Tungsten sources, transport and screening in WEST: experimental analyses and comparison with numerical modeling

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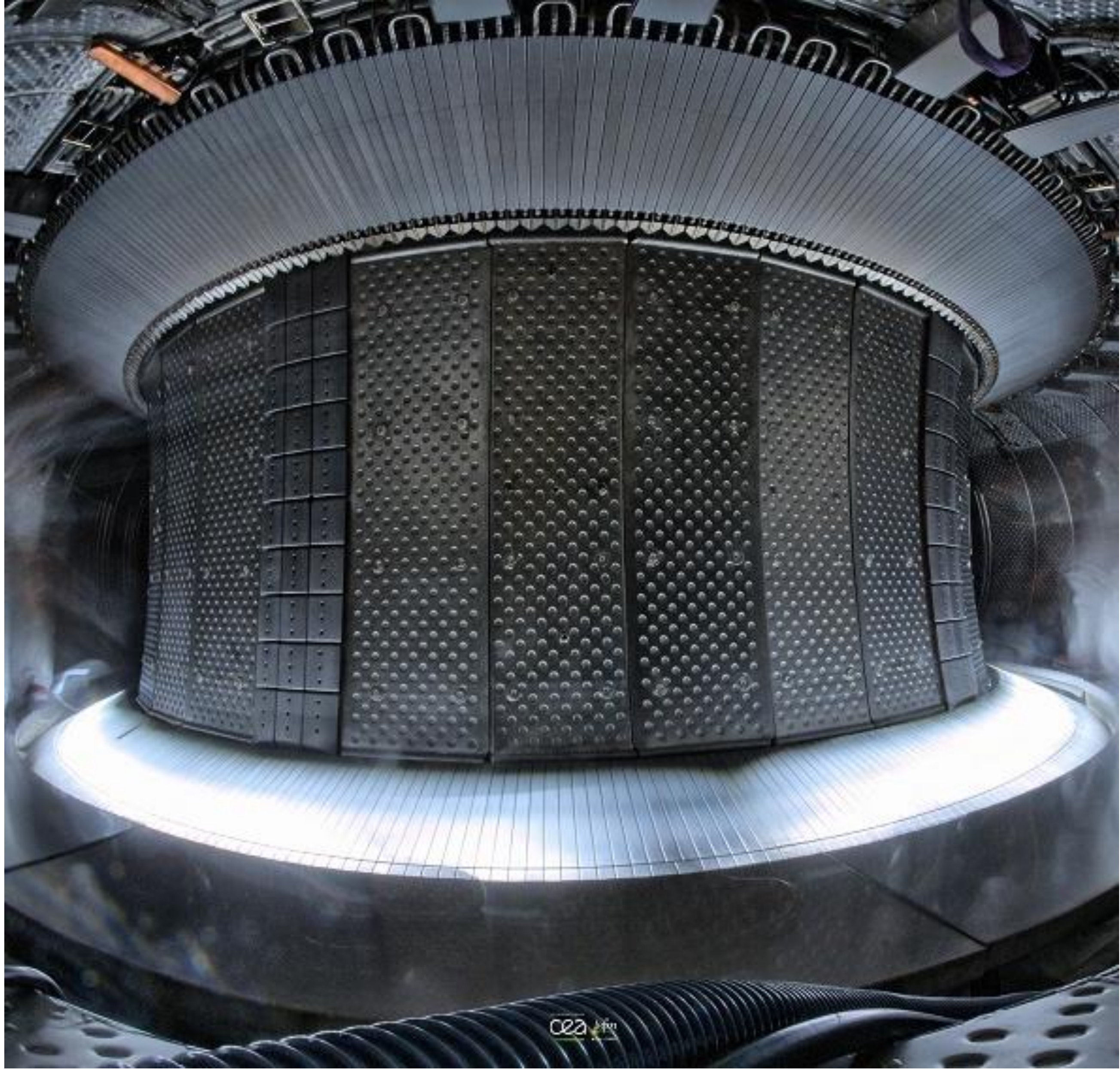
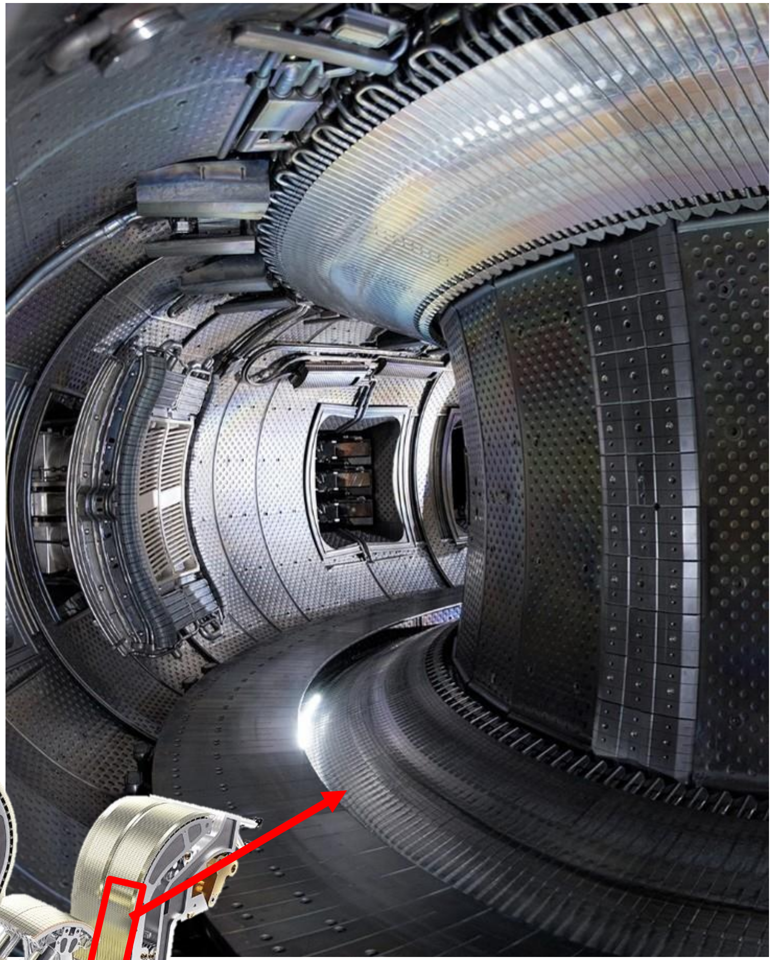
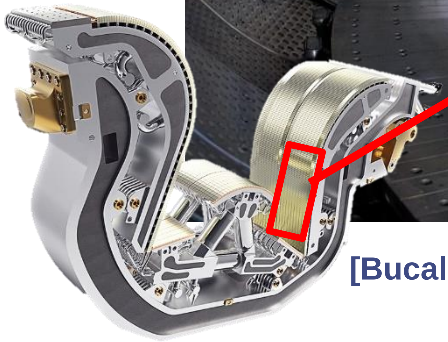


Outline

- Motivation and context: WEST tokamak and W-core contamination
- SOLEDGE3X-ERO2.0 modeling efforts for interpreting experimental results
- Erosion in the high fluence campaign in attached plasma conditions
- Edge modelling account for WEST ripples and first estimates of W-sputtering
- Summary & Outlook

WEST: superconducting and actively cooled tokamak for long pulse studies

- Tungsten (W) Environment Steady-state Tokamak:
  - Superconducting toroidal field coils
  - Full tungsten environment
  - ITER-grade lower divertor (since 2022)
- Main objective is investigate long-pulse operation in full W-environments in preparation for the future reactor (ITER, DEMO, SPARC)
- W-core contamination is a major concern and understanding of migration process is fundamental to provide solutions

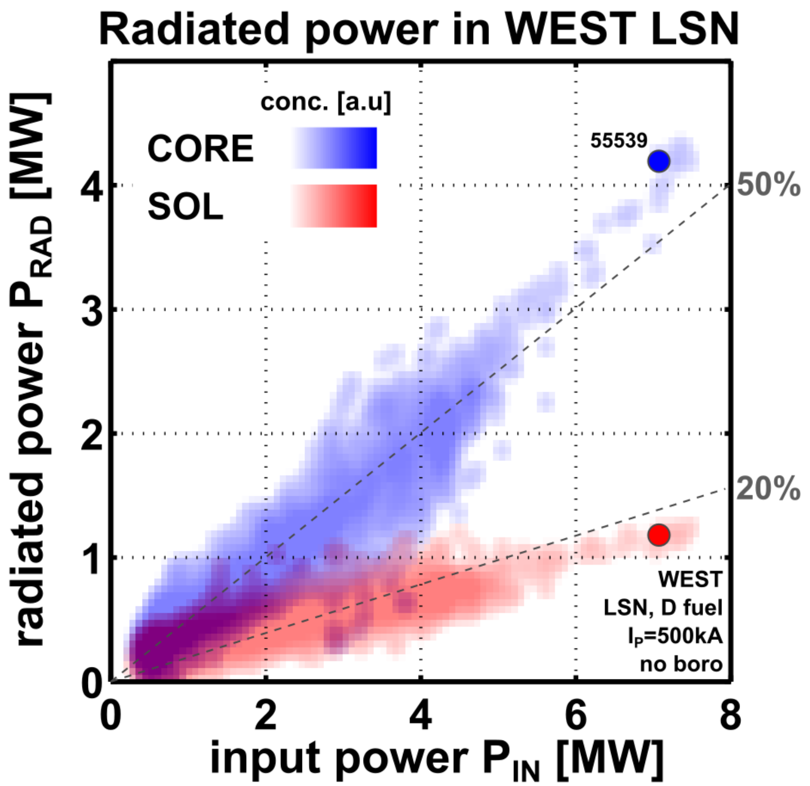
[Bucalossi NF 2024]

WEST operation and core radiation from tungsten contamination

- Standard scenario: LSN, $B_T = 3.7\ T, q_{95} \sim 4.5$
  - Line averaged density from 2 to $6e^{19}m^{-3}$,
  - Input power up to 8.5 MW (**Ω** + LHCD + ICRH)

- “Stiff” radiated fraction :
  - Edge/Core radiation ~20%/50% of P_{in}
  - Weak dependency with plasma density and input power

- Complex phenomena: Limited experimental access /intrinsic 3D → Modelling is indispensable for investigation



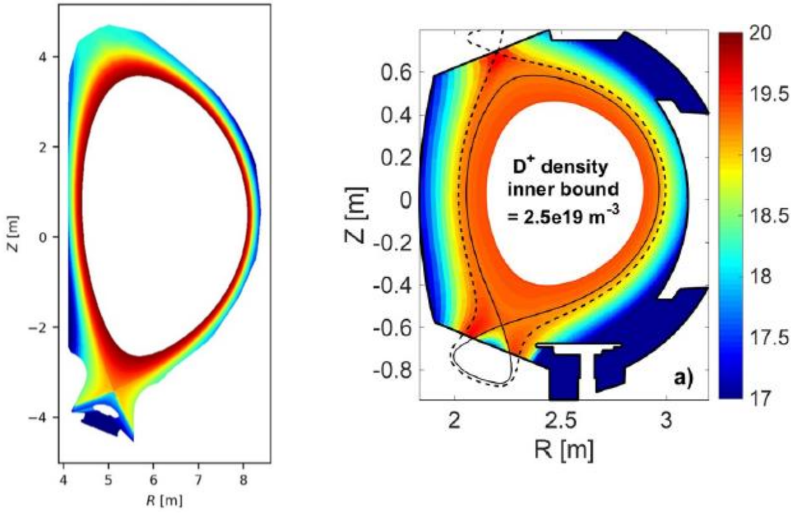
Plasma modeling using SOLEDGE3X code suite

