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.

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DE LA RECHERCHE À L'INDUSTRIE

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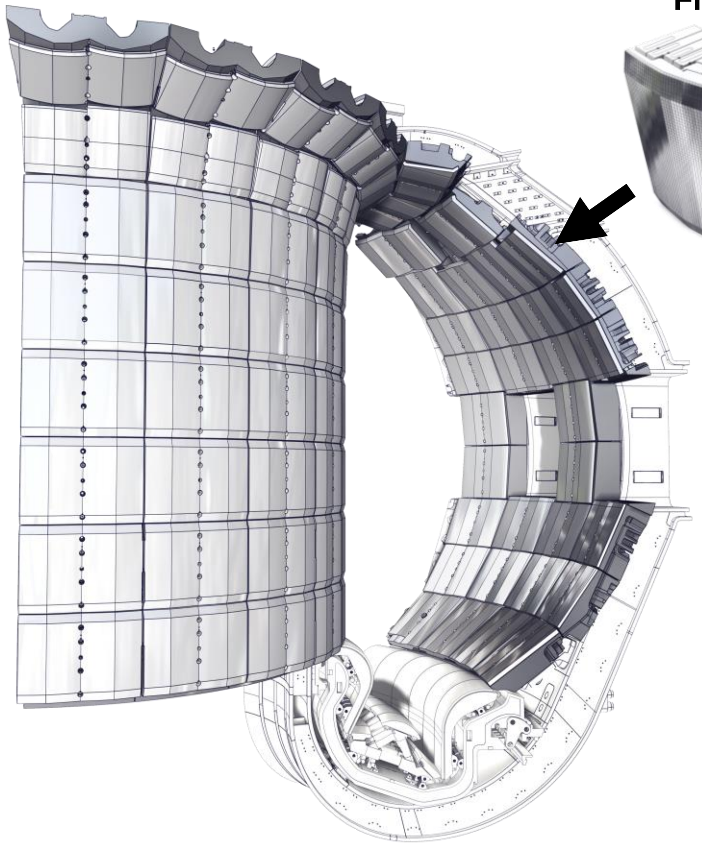
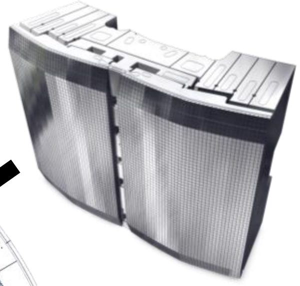
Outline

- 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

Outline

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

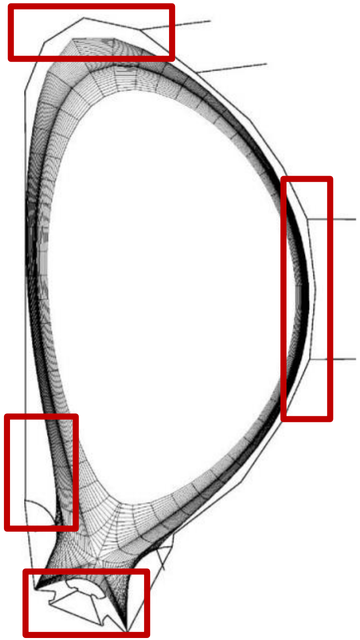
Requires a tool for estimating **FW fluxes** and **full vessel plasma backgrounds** of key plasma scenarios
➔ ***SOLEDGE3X***

Feed input for other codes:

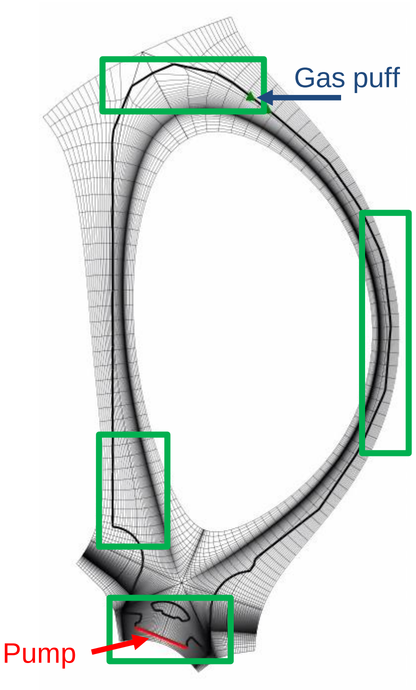
→ **ERO2.0**
WALLDYN
…

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**

Simulations setup

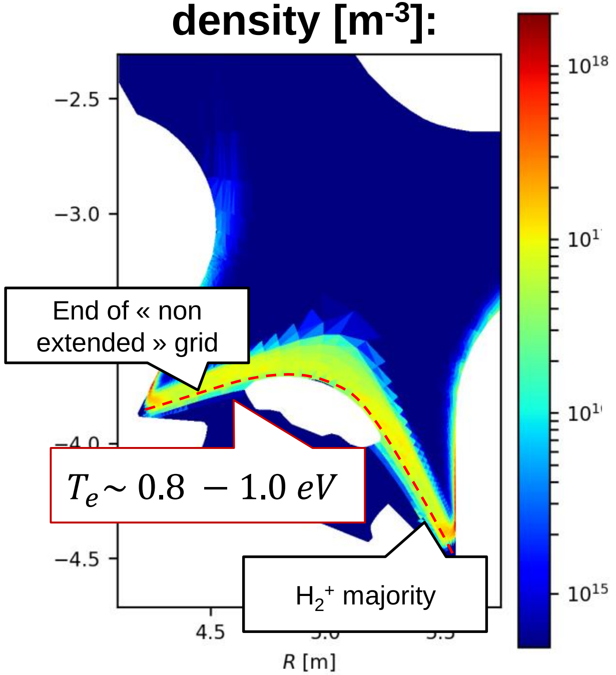
The SOLEDGE3X code and setup:

- **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.)

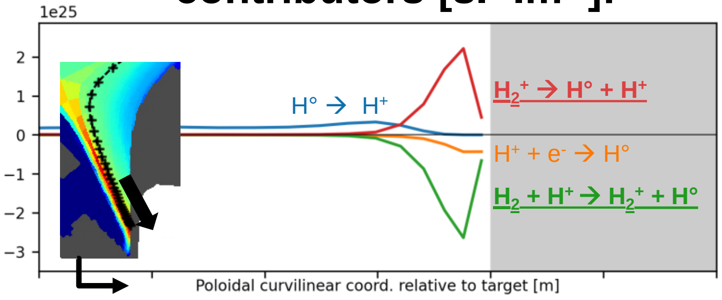
Outline

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:

- **H2+ : intermediate product** in "molecule-assisted" processes (MAR, MAI)
- Significant $n_{H_2^+}$ just below the end of "common SOL" domain, even majority species there
- $\lambda^{pol}_{mfp\ H_2^+} \sim 5cm > d_{cell}$

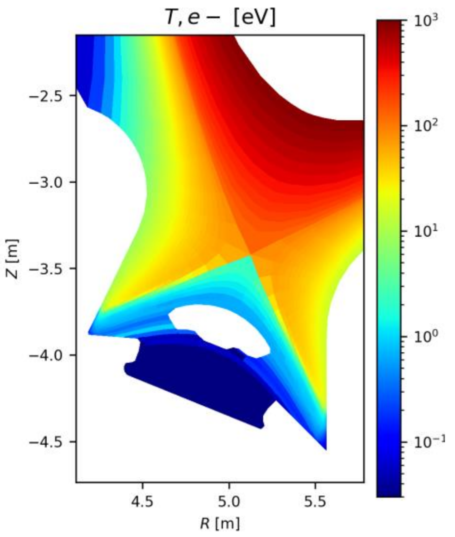
➔ **requires transport** tracking (esp. in transients)

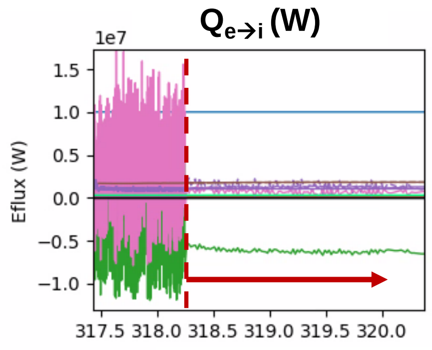
Stiffness of physics in cold divertor conditions

Example: Electron-ion energy equipartition:

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

Strong at low temperature !



