WP PWIE Meeting, Prague, March 2025
SP-D report on FZJ activities on ERO/ERO2.0 work

Impurity migration modelling for W7-X, JET and ITER

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JÜLICH Forschungszentrum

Outline

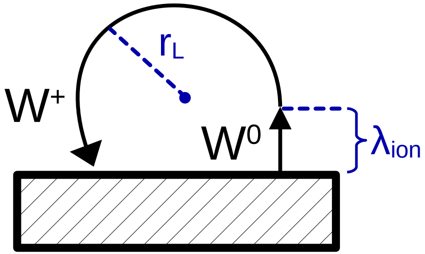
WP PWIE

SP D.3 Impurity Migration Modelling

D003 (FZJ)

ITER full-W | JET | W7-X C, full-W

W prompt redeposition

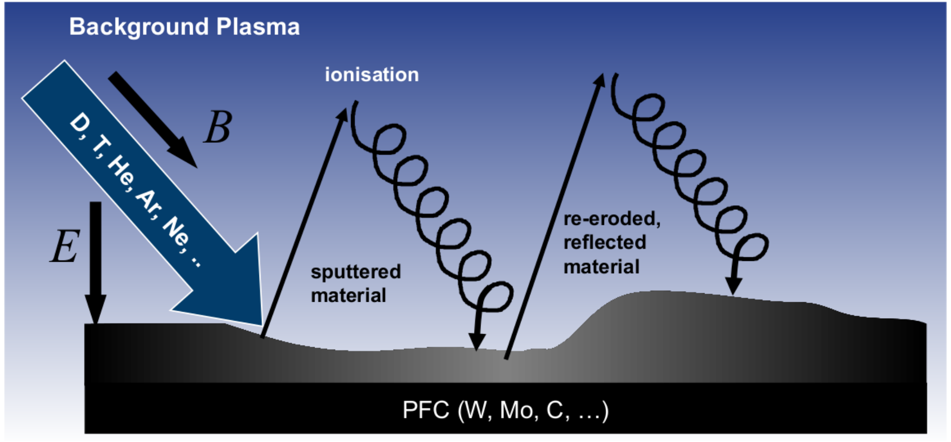


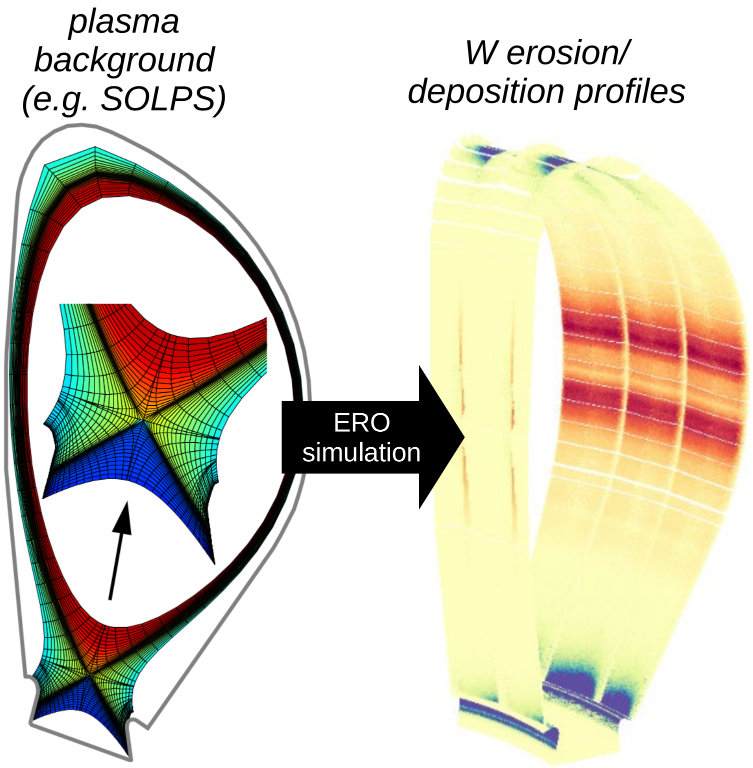
see WP PWIE SP D Activity Descriptions documents for 2024 & 2025 on EUROfusion IDM

D003	**ERO** modelling of **^{13}C injection** experiments (local) in comparison to post-mortem data in **W7-X** and steady-state simulations. **ERO2.0 predictive** modelling for **full W environment in W7-X** (inclusive role of CX neutrals). **ERO and ERO2.0** modelling of **W prompt redeposition** (focus on JET experiment with varying B field), in combination with sheath characteristics from PIC. Initial simulations of **ITER with full-W** plasma-facing components and Ne seeding. Modelling of **tungsten (prompt) redeposition** at inner wall during **ITER ramp-up** phases. (FZJ)

Modelling tool: ERO / ERO2.0

3D Monte-Carlo code for erosion and kinetic impurity transport in trace approximation