SOLEDGE3X: Fluid, flux aligned, fine volume drift-reduced Braginskii code

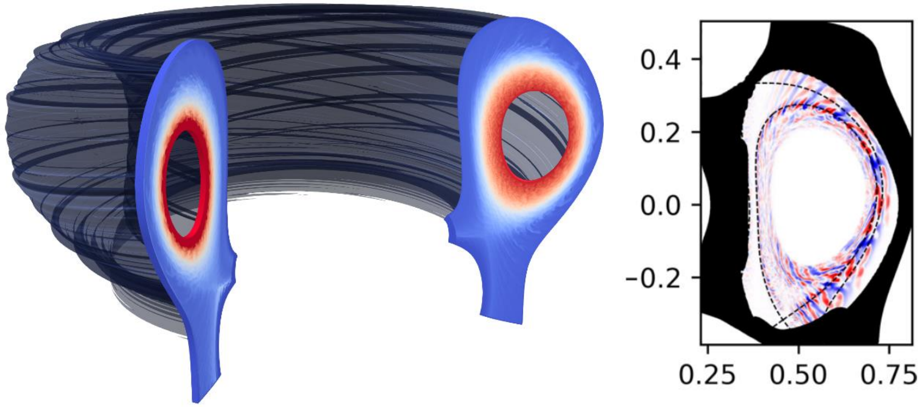
- Suitable for modelling the collisional edge/SOL plasmas
- Arbitrary species number → Zhdanov closure for multi-component plasmas
- Neutral fluid (embedded) or kinetic (EIRENE)
- Immersed boundary conditions allowing for any wall shaping
- Able to run in mean-field or self-consistent turbulence modes
- Electromagnetic model

[Bufferand et al, NF 2021]

2D transport simulations



3D turbulence simulations



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[Bufferand et al, NF 2021]

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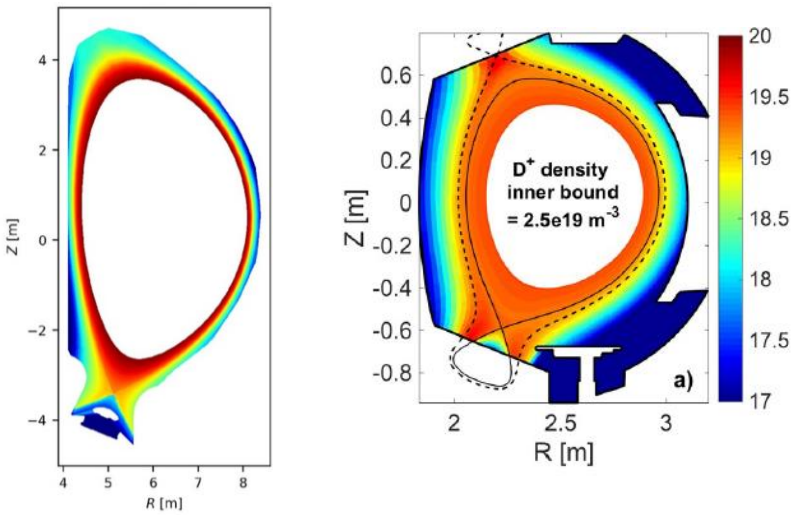
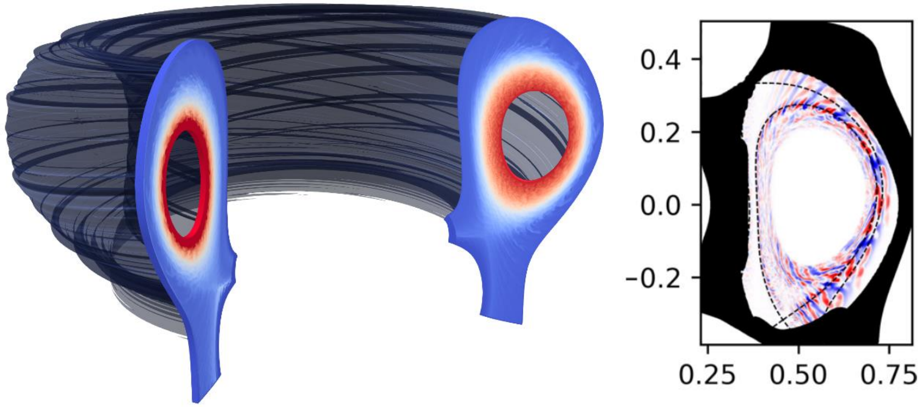


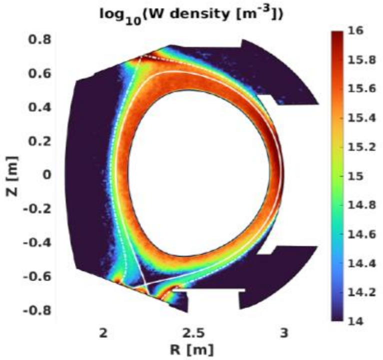
3D turbulence simulations



ERO2.0: kinetic 3D Monte Carlo impurity tracker

Main input parameters:
- Plasma background, **light impurity concentration**
- Radial diffusion coefficient $D^{\perp}$

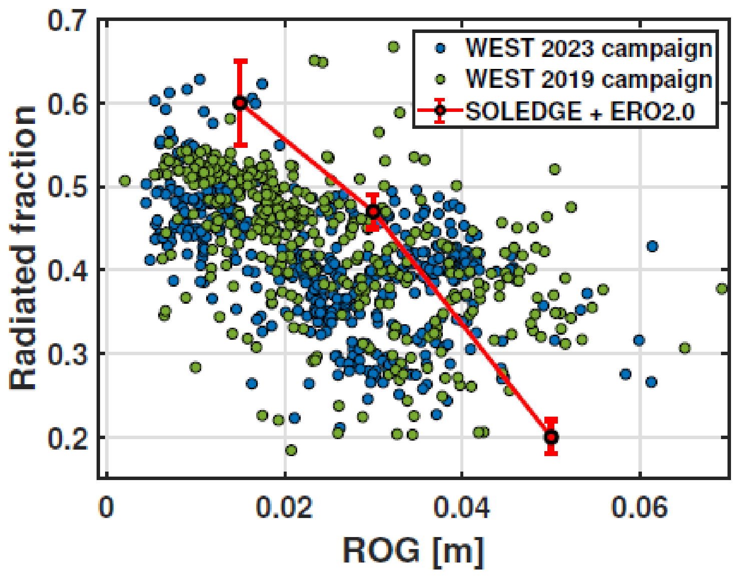
[Romazanov et al., NME 2019; NF 2022]

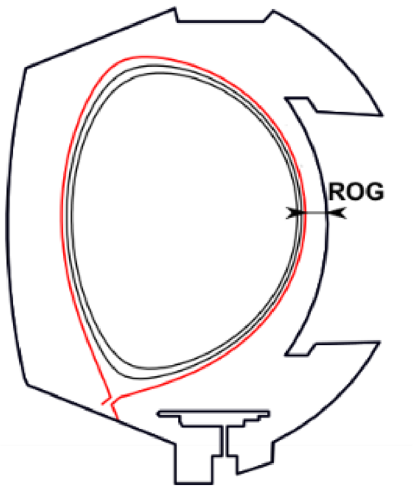


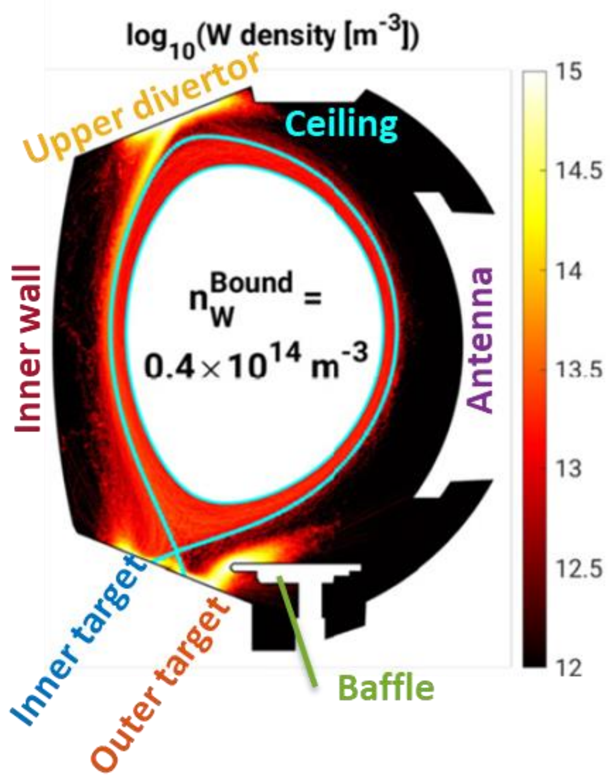
Past studies of W-migration on WEST

- 2D axisymmetric magnetic geometry was considered
  - Low divertor dominates the source, but low core penetration
  - Upper divertor and baffle dominates the contamination
    - Upper divertor high-sputtering not observed in the experiment

- Core contamination highly sensitive to plasma regimes and PFC interface





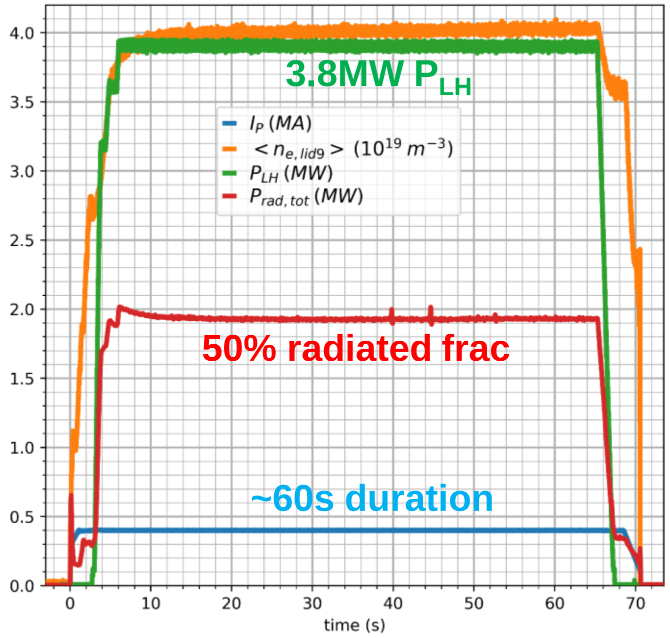


[Ciraolo et al., Nuc. Fus. 2021]
[Di Genova et al., NME 2023]
[Di Genova et al., Nuc. Fus. 2024]