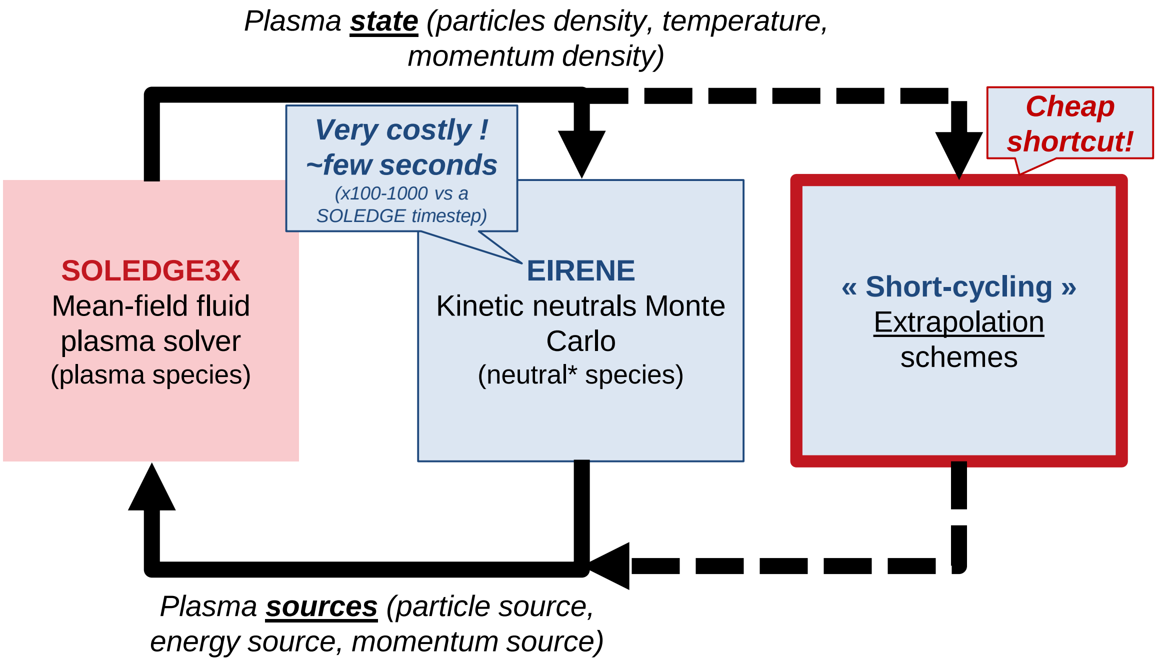


Semi-Analytical solution

- 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→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 ~10^{-7}s (CFL)
- ITER solution equilibrium time: ~ 1s
- **Requires "shortcuts" i.e. extrapolations**

Sources extrapolation:

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

Updated from plasma background (n_e, $< \sigma_{iz} v >$)

Keep spatial distrib. (n_{atom})

Extrapolated source from neutrals (S_n)

[Details to be published]

Outline

- 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)
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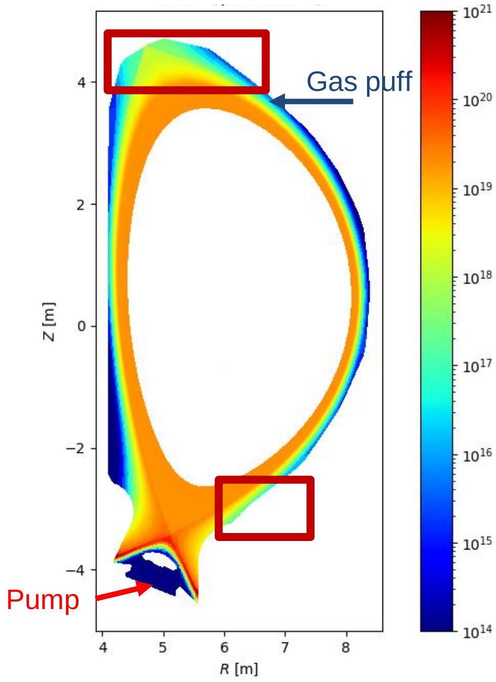
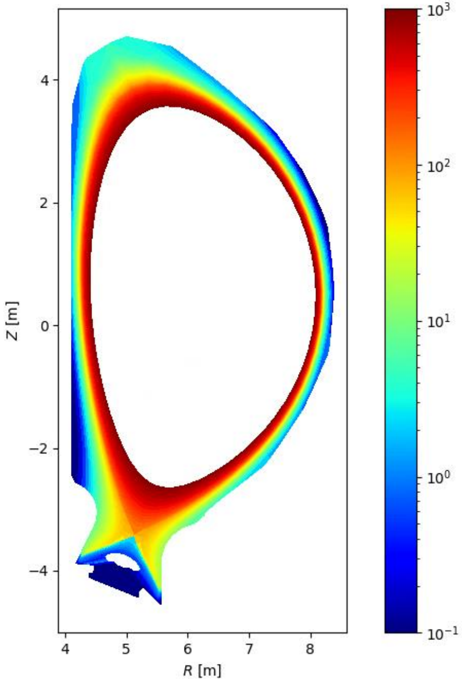
Illustration case at medium throughput (3.31 x 10^{22} $e^{-}.s^{-1}$):

n_e[m^{-3}]

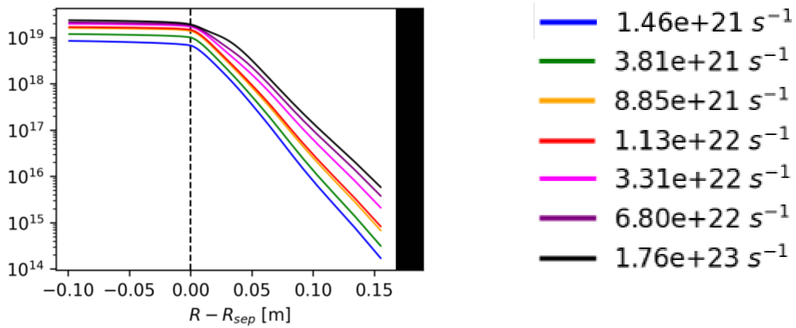


T_e[eV]

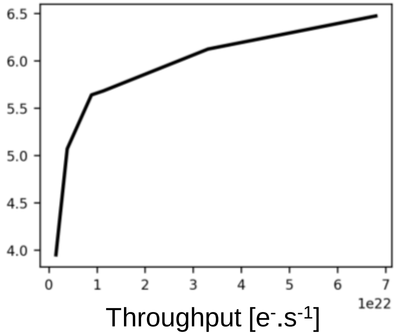


n_e[m^{-3}] OMP

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



λ_q[mm]



- **Probable plasma-wall interactions**:
  - Top
  - Outer lower wall
- λ_q increase with throughput

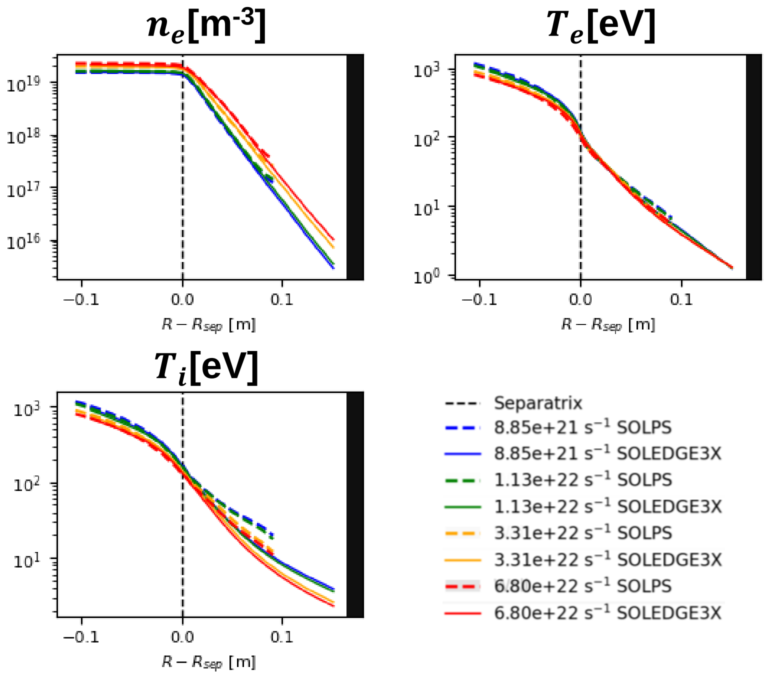
Overall good agreement with SOLPS-ITER runs

