



First wall fluxes in ITER from full vessel edge-plasma simulations

Nicolas Rivals, Tamain P., Marandet Y., Bonnin X., Bufferand H., Pitts R.A.,
Falchetto G., H. Yang, Ciraolo G.

► To cite this version:

Nicolas Rivals, Tamain P., Marandet Y., Bonnin X., Bufferand H., et al.. First wall fluxes in ITER from full vessel edge-plasma simulations. AAPPS DPP 2022 - 6th Asia-Pacific Conference on Plasma Physics, Oct 2022, Remote due to Covid-19, Japan. cea-03949436

HAL Id: cea-03949436

<https://cea.hal.science/cea-03949436>

Submitted on 20 Jan 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



First wall fluxes in ITER from full vessel edge-plasma simulations

MF2-I27 - 6th Asia-Pacific Conference on Plasma Physics, Oct 9-Oct14, 2022, Remote e-conference

DE LA RECHERCHE À L'INDUSTRIE

Nicolas RIVALS (CEA IRFM)

P. TAMAIN (CEA IRFM), Y. MARANDET (CNRS, Aix-Marseille Université), X. BONNIN (ITER Organization), H. BUFFERAND (CEA IRFM), R.A. PITTS (ITER Organization), G. FALCHETTO (CEA IRFM), H. YANG (CEA IRFM), G. CIRAOLO (CEA IRFM),

- **1. Context and motivation**
- **2. Up-to-the-wall domain challenge for ITER cases**
- **3. Impact of throughput**
- **4. Impact of enhanced far-SOL transport (shoulder formation)**
- **5. Summary**

- **1. Context and motivation**
- 2. Up-to-the-wall domain challenge for ITER cases
- 3. Impact of throughput
- 4. Impact of enhanced far-SOL transport (shoulder formation)
- 5. Summary

1. Context and motivation

ITER simulations: addressing the First Wall (FW) challenge



Impacts of plasma-FW Panels interaction

■ Panel erosion:

- FW lifetime (incl. # of spares)
- Dust generation (Be)
- Fuel retention

■ Plasma performance:

- Contamination (sputtering)
- Impurity transport & redeposition

Requires a tool for estimating
FW fluxes and **full vessel**
plasma backgrounds of key
plasma scenarios
➔ **SOLEGE3X**

Feed input for
other codes:

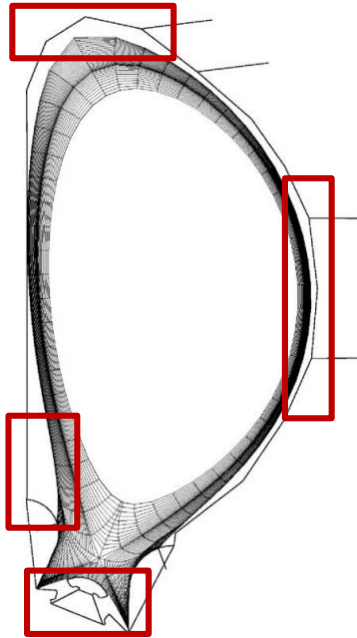
ERO2.0
WALLDYN

...

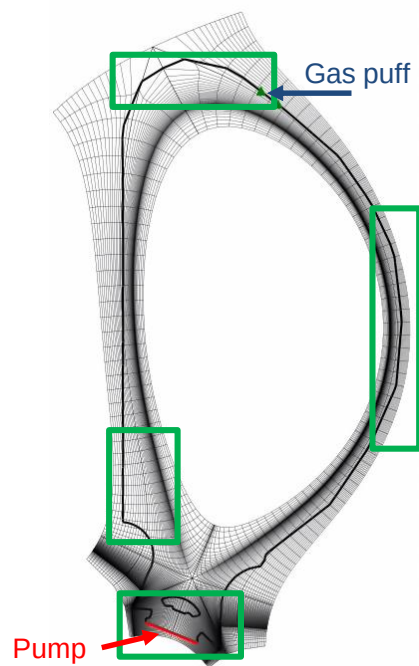
1. Context and motivation

Full vessel plasma numerical domain with SOLEDGE3X

**SOLPS-ITER
domain**



**SOLEDGE3X
domain**



- Divertor design mainly based on **SOLPS-ITER simulations**, domain restricted to common SOL

[R.A. Pitts et al. 2019 NME 20 100696]

- New **self-consistent plasma simulations** with numerical **grid extended to all plasma-facing components**

The SOLEDGE3X code and setup:

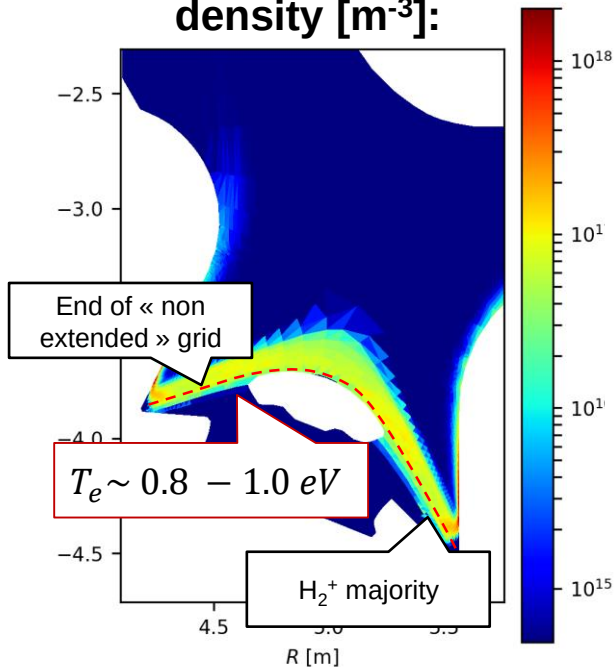
- **SOLEDGE3X:** Fluid multispecies (Zhdanov closure), 3D-turbulent or 2D-mean-field plasma solver coupled to kinetic neutrals from EIRENE or fluid neutrals *[H. Bufferand et al. 2021 Nucl. Fusion 61 116052]*
- **Simulation setup:**
 - Based on SOLPS-ITER cases (#103027-#103030) *[J.S. Park et al. 2021 Nucl. Fusion 61 016021]*
 - 2D-mean-field (transport) mode, prescribed diff. coeffs.
 - **L-mode** transport
 - **Most recent magnetic equilibrium** from DINA scenarios & wall contour
 - Pure H
 - **20MW** (PFPO-1)
 - No fluid drifts
 - **Advanced options in EIRENE** (elastic ion col., MAR, neutral-neutral col.)

- 1. Context and motivation
- 2. Up-to-the-wall domain challenge for ITER cases
- 3. Impact of throughput
- 4. Impact of enhanced far-SOL transport (shoulder formation)
- 5. Summary

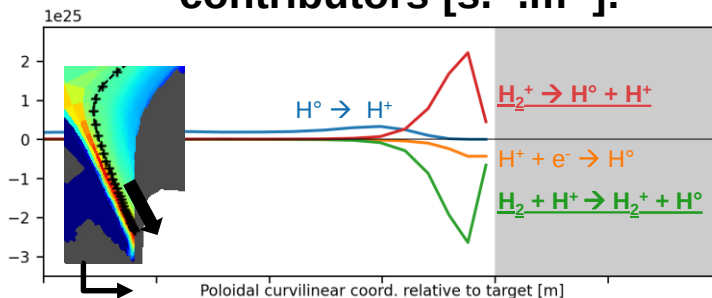
2. Up-to-the-wall domain challenge for ITER cases

Key role of H_2^+ molecular ion near divertor legs

Molecular ion H_2^+
density [m^{-3}]:



H^+ particle source main
contributors [$s^{-1}.m^{-3}$]:



H_2^+ ion role:

- H_2^+ : intermediate product in “molecule-assisted” processes (MAR, MAI)
 - Significant $n_{H_2^+}$ just below the end of “common SOL” domain, even majority species there
 - $\lambda_{mfp H_2^+}^{pol} \sim 5cm > d_{cell}$
- ➔ requires transport tracking (esp. in transients)