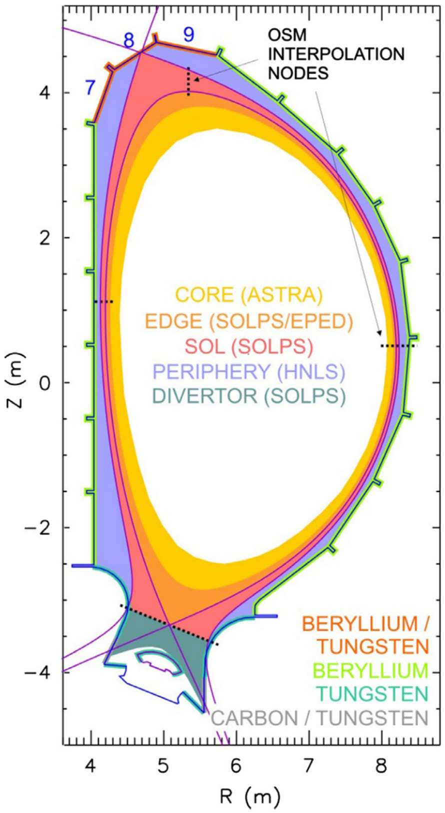


ITER: previous work with ERO/ERO2.0

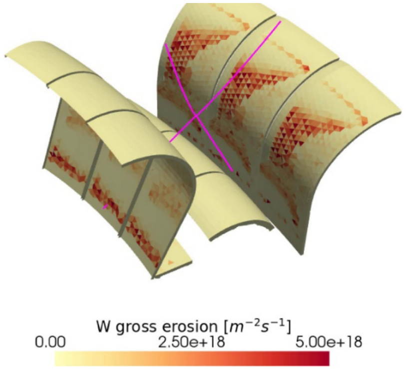
[1] Lisgo, JNM 2013
[2] Borodin, Phys. Scr. 2011
[3] Borodin, NME 2019
[4] Romazanov, CPP 2019
[5] Romazanov, NME 2021
[6] Romazanov, NF 2022
[7] Romazanov, NF 2024
[8] Rode, NME 2024
[9] Rode, NF 2024
[10] Eksaeva, Phys. Scr. 2022
[11] Zhang, submitted NF 2025
[12] Baumann, DPG 2025
[13] Rode, PhD thesis 2024

- OEDGE wide-grid plasma backgrounds [1]
  - <u>Be/W wall</u> studies:
    - main chamber Be erosion by D + W divertor erosion by Be [2-7]
    - erosion/deposition of first mirrors [8-9]
  - <u>Full-W wall</u> predictions w/ simple seeding species assumptions [10]
- **this talk:** simulations using new SOLPS-ITER solutions and/or focussing on W+B ITER wall

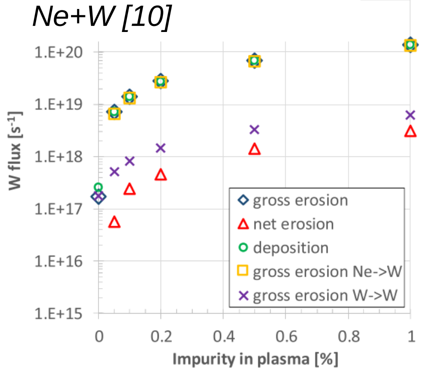
<u>OEDGE setup [1]</u>



<u>ITER Be/W wall:</u>
W divertor erosion by Be+W [6]