Throughput scan, from attached to partially detached

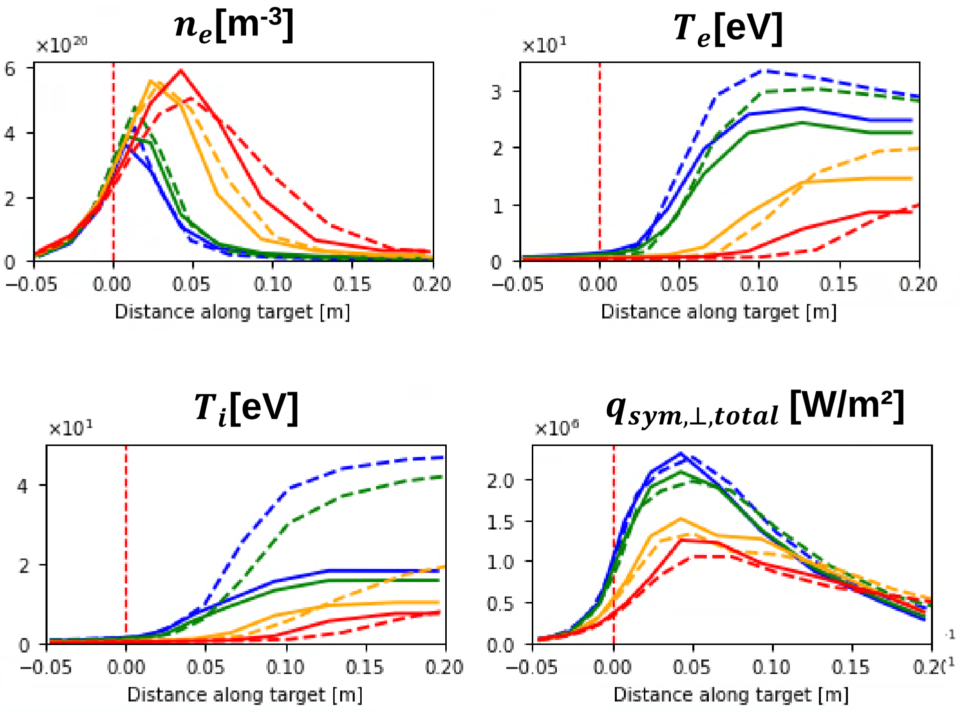
(colors are different throughputs – blue: low → red: high)

Solid lines: SOLEDGE3X **Dashed lines:** SOLPS-ITER

Upstream (Outer midplane)



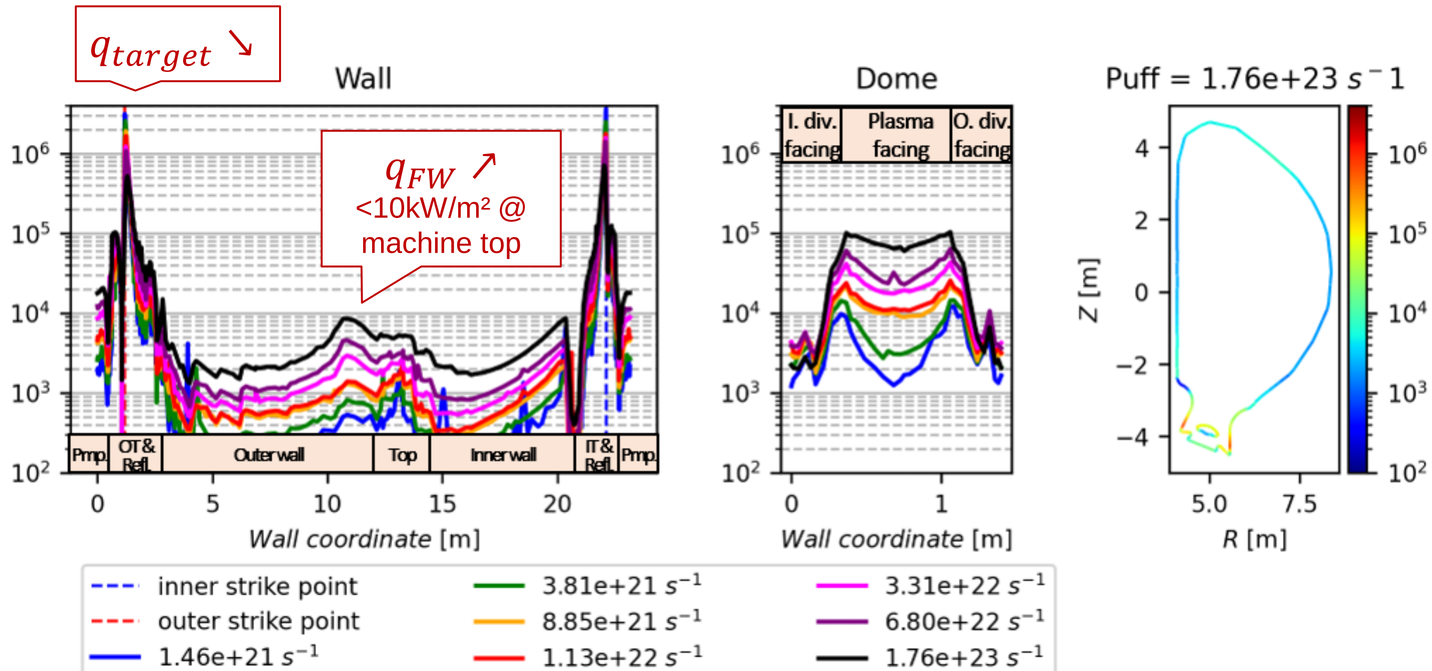
Outer Target



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)

