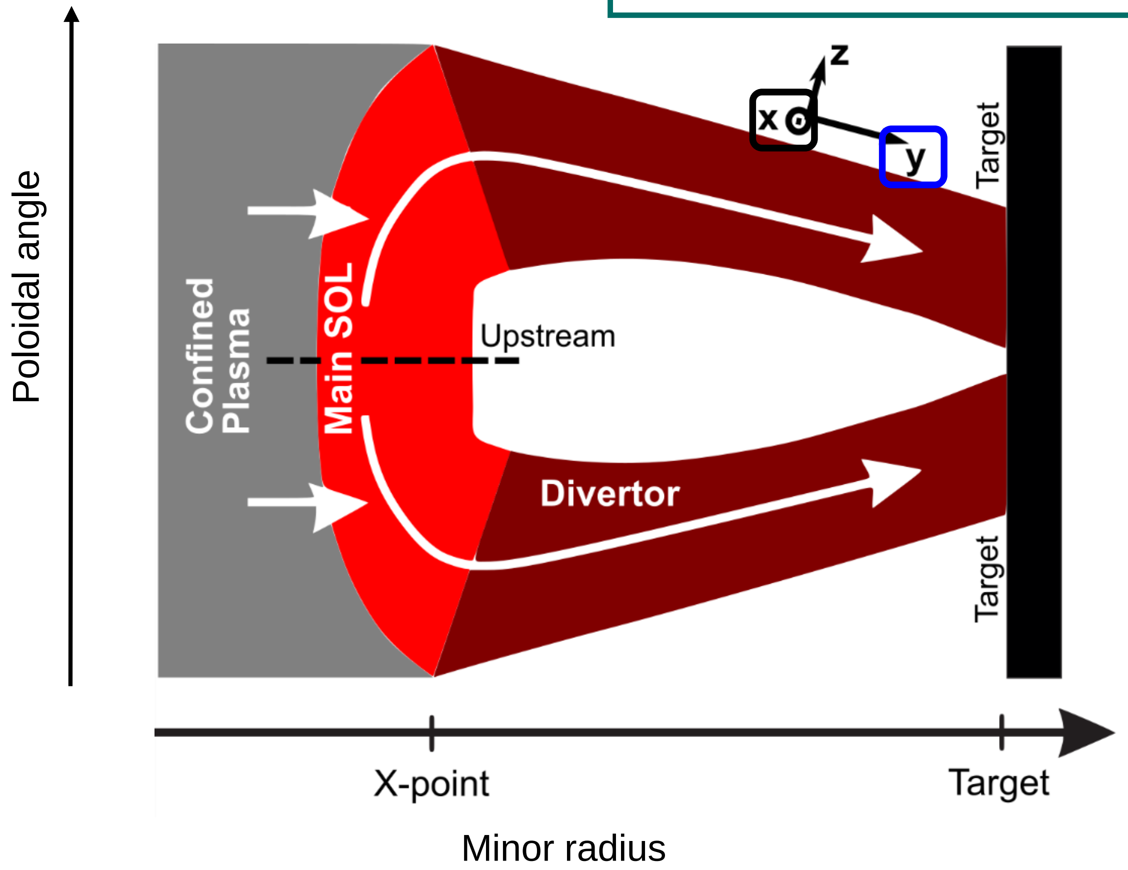


Recall:
$\Theta_i = 10^{-3}$ W7-X
$\Theta = 10^{-1}$ Tokamak

$$\Theta \frac{d}{dy}\left(-\kappa_e T^{\frac{5}{2}} \Theta \frac{dT}{dy}\right) + \frac{d}{dy}\left(-\chi n_e \frac{dT}{dy}\right) = S_{loss}$$

Parallel **Bi-normal**

$$\Theta \frac{d}{dy}\left(m n_e v_\parallel^2 + p\right) = S_{mom}$$

$$q_{tar} = \gamma\, n_{tar}\, c_s\, T_{tar}\,(1 - f_{rad})$$

$$q^*_{\parallel,up} = q_\parallel (1 - f_{conv})$$

Strong implicit assumptions:

- Fluxsurface perp.transport (z) neglected
- Toroidal symmetry (target conditions)

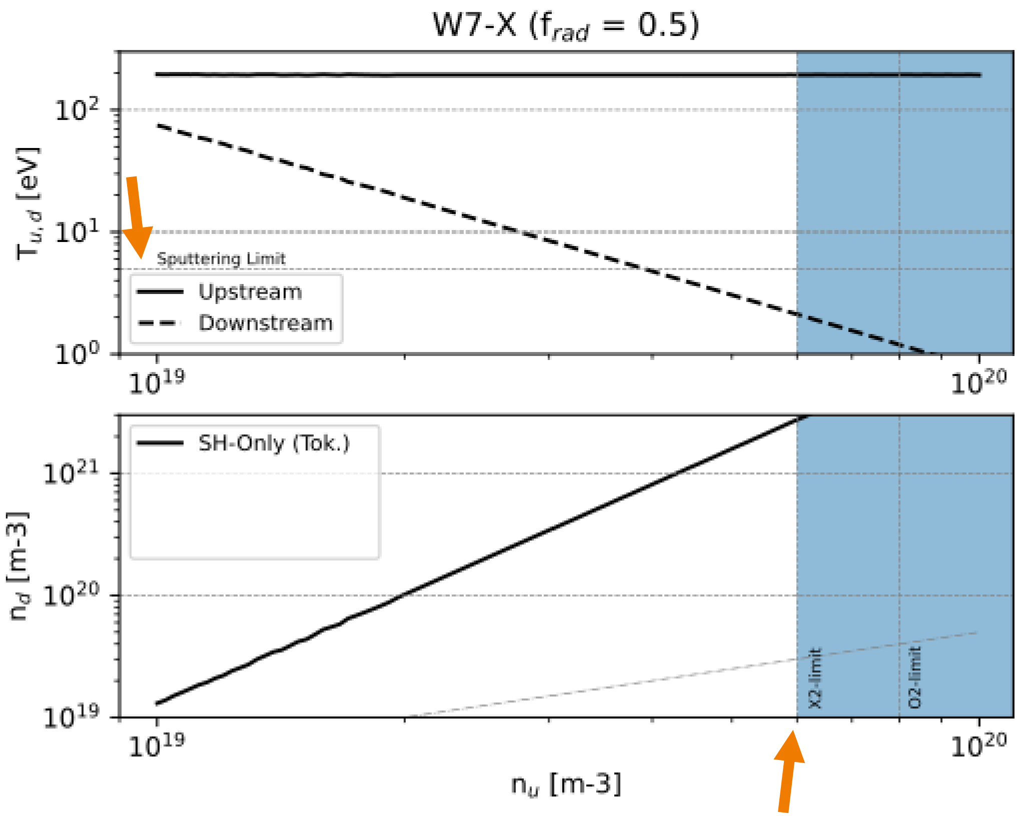
→ **Following educational due to limited physics!**