High Fluence C7-campaign attached plasma scenario

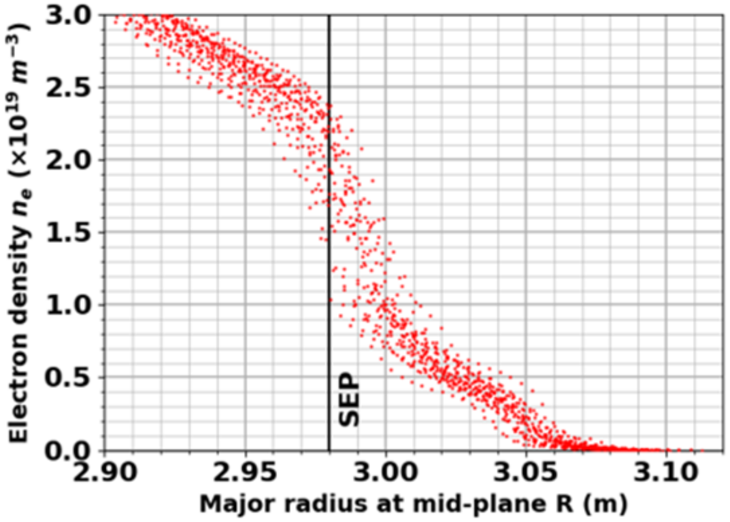
- High fluence experiment (2023)
  - Repetition of the same attached plasma scenario for hundreds of times → 180 min of plasma time
  - Cumulated fluence on the divertor up to $5 \times 10^{26}\ part/m^2$ (~few ITER SRO pulses)

Time traces of shot #58245

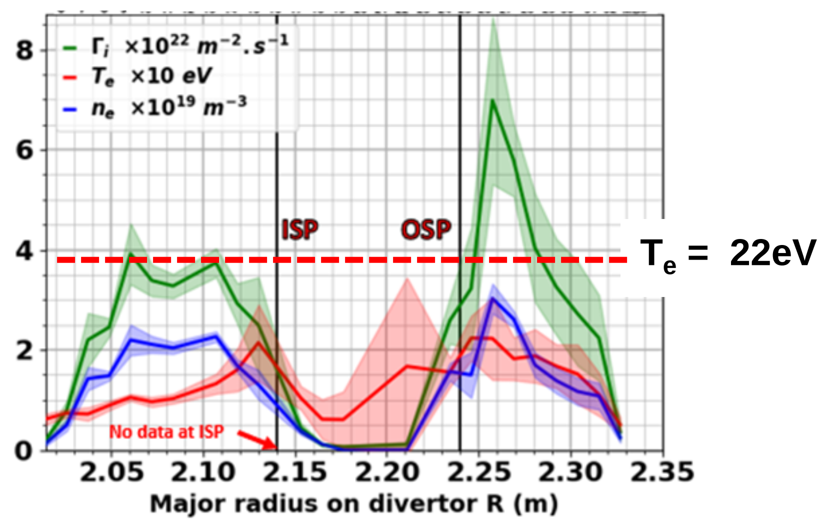


$P_{rad,div}$ ~ 250kW
$P_{rad,bulk}$ ~ 1.650MW

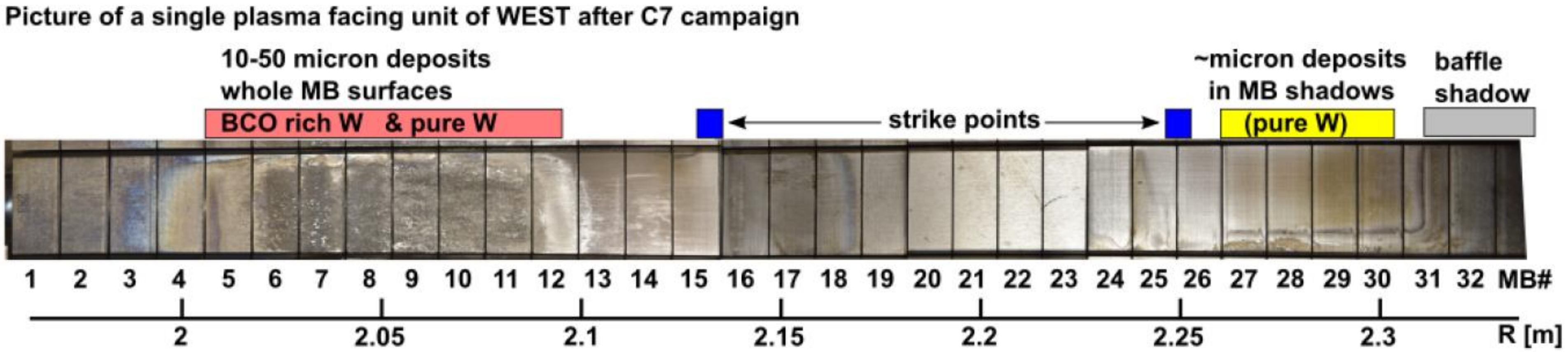
Outer midplane density profile



Divertor target profiles

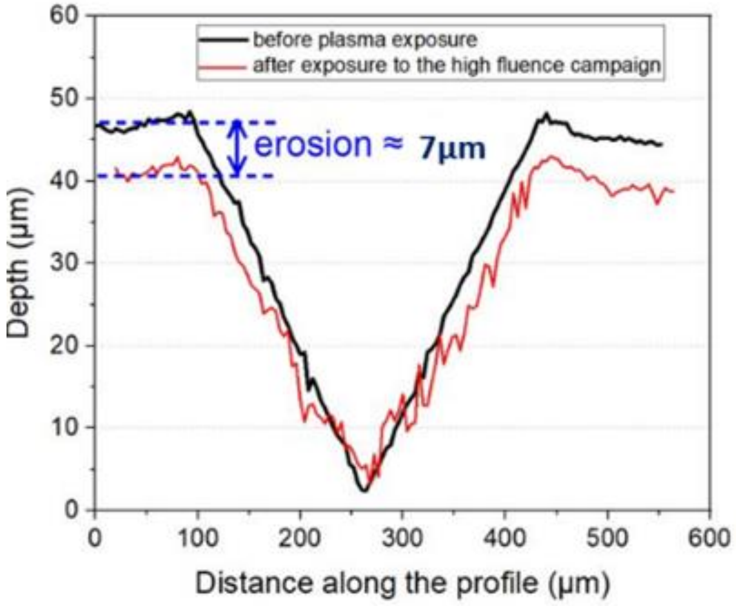


Erosion estimates from post-mortem analysis

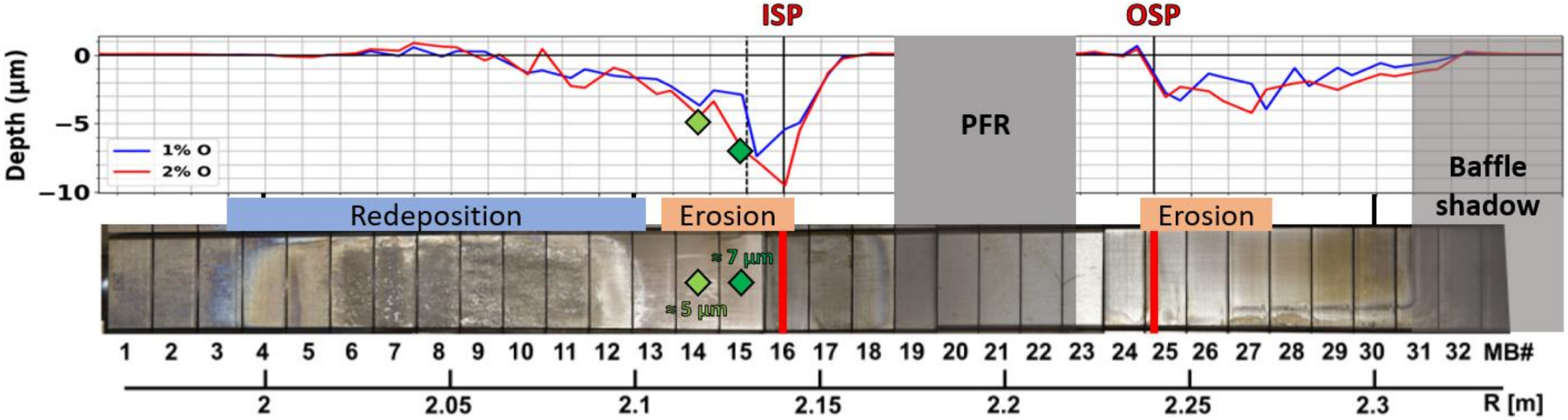


[Fedorczak et al, NME 2024]

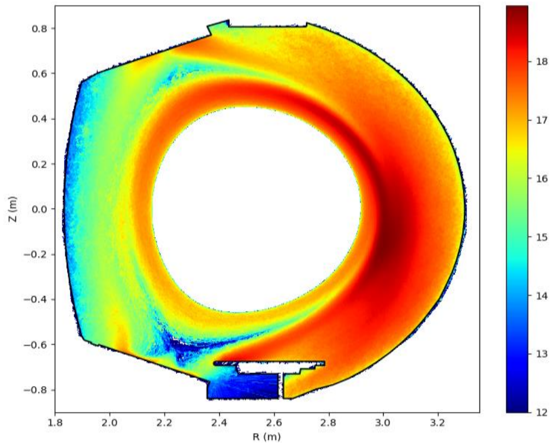
- Post-mortem analysis of the monoblocs 14-15 close to ISP after the C7 campaign
- Erosion and re-deposition estimated close to the SP from microscopic analysis (5-7µm)



Erosion estimated by SOLEDGE3X-ERO2.0 matching the post-mortem measurements



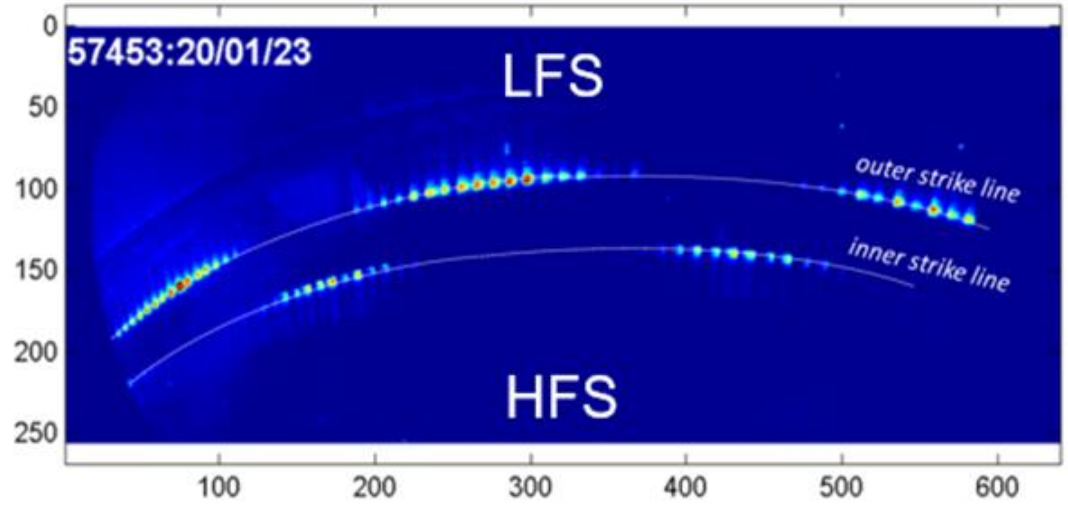
- Simulations setup
  - 2D mean-field axisymmetric standard SOLEDGE3X WEST case
  - Gas fuelling and P_{in} to match experimental conditions
  - Oxygen include as proxy impurities (1%, 2%, and 5%)
  - No drifts
- 2% Oxygen looks the best compromise as a proxy for light impurity concentration
- Redeposition layer in far inner region not reproduced in the simulations