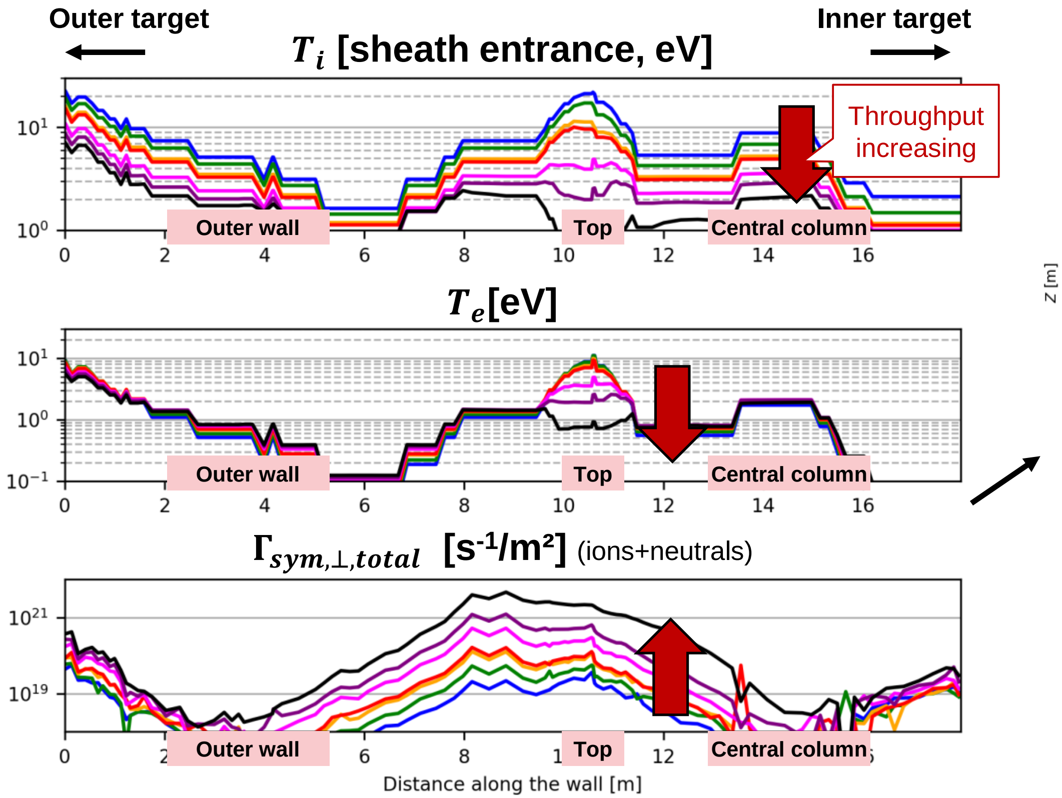


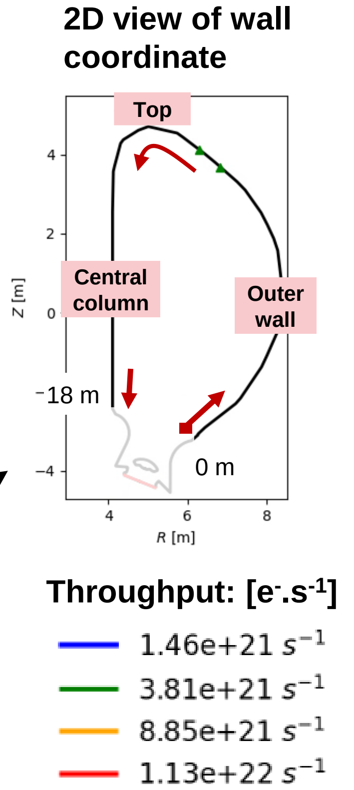
- FW material limits:
  - Inner: 5MW/m²
  - Outer: 3MW/m²,
  - Top: 2MW/m²

    [ITER Research Plan, 2018]
- Max FW load: **up to 20 % of input power** at highest throughput

Quantities at the FW: counter action of Γ vs *T*

Impact of throughput on FW T and total particle flux:

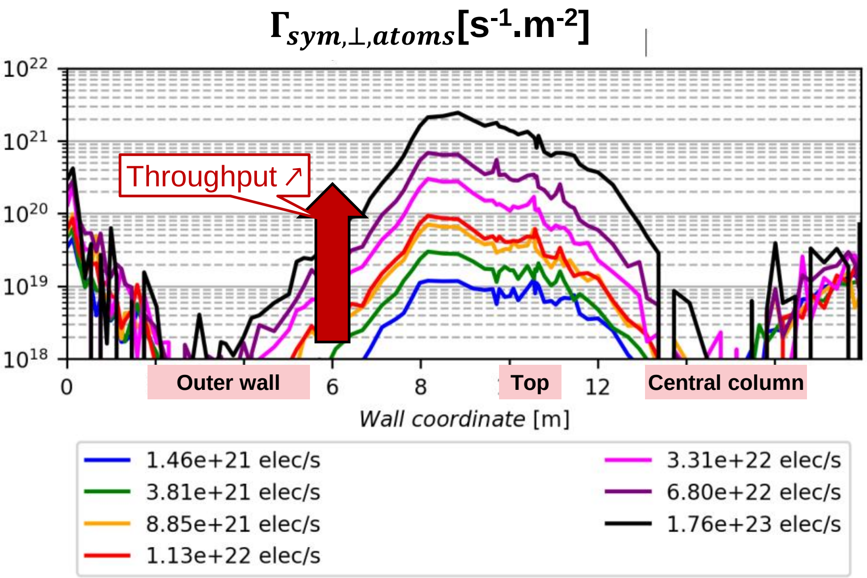


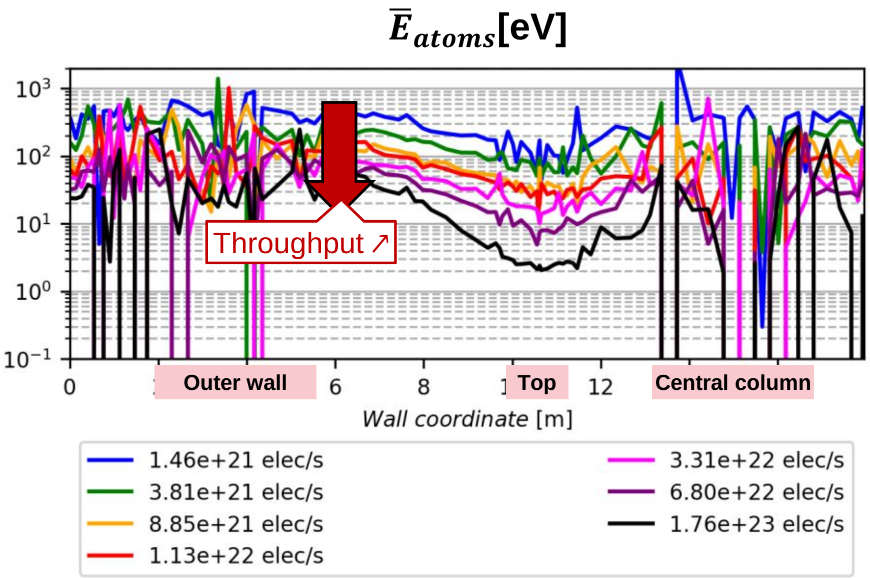


When increasing throughput:

- $T_{i,wall}$ ↘ : 20 → 7 eV
- $T_{e,wall}$ → : No effect (except machine top: 10 ↘ 1 eV)
- FW part. fluxes x 100
- **Counter action *Γ* ↗ while *T* ↘**

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





Impact on incident atom flux density:

- **Large increase** at machine **top and outer top: x100**

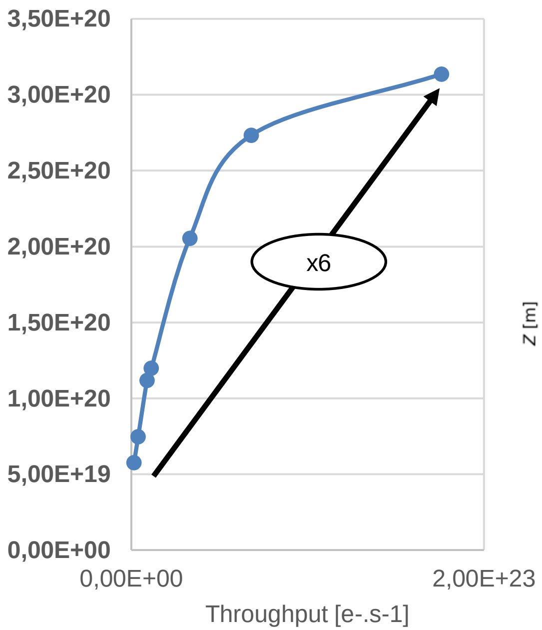
Impact on average atom energy:

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

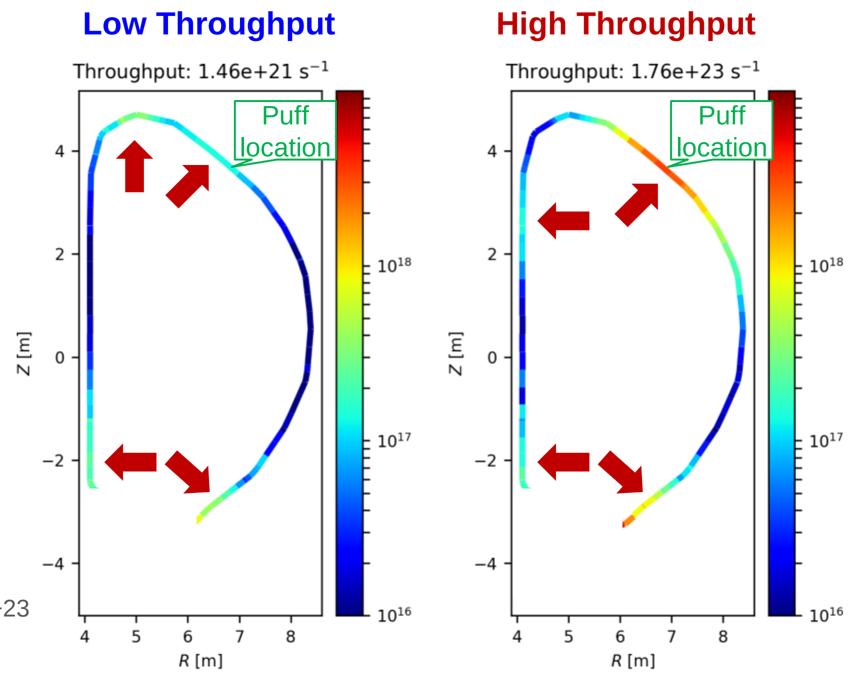
3. Impact of throughput
Gross Be erosion figures: x6 between scan extremes