Analyzing the W7-X divertor limits with the STPM

Elements of Density Build-Up in W7-X

- Target temperature drop at high T_e set by SH-heat conduction
- T_d drop limited by bi-normal (BN) transport
  → Density build-up limited: no high recycling ($n_d \propto n_u^3$)
- Stellarator pressure losses limit divertor density
  → Often strong limitation
- Strong parallel convection compared to tokamaks
  → Strong role of convective loss factor f_{conv}
  → Driven by: ionization, BN-diffusion & drifts (!)

Note: Consistent already with EMC3-Eirene (no drifts!)



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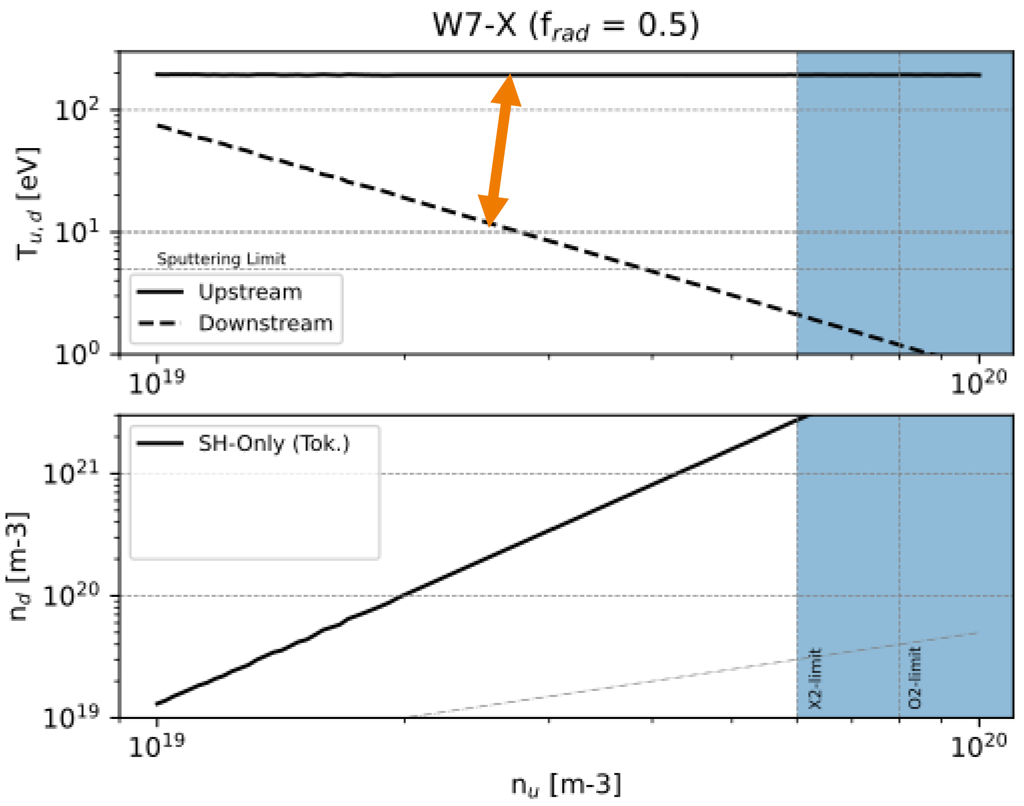

