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

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# 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

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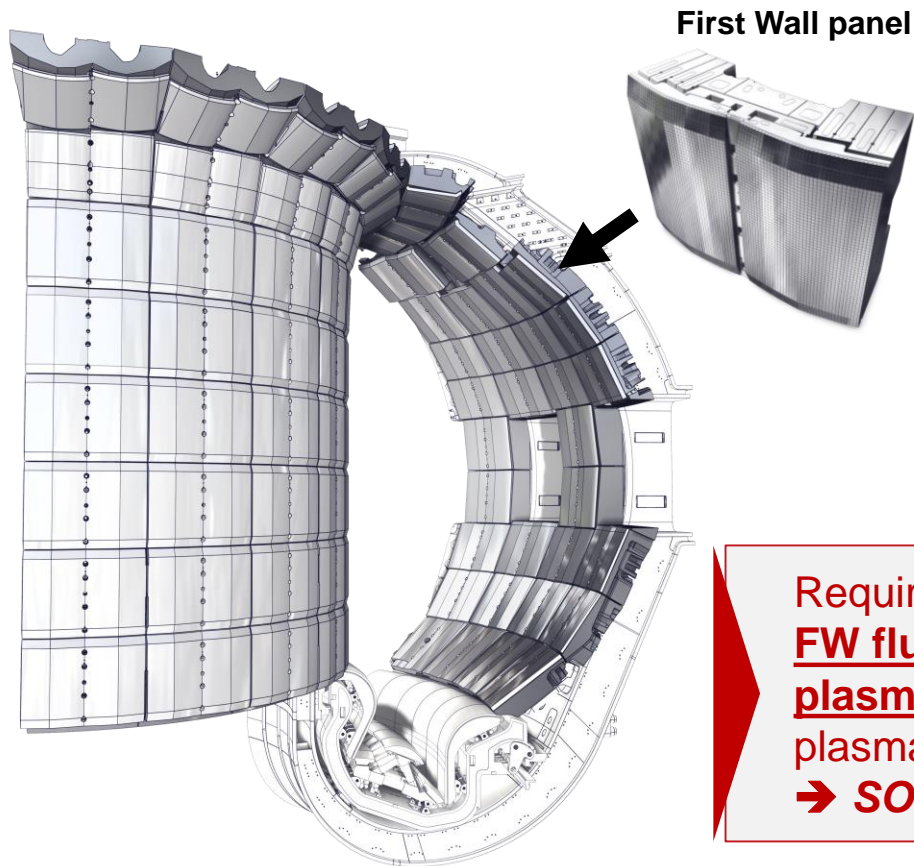
*P. TAMAIN (CEA IRFM), Y. MARANDET (CNRS, Aix-Marseille Université), X. BONNIN (ITER Organization), H. BUFFERAND (CEA IRFM), R.A. PITTS (ITER Organization), G. FALCHETTO (CEA IRFM), H. YANG (CEA IRFM), G. CIRAOLO (CEA IRFM),*

- **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
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# 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  
→ **SOLEEDGE3X**

Feed input for other codes:

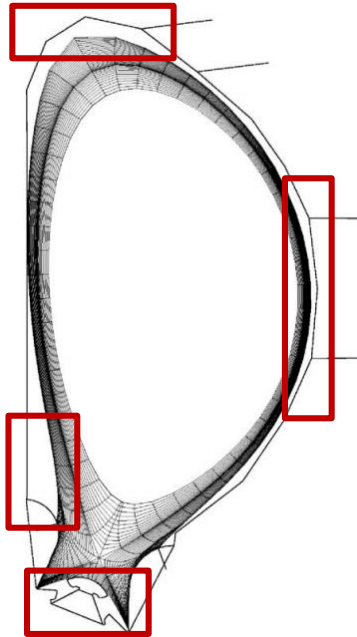
→ **ERO2.0**  
**WALLDYN**

...

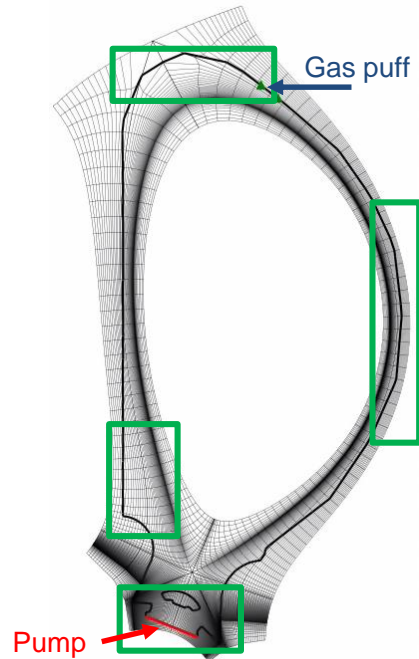
# 1. Context and motivation

## 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**

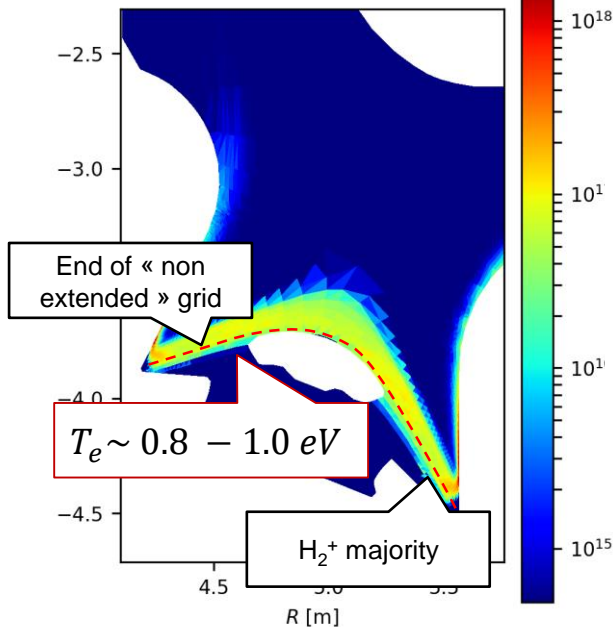
### The SOLEDGE3X code and setup:

- **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.)

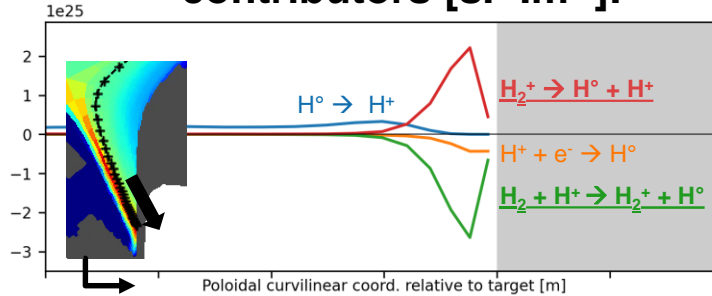
- 1. Context and motivation
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#### Molecular ion $H_2^+$ density [ $m^{-3}$ ]:



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



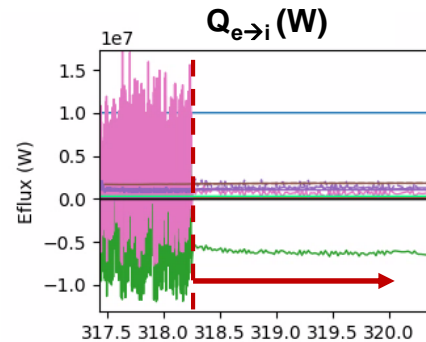
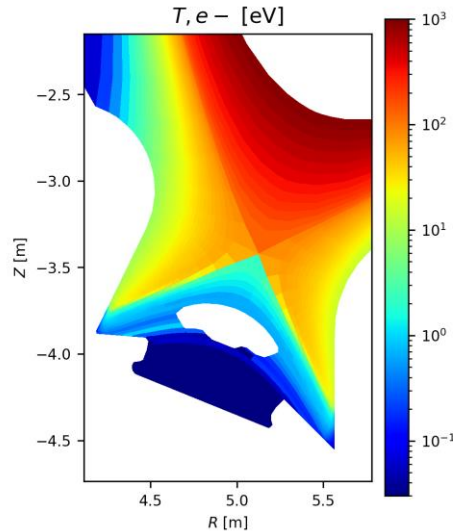
#### $H_2^+$ ion role:

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

#### Example: Electron-ion energy equipartition:

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

**Strong at low temperature !**



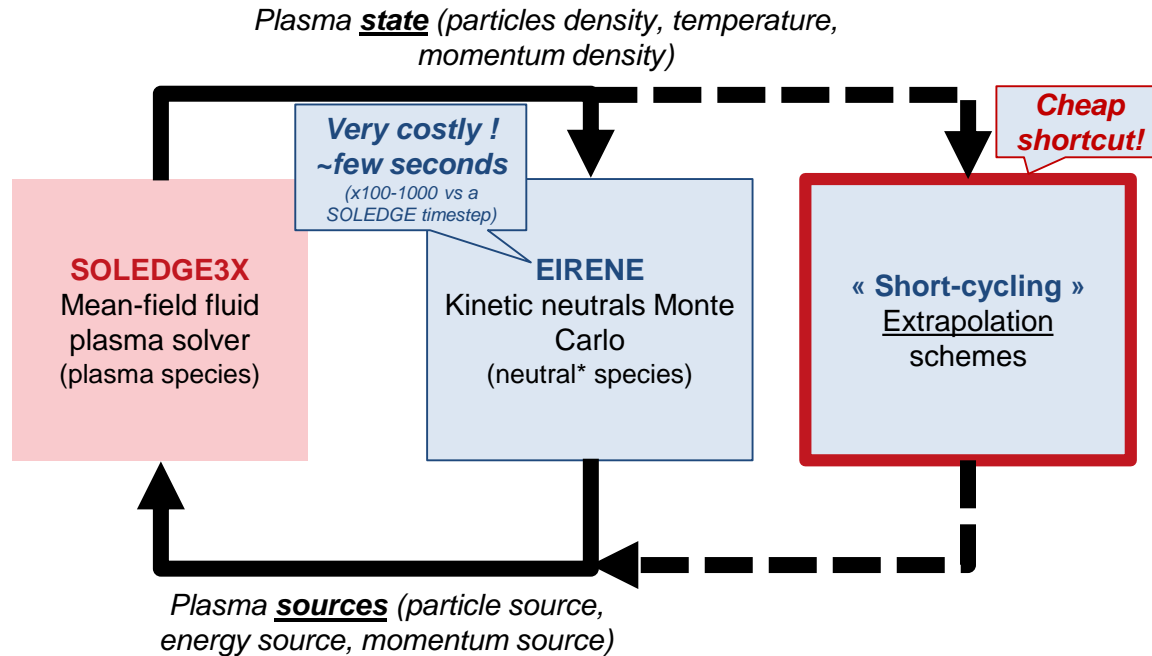
*Semi-Analytical solution*

- Collisional energy & momentum exchange terms become very large at **low T**, especially during transients
- Coulomb Log  $\Lambda$**  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

#### SOLEEDGE3X-EIRENE coupling workflow:



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

#### Sources extrapolation:

■  $S_n = n_{\text{atom}} n_e \langle \sigma_{iz} v \rangle$

Updated from plasma background

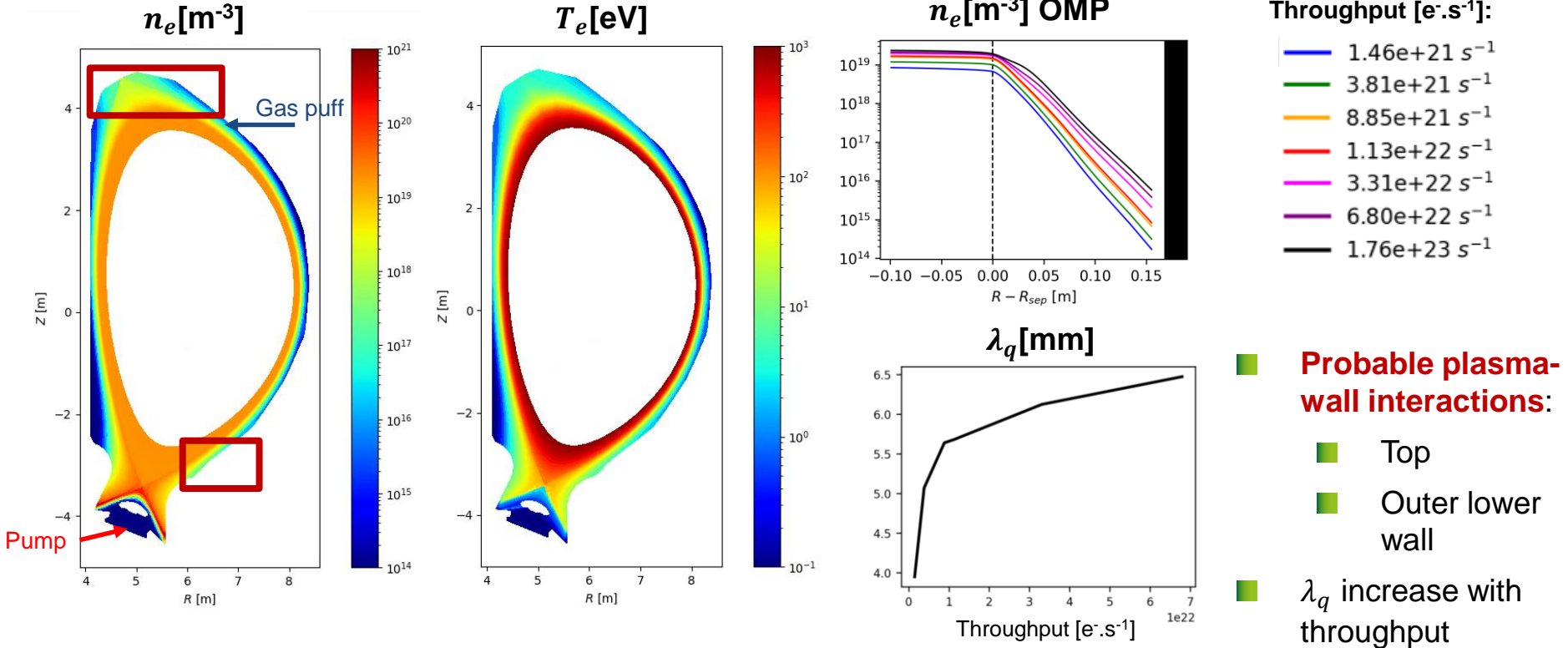
Keep spatial distrib.

Extrapolated source from neutrals

[Details to be published]

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



# 3. Impact of throughput

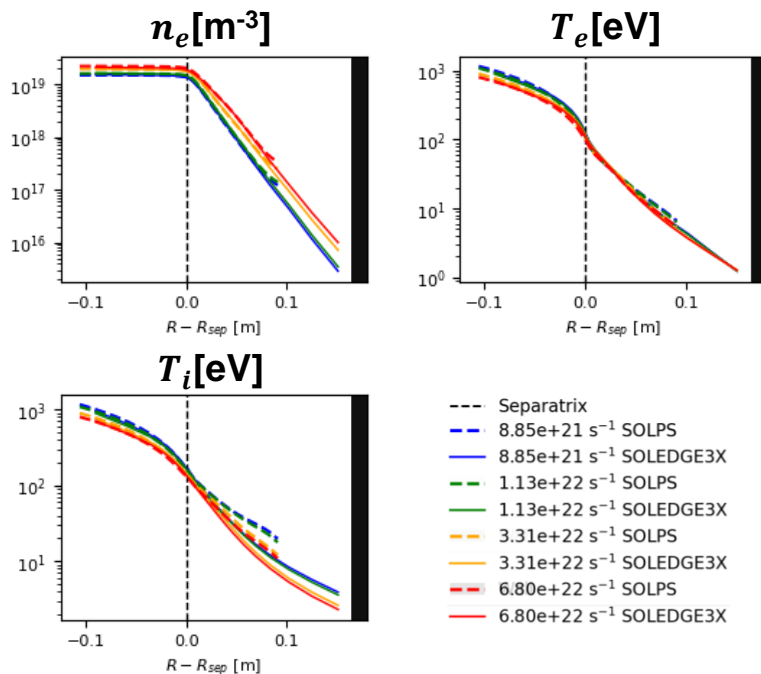
## Overall good agreement with SOLPS-ITER runs