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

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



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

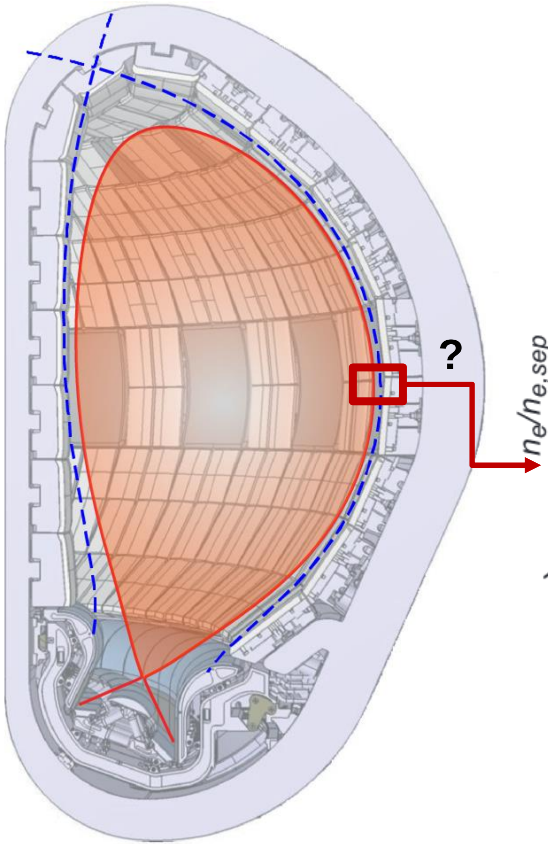


Trends:

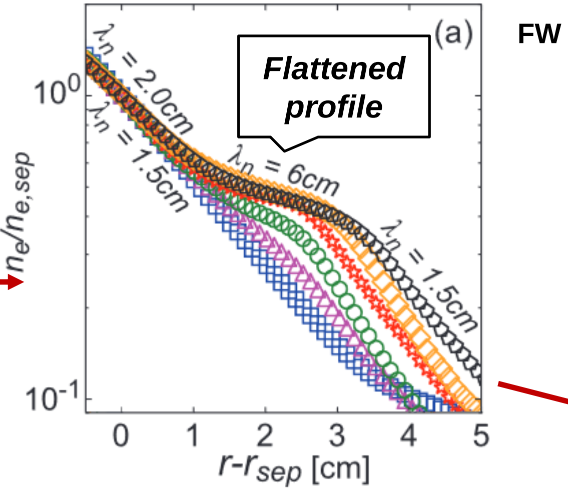
- ~90% from **CX atoms**, **increasing** with throughput
- From **ions**: ~**independent** of throughput
- Factor 4 underestimation vs more complete ERO2.0 (not same bg, 3D effects?) [J. Romazanov et al 2022 Nucl. Fusion 62 036011]

Outline

FW & far-SOL impact with formation of shoulders?



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



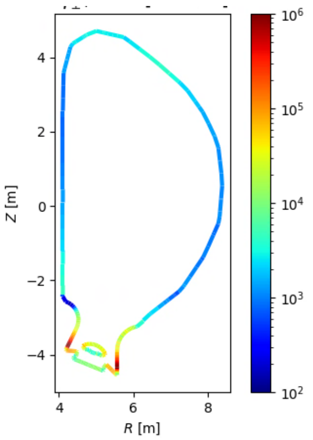
[A. Wynn et al 2018 Nucl. Fusion 58 056001]

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]:

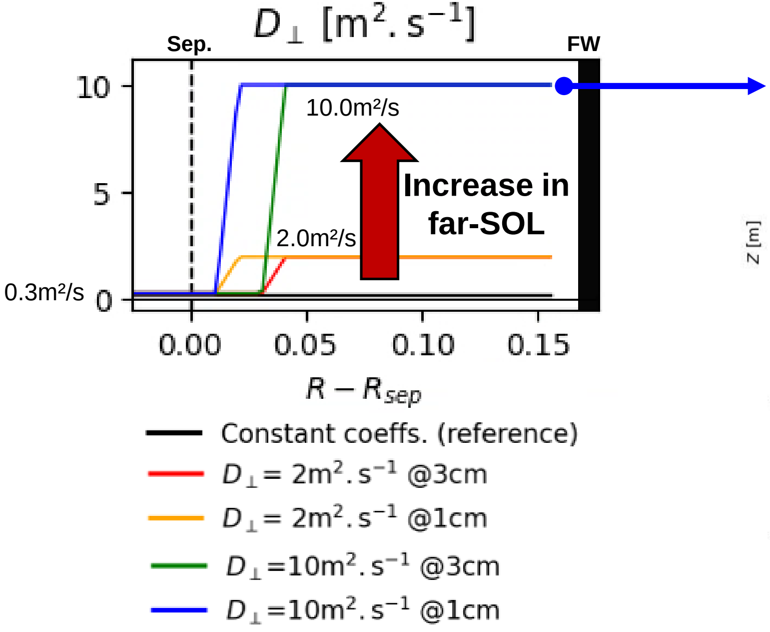
?



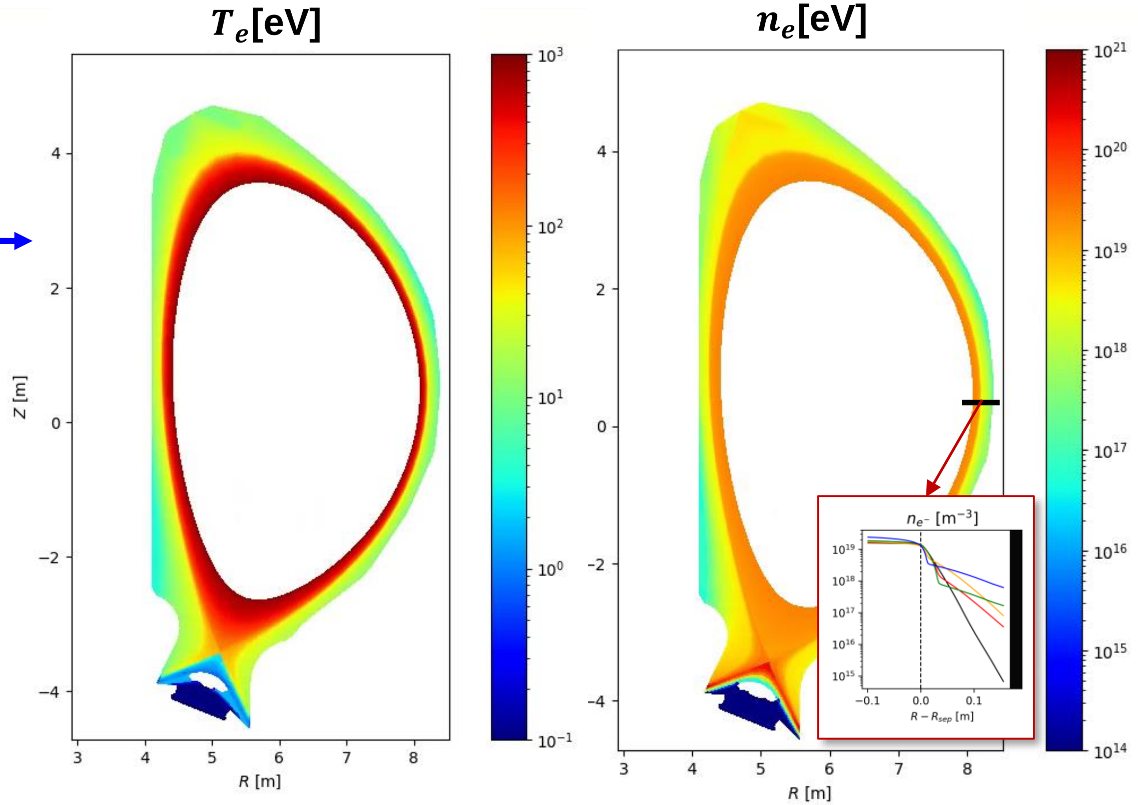
Modelling through increased coeff. in far-SOL