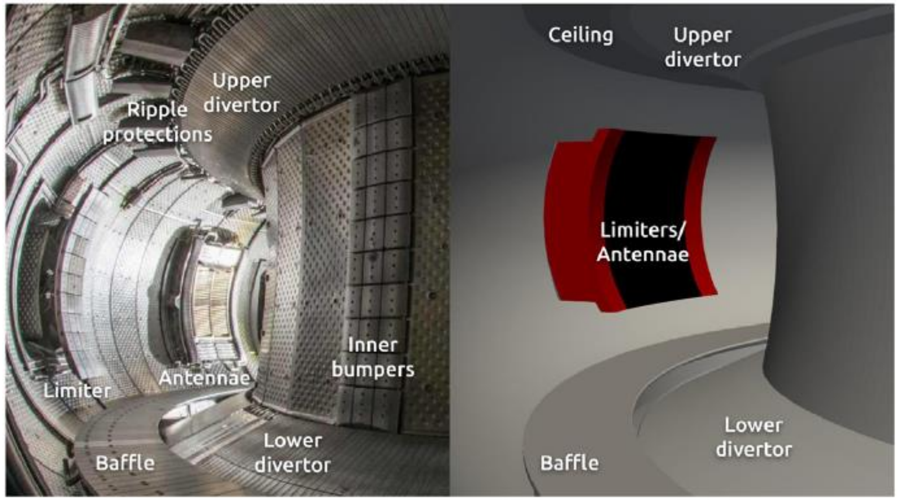
2D W density map from ERO2.0

Non-axisymmetric plasmas in WEST

IR top view of lower divertor



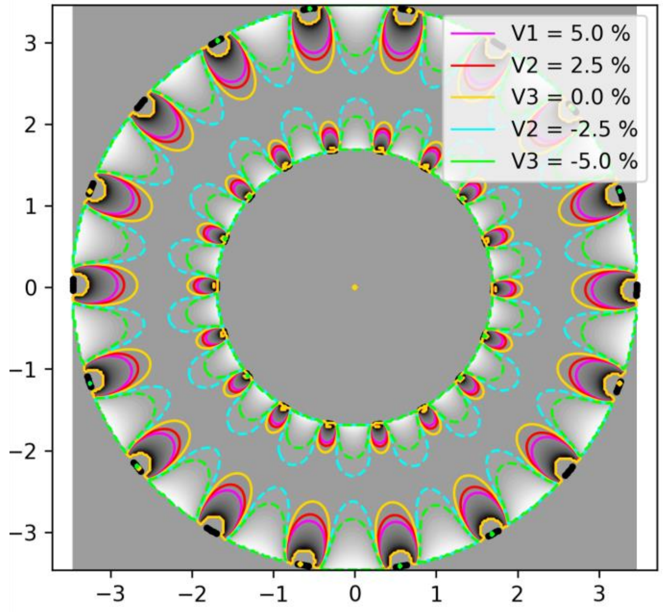
WEST vs SOLEDGE3X wall

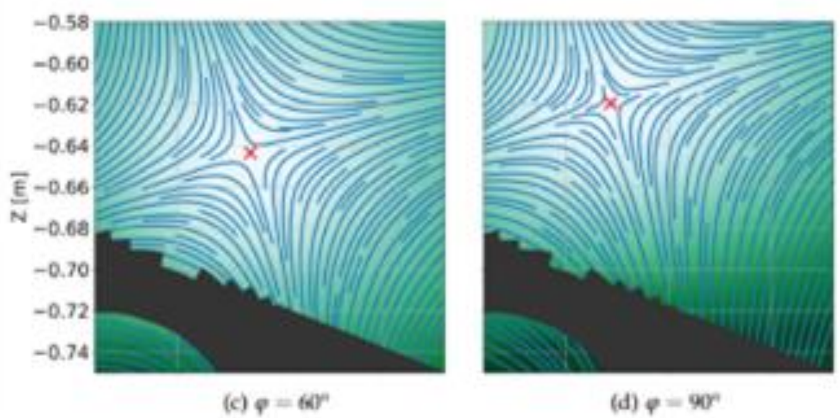


- Coil discreteness perturbation B-field leading to the modulation of plasma outflux
- Localized PFC (antennas) another important element in the modelling

Modelling ripples with SOLEDGE3X

- Exploit the new EM model by including ripples as a perturbation on top of the axisymmetric grid
- Perturbation estimated via Biot-Savat law
- Grid not regenerated, but the numerical values of the magnetic field on the mesh point updated by adding the perturbation (B_{pert}) value
  - Advection terms: $\nabla \cdot \left(X\, v_{\parallel}(\boldsymbol{b_{eq}} + \boldsymbol{b_{rip}})\right)$
  - Parallel terms: $(\boldsymbol{b_{eq}} + \boldsymbol{b_{rip}}) \cdot \nabla_{\parallel}$

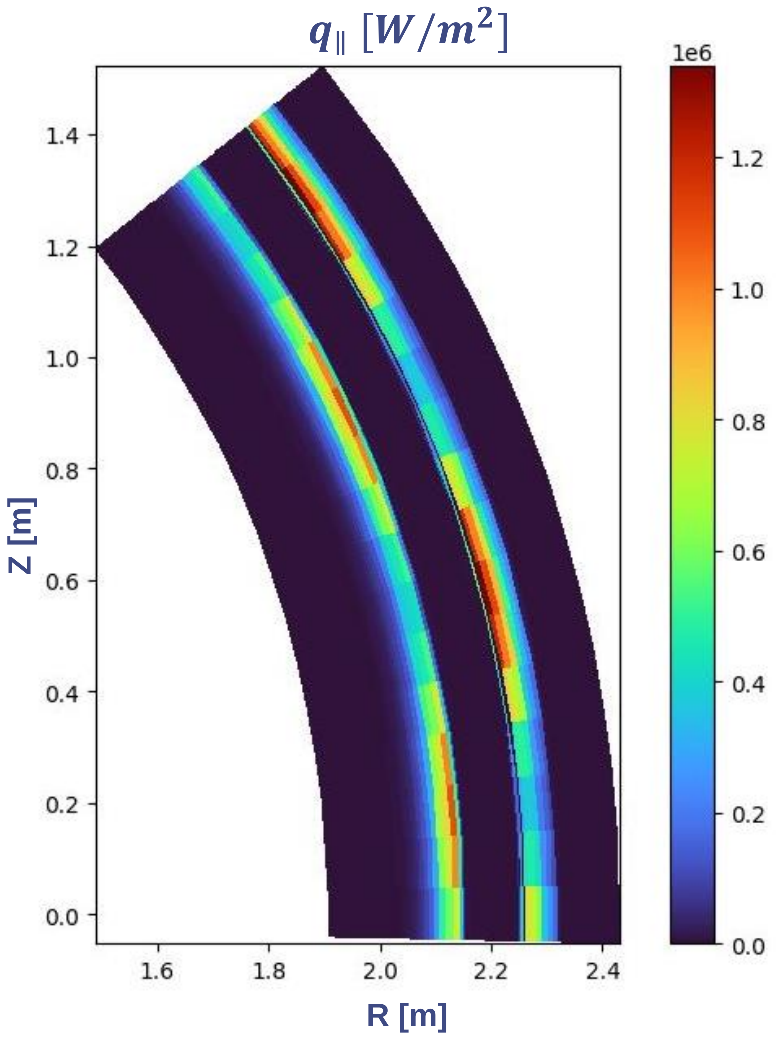




[Dull et al, NF 2024]

Ripple effect recovered in SOLEDGE3X simulations

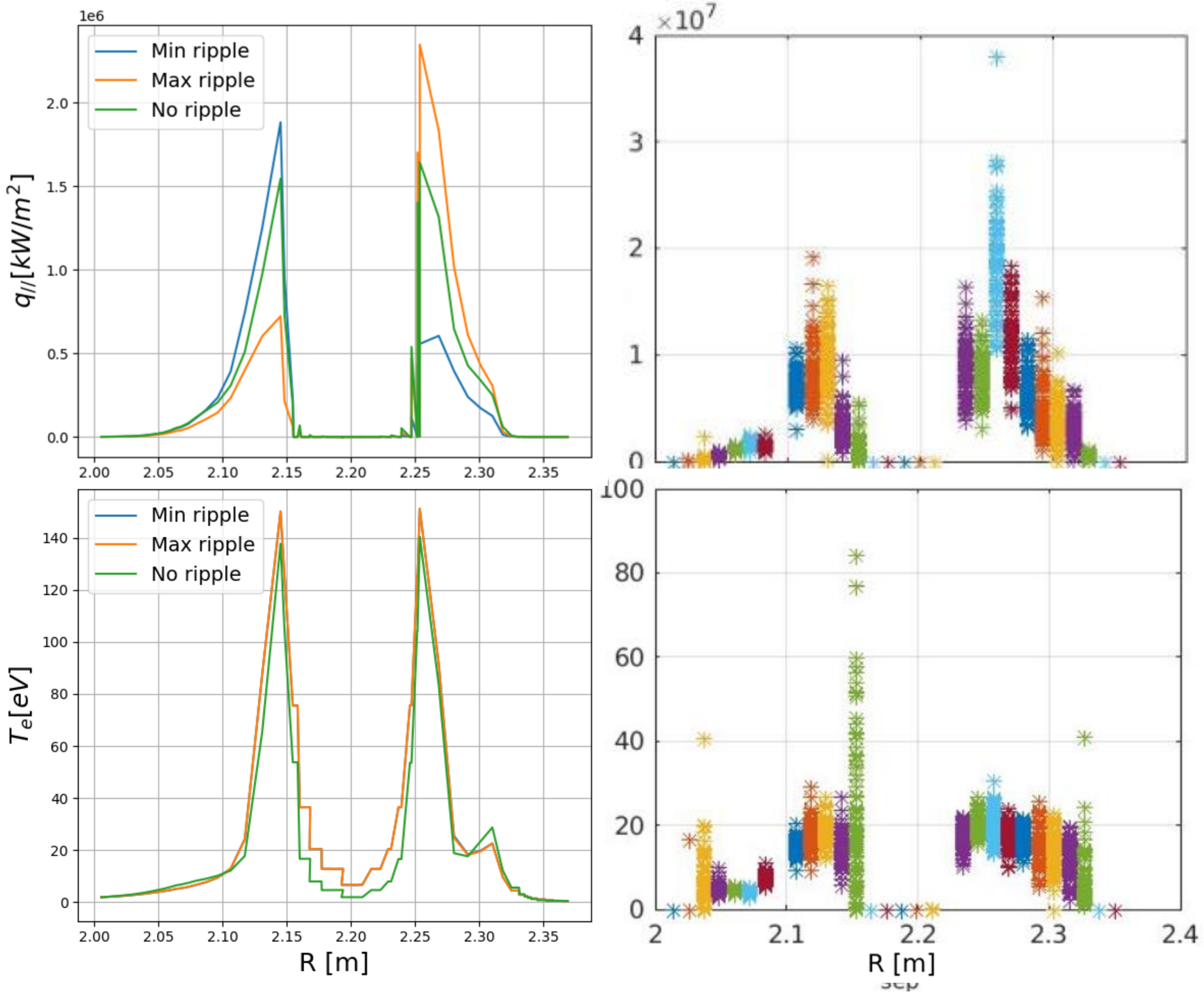
- Simulations: $P_{SOL} = 2MW$, pure D, and fluid neutral model
- Mesh generated from the experimental magnetic equilibrium reconstruction
  - Power and density scans performed and will be broaden
  - No drifts and axisymmetric walls
- Goal is to access the ripple effect on the divertor targets
- Caveat: $\boldsymbol{b}_{\boldsymbol{\psi},\boldsymbol{rip}} = 0$ due to numerical instabilities in the heat flux → possible impact on main chamber, but smaller at the targets