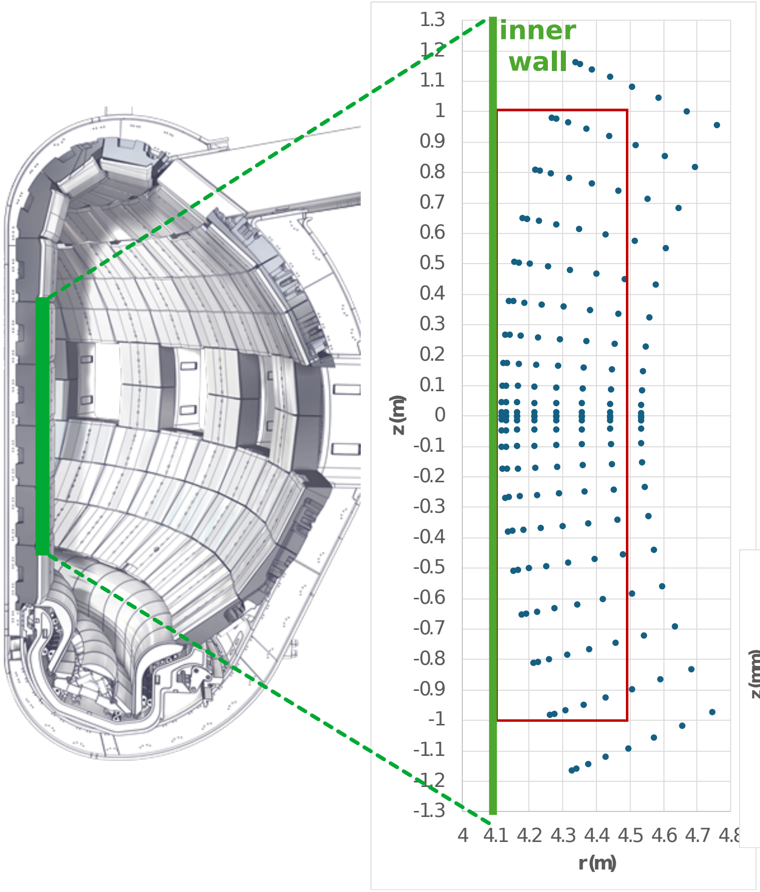


<u>ITER full-W wall:</u>
W divertor erosion by Ne+W [10]



ITER ramp-up: ERO1.0 studies with SOLPS-ITER plasma BG

A. Kirschner -> included in Zhang et al. NF 2025



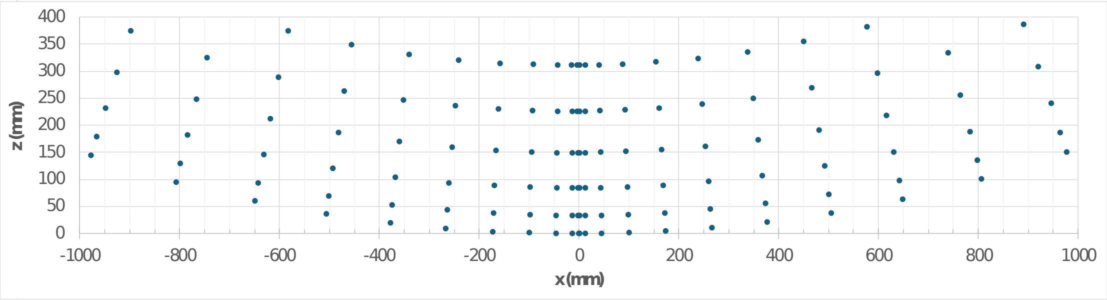
SOLPS-ITER grid

Two SOLPS-ITER simulations provided by IO

i) 002_15e18_3mw (case 1)

ii) 005_3e19_3mw (case 2)