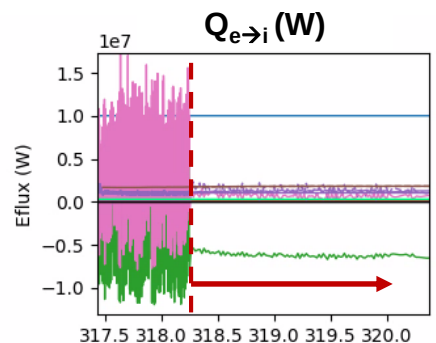
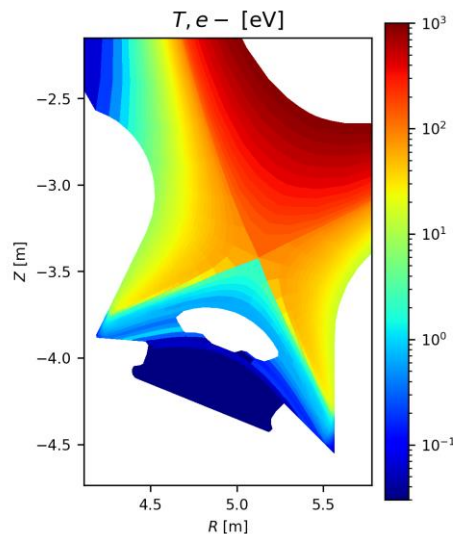
2. Up-to-the-wall domain challenge for ITER cases

Stiffness of physics in cold divertor conditions

Example: Electron-ion energy equipartition:

$$Q_{e \rightarrow i} = \frac{m_e Z^2 e^4 \Lambda}{m_i (2\pi)^{\frac{3}{2}} \varepsilon_0^2 \sqrt{m_e}} n_e n_i \frac{1}{T_e^{\frac{3}{2}}} (T_i - T_e)$$

Strong at low temperature !



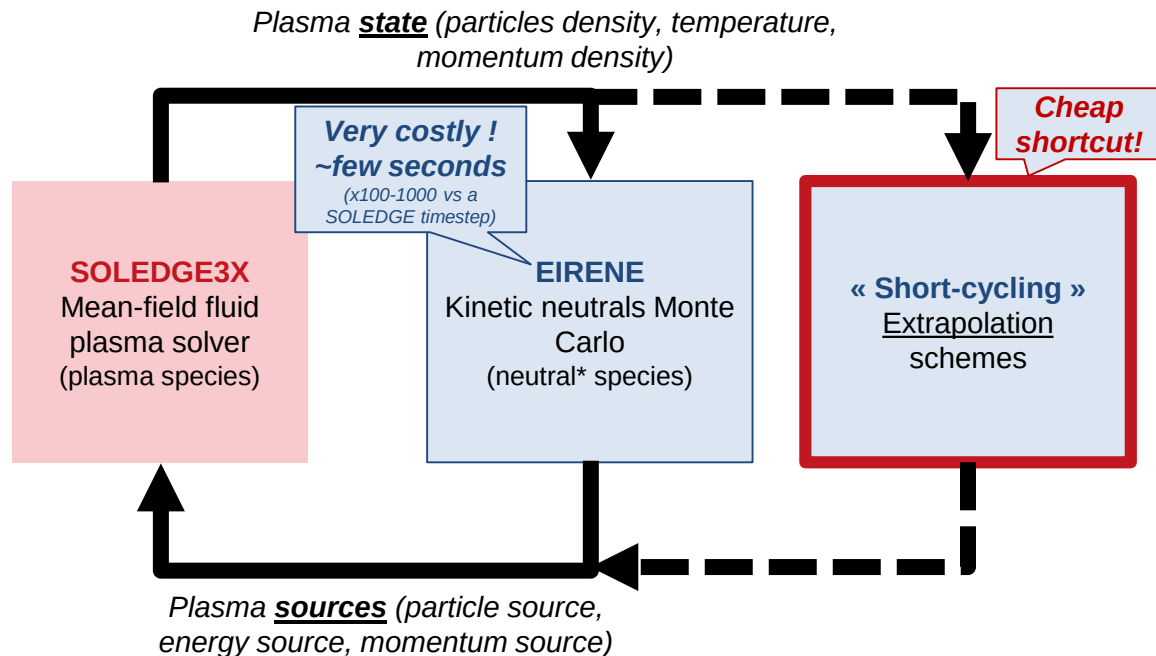
Semi-Analytical solution

- Collisional energy & momentum exchange terms become very large at **low T**, especially during transients
- Coulomb Log Λ** produces unphysical values in Braginskii/Zhdanov formulation at $T \rightarrow 0$: Quantum effects correction [Hong-sup Hahn and E. A. Mason, The Physics of Fluids 14, 278 (1971)]
- Revisited numerical scheme** for collisional terms for increased stability [Details to be published]

2. Up-to-the-wall domain challenge for ITER cases

Computation time: neutral sources extrapolation schemes

SOLEDGE3X-EIRENE coupling workflow:



- Time step $\sim 10^{-7}$ s (CFL)
- ITER solution equilibrium time: ~ 1 s
- Requires “shortcuts” i.e. extrapolations

Sources extrapolation:

$$S_n = n_{\text{atom}} n_e < \sigma_{iz} v >$$

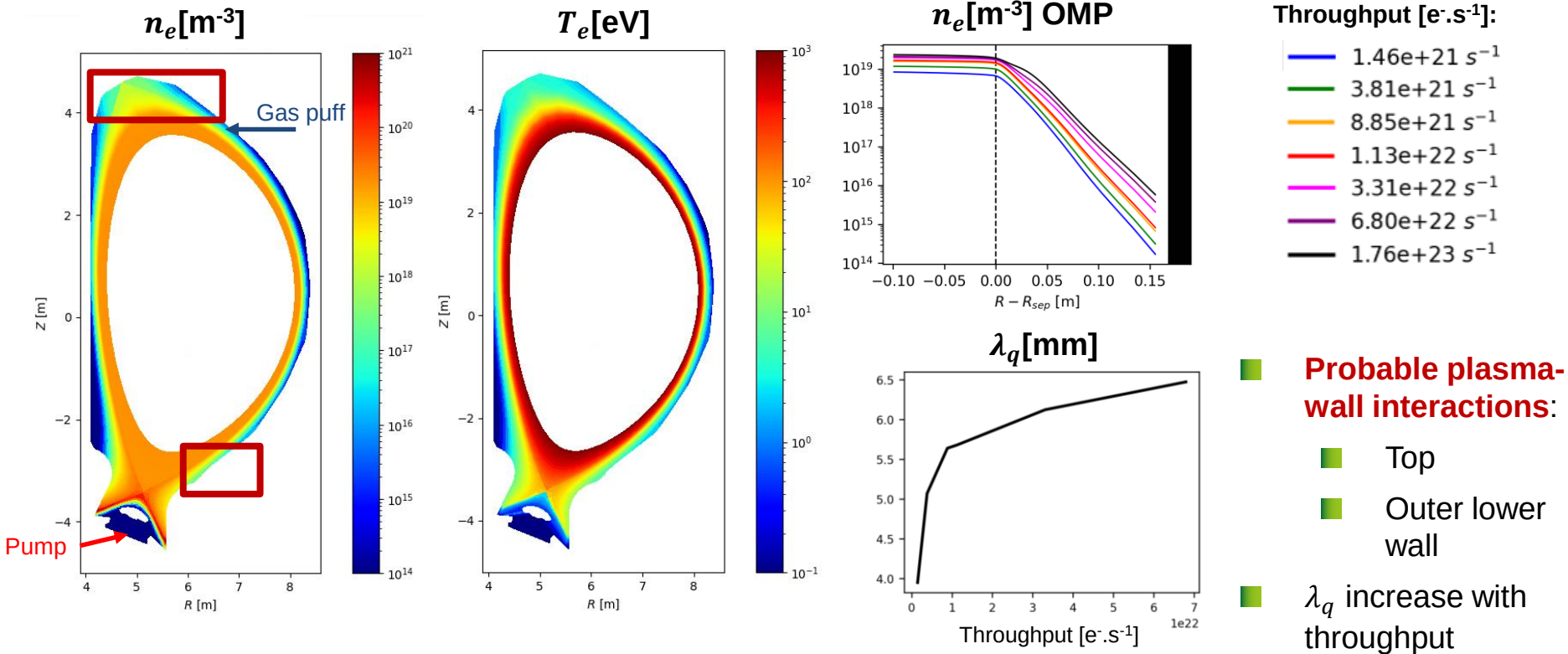
Extrapolated source from neutrals (points to n_{atom})
 Keep spatial distrib. (points to n_e)
 Updated from plasma background (points to $< \sigma_{iz} v >$)

[Details to be published]

- 1. Context and motivation
- 2. Up-to-the-wall domain challenge for ITER cases
- **3. Impact of throughput**
- 4. Impact of enhanced far-SOL transport (shoulder formation)
- 5. Summary