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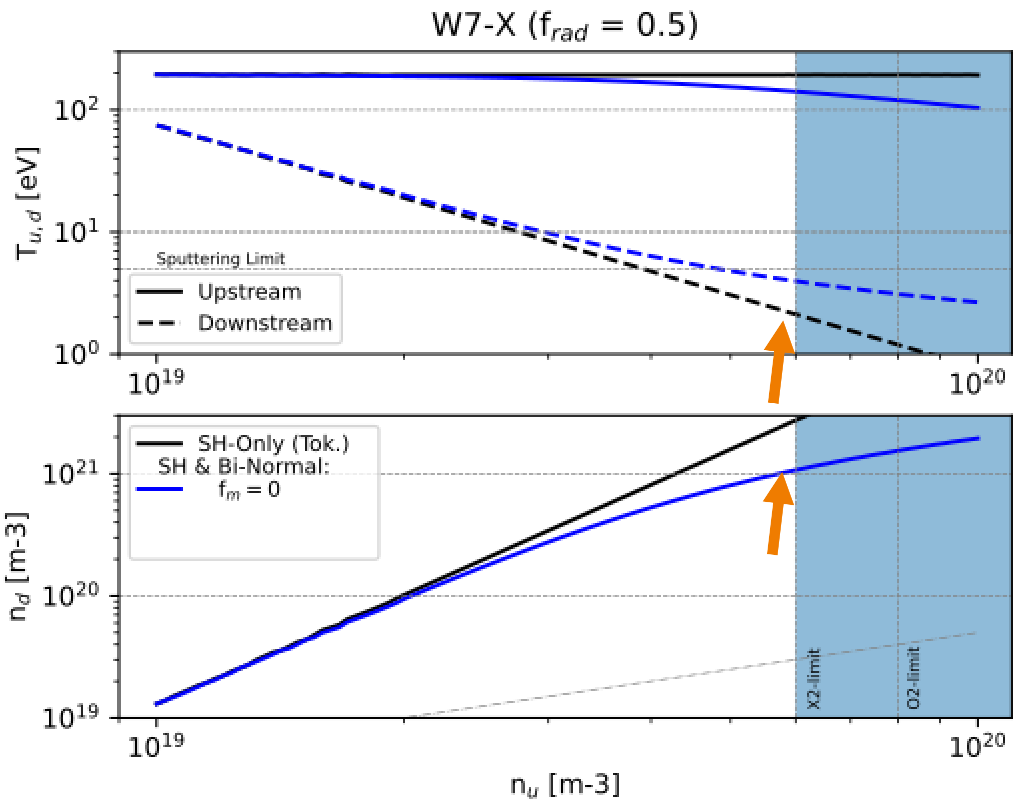

$$\frac{q_\parallel}{q_\perp} \propto \frac{\kappa T^{5/2} \langle \Theta \rangle^2}{\chi n}$$

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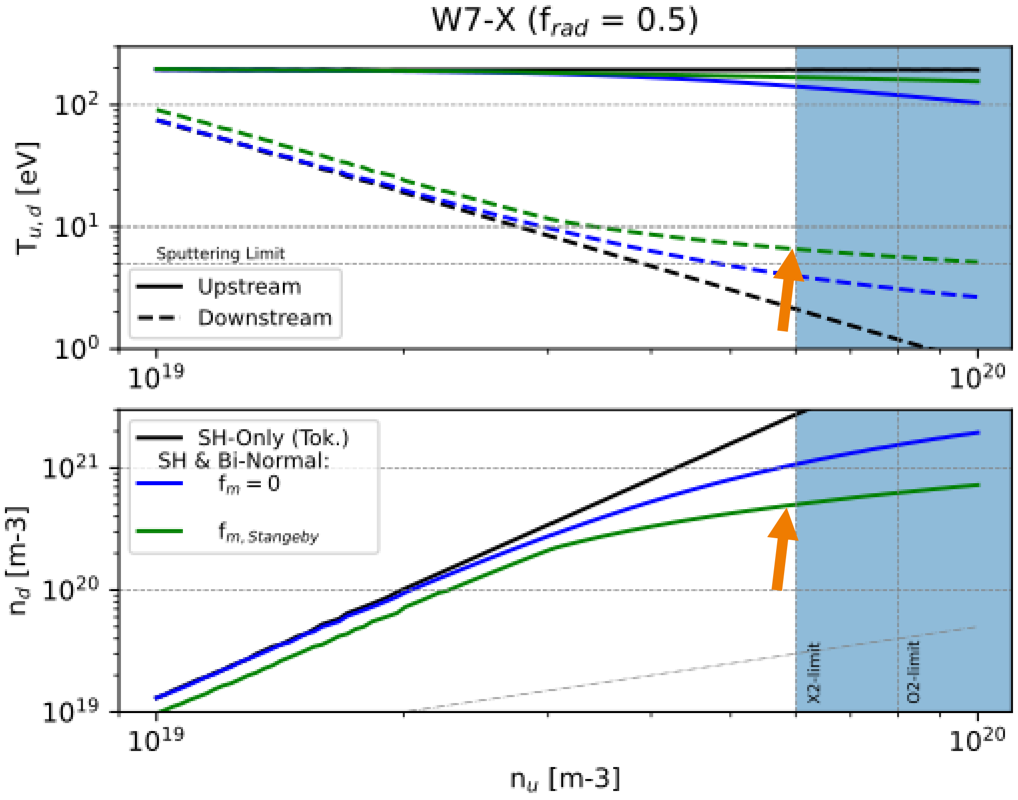