Modelling:

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



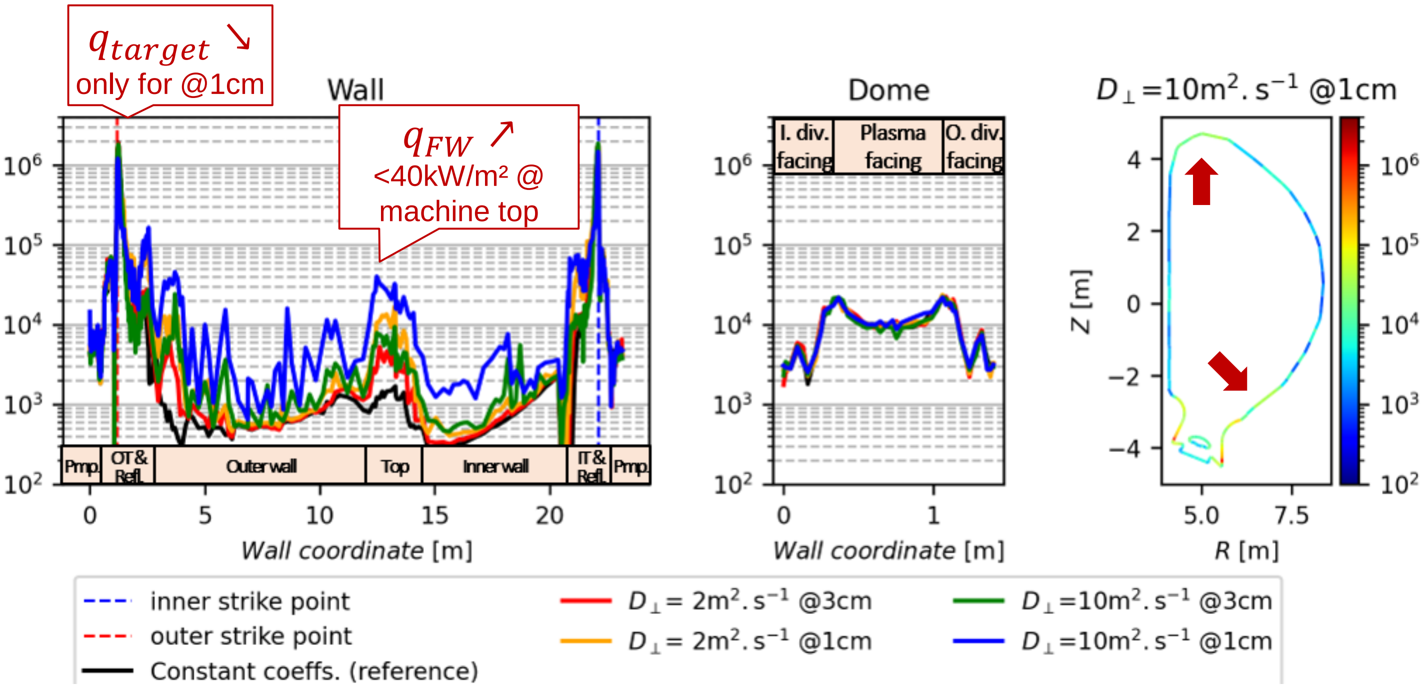
Example: Strongest & closest shoulder (in blue):



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)

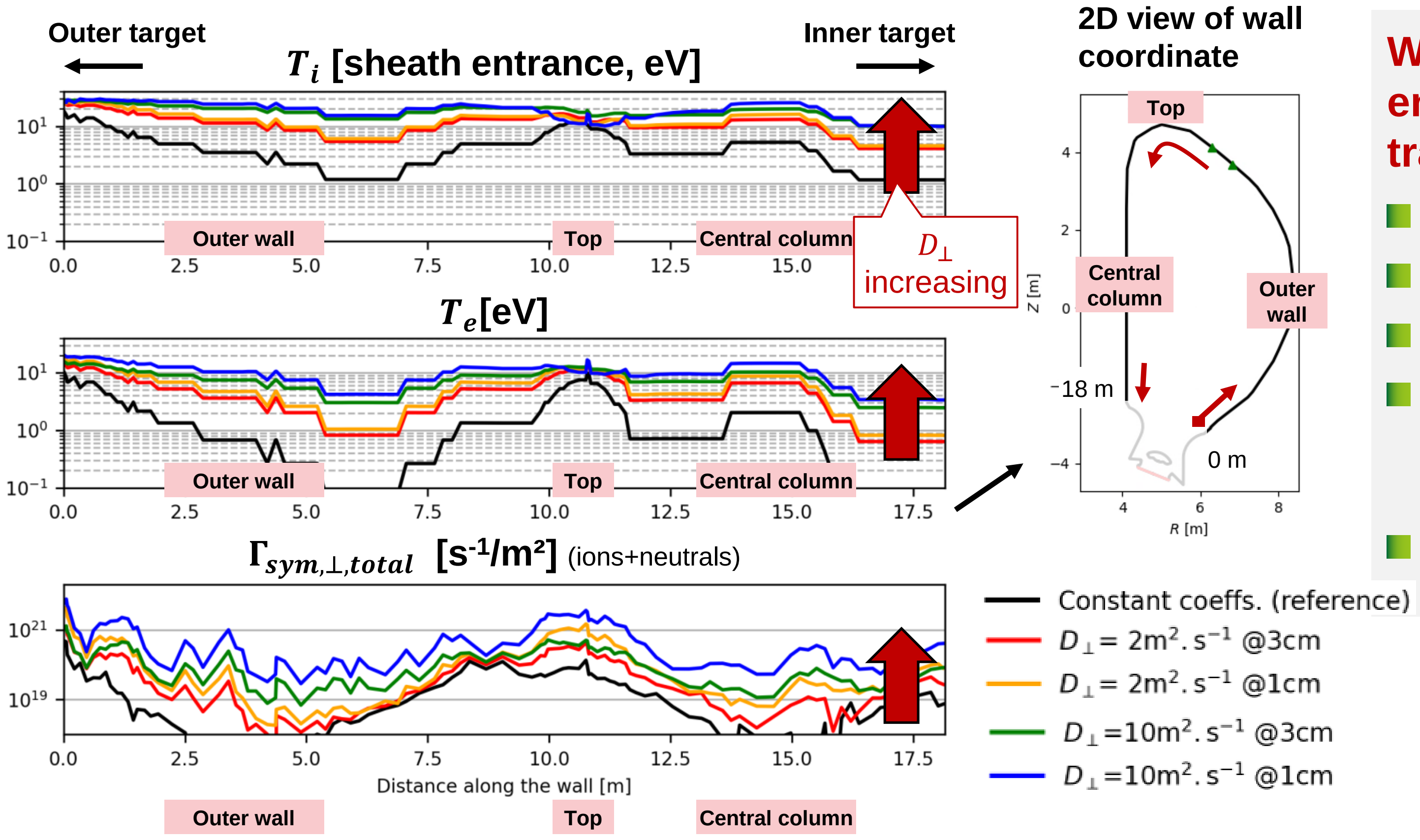


- FW material limits:
  - Inner: 5MW/m²
  - Outer: 3MW/m²,
  - Top: 2MW/m²

  [ITER Research Plan, 2018]
- Max FW load: **up to 30 % of input power** at highest throughput