### Throughput scan, from attached to partially detached

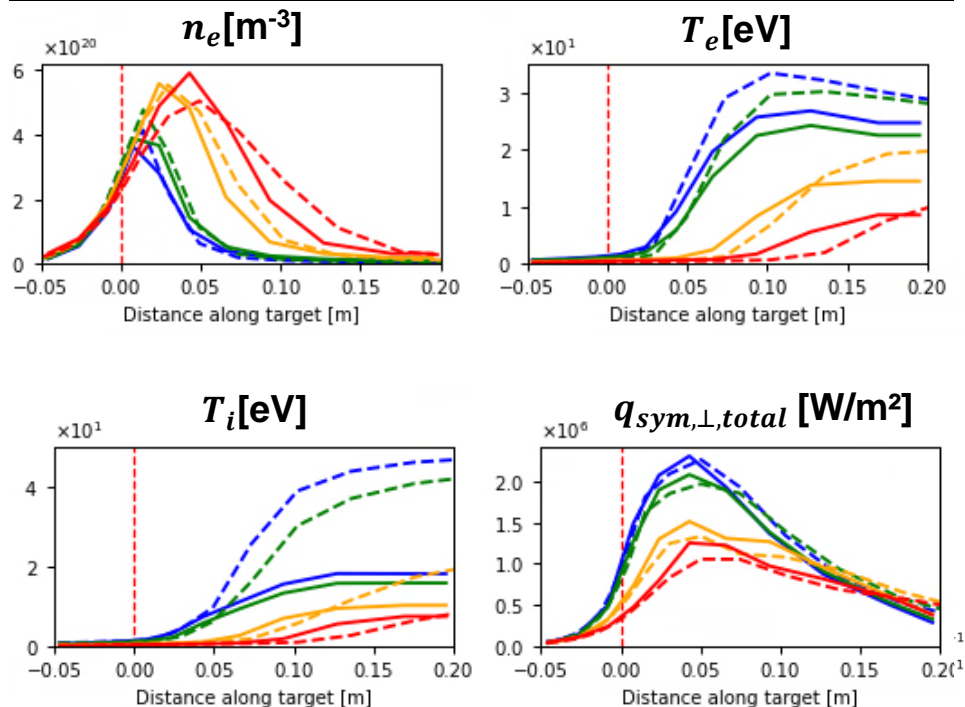
(colors are different throughputs – blue: low → red: high)

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

#### Upstream (Outer midplane)

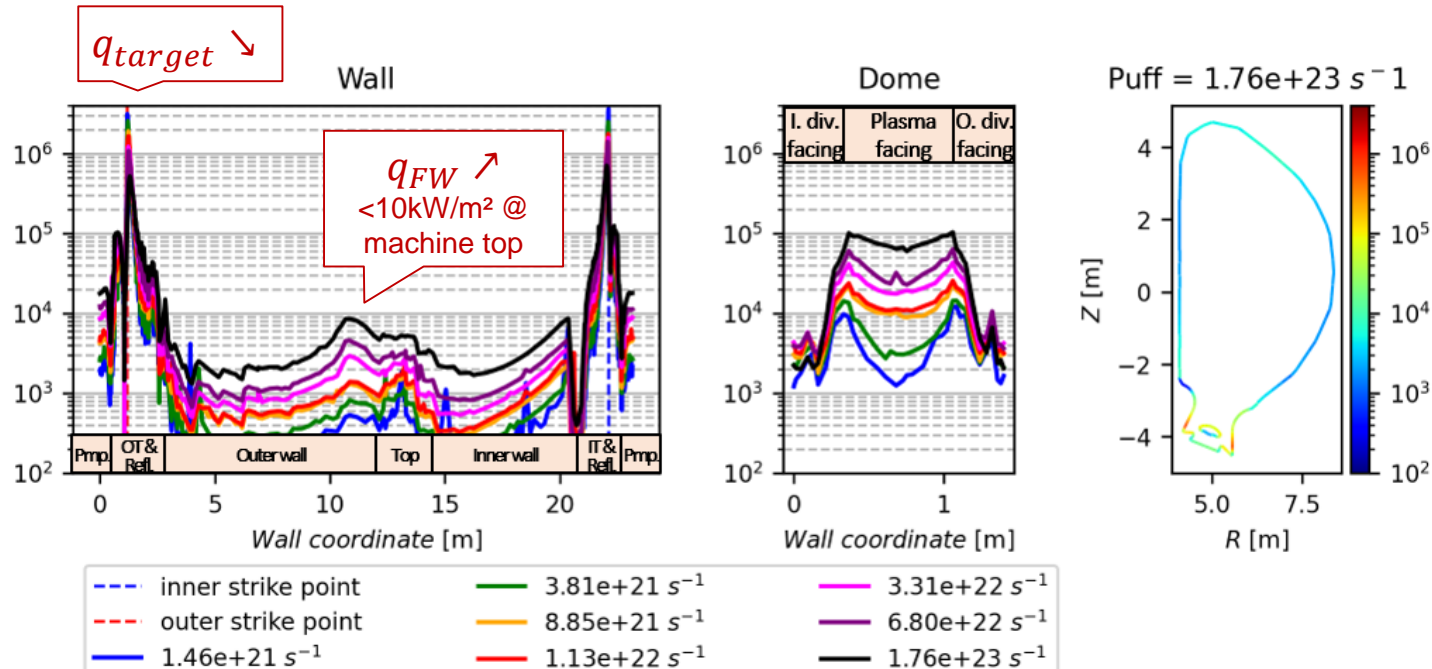


#### Outer Target



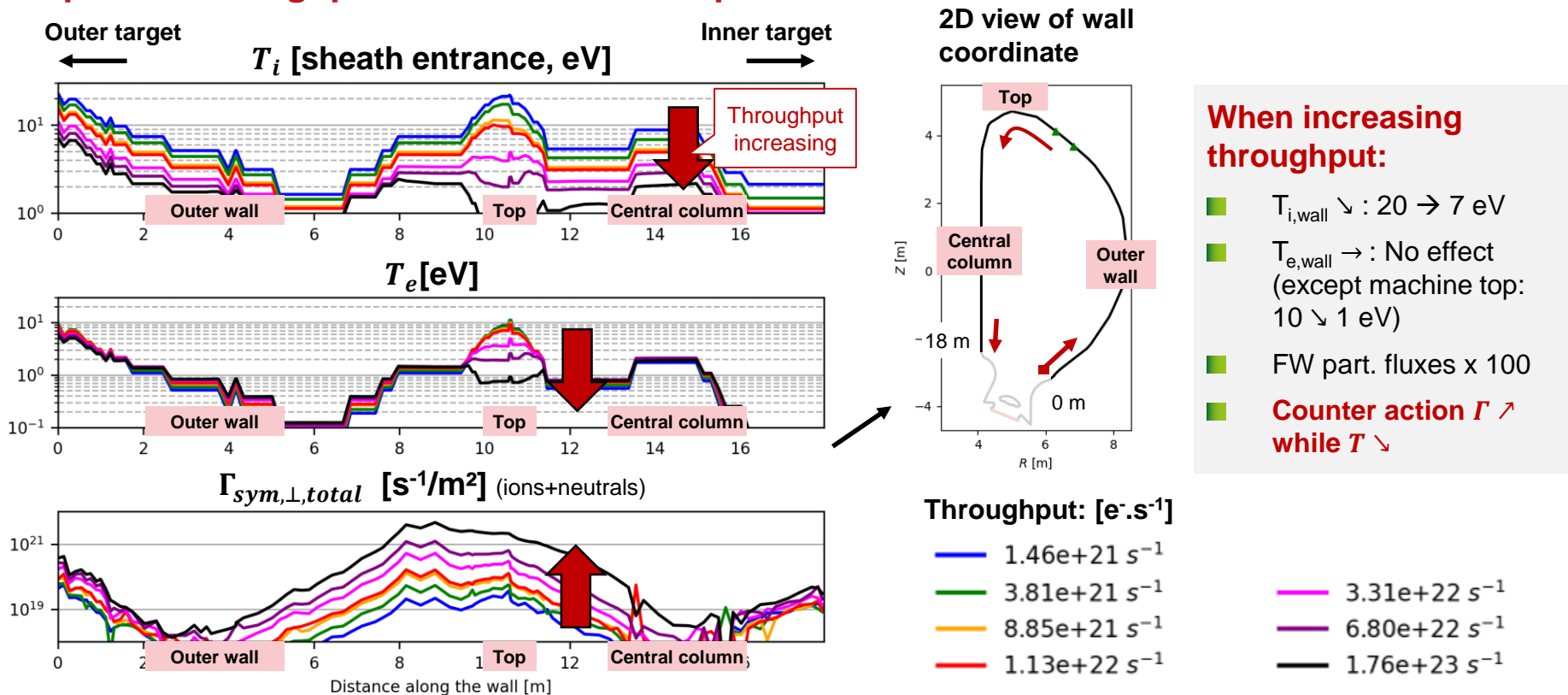
## Heat flux density deposition on the FW $q_{sym,\perp,total}$ [W/m<sup>2</sup>]:

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



- FW material limits:
  - Inner: 5MW/m<sup>2</sup>
  - Outer: 3MW/m<sup>2</sup>,
  - Top: 2MW/m<sup>2</sup>
- [ITER Research Plan, 2018]
- Max FW load: **up to 20 % of input power** at highest throughput

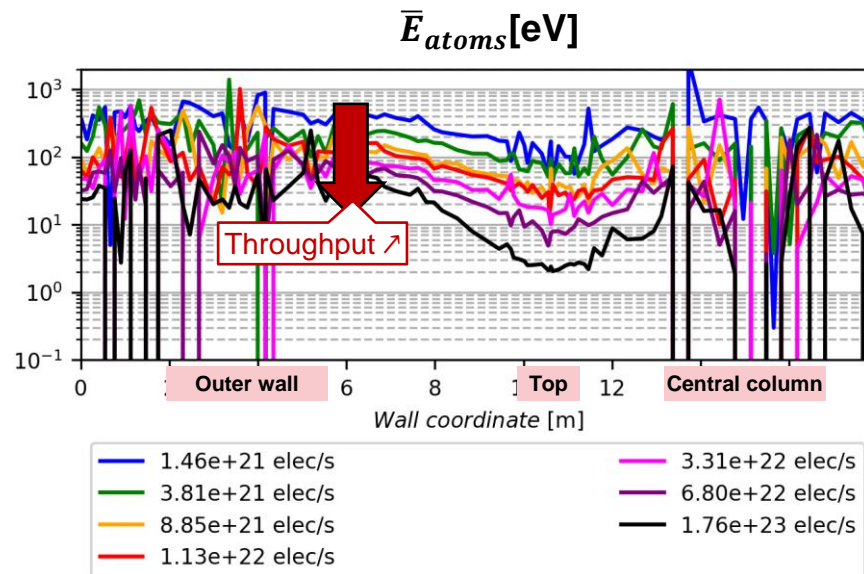
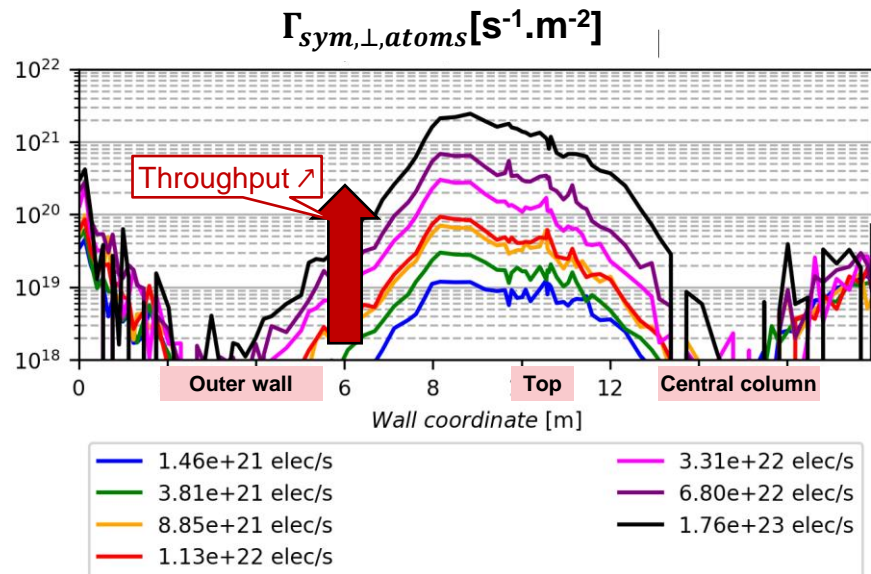
## 3. Impact of throughput

Quantities at the FW: counter action of  $\Gamma$  vs  $T$ Impact of throughput on FW  $T$  and total particle flux:



## 3. Impact of throughput :

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



## Impact on incident atom flux density:

- Large increase at machine top and outer top: x100

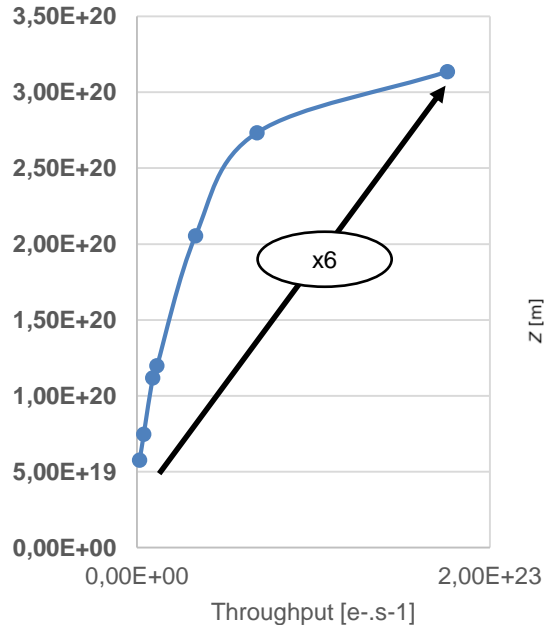
## Impact on average atom energy:

- Large decrease  $\div 10 - 100$
- 100 eV  $\rightarrow$  3 eV at machine top

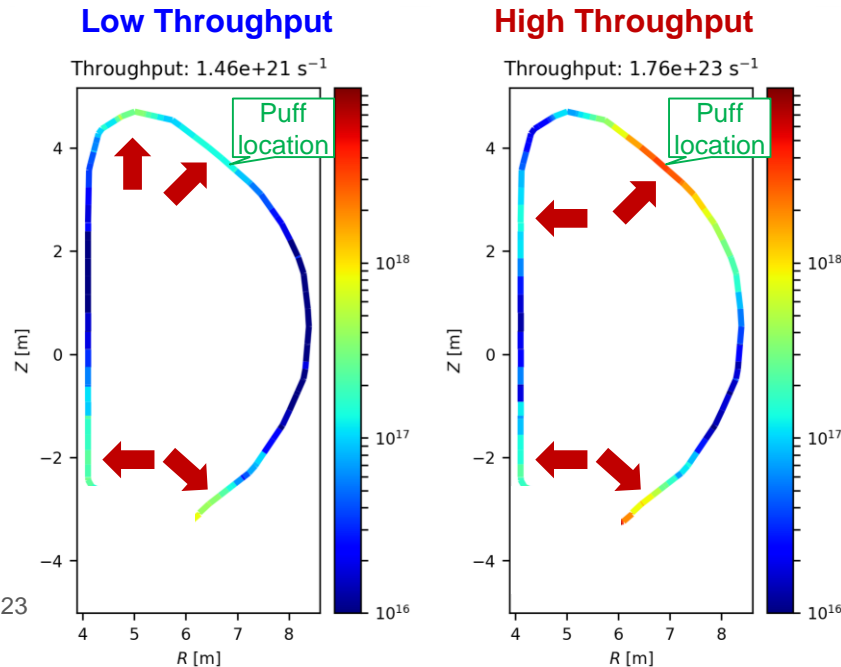
# Gross Be erosion figures: x6 between scan extremes