Results in qualitative agreement LP data

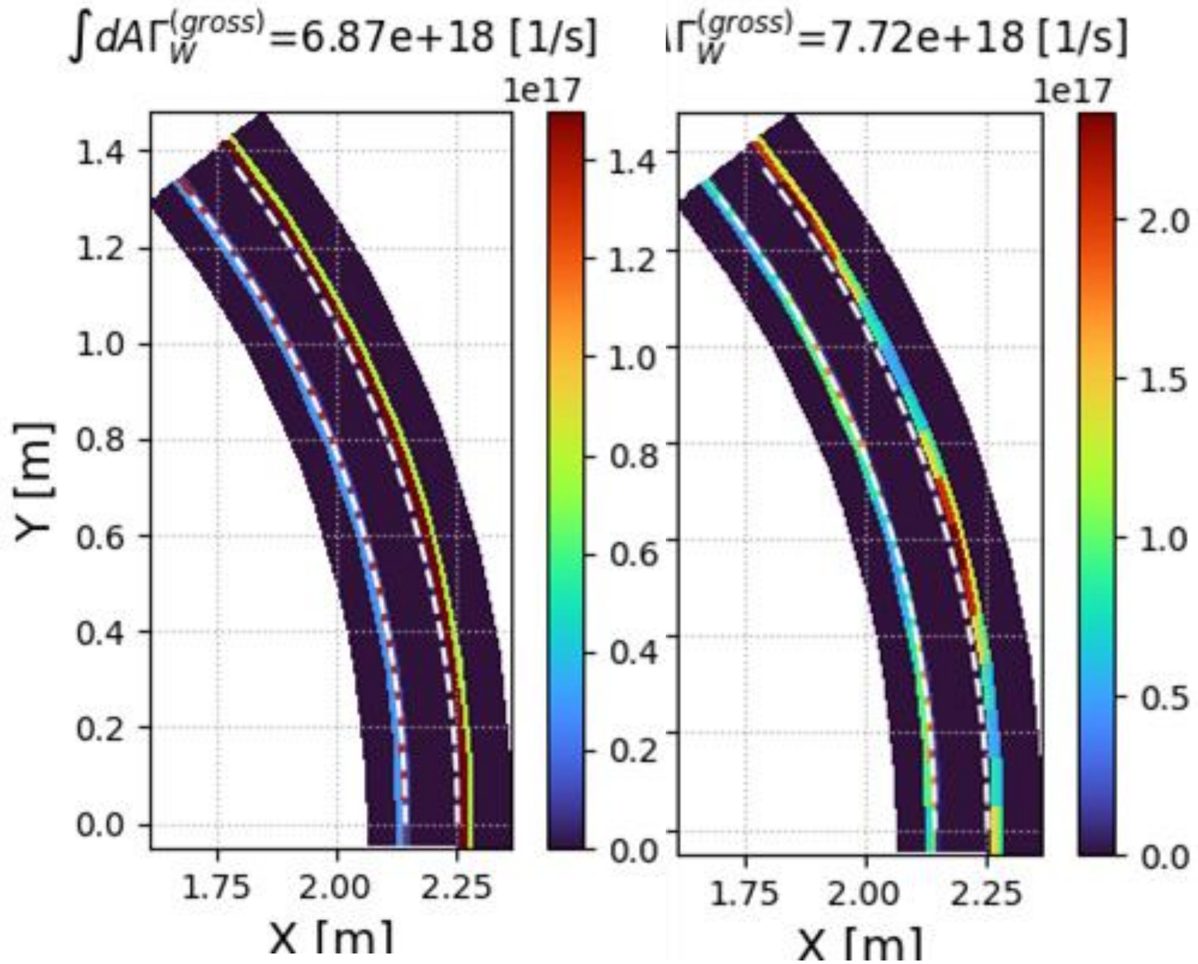
- Fluxes depending on the ripple period, $q_{\parallel,max} > q_{\parallel,min}$, while T_e not

- Extensive experimental dataset being collect (first discharges past Friday)



Analytical sputtering yield estimation

- Sputtering yields estimated by
  - Gross: Bohdansky formulation [Rosales JNM 1994]
  - Net: Tskakhaya formulation [Tskakhaya et al, JNM 2015]
- Assuming inc angle =60° corresponding to the max sputtering yield

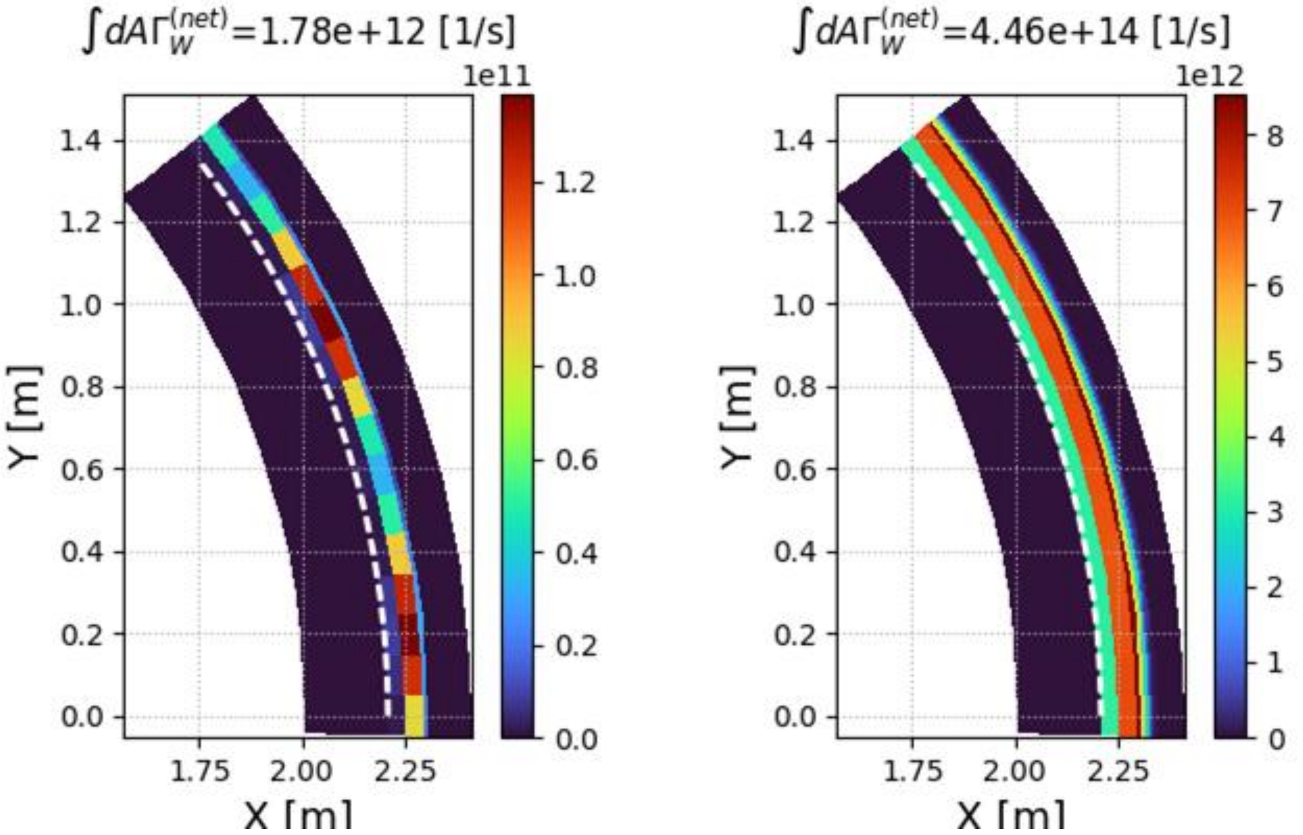


Higher sputtering yield in the ripple case for the lower divertor

	Gross Γ_W [1/s]		Net Γ_W [1/s]	
Ripples	w/o	w/	w/o	w/
OSP	3.91e+18	4.12e+18	1.61e+17	2.30e+17
ISP	2.96e+18	3.60e+18	1.13e+17	2.07e+17
Total	6.87e+18	7.72e+18	2.74e+17	4.37e+17

- Integrated sputtering yield, gross and net, is higher on both SP
- Sputtering yield increasing is larger in ISP than in OSP

Strong reduction of the W-sputtering in the upper divertor due ripples



	Gross Γ_W [1/s]		Net Γ_W [1/s]	
Ripples	w/o	w/	w/o	w/
Total	2.01e+15	1.11e+13	4.46e+14	1.78e+12

Summary & Outlook

- SOLEDGE3X was used to model de edge/SOL plasmas; W-dynamics in the lower divertor is investigated using ERO2.0 and analytical formulas
  - Erosion in the ISP region estimated by SOLEDGE3X+ERO2.0 is in excellent agreement with the experimental post-mortem measurements
    - The re-deposition in the ISP far-SOL is not capture by the modelling
    - Candidates for the differences: Magnetic geometry, PFC modelling, drifts
- Simulations with ripples reproduce qualitative features of experiments.
  - Analytical estimations show larger sputtering yields in the lower divertor and a strong reduction in the upper divertor → hints to W-source overestimation in previous modelling due to missing elements
  - These findings (and broader simulation scans including impurities) will be tested against detailed experimental data and interpretative ERO2.0 simulations

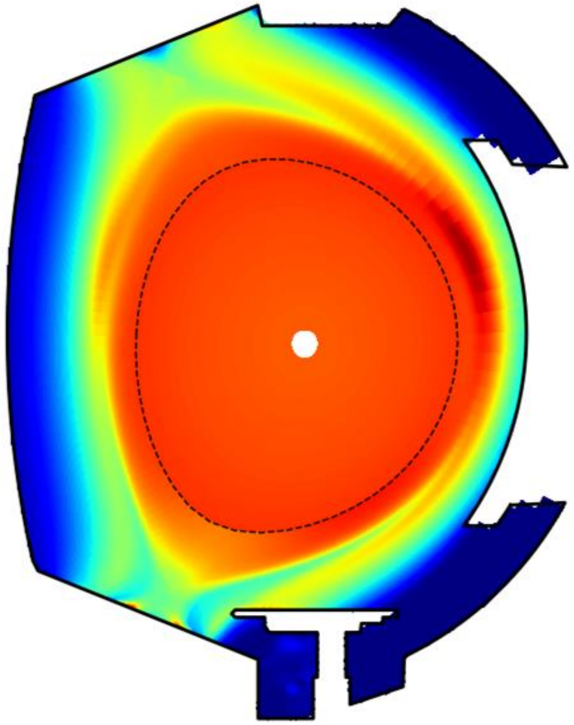
Summary & Outlook: Simplified integrated modelling