$f_{m,Stangeby} = A(1-e^{-Tt/T^*})^n$

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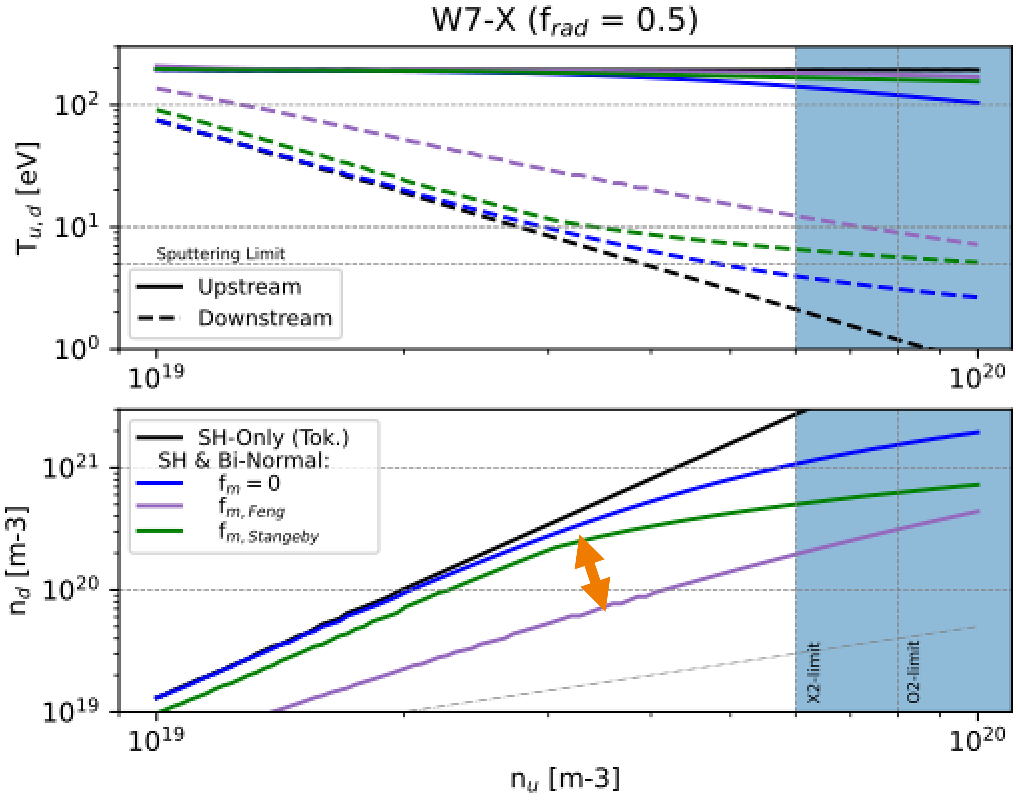

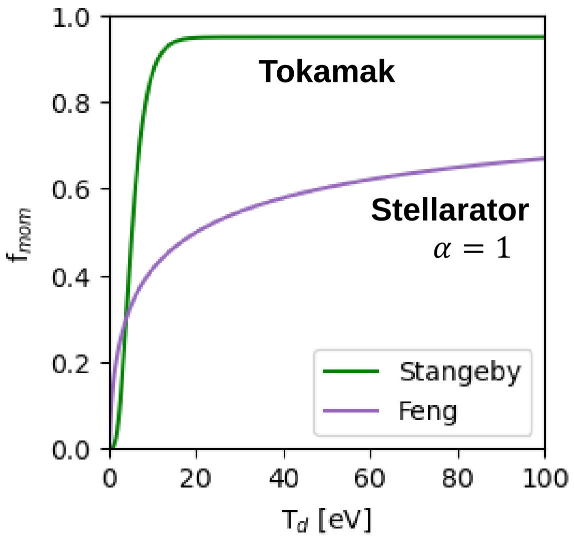

Dominant processes different:

- Plasma-Neutral Interaction (Tokamak)

$$f_{m,Stangeby} = A(1-e^{-Tt/T^*})^n$$

- Momentum Transport (Stellarator)

$$f_{m,Feng} = \frac{\alpha}{\sqrt{T}}$$

Feng NF 46 (2006)
Stangeby NF 60 (2018)

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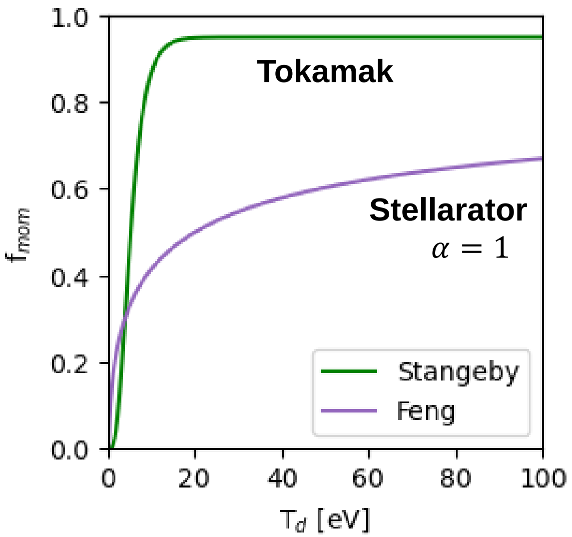

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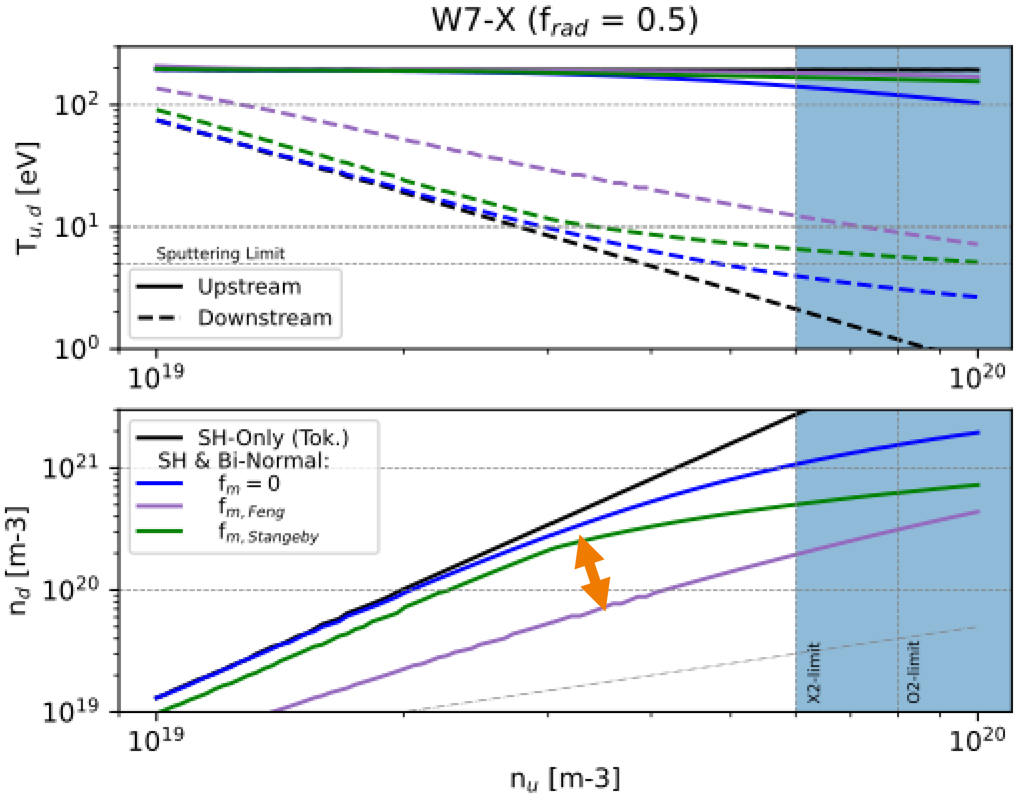