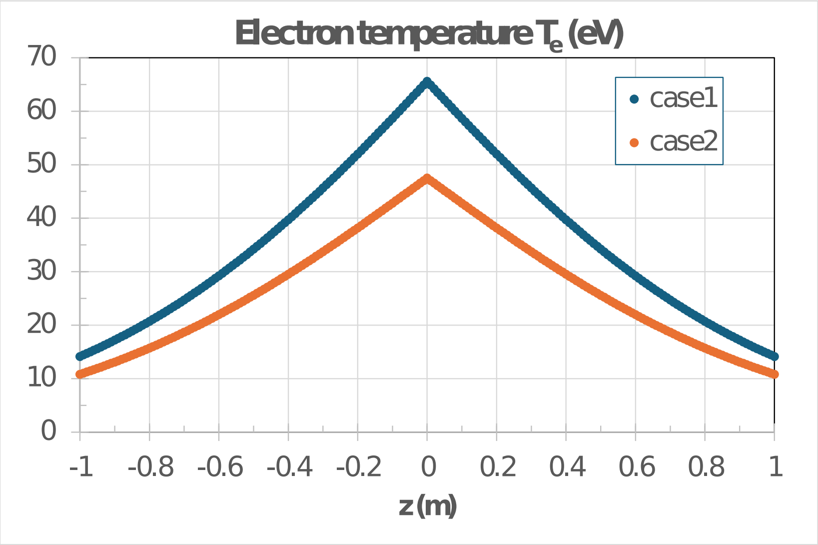
ERO local coordinate system

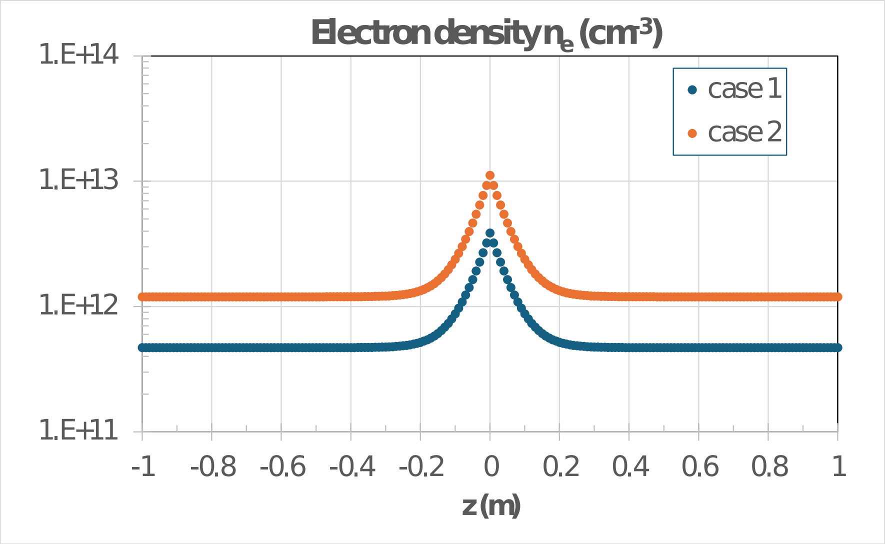


ITER ramp-up: plasma profiles along inner wall

A. Kirschner -> included in
Zhang et al. NF 2025

electron temperature and density
at the wall along z-coordinate



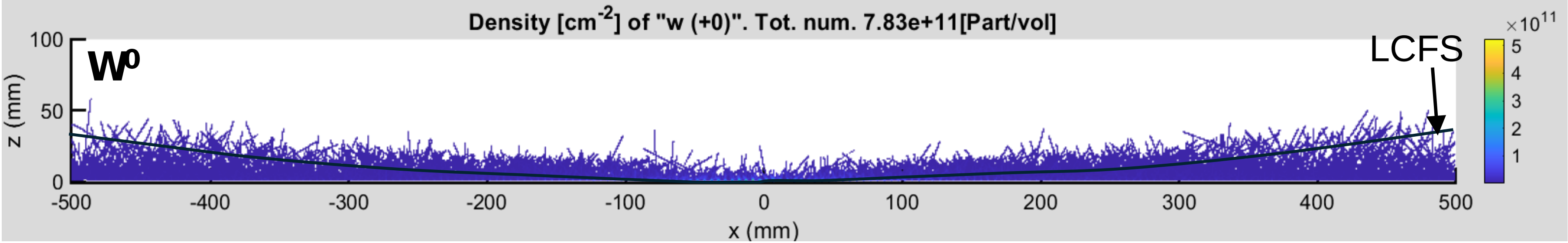


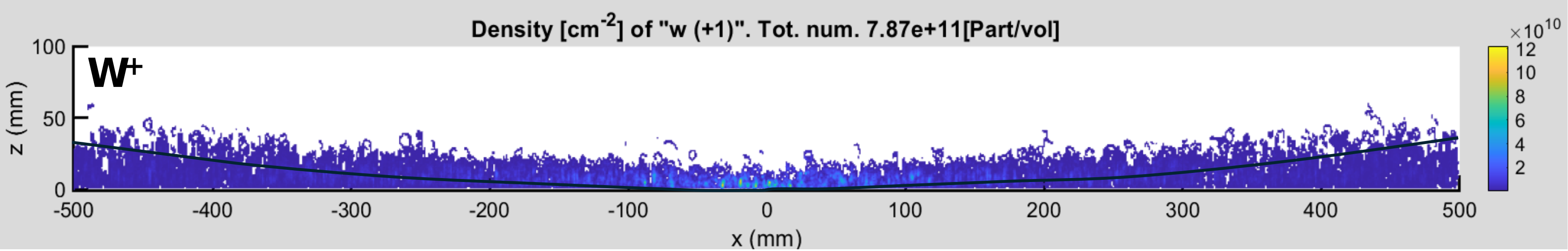
case 1: low density, high temperature (4e18 m^{-3}, 65 eV)
case 2: high density, low temperature (1e19 m^{-3}, 47 eV)