3. Impact of throughput First view

Illustration case at medium throughput ($3.31 \times 10^{22} \text{ e}^- \cdot \text{s}^{-1}$):



3. Impact of throughput

Overall good agreement with SOLPS-ITER runs

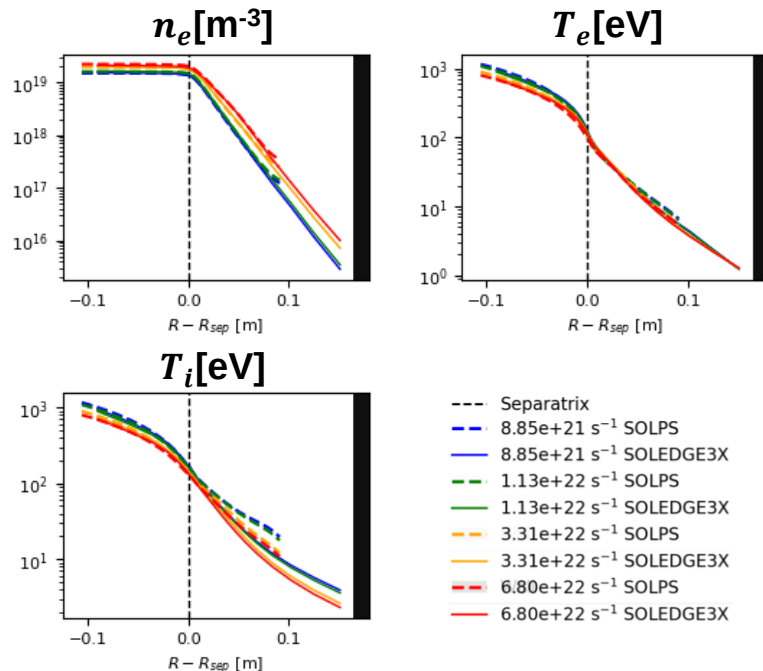
Throughput scan, from attached to partially detached

(colors are different throughputs – blue: low → red: high)

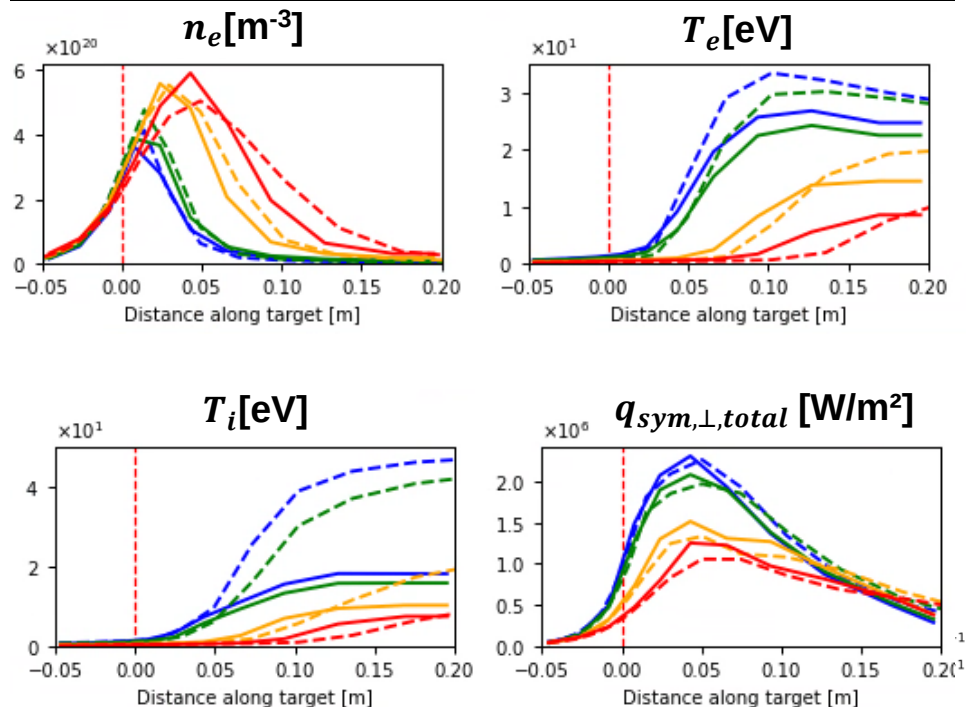
— Solid lines:
SOLEDGE3X

- - - Dashed lines:
SOLPS-ITER

Upstream (Outer midplane)



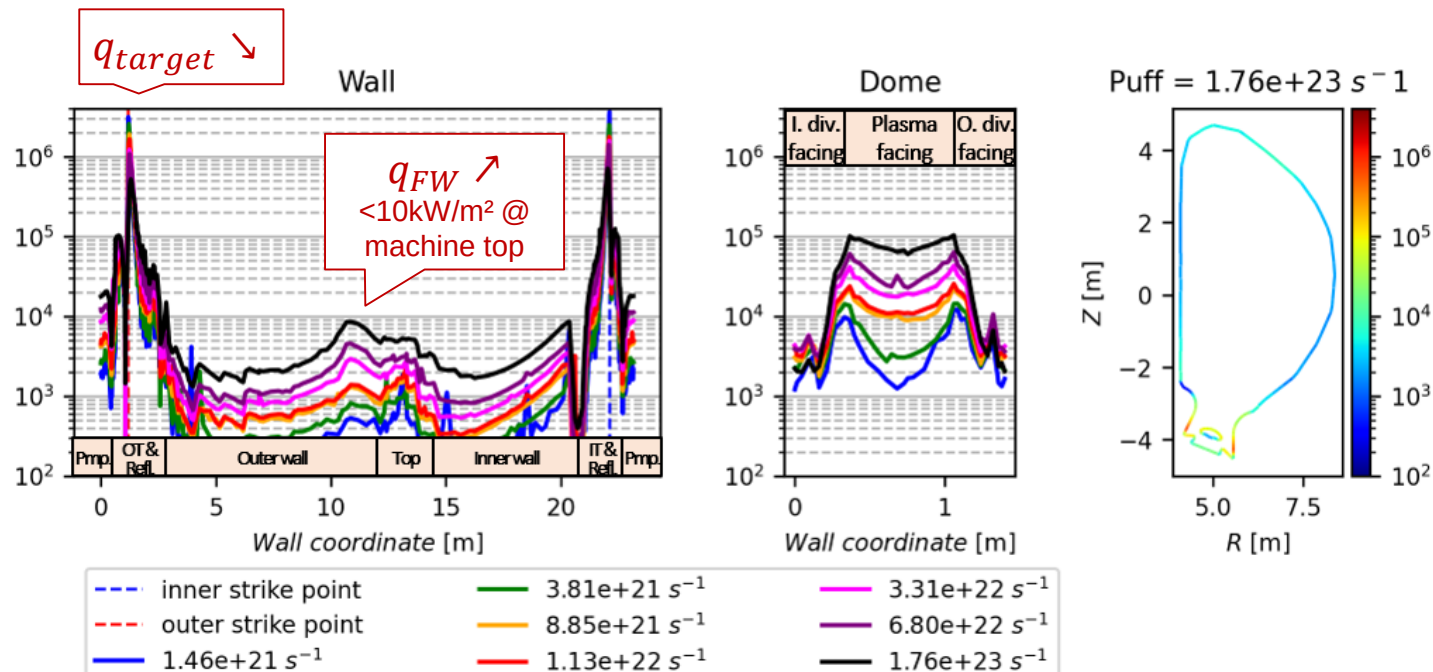
Outer Target



3. Impact of throughput FW heat load: well within design limits

Heat flux density deposition on the FW $q_{sym,\perp,total}$ [W/m²]:

(2D-axisym., perp. no shaping, pl+neut.+rad)



FW material limits:

Inner:
5MW/m²

Outer:
3MW/m²,

Top:
2MW/m²

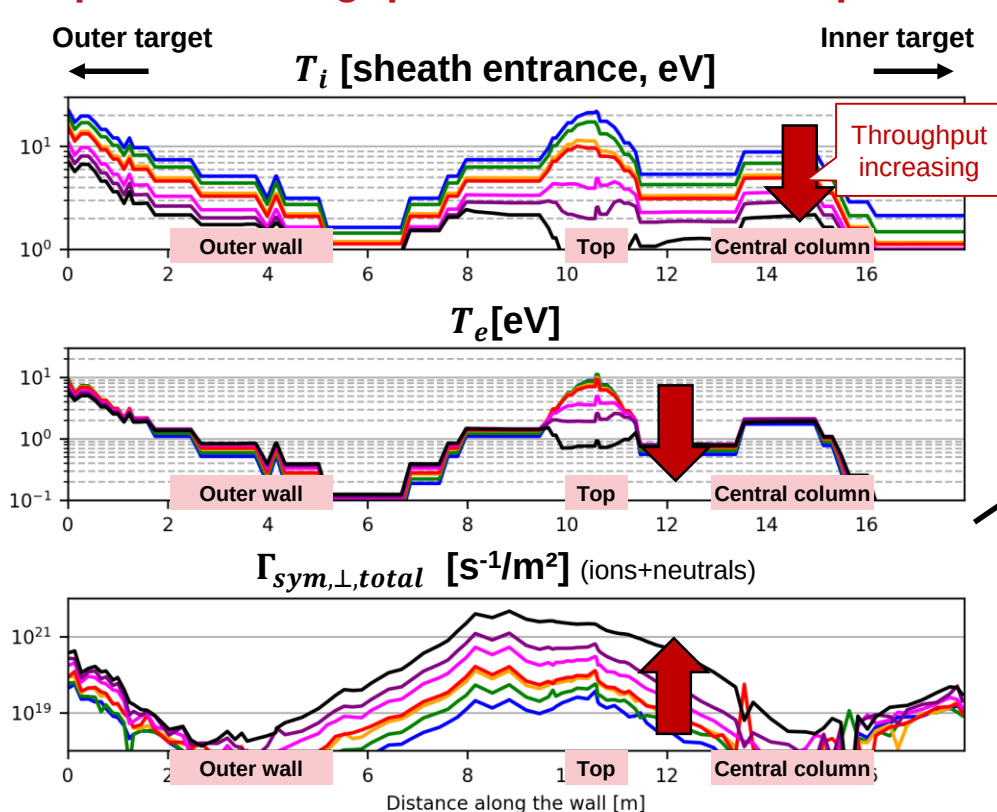
[ITER Research
Plan, 2018]

Max FW load: **up to 20 % of input power** at highest throughput

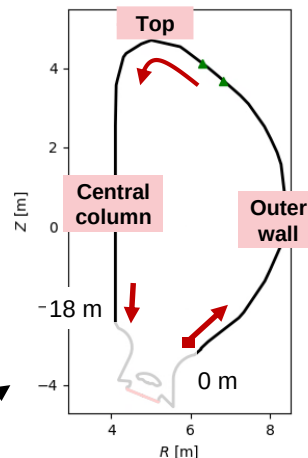
3. Impact of throughput

Quantities at the FW: counter action of Γ vs T

Impact of throughput on FW T and total particle flux:



2D view of wall coordinate



When increasing throughput:

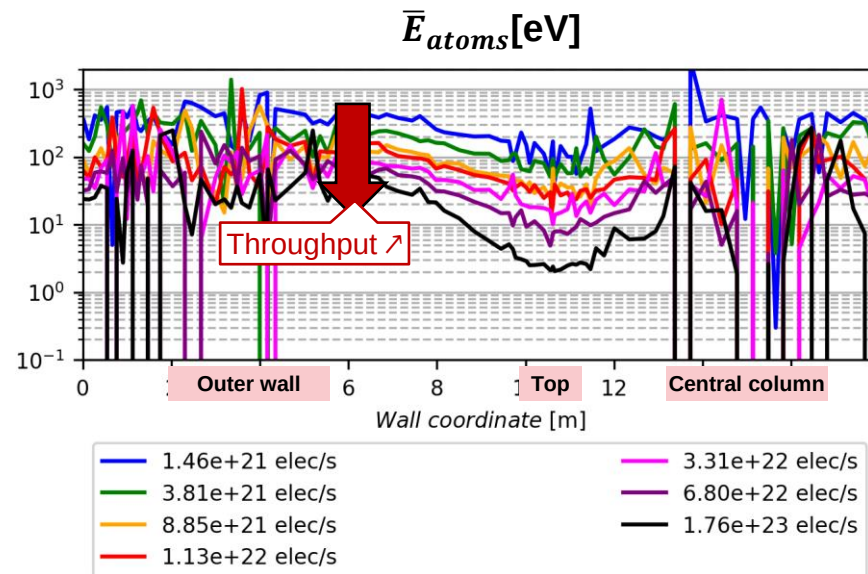
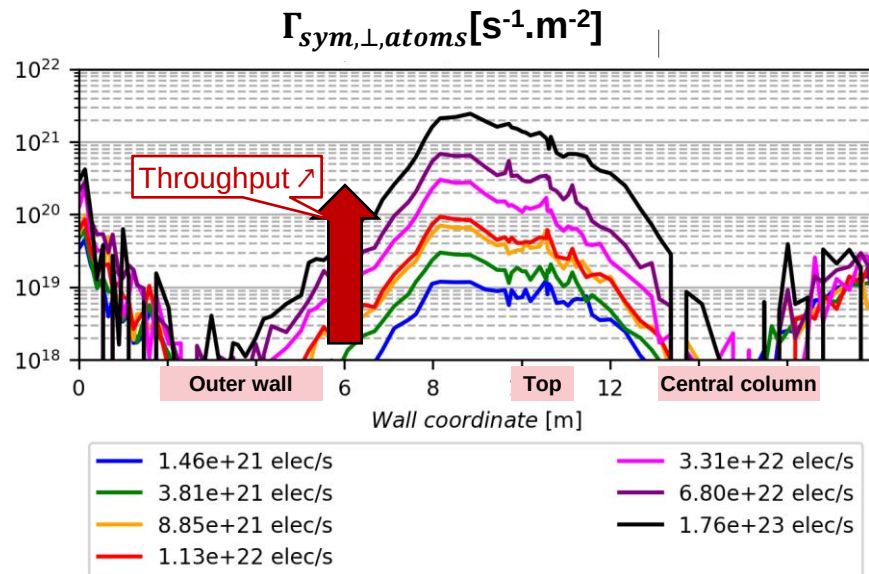
- $T_{i,wall} \searrow : 20 \rightarrow 7$ eV
- $T_{e,wall} \rightarrow$: No effect (except machine top: $10 \searrow 1$ eV)
- FW part. fluxes $\times 100$
- Counter action $\Gamma \nearrow$ while $T \searrow$

Throughput: [$e^- \cdot s^{-1}$]

- 1.46e+21 s^{-1}
- 3.81e+21 s^{-1}
- 8.85e+21 s^{-1}
- 1.13e+22 s^{-1}
- 3.31e+22 s^{-1}
- 6.80e+22 s^{-1}
- 1.76e+23 s^{-1}

3. Impact of throughput :

CX atoms: FW incident flux & average energy, counter action



Impact on incident atom flux density:

- Large increase at machine top and outer top: x100

Impact on average atom energy:

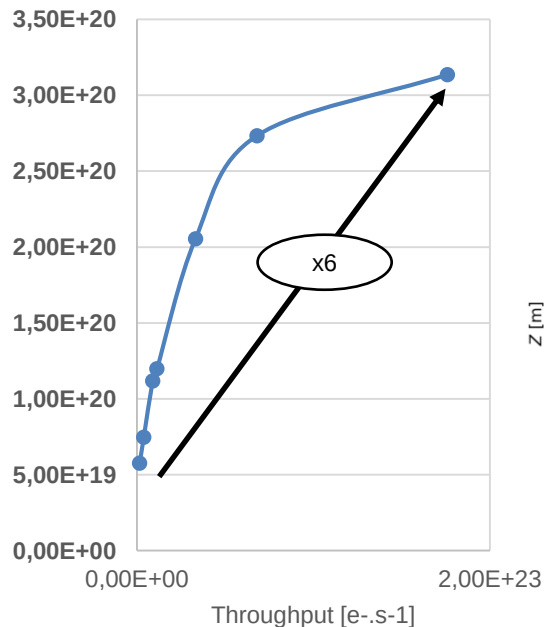
- Large decrease ÷10 – 100
- 100 eV → 3 eV at machine top

3. Impact of throughput

Gross Be erosion figures: x6 between scan extremes

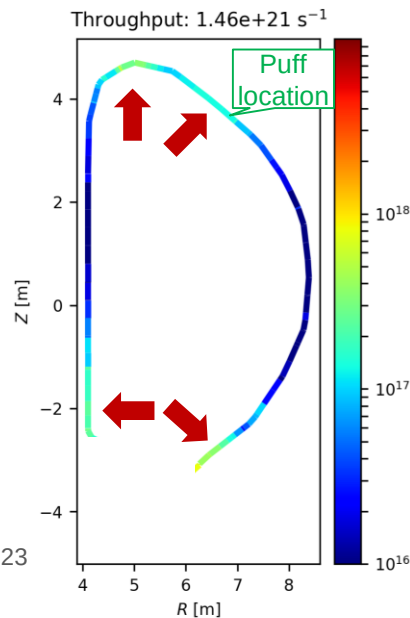
Caveat: Trends analysis only (rough estimation, H^+ & H^0 only, no 3D), better calculations done with specialized codes (ERO, WALLDYN)