High priority:
→ Determination of pressure loss function required
(challenge for diagnostics in 3D!)

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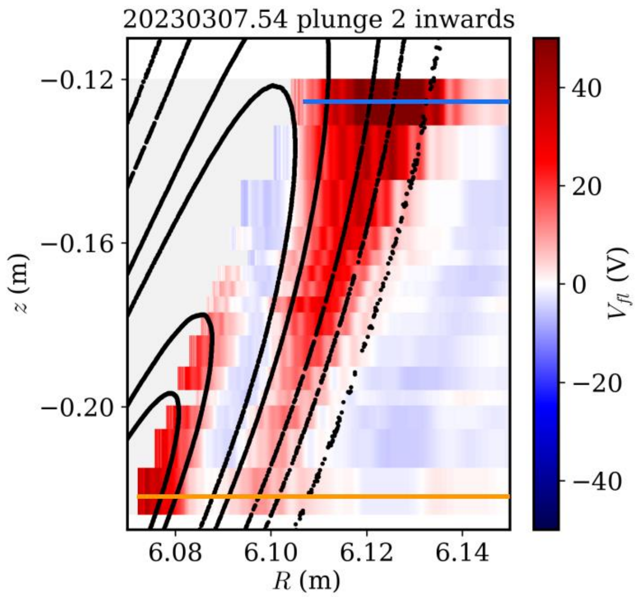
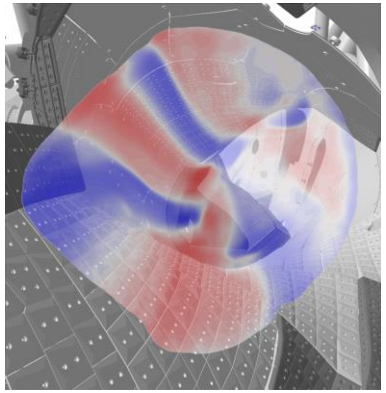
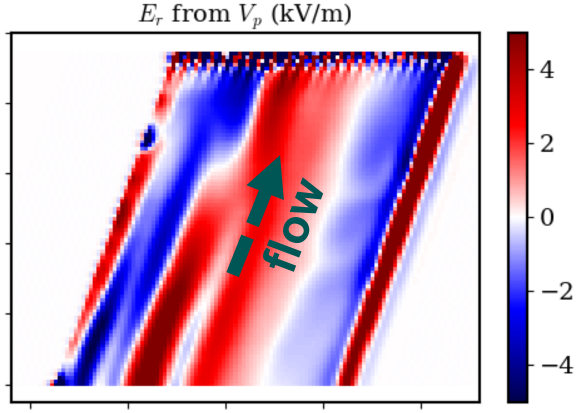
D. M. Kriete NF 63 (2023)
D. Cipciar EPS 2023
C. Killer EPS 2023
S. Ballinger EPS 2023
A. v. Stechow EPS 2023
E. Flom NF (submitted)



Perseo NF 61 (2022)



Parallel Flows (CIS)
V. Perseo (Poster)



Drift Flows
S. Ballinger (Talk), C. Killer (Poster)

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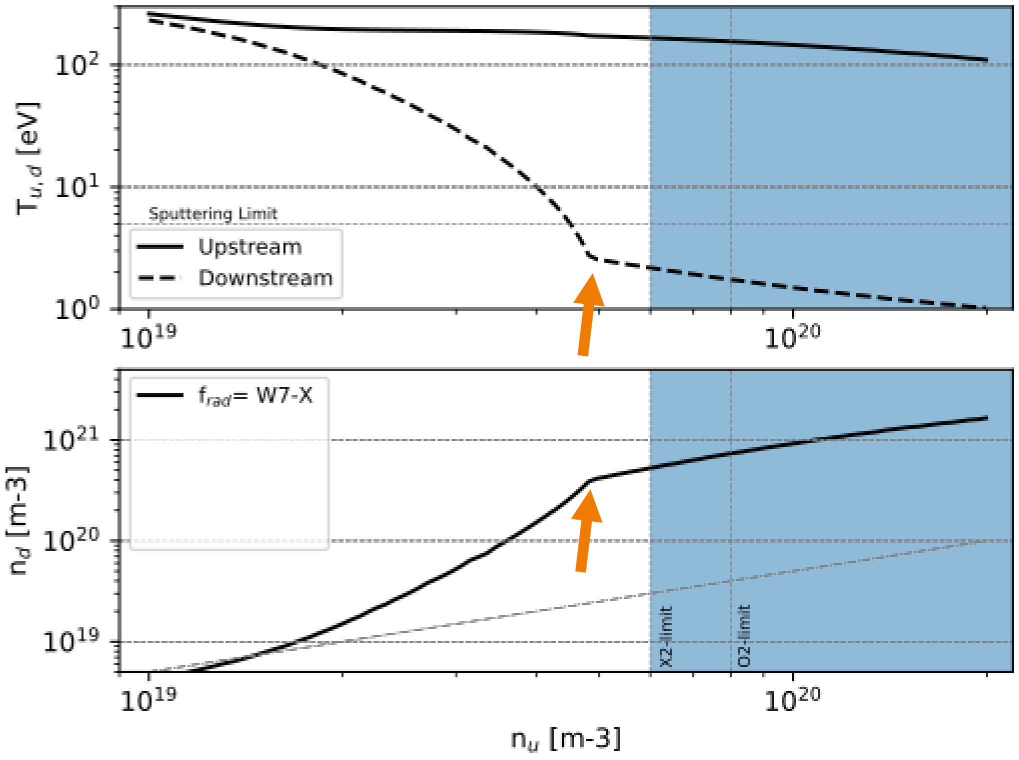