*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 [ $s^{-1} \cdot m^{-2}$ ]**

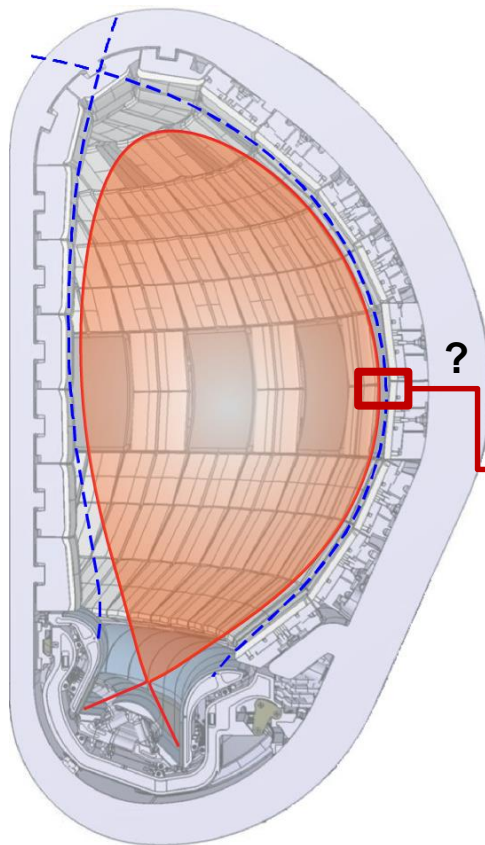


**Trends:**

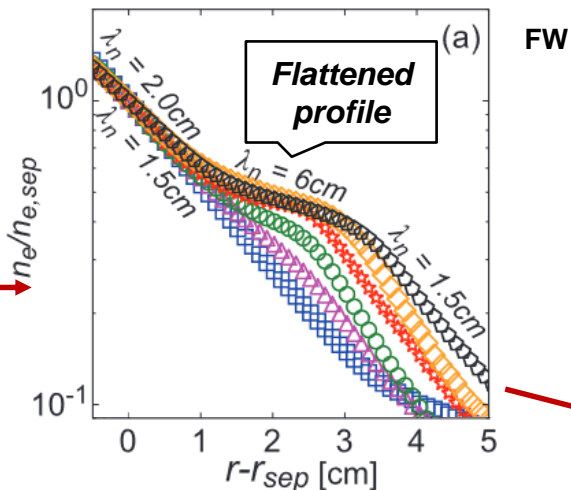
- ~90% from **CX atoms, increasing** with throughput
- From **ions**: ~**independent** of throughput
- Factor 4 underestimation vs more complete ERO2.0 (not same bg, 3D effects?)  
[J. Romazanov et al 2022 Nucl. Fusion 62 036011]

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# 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)

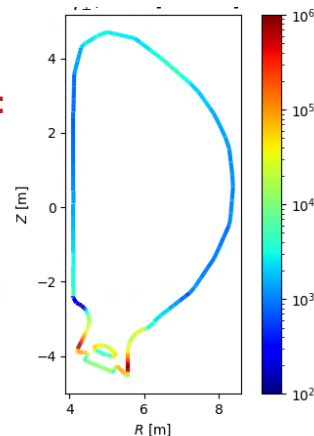


[A. Wynn et al 2018 Nucl.  
Fusion 58 056001]

**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?

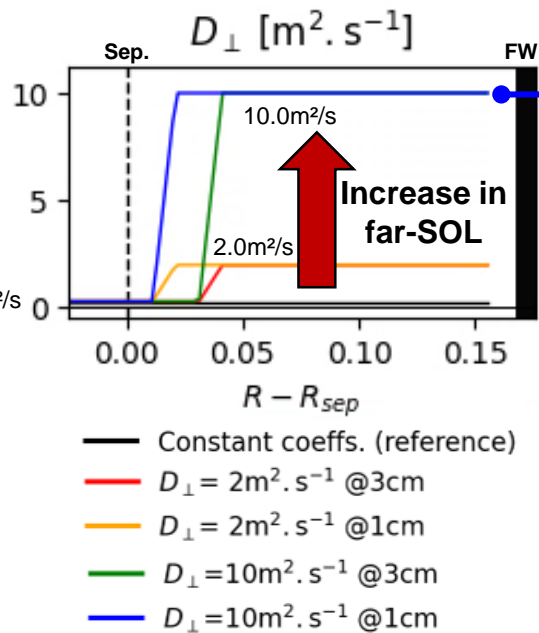
**Wall heat flux  
(total,  $q_{\perp}$ ) [W/m<sup>2</sup>]:**



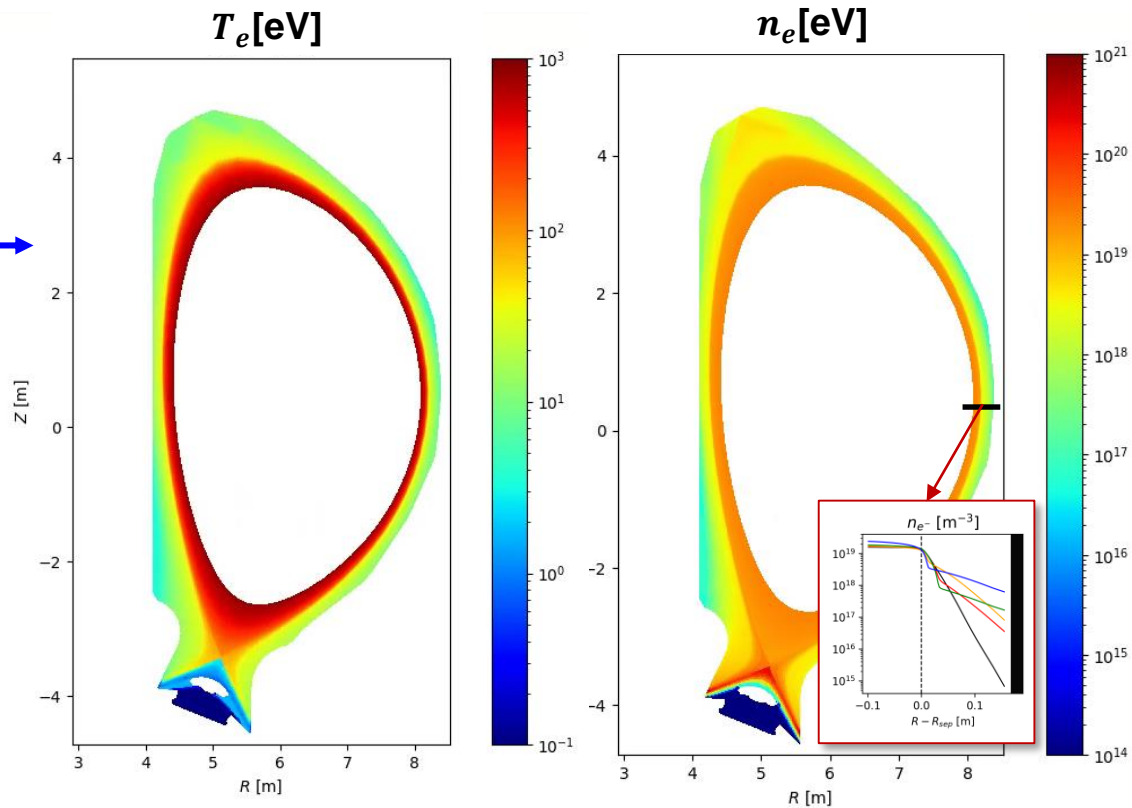
# 4. Impact of enhanced far-SOL transport (shoulder formation): Modelling through increased coeff. in far-SOL