ITER ramp-up: W local transport

A. Kirschner -> included in
Zhang et al. NF 2025

Example: W^0 and W^+ density for case 1 with $D_{perp} = 1\ m^2/s$

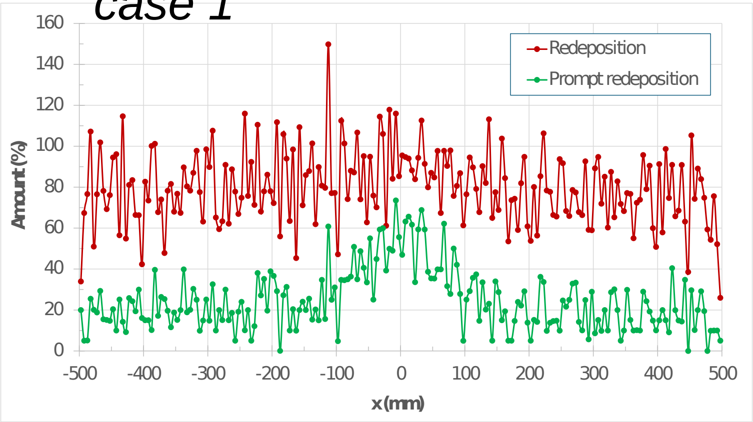




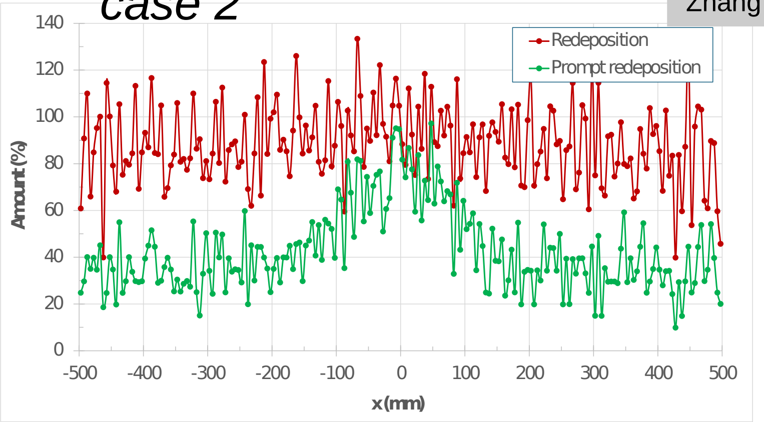
Overall redeposition and prompt redeposition along inner wall

A. Kirschner -> included in Zhang et al. NF 2025

case 1



case 2



W prompt redeposition fraction:

- varies between 20% and 80%, larger for case 2, strongly depends on plasma parameter, maximum at tangency point
- simulated fractions used as input for SOLPS-ITER simulations

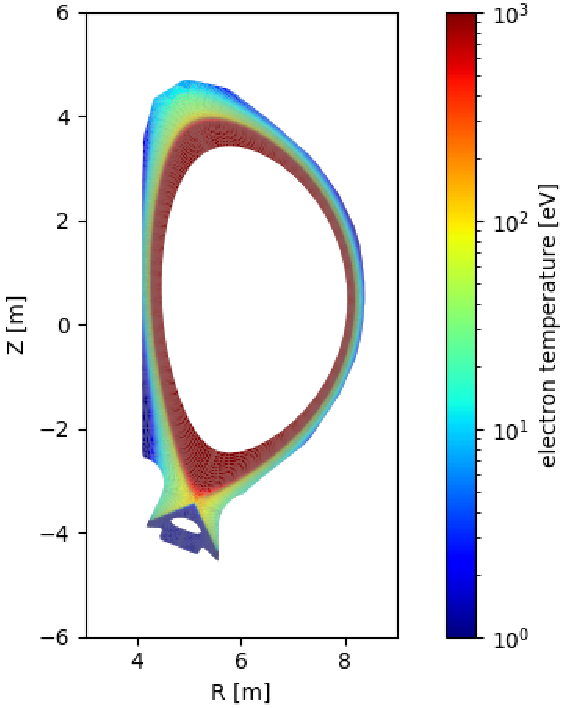
Further studies ongoing:

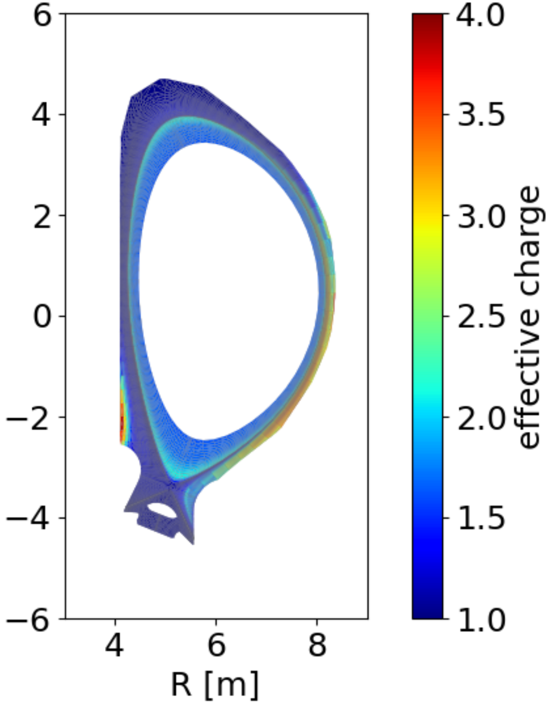
- D_{perp}, flow velocity, n_e Boltzmann decay within sheath …

ITER: full-W wall: global migration in Ne-seeded baseline plasma

- ERO2.0 modelling for 1.2% Ne-seeded case number 1233-61
- (relatively) new ERO2.0 features included:
  - triangular mesh aligned with EIRENE grid -> better accuracy
  - thermal force included
  - spatially resolved fluxes and energies of Ne impurities
  - D-CXN: total fluxes + mean energies
  - constant $D_\perp$=1 m²/s