First Wall total gross sputtering rate [s^{-1}]

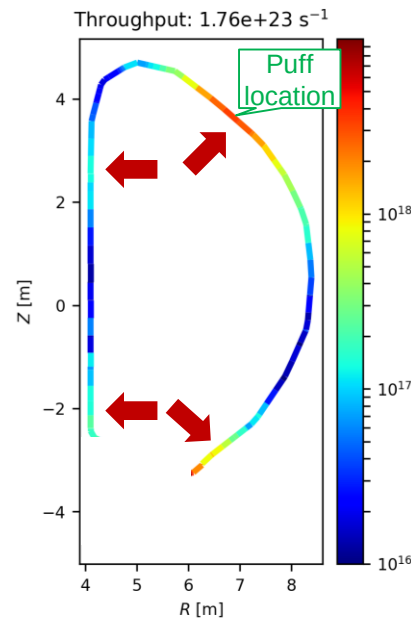


Gross sputtering rate density [$s^{-1}.m^{-2}$]

Low Throughput



High Throughput



Trends:

■ ~90% from **CX atoms**, increasing with throughput

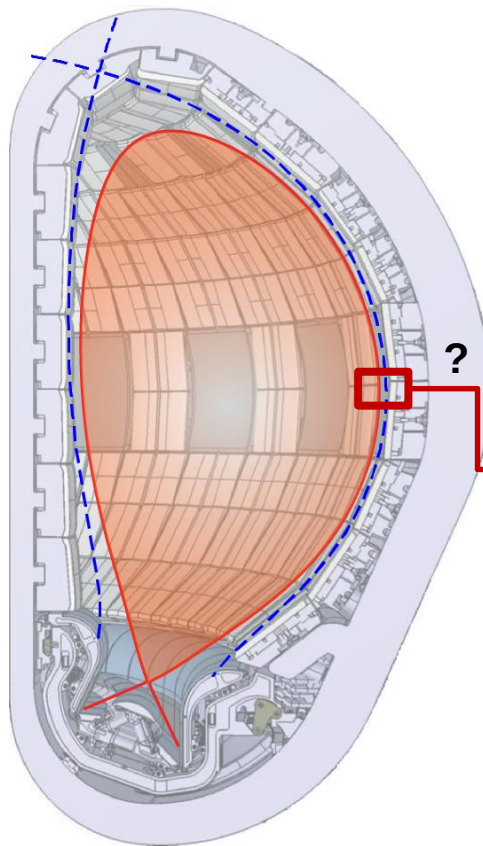
■ From **ions**: ~**independent** of throughput

■ Factor 4 underestimation vs more complete ERO2.0 (not same bg, 3D effects?)

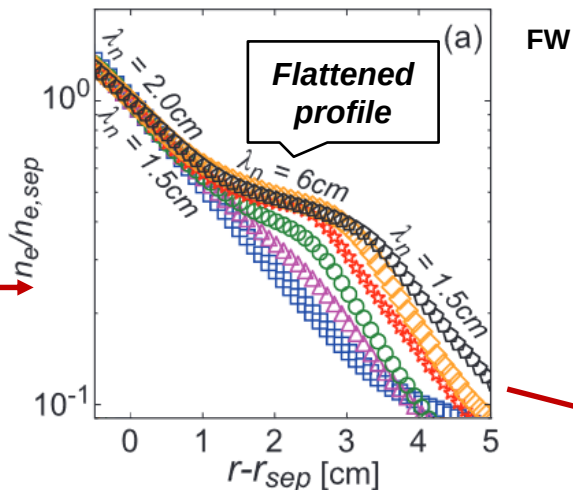
[J. Romazanov et al 2022 Nucl. Fusion 62 036011]

- 1. Context and motivation
- 2. Up-to-the-wall domain challenge for ITER cases
- 3. Impact of throughput
- **4. Impact of enhanced far-SOL transport (shoulder formation)**
- 5. Summary

4. Impact of enhanced far-SOL transport (shoulder formation): FW & far-SOL impact with formation of shoulders?



Possible formation of
“shoulders” in OMP profiles:
(JET example)



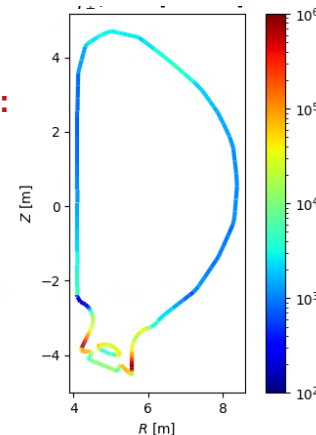
[A. Wynn et al 2018 Nucl.
Fusion 58 056001]

**Precise shape of profiles in
ITER? = Unknown**

- Probable formation of
shoulders (turbulence) – not
modelled in mean-field codes
- What happens for the FW
and the far-SOL then?

**Wall heat flux
(total, $q_{\perp}$) [W/m²]:**

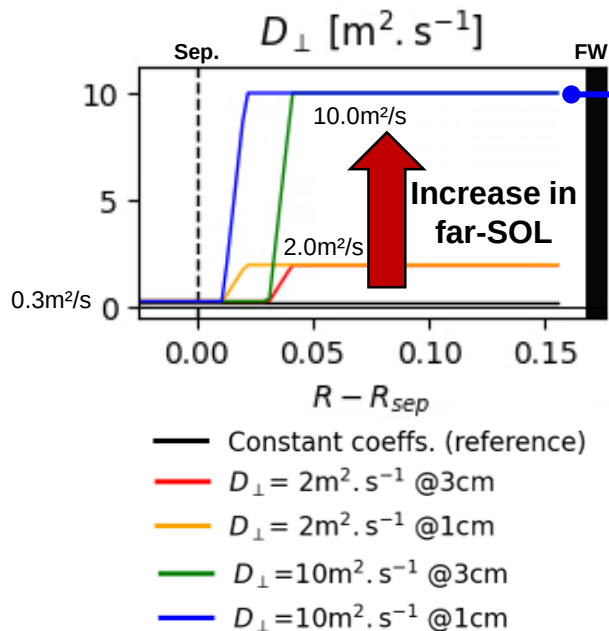
?



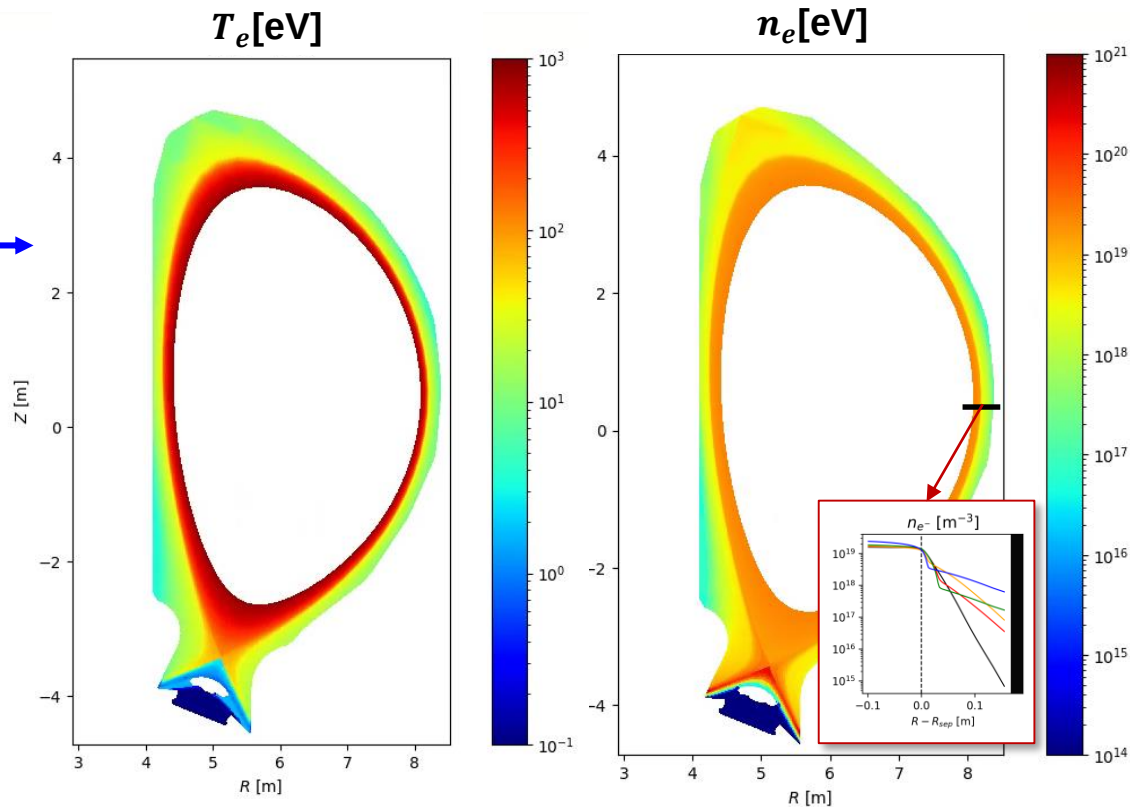
4. Impact of enhanced far-SOL transport (shoulder formation): Modelling through increased coeff. in far-SOL