Use W7-X radiation scaling

Analyzing the W7-X divertor limits with the STPM

Elements of Density Build-Up in W7-X

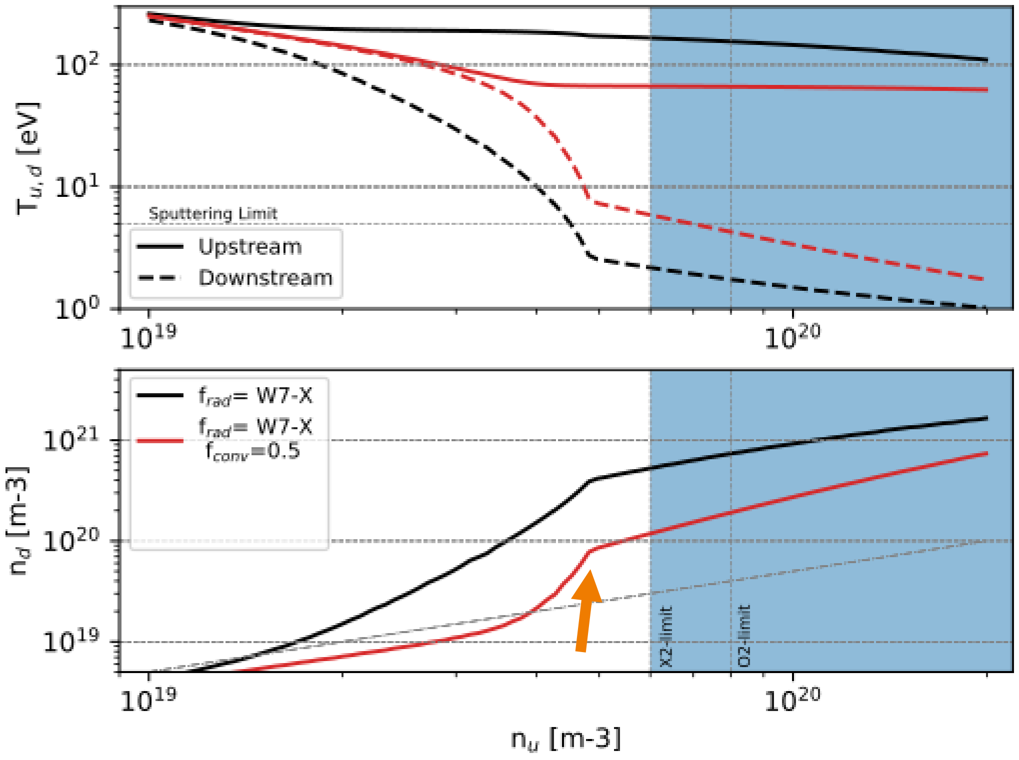
- Target temperature drop at high T_e set by SH-heat conduction

- T_d drop limited by bi-normal (BN) transport
  → Density build-up limited: no high recycling $(n_d \propto n_u^3$

- Stellarator pressure losses limit divertor density
  → Often strong limitation

- Strong parallel convection compared to tokamaks
  → Strong role of convective loss factor f_{conv}
  → Driven by: ionization, BN-diffusion & drifts (!)

Note: Consistent already with EMC3-Eirene (no drifts!)



Add convective heat transport

Where do we stand now?

Experiment shows limited divertor density build-up in W7-X

→ Particle exhaust limitations (pumping)

→ Power exhaust limitations (detachment access)