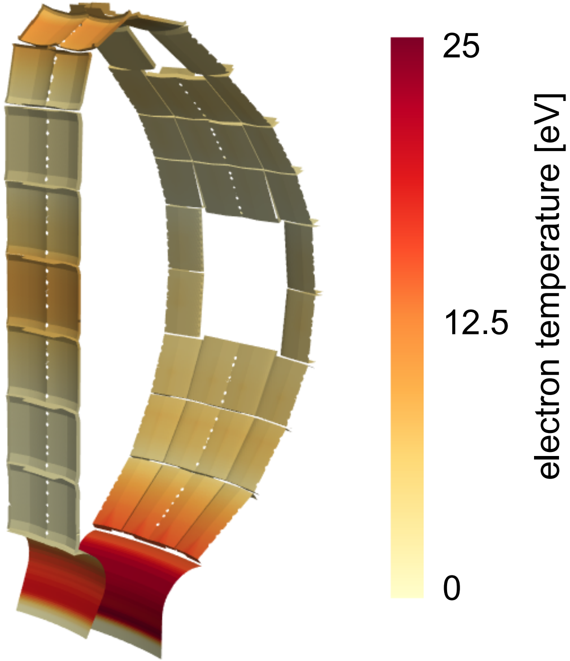
Baumann, DPG 2025

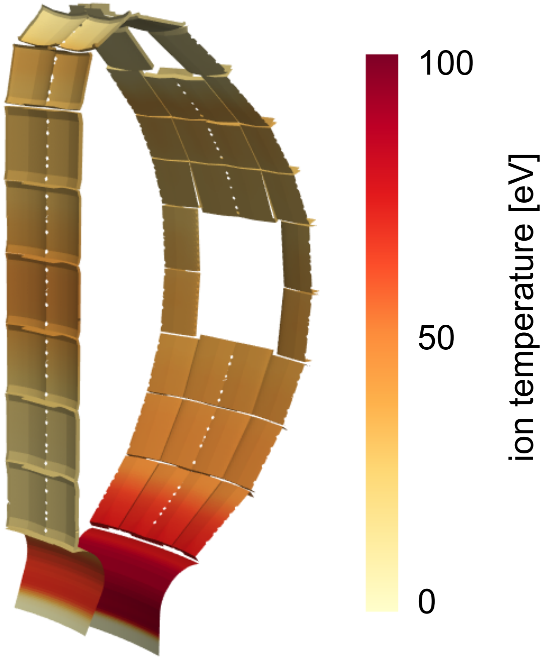




ITER: electron/ion temperature near the surface

Baumann, DPG 2025

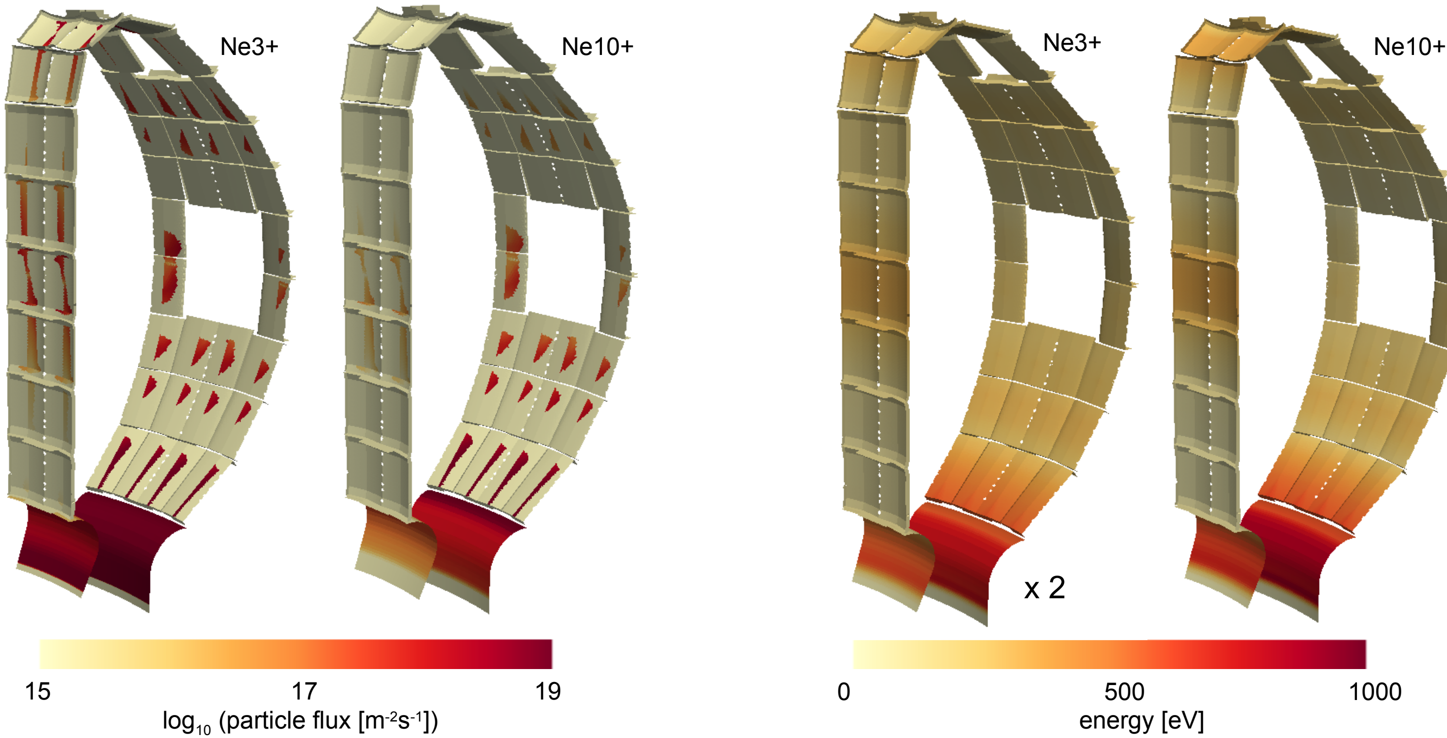




high temperatures up to **Te~25 eV, Ti~100 eV** lead to high ion impact energies and erosion

ITER: Ne fluxes and energies