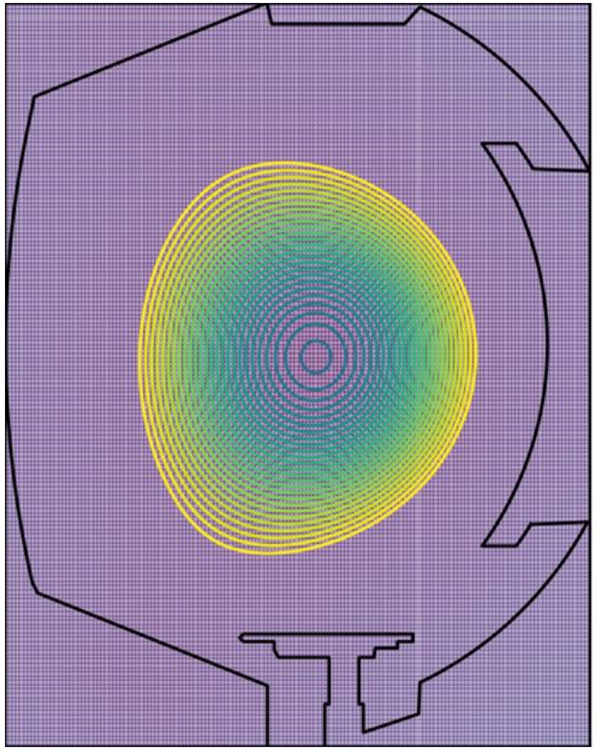
$$\partial_t n_s + \nabla.\Gamma_{n_s} = S_{n_s}^{iz/rec} \quad \Big| \quad \partial_t E_s + \nabla.\Gamma_{E_s} = P_s^{in} + P_s^{rad} + Q_{ss'}^{coll}$$

Diffusion + Pinch velocity

Diffusion coefficients obtained by **QLKNN-10D**, a neural network trained on a database of ~3e8 QuaLiKiz simulations → better performance

[K.L. van de Plassche PoP 2020]





Summary & Outlook: Full 3D non-axisymmetric SOLEDGE3X

- New mesh determined by field line trace → cells are deformed to preserve flux alignment

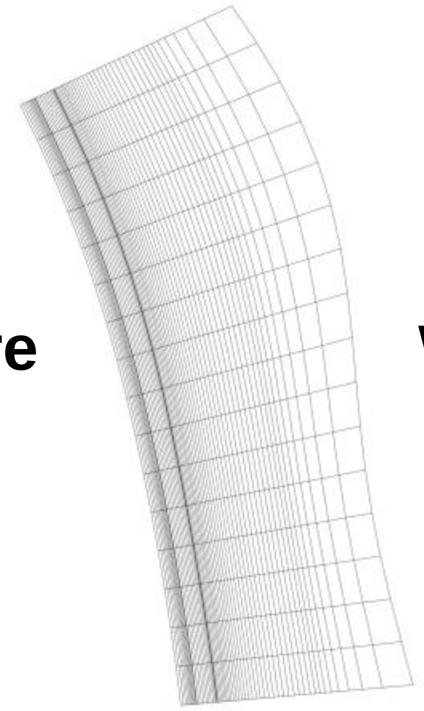
$$\begin{bmatrix} R(\bar{\varphi}) \\ Z(\bar{\varphi}) \end{bmatrix} = \begin{bmatrix} R_0 \\ Z_0 \end{bmatrix} + \int_{\varphi_0}^{\bar{\varphi}} \left(R\frac{[B_R, B_Z]^T}{B_\varphi} \cdot \frac{\nabla\psi}{\|\nabla\psi\|} \right) \frac{\nabla\psi}{\|\nabla\psi\|} d\varphi$$

- Cylindrical approach for the metric/operators is not possible anymore

Metric tensor completely filled:
(Previously $g^{\psi\varphi} = g^{\theta\varphi} = 0$)

$$g = \begin{pmatrix} g^{\psi\psi} & g^{\psi\theta} & g^{\psi\varphi} \\ g^{\psi\theta} & g^{\theta\theta} & g^{\theta\varphi} \\ g^{\psi\varphi} & g^{\theta\varphi} & g^{\varphi\varphi} \end{pmatrix}$$

OMP top view



Merci

Main results from ERO2.0 computations on 2D SOLEDGE plasma background

[*S. Di Genova et al., Nucl. Fusion 2021*]

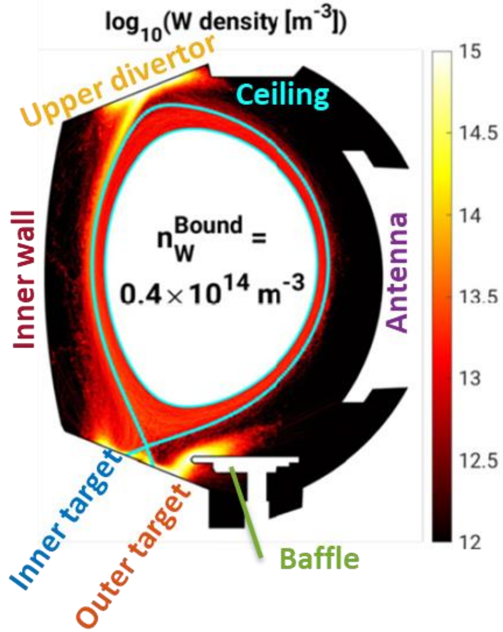
Lower divertor (main) dominates the source, but low penetration to core

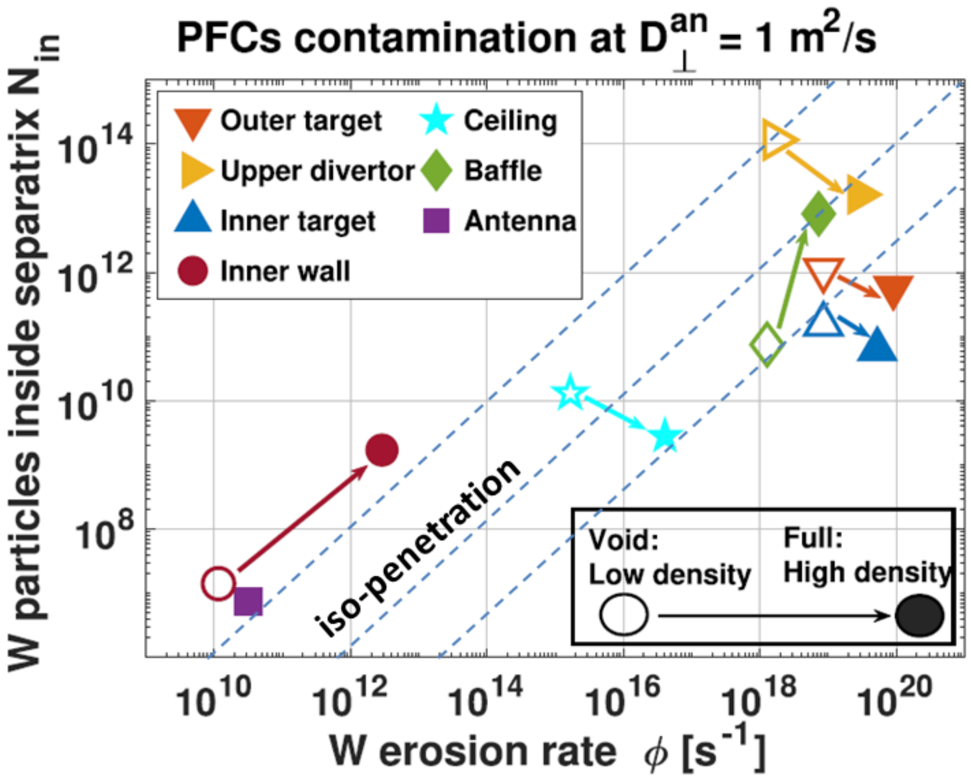
- Importance of accurate frictions & thermal forces in ERO2.0 + accurate flows & // profiles in 2D backgrounds
- Impact of drifts under investigation

Upper divertor & baffle dominate contamination

Contamination highly sensitive to:

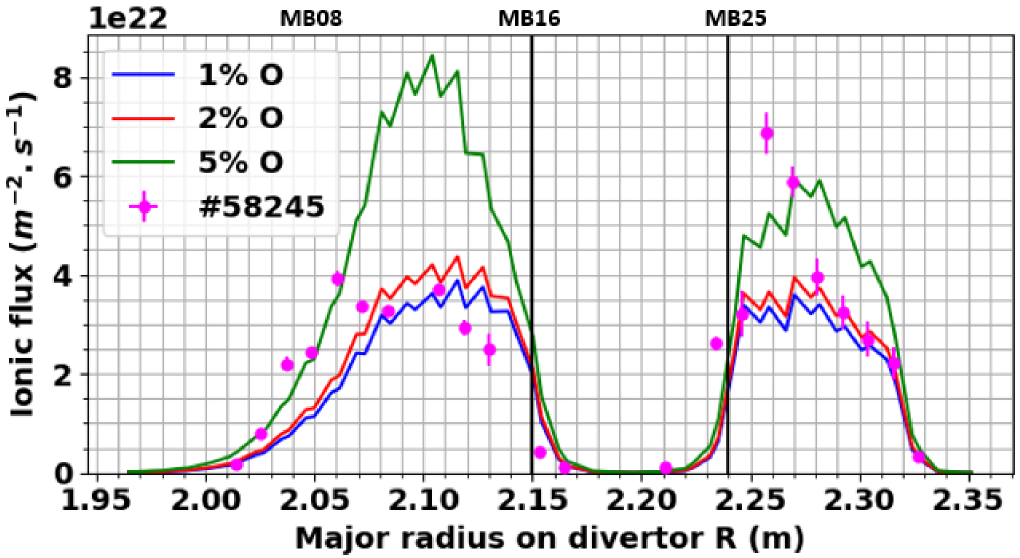
- **SOL regimes, PFC/plasma gaps**
- **Accurate PFC geometry**