## Modelling:

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



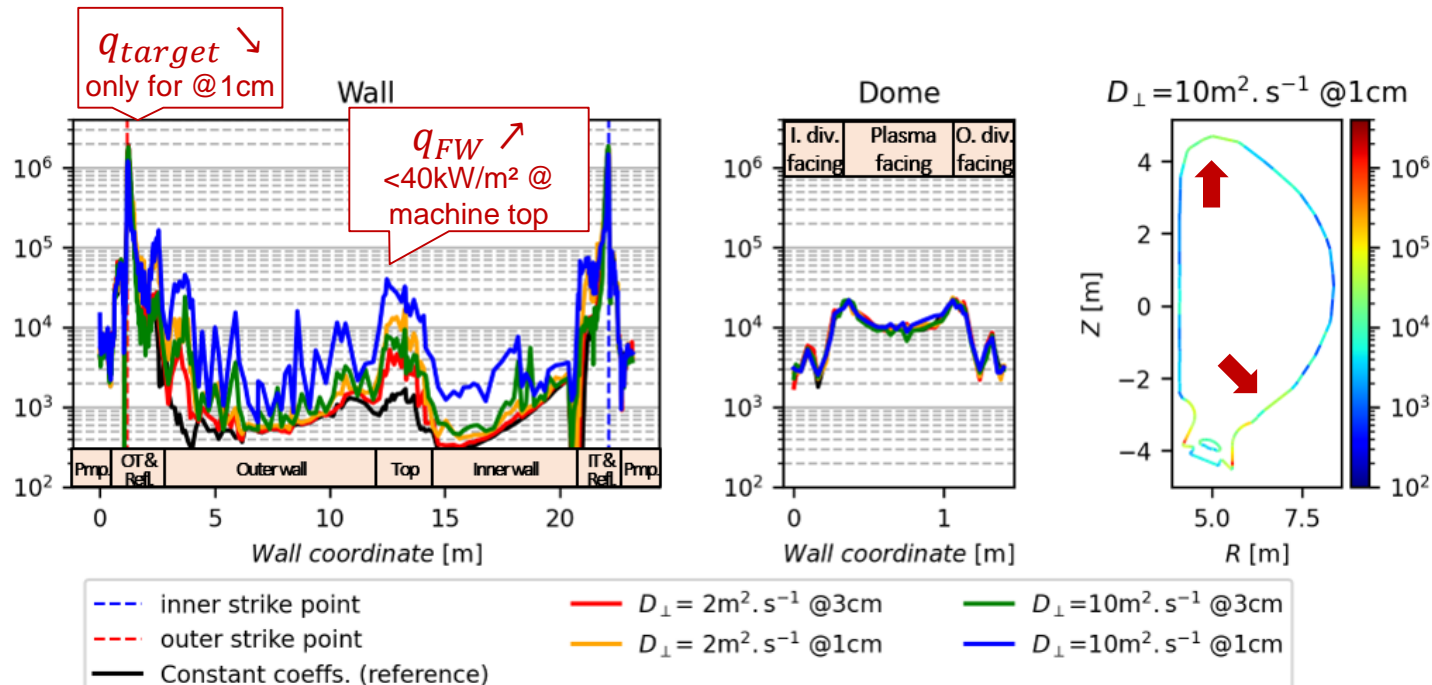
## Example: Strongest & closest shoulder (in blue):



# 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/m<sup>2</sup>]:

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



### FW material limits:

Inner:  
5MW/m<sup>2</sup>

Outer:  
3MW/m<sup>2</sup>,

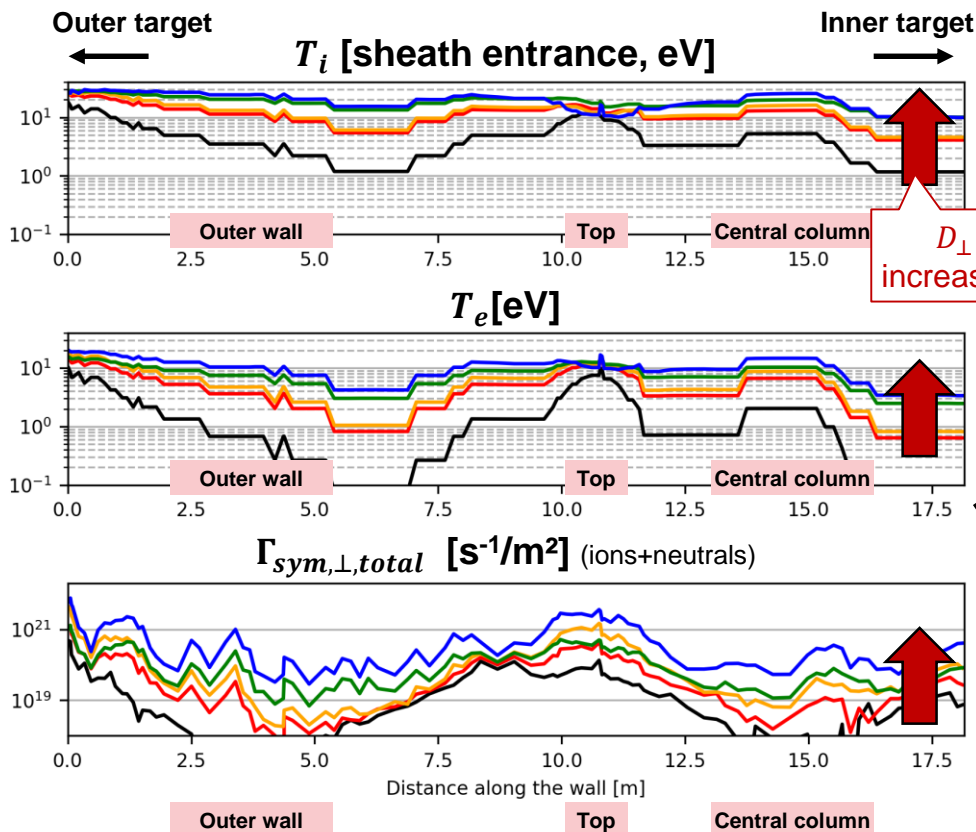
Top:  
2MW/m<sup>2</sup>

[ITER Research Plan, 2018]

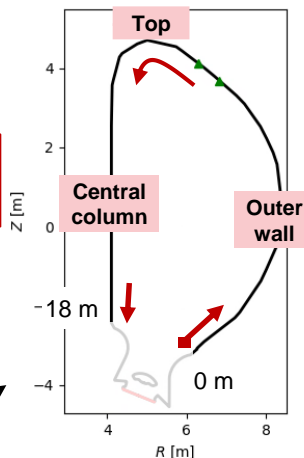
Max FW load: **up to 30 % of input power** at highest throughput

# 4. Impact of enhanced far-SOL transport (shoulder formation): Impact on quantities at the FW: combined action of $\Gamma$ & $T$