Baumann, DPG 2025

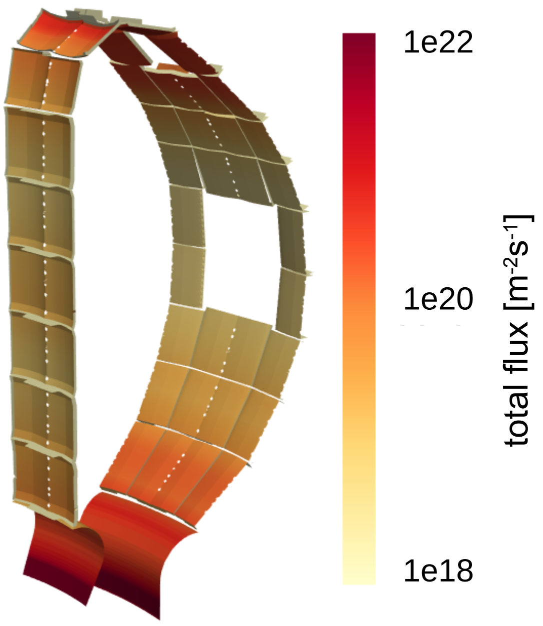


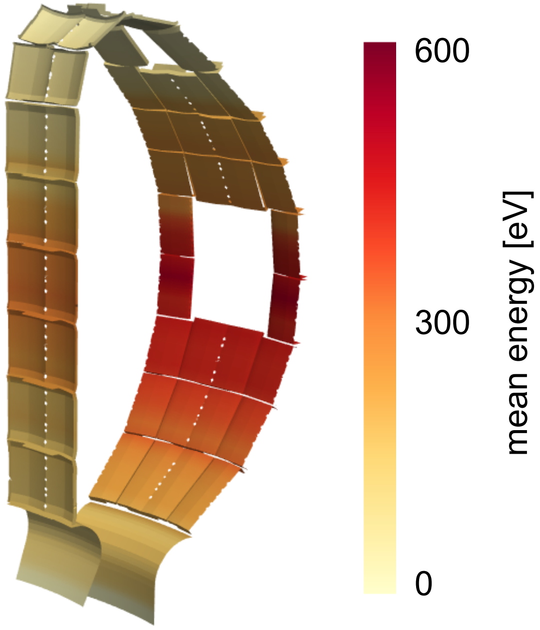
- significant Ne fluxes even for highest Z=10 charge state
- Ne dominate erosion due to high energies up to ~1 keV

ITER: D-(CX)N fluxes and energies

Baumann, DPG 2025

attention: these plots contain both CX and recycled neutrals!