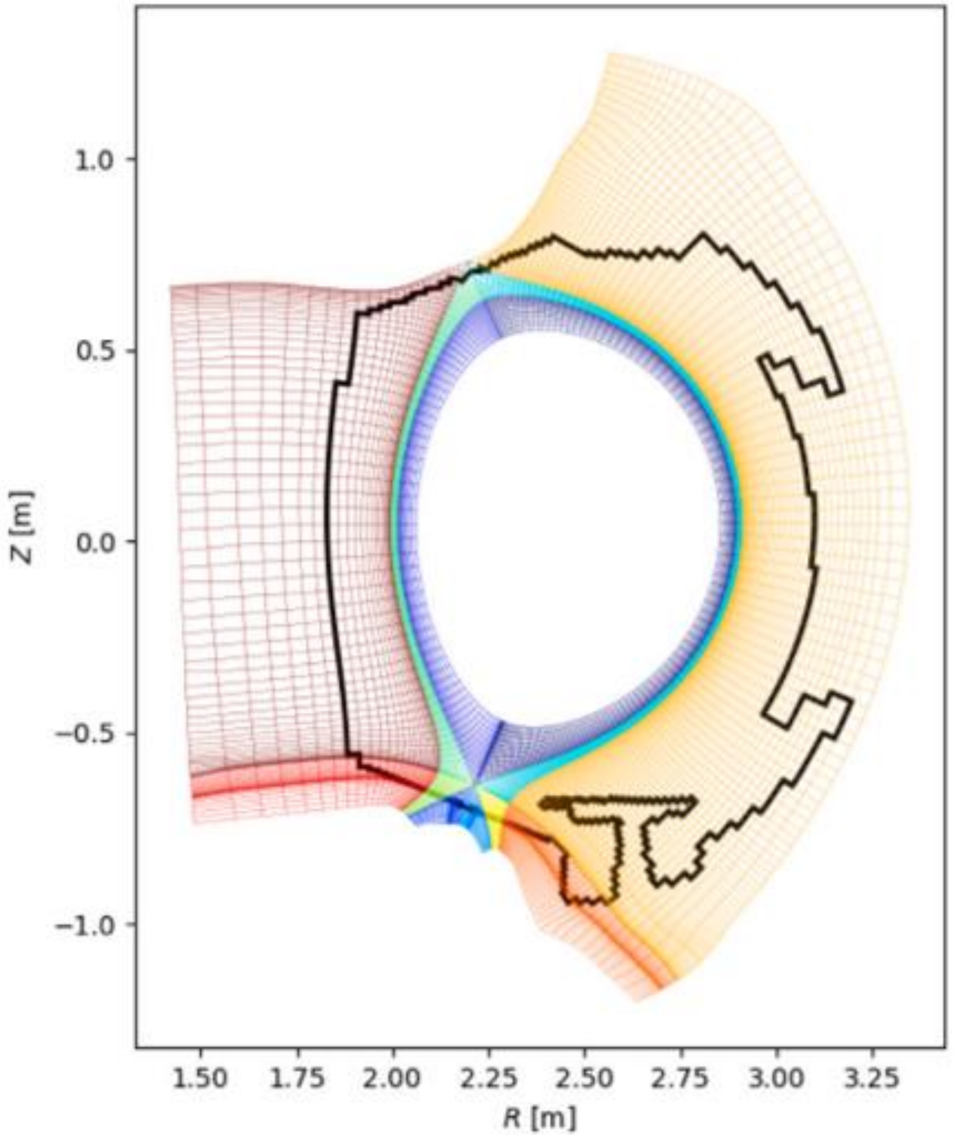




Simulation setup for typical WEST simulations

- $D_{\perp} = 0.3$ and $\chi_{\perp e,i} = 0.8$
- $P_{in} = 1MW$ and $n_{OMP} = 1.4e19m^{-3}$
- Oxygen impurities set from inner boundary to be 1, 2, or 5%
- No drifts
- No $E_{\parallel}$ or thermal currents in ERO2.0





Predicted erosion by SOLEDGE3X+ERO2.0 confirmed by post-mortem analysis

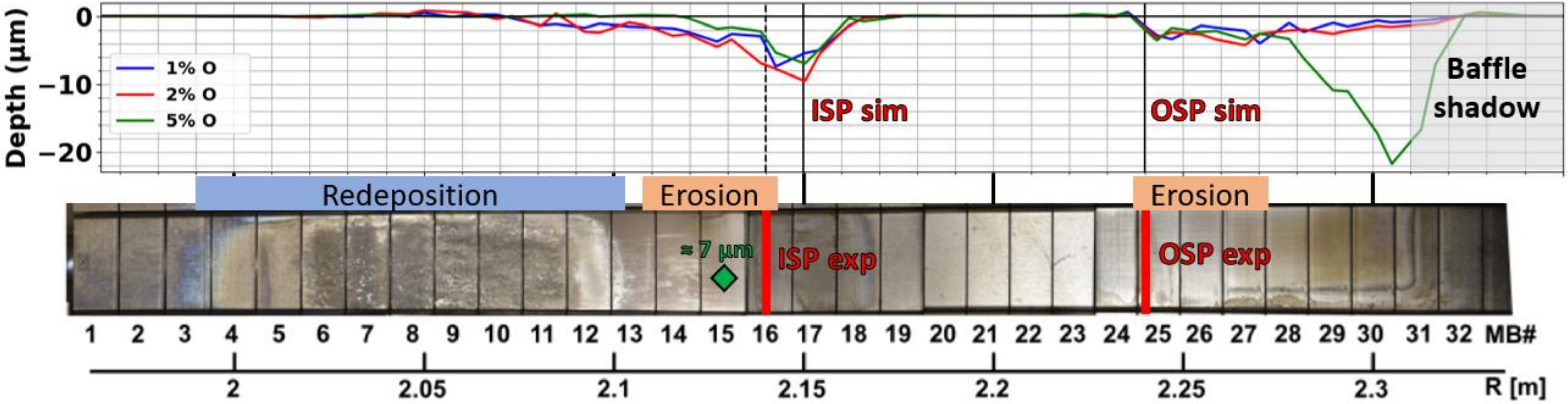
$$erosion = \frac{\Gamma_{W,gross}\,(1 - f_{redep})t_{exposure}}{d_w 10^{-6}}$$

$$d_w = 6 \times 10^{28} m^{-3}$$
$$t_{exposure} = 10790s$$

[Fedorczak NM 2024.]

[Capelli PPFC 2023]]

- Both location and magnitude of the ISP erosion matching the post-mortem analysis
- Large region with re-deposited W in the ISP far-SOL → weakly predicted in the simulations

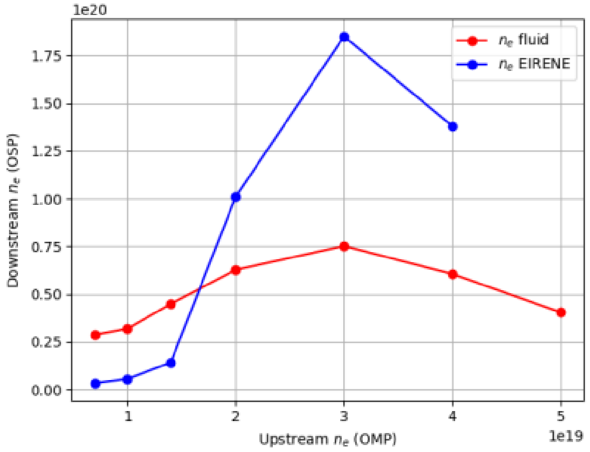


Kinetic vs fluid neutrals

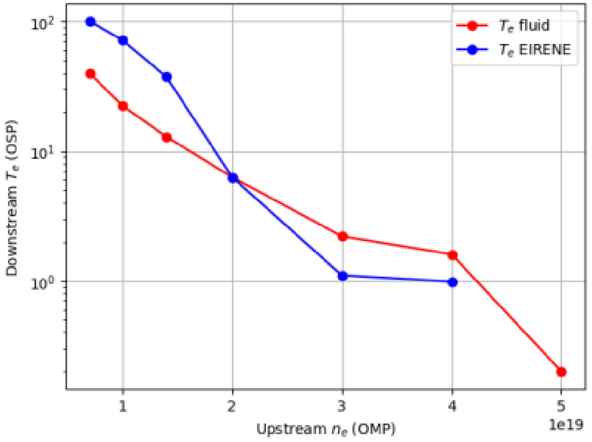
- For $n_{up} \sim 1.5e^{19} m^{-3}$, difference between kinetic and fluid neutrals by the 2PM is small

Set-up: $D_\perp = \chi_e = \chi_{D^+} = 1\ m^2/s$, $P_{\text{core}} = 1.5\ MW$, R_n-ecyclyng coeff. $= 99\%$

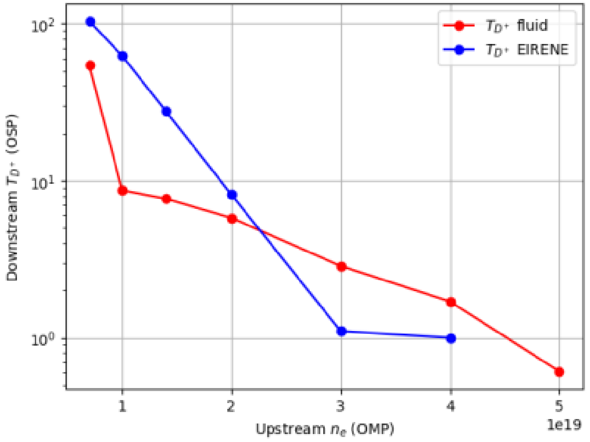
$n_{\text{OMP}} = [0.7,\ 1.0,\ 1.4,\ 2.0,\ 3.0,\ 4.0,\ 5.0] \times 10^{19}\ \text{m}^{-3}$



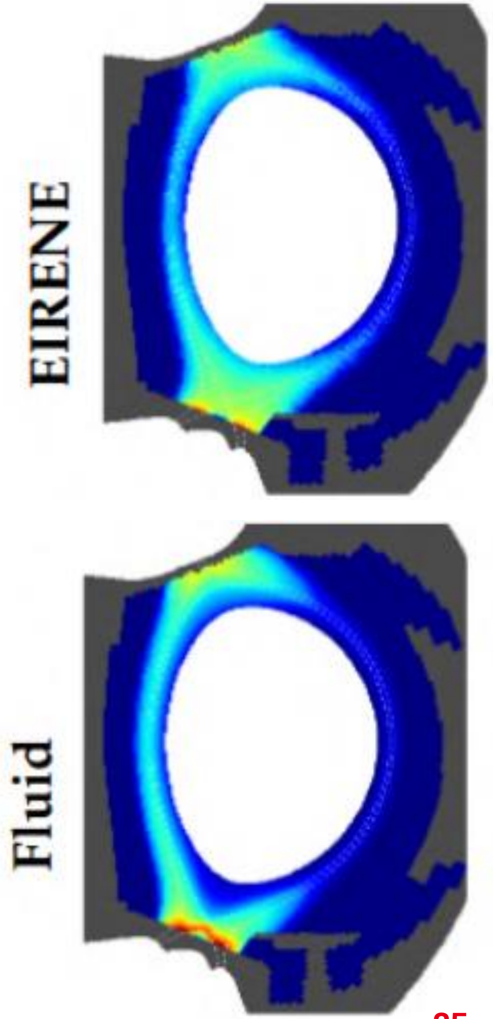
(a) $\mathbf{n_e}$ (lin-scale)



(b) $\mathbf{T_e}$ (log-scale)



(c) $\mathbf{T_{D^+}}$ (log-scale)