Different scaling of heat transport in bi-normal channel

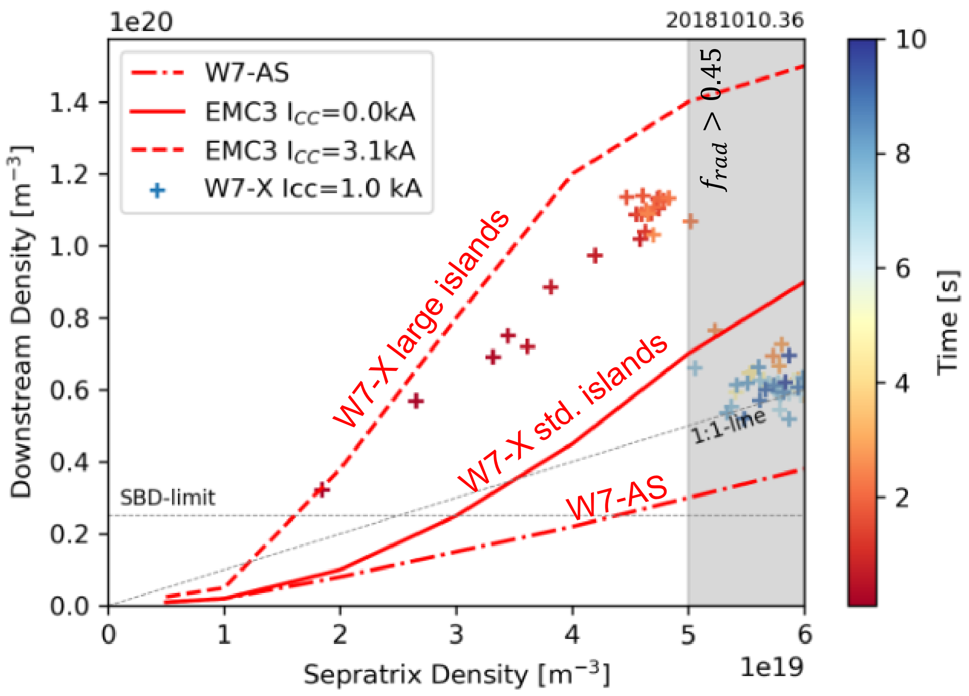
– Fieldline pitch & connection length important

Strong effect of pressure losses are present

– Additional processes likely (momentum transport)

Convection (& power starvation) provide additional limits

→ Weak(er) density scaling - no "high"-recycling



Reimold IAEA (2023)

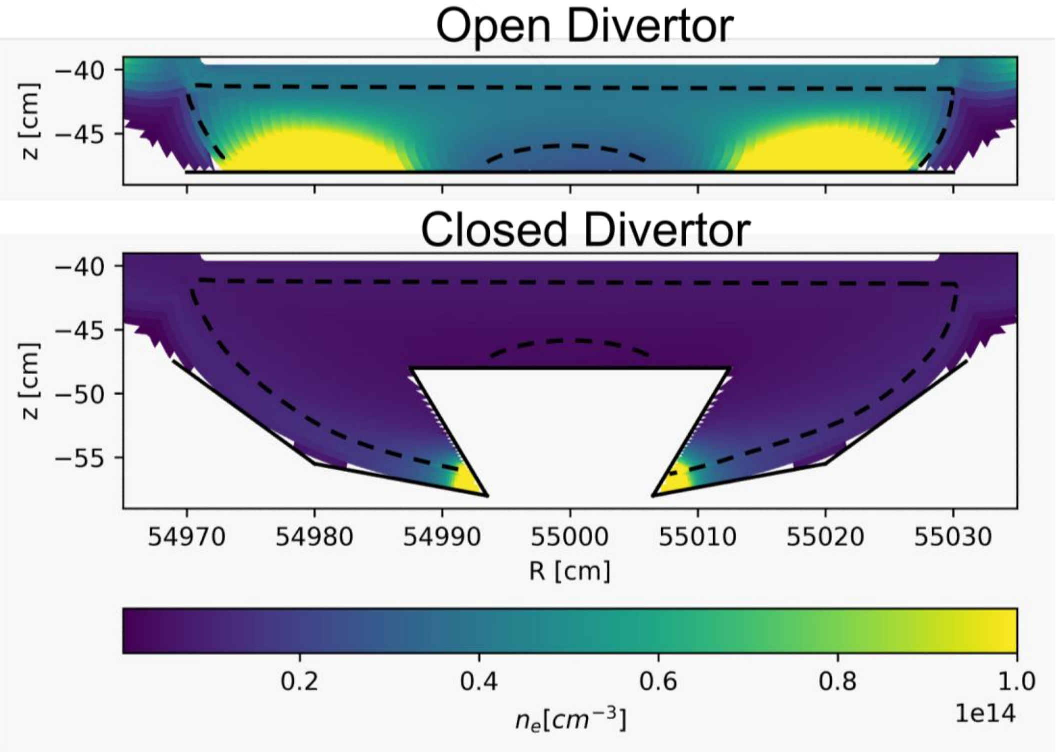
Feng PPCF 53 (2011)

What is the way forward towards a reactor?

Using a simplified slab island like geometry to investigate the role of guiding parameters individually

Promising results recently obtained for a closed divertor

- Better neutral retention & recycling in power carrying layer
- Less convection (neutral & plasma screening)
- Likely access to more favorable momentum losses distribution



Density build up (EMC3)
N. Mazziz (Poster)