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



## 2D view of wall coordinate

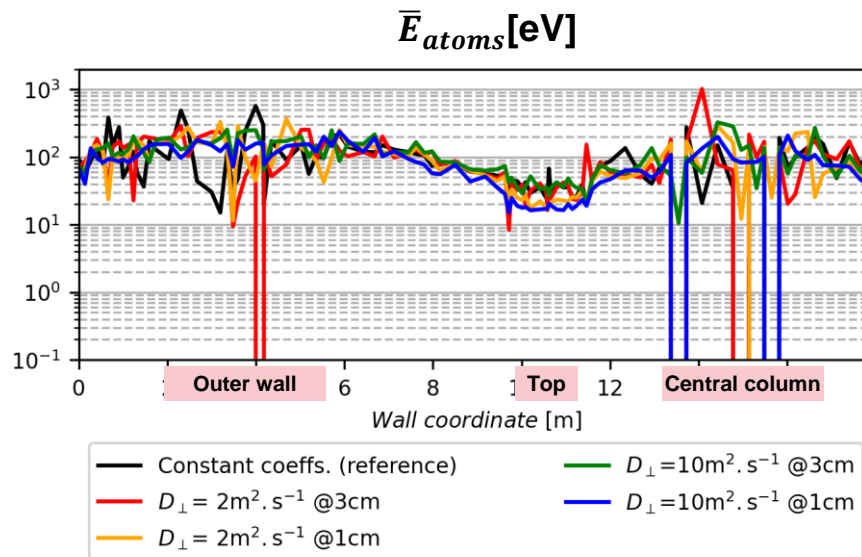
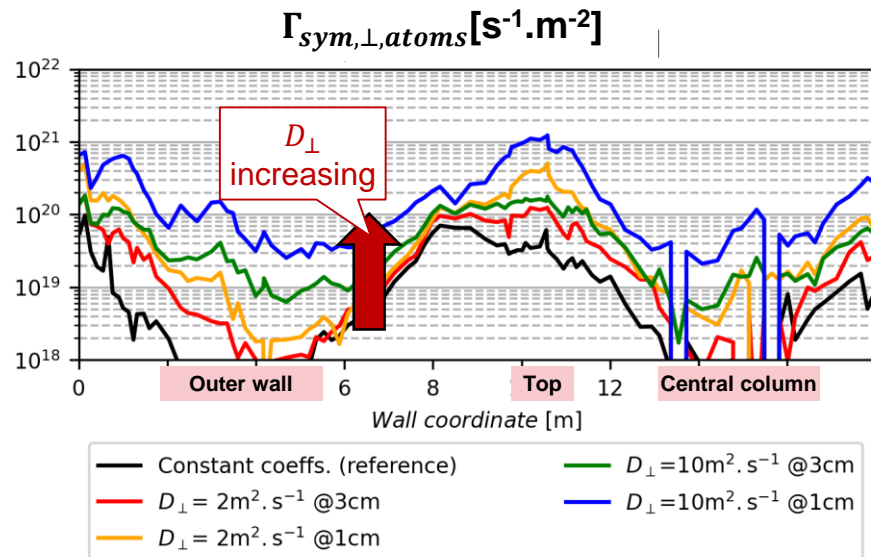


## With strongly enhanced far-SOL transport:

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

- Constant coeffs. (reference)
- $D_{\perp} = 2m^2 \cdot s^{-1}$  @3cm
- $D_{\perp} = 2m^2 \cdot s^{-1}$  @1cm
- $D_{\perp} = 10m^2 \cdot s^{-1}$  @3cm
- $D_{\perp} = 10m^2 \cdot s^{-1}$  @1cm

## 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**

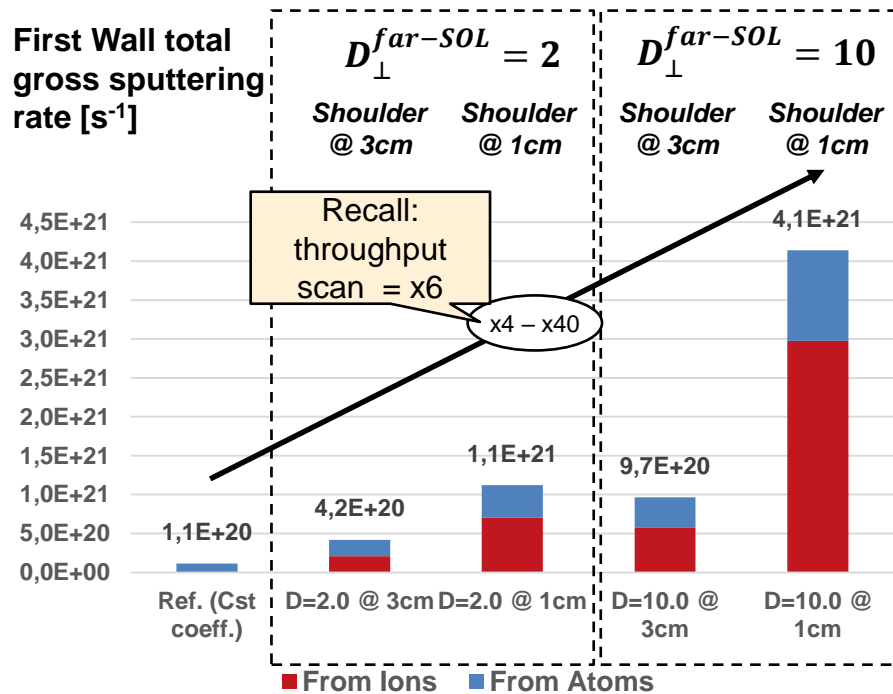
### Impact on average atom energy:

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

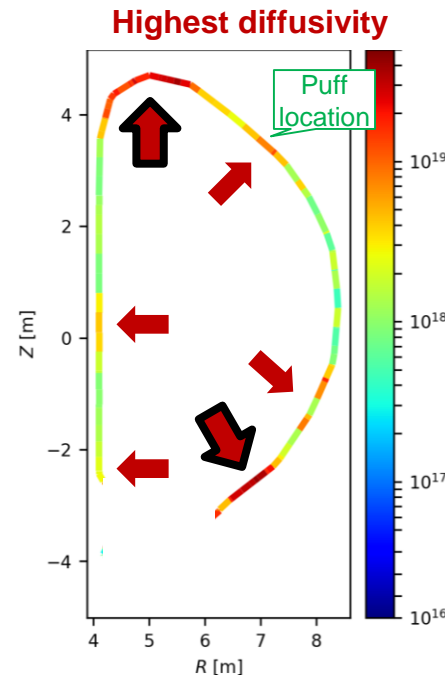


# 4. Impact of enhanced far-SOL transport (shoulder formation): Gross Be erosion figures: x40 between scan extremes

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



## Gross sputtering rate density [ $s^{-1} \cdot m^{-2}$ ]



## 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]

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- 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.*