Modelling:

Prescribed perpendicular diffusivity coefficients $D_{\perp}, \chi_{\perp e}, \chi_{\perp i}, \nu_{\perp}$ profile at the outer midplane:



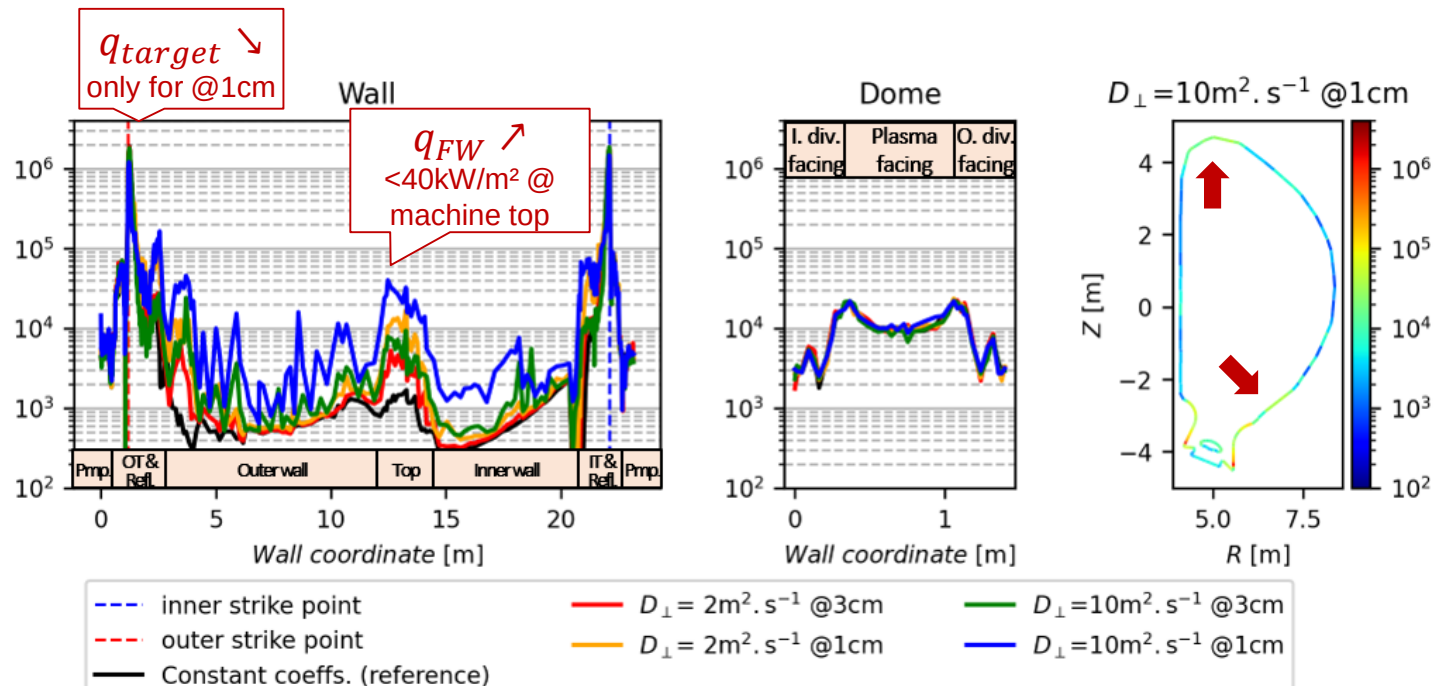
Example: Strongest & closest shoulder (in blue):



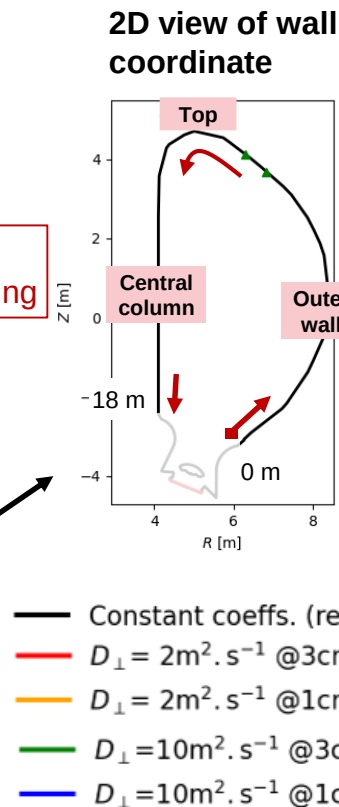
4. Impact of enhanced far-SOL transport (shoulder formation): Increased FW heat load above outer baffle and machine top

Heat flux density deposition on the FW $q_{sym,\perp,total}$ [W/m²]:

(2D-axisym., perp. no shaping, pl+neut.+rad)



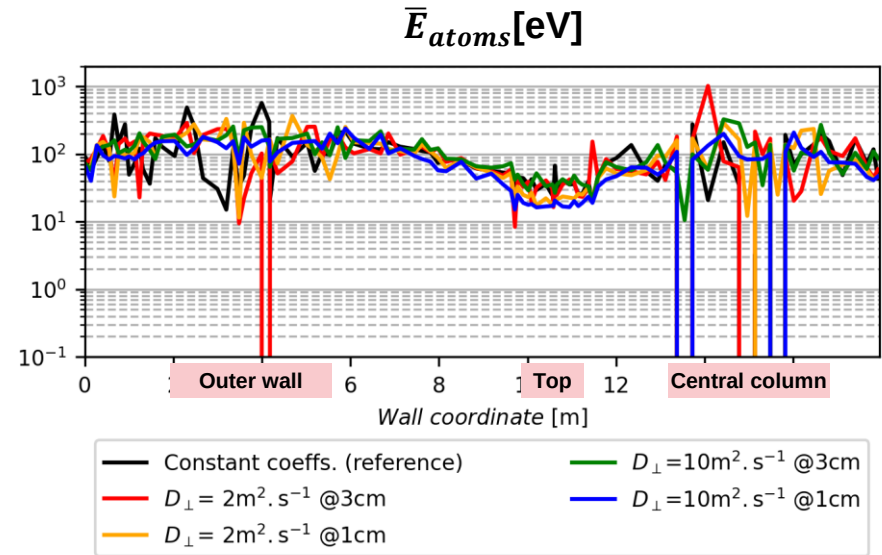
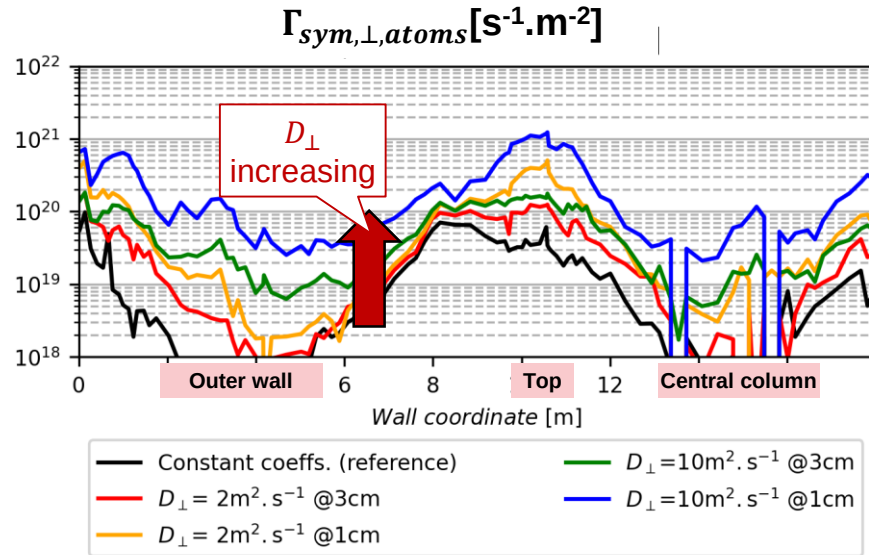
Impact of high far-SOL transport (low throughput):