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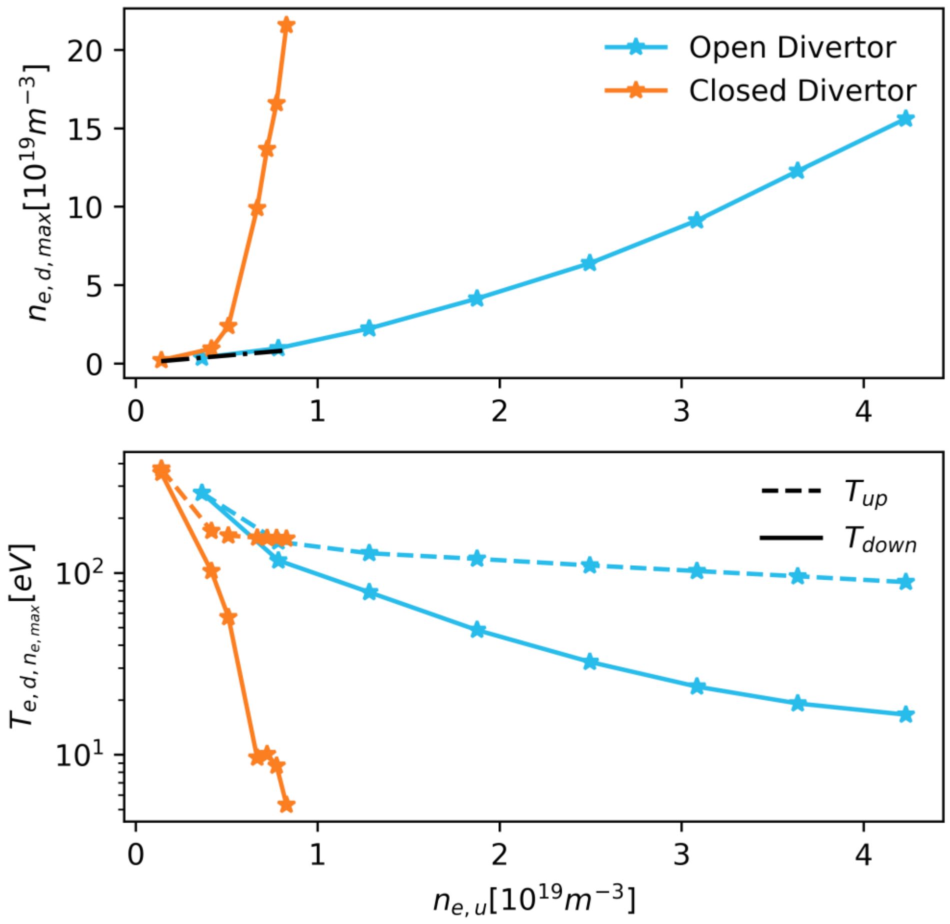
→ **More favorable density scaling**



Density build up (EMC3)
N. Mazziz (Poster)

Conclusions

Experiment shows limited divertor density build-up in W7-X

→ Particle exhaust limitations (pumping)

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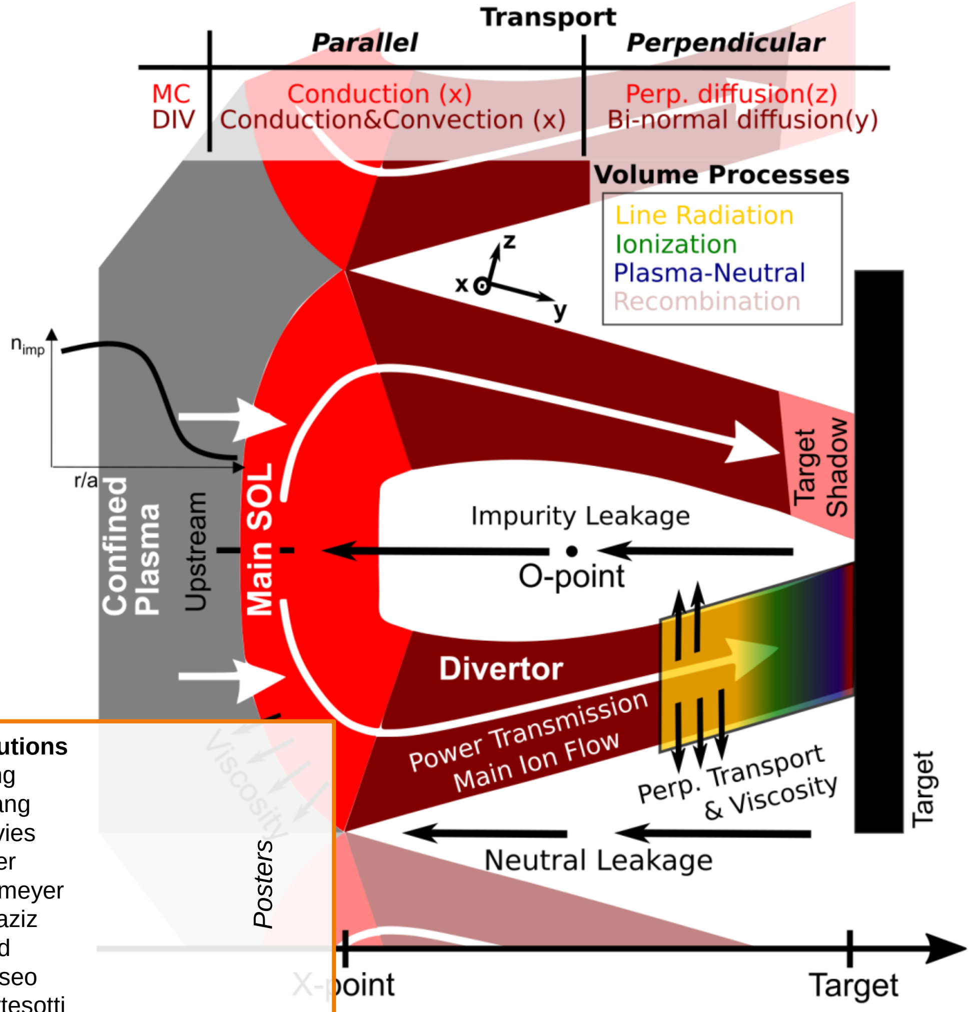
– Additional processes likely (momentum transport)

Convection (& power starvation) provide additional limits

→ **Weak(er) density scaling - no "high"-recycling**

Way forward seems possible with closed divertor



W7-X contributions

Posters

P1-008 Y. Feng
P1-014 D. Zhang
P1-081 R. Davies
P2-023 C. Killer
P2-031 T. Kremeyer
P2-032 N. Maaziz
P2-037 D. Bold
P2-049 V. Perseo
P4-006 G. Partesotti
P4-018 F. Henke

Talks

V. Winters (Tues.)
D. M. Kriete Diagnostics (Thurs.)
S. Ballinger Diagnostics (Thurs.)