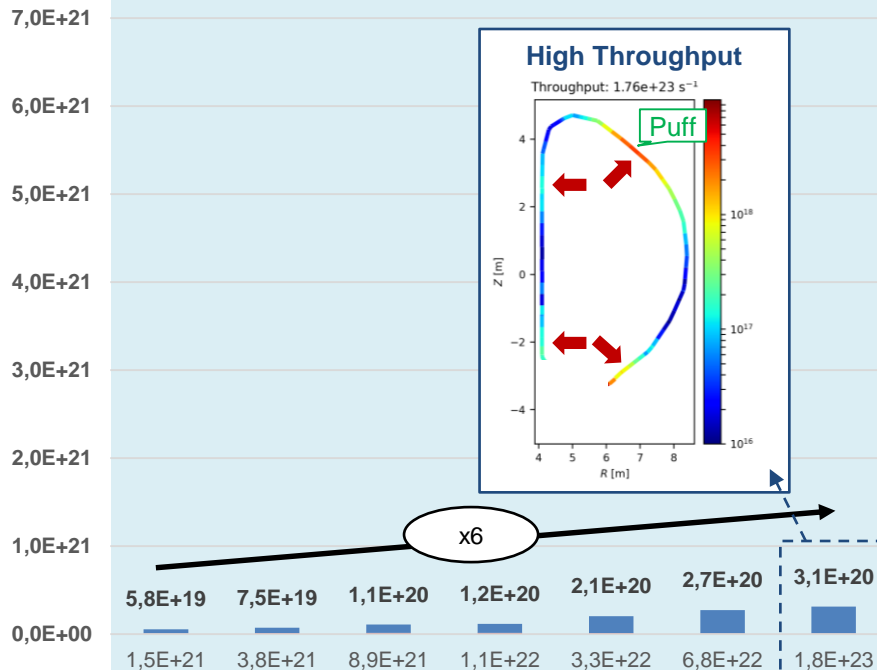
# ***Backup slides***

# Summary of throughput and shoulder formation on FW gross erosion rate

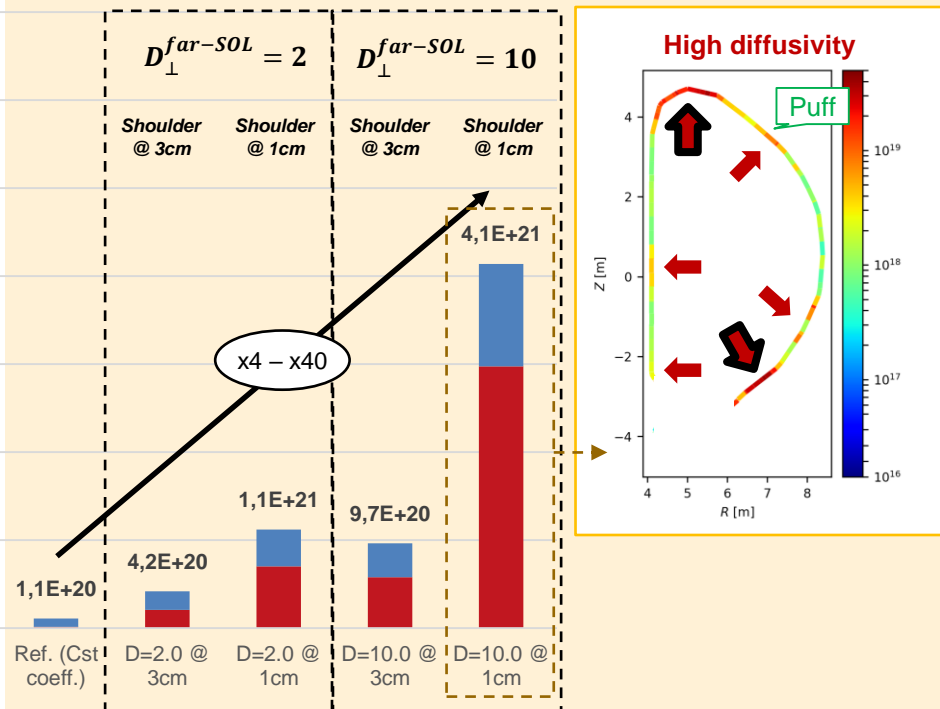
First Wall total gross sputtering rate [ $s^{-1}$ ]:

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

## Throughput scan

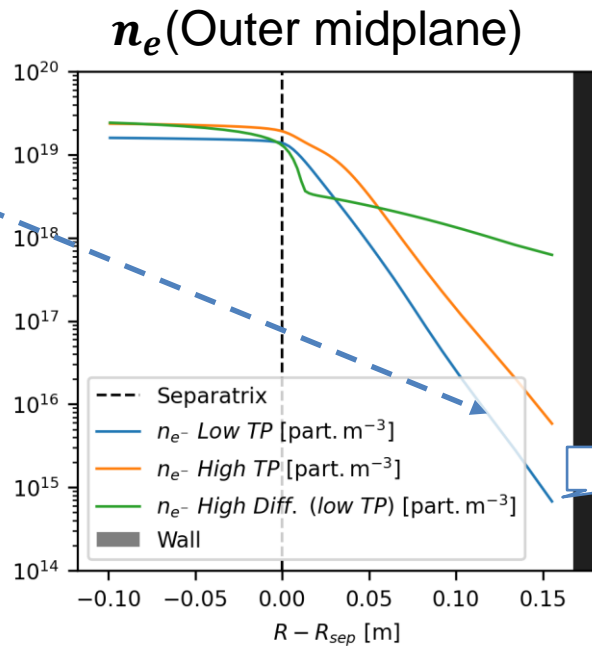
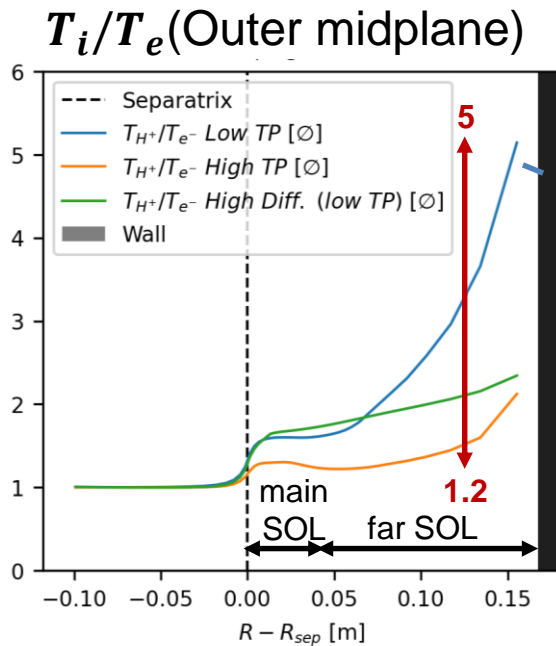


## Shoulder formation scan (enhanced far-SOL transport)



■ From Ions ■ From Atoms

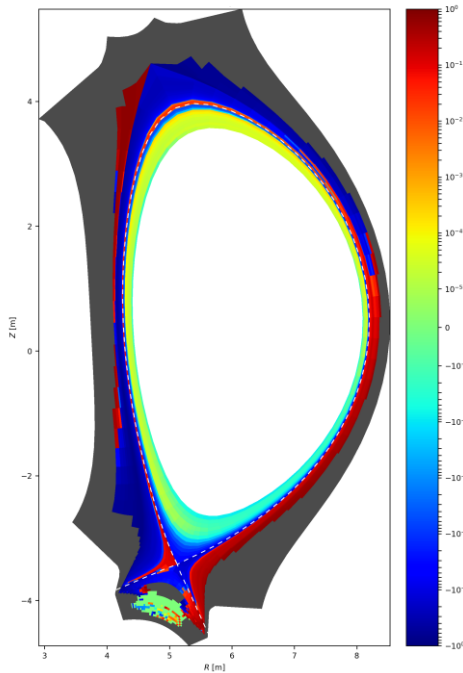
# 4. Impact of enhanced far-SOL transport (shoulder formation): Plasma conditions in far-SOL: $T_i/T_e$ ratio



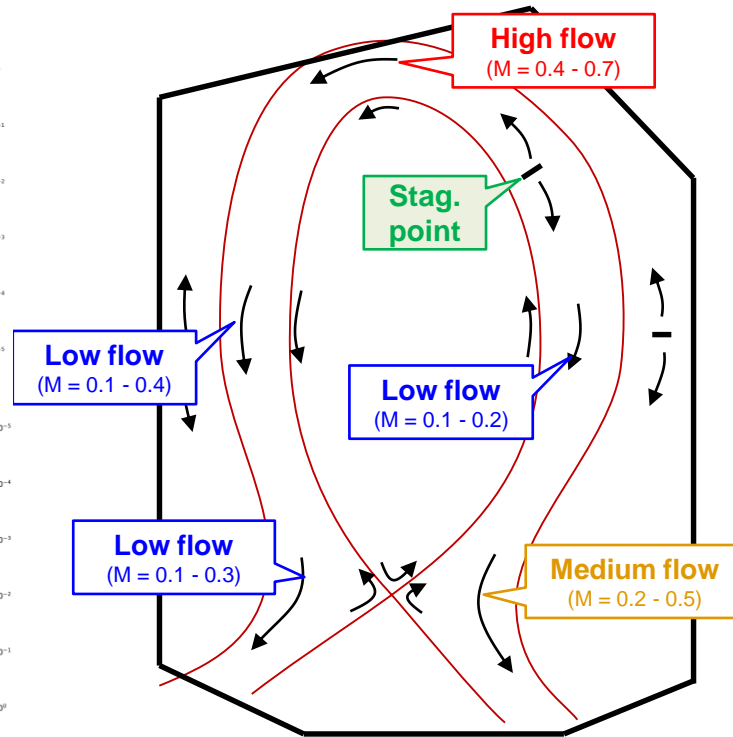
## $T_i/T_e$ ratio in far-SOL:

- 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)

## 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