With strongly enhanced far-SOL transport:

- FW fluxes $\times 10^{-20}$
- $T_{i,wall} \nearrow : 20 - 30 \text{ eV}$
- $T_{e,wall} \nearrow : 10 - 20 \text{ eV}$
- $q_{sym,\perp,total} = 40 \text{ kW/m}^2$ @ machine top
- Combined increase $\Gamma \nearrow$ and $T \nearrow$**

4. Impact of enhanced far-SOL transport (shoulder formation): CX atoms: FW incident flux & average energy, flux increased



Impact on incident atom flux density:

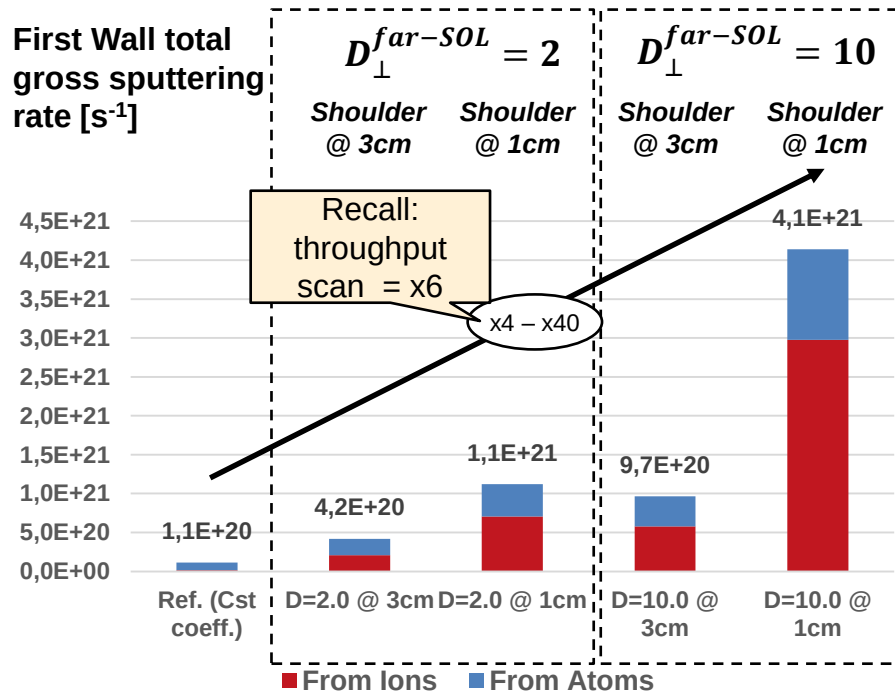
- Machine **top**: **x10 – 20**
- Above inner & outer **baffles**: **x10 – 20**

Impact on average atom energy:

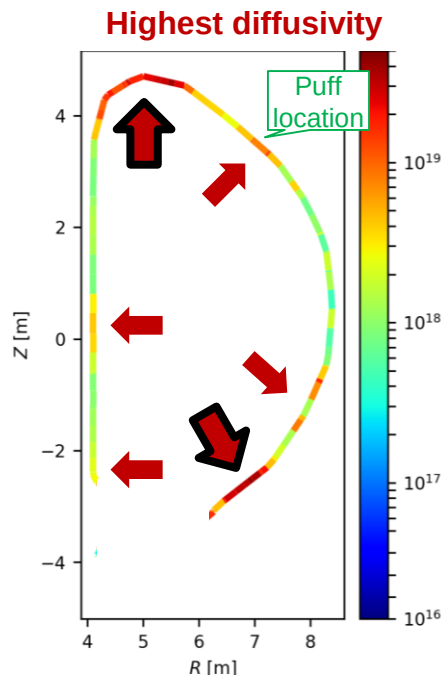
- Almost **no impact** from **shoulders**

4. Impact of enhanced far-SOL transport (shoulder formation): Gross Be erosion figures: x40 between scan extremes

Caveat: Trends analysis only (sputtering from H^+ & H° only), rough estimation, better calculations done with specialized codes ERO, WALLDYN



Gross sputtering rate density [$s^{-1}.m^{-2}$]



Trends:

- Shoulders → **ions now dominant** (50-70%)
 - Large increase**
 - Top & outer lower tiles (#8, #9 & #18)
 - Factor 10 underestimation vs ERO2.0 (not same bg, 3D effects)
- [J. Romazanov et al 2022 Nucl. Fusion 62 036011]

- 1. Context and motivation
- 2. Up-to-the-wall domain challenge for ITER cases
- 3. Impact of throughput
- 4. Impact of enhanced far-SOL transport (shoulder formation)
- **5. Summary**

5. Summary

- First **self-consistent full vessel simulations for ITER with SOLEDGE3X** applied to ITER low power phase (20MW): **grid up to the FW in main chamber critical for FW impact studies**
- Overall **good agreement with SOLPS** on throughput scan **on common parts of the domain**
- In both scans, increase in $q_{\perp, sym}$ on FW, but still very low values (for 20MW cases)
- Impact of **throughput**:
 - **Counter action $\Gamma \nearrow$ while $T \searrow$ at the FW**
 - Overall throughput **impact moderate on FW gross erosion rate** (x6 between scan extremes, only from CX atoms)
- Impact of **enhanced far-SOL transport (shoulders)**:
 - **Combined increase of $\Gamma \nearrow$ and $T \nearrow$ at the FW**
 - Much **greater impact than throughput on FW gross erosion rate** (x40 between scan extremes, mainly from ions)

Thank you

Acknowledgement:

This work was performed under the auspices of the ITER Scientist Fellow Network. The views and opinions expressed herein do not necessarily reflect those of the ITER organization.

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.