Impact on quantities at the FW: combined action of Γ & T

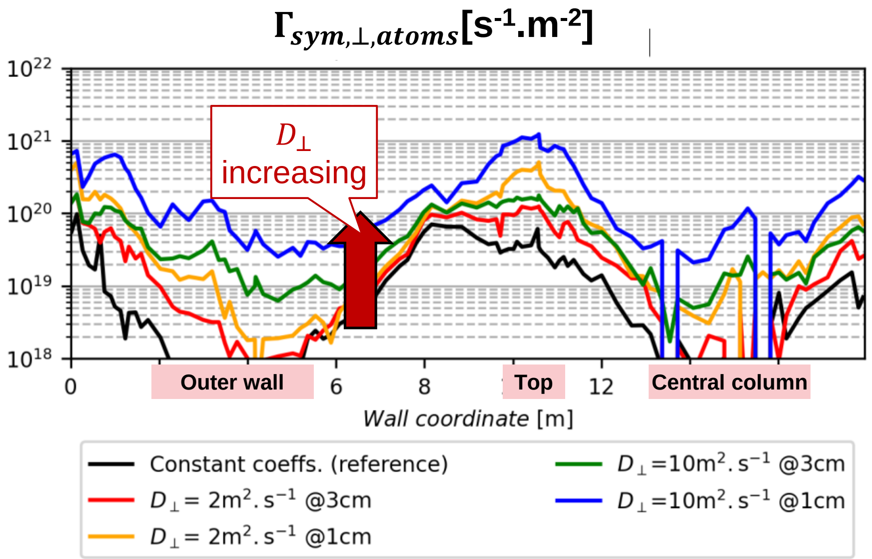
Impact of high far-SOL transport (low throughput):

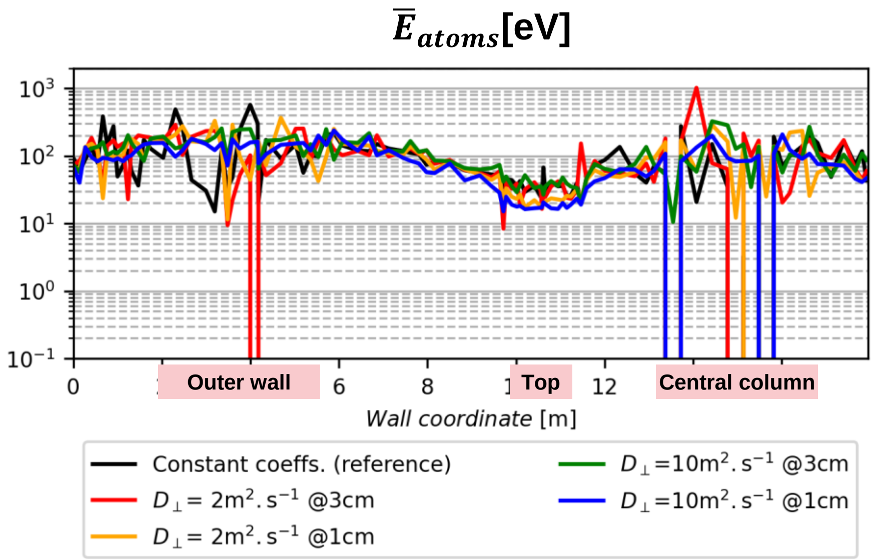


With strongly enhanced far-SOL transport:

- FW fluxes x 10-20
- $T_{i,wall}$ ↗ : 20 - 30 eV
- $T_{e,wall}$ ↗ : 10 - 20 eV
- $q_{sym,\perp,total}$ = 40kW/m² @ machine top
- **Combined increase *Γ* ↗ and *T* ↗**

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**

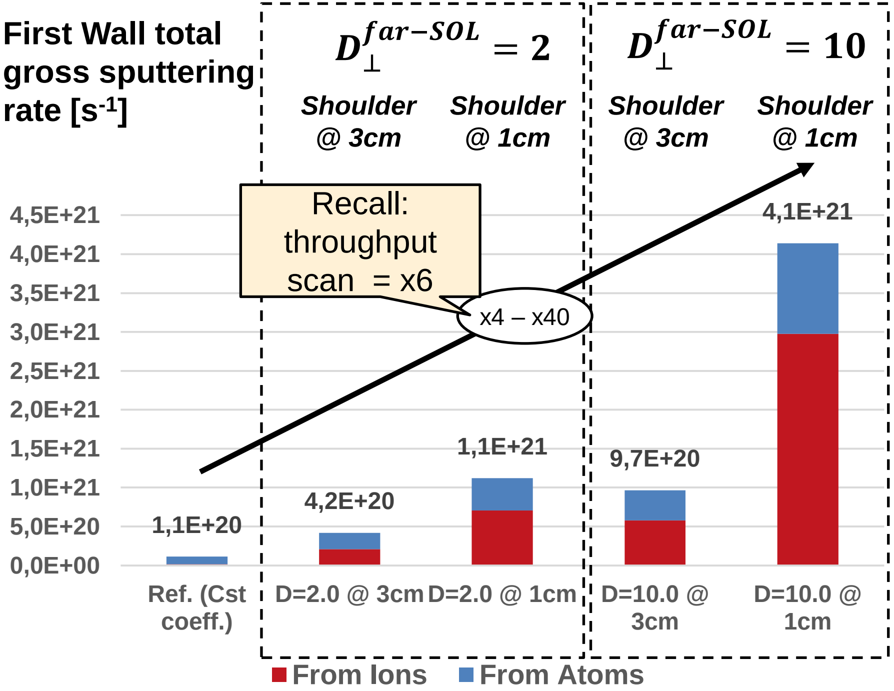
Impact on average atom energy:

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

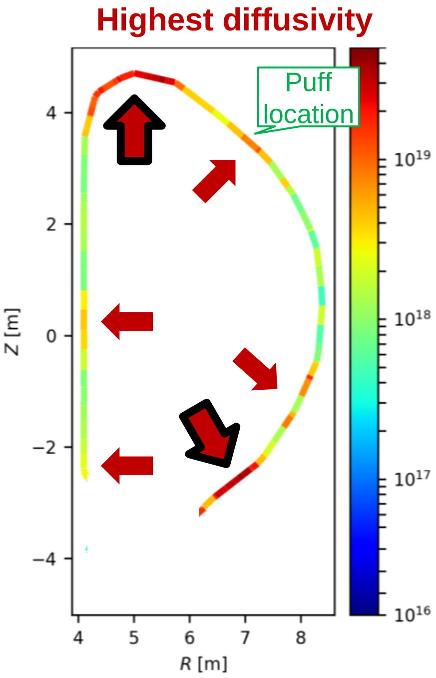
4. Impact of enhanced far-SOL transport (shoulder formation): **Gross Be erosion figures: x40 between scan extremes**

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

First Wall total gross sputtering rate [s⁻¹]



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]

Outline

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 $\boldsymbol{q_{\perp,sym}}$ on FW, but still very low values (for 20MW cases)
- Impact of **throughput**:
  - **Counter action Γ ↗ while T ↘ 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 *Γ* ↗ and T ↗ at the FW**
  - Much **greater impact than throughput on FW gross erosion rate** (x40 between scan extremes, mainly from ions)