Analytical sputtering yield formulation

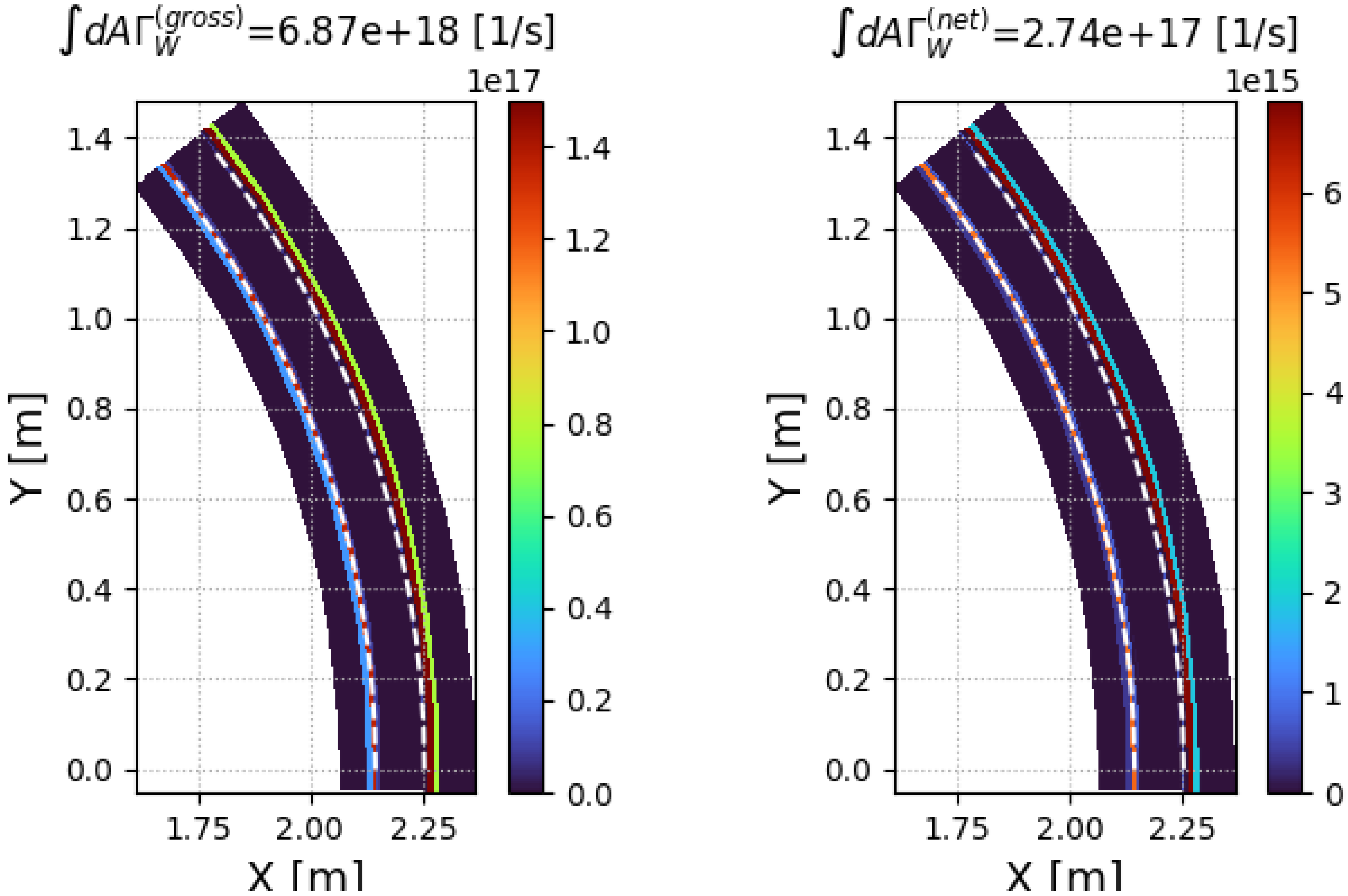
- Bohdansky formulation: $Y(E_0, \alpha) = Y(E_0)Y(\alpha)$, assuming max in angle $(\alpha = 60°)$

$$Y(E_0) = Q\ s_n^{TF}(\epsilon)\left(1 - \left(\frac{E_{th}}{E_0}\right)^{\frac{2}{3}}\right)\left(1 - \frac{E_{th}}{E_0}\right)^2$$

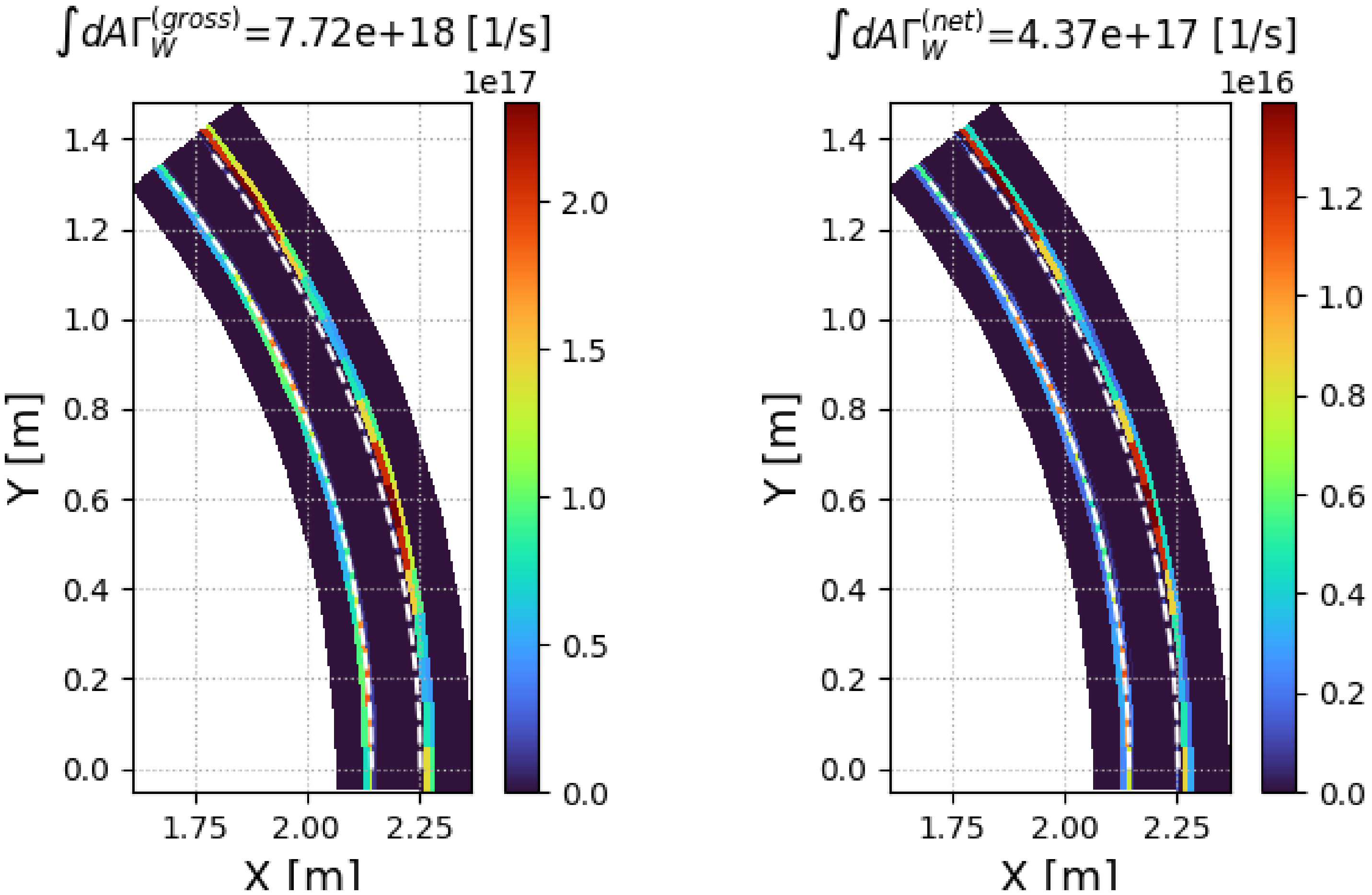
- Net sputtering estimated by [Tskakhaya et al, JNM 2015]

$$f_{nr} = \frac{1}{1 + 0.01T_i/T_e\lambda_{iz}/\rho_{Li}}$$

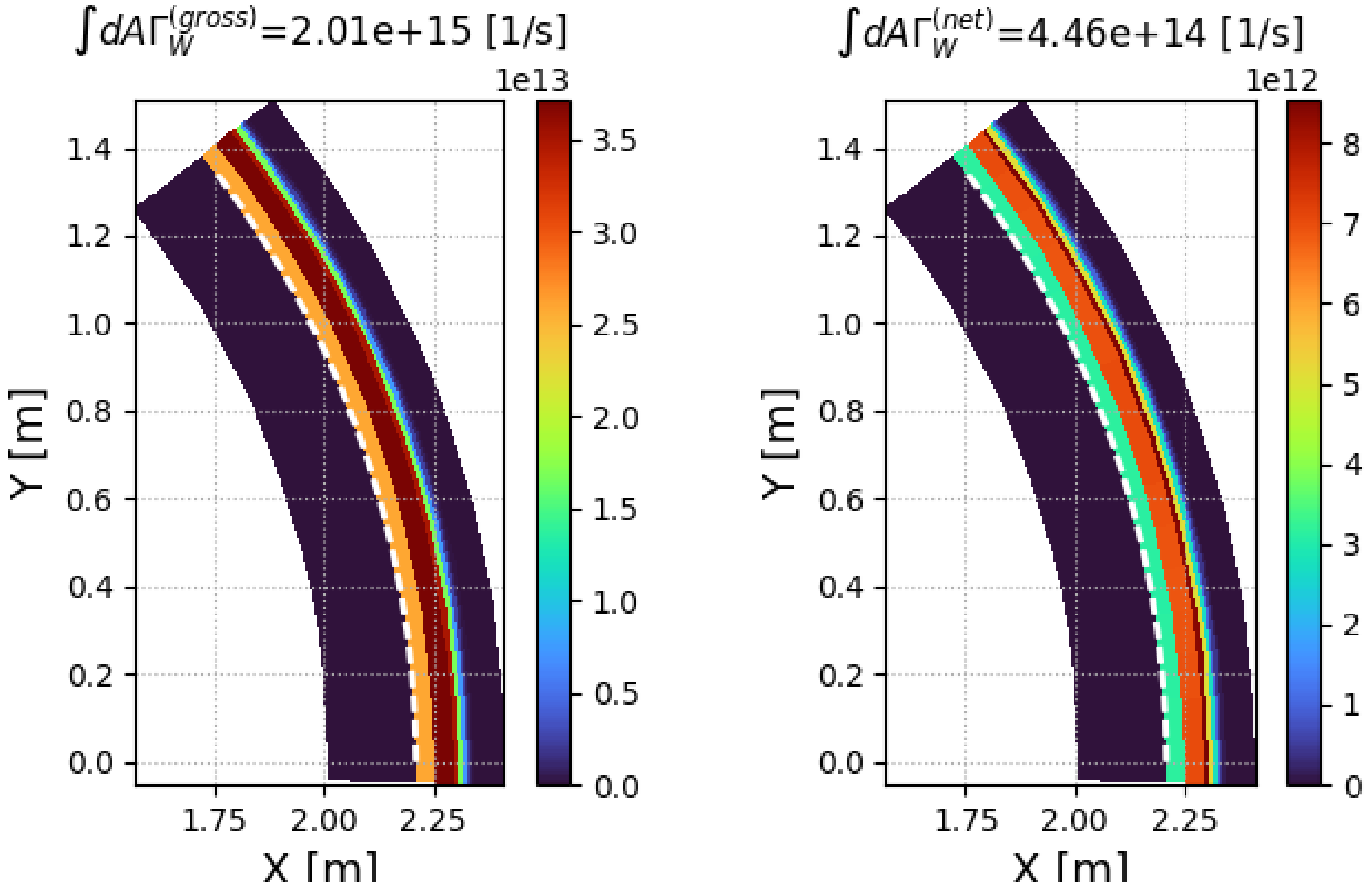
Gross and net sputtering in the lower divertor in the no ripple case - the white line is position of the SPs in the equilibrium geometry



Gross and net sputtering in the lower divertor in the ripple case - the white line is position of the SPs as before



Upper divertor sputtering for the no ripple case - same layout as before - Only one line for the SPs as the Xpt is on the wall



Upper divertor sputtering for the ripple case - same layout as before - Only one line for the SPs as the Xpt is on the wall