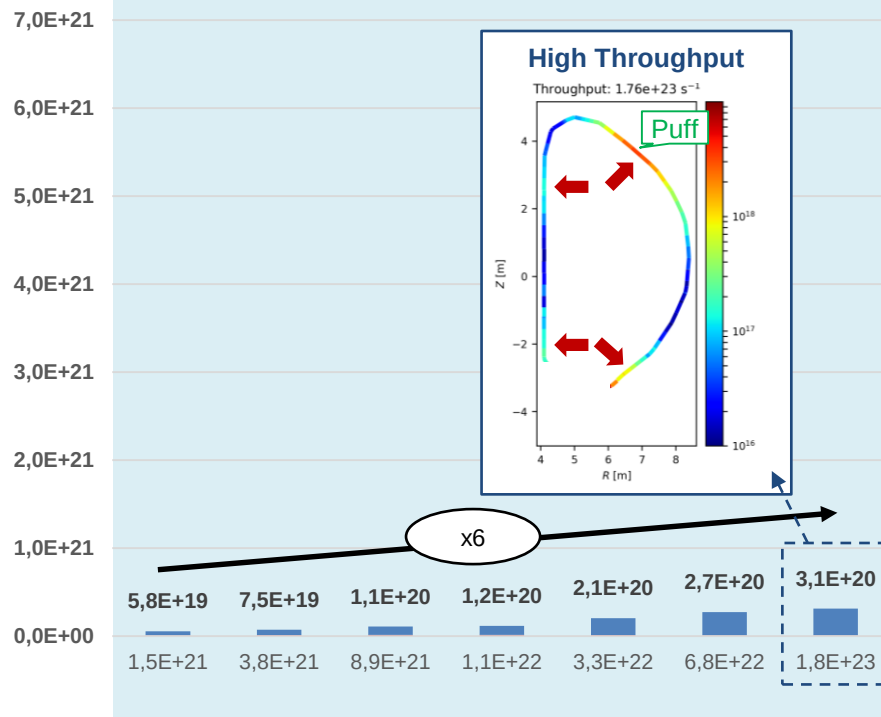
Backup slides

Summary of throughput and shoulder formation on FW gross erosion rate

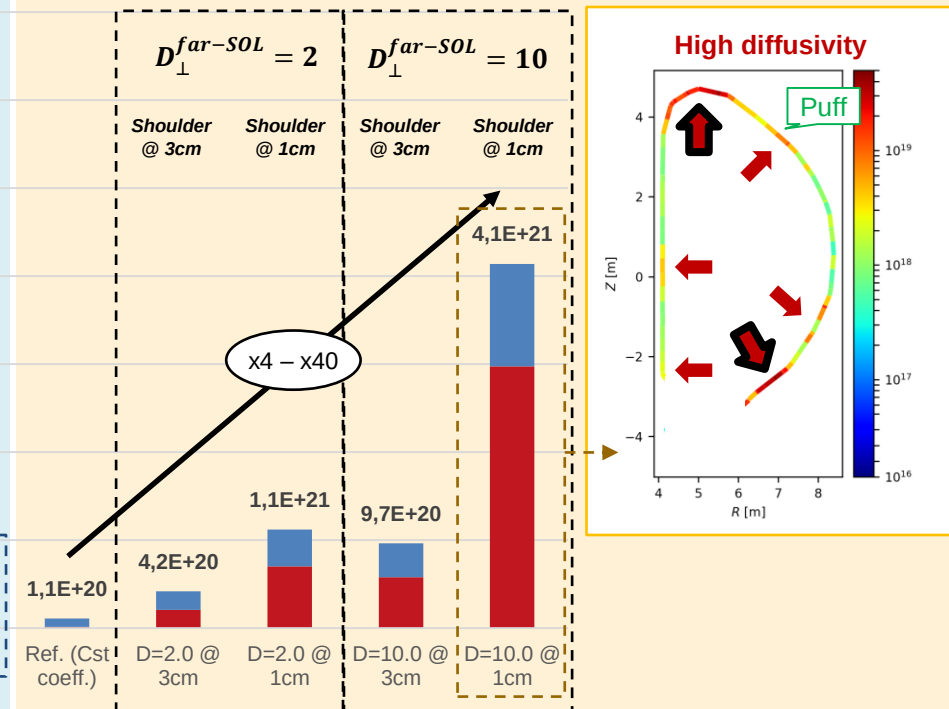
First Wall total gross sputtering rate [s^{-1}]:

Caveat: *Trends analysis only* (sputtering from H^+ & H^0 only), rough estimation, better calculations done with specialized codes ERO, WALLDYN

Throughput scan

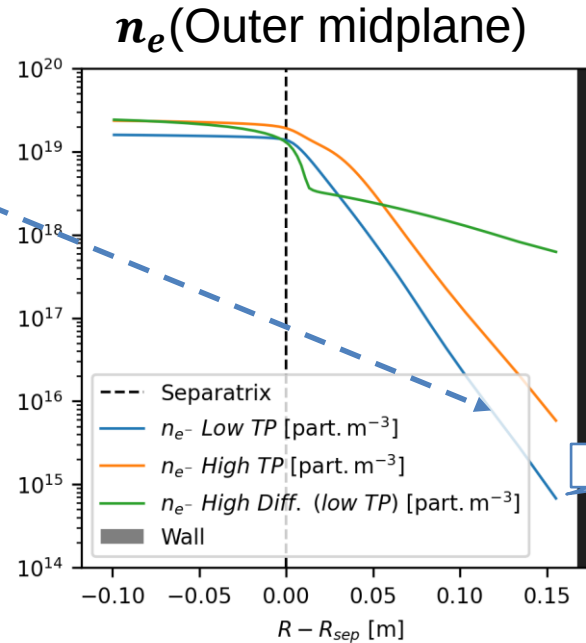
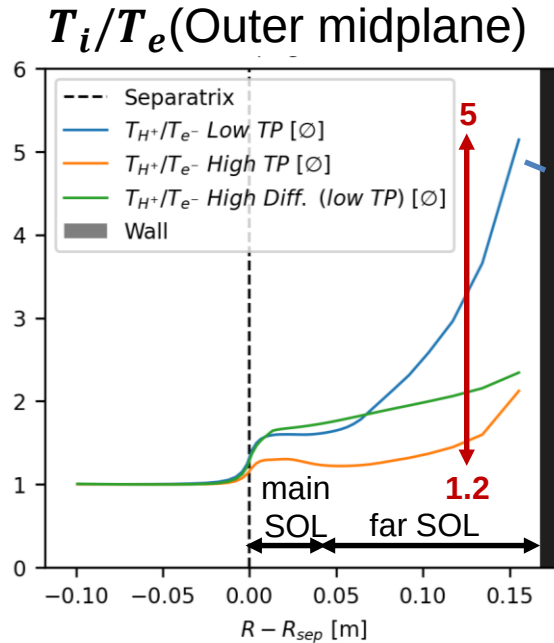


Shoulder formation scan (enhanced far-SOL transport)



■ From Ions ■ From Atoms

4. Impact of enhanced far-SOL transport (shoulder formation): Plasma conditions in far-SOL: T_i/T_e ratio

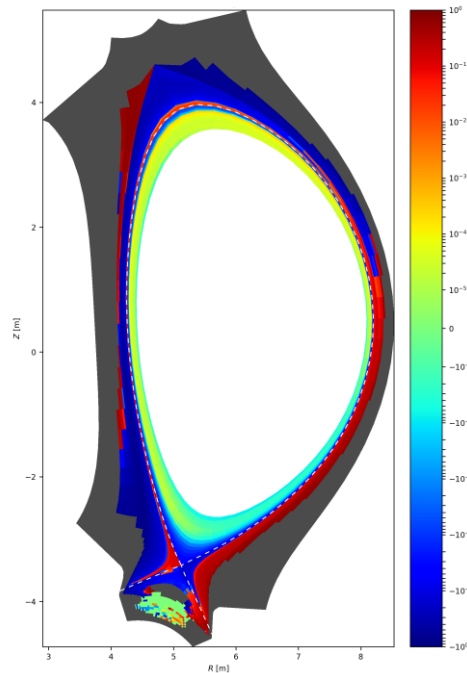


T_i/T_e ratio in far-SOL:

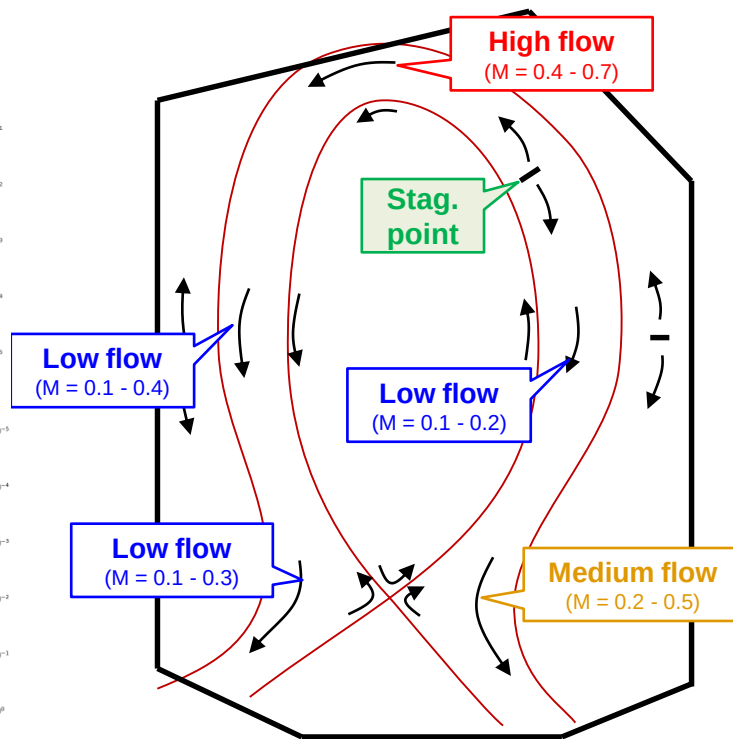
- Key input for erosion codes and impurity transport
- Main SOL: $T_i/T_e \sim 1.2 - 2$
- Far SOL: $T_i/T_e \sim 1.2 - 5$
- Ratio $\searrow$ with throughput and diffusivity (low: 5, high: 2)
- Correlation with n_e , but not only (collisionality)

4. Impact of enhanced far-SOL transport (shoulder formation): Plasma conditions in far-SOL: SOL flows

Mach Number



Low throughput



SOL flows:

- Key input for erosion codes and impurity transport
- **Mach** $\nearrow$ with **increasing throughput**
- **Mach** $\searrow$ in presence of **shoulder**
- Stagnation point around the upper outer section

4. Impact of enhanced far-SOL transport (shoulder formation): Targets heat fluxes