Thank you

Acknowledgement:
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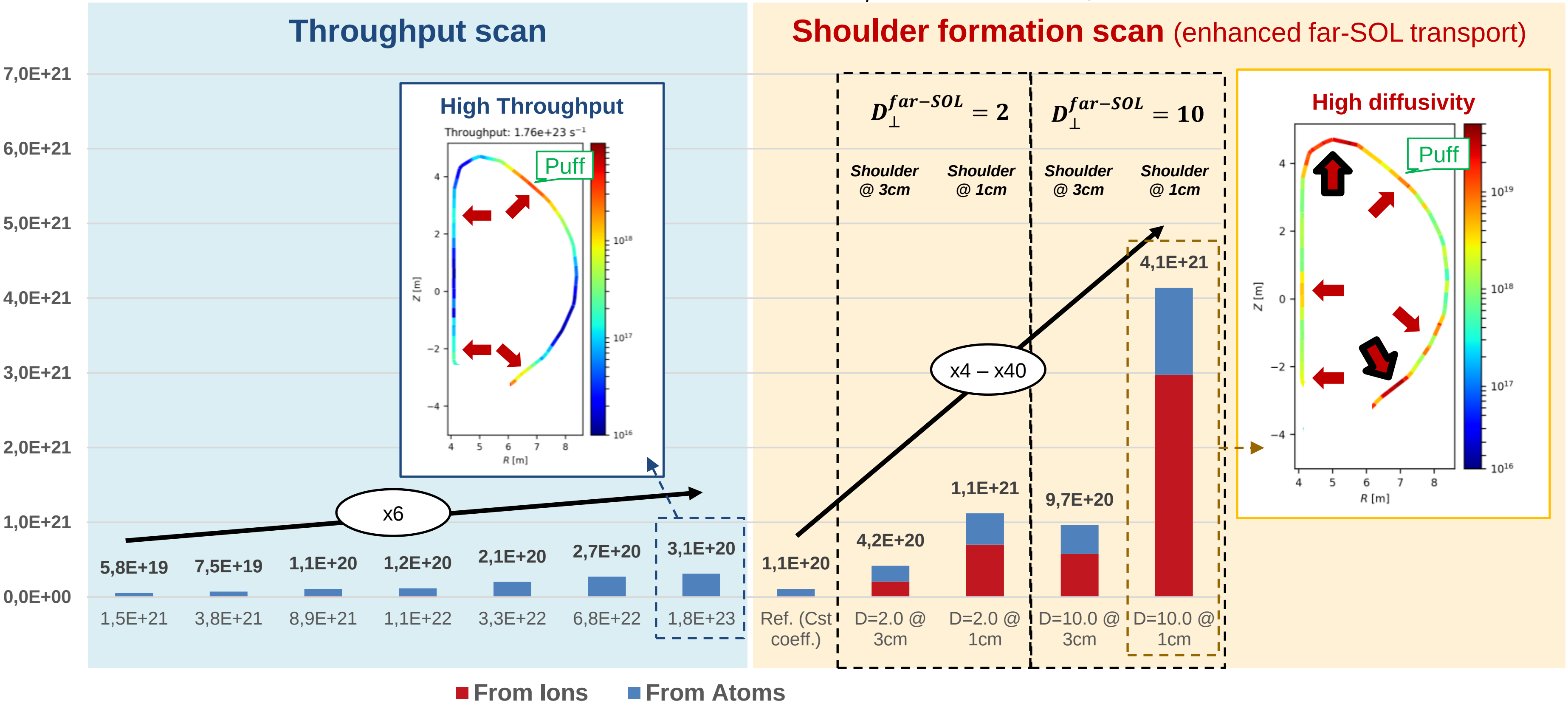
Backup slides

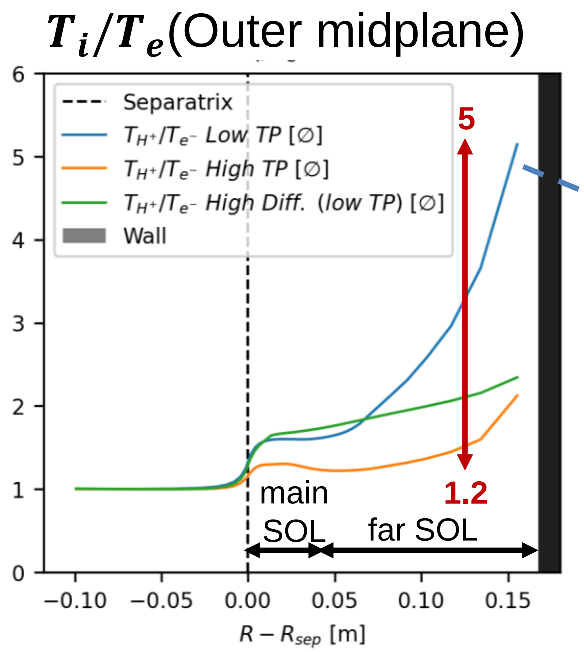
Summary of throughput and shoulder formation on FW gross erosion rate

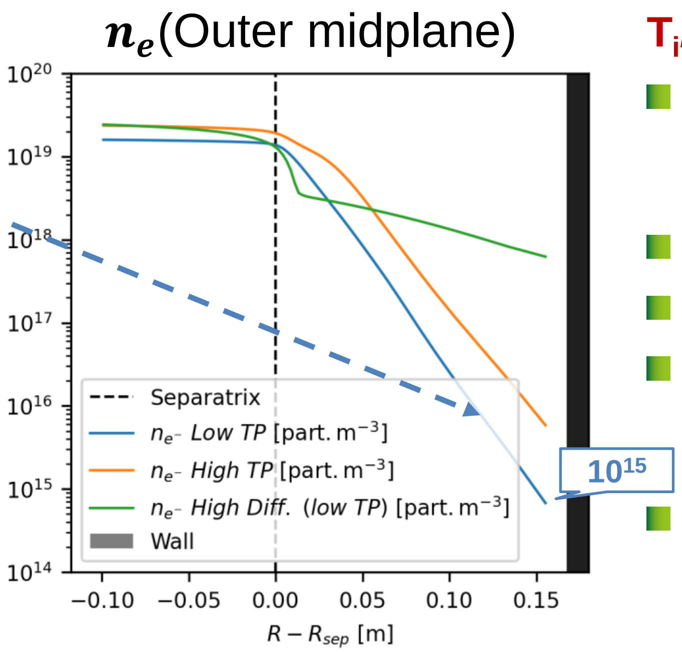
First Wall total gross sputtering rate [s^{-1}]:

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



Plasma conditions in far-SOL: T_i/T_e ratio



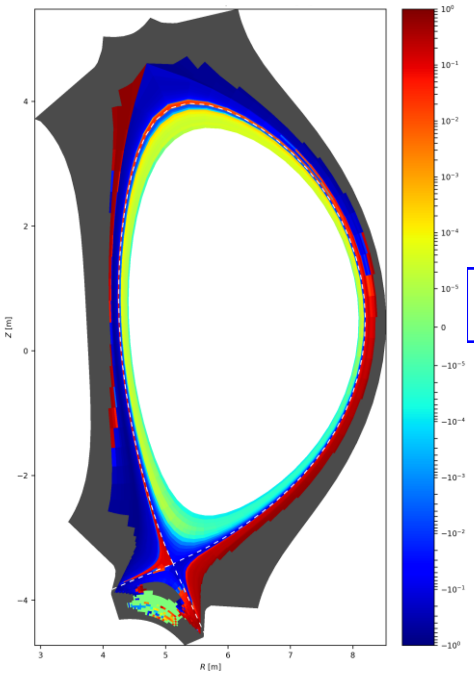


T_i/T_e ratio in far-SOL:

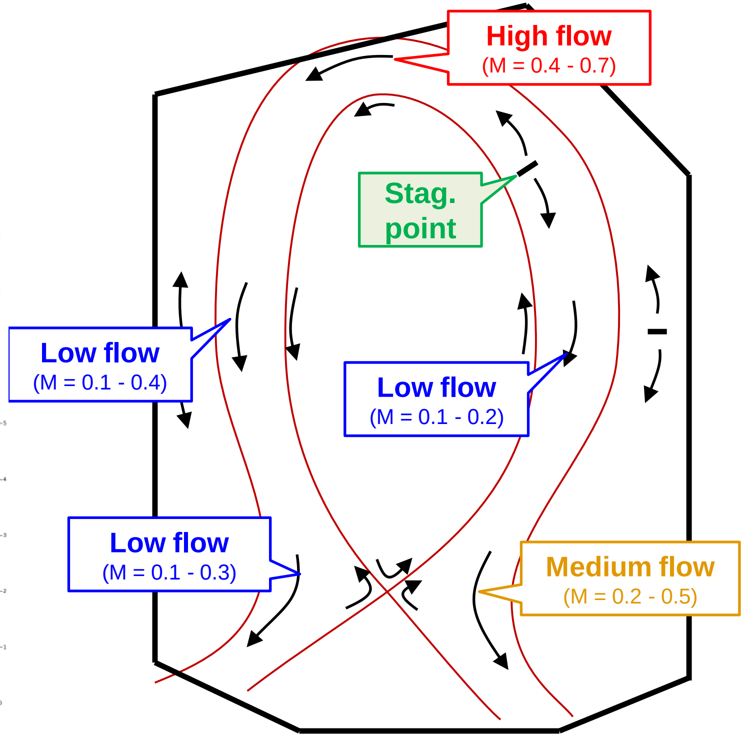
- Key input for erosion codes and impurity transport
- **Main SOL: T_i/T_e ~ 1.2 – 2**
- **Far SOL: T_i/T_e ~ 1.2 – 5**
- Ratio ↘ **with throughput and diffusivity (low: 5, high: 2)**
- Correlation with n_e, but not only (collisionality)

Plasma conditions in far-SOL: SOL flows

Mach Number



Low throughput



SOL flows:

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

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