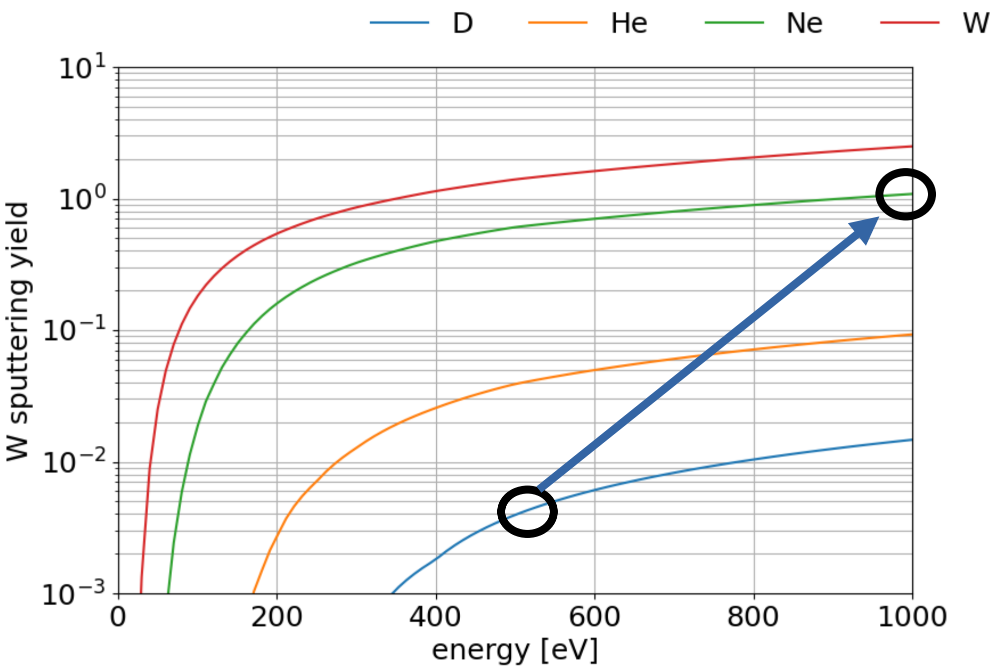




- D neutrals: up to ~0.5 keV around mid-plane due to CXN, but these have lower fluxes
- despite higher total flux, erosion by D neutrals is negligible compared to Ne

ITER: sputtering yields

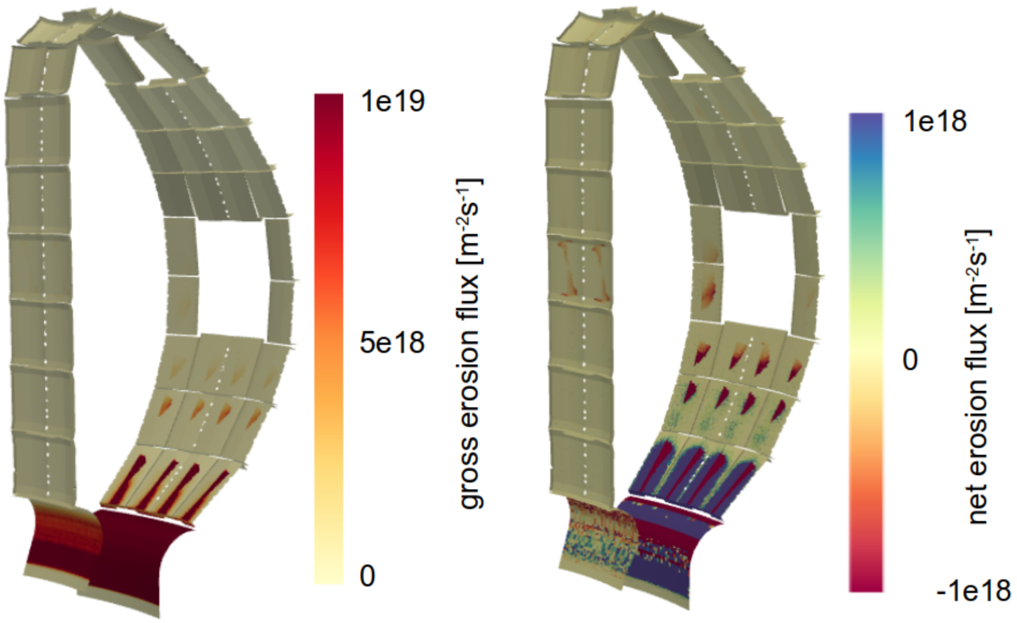
Baumann, DPG 2025

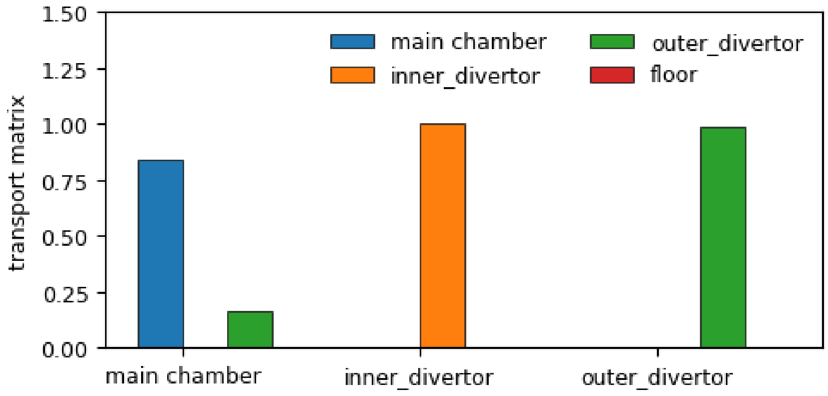


at present impact energies, Ne ions have > 2 orders of magnitude higher sputtering yield than D CXN

ITER: W gross and net erosion + transport matrix

Baumann, DPG 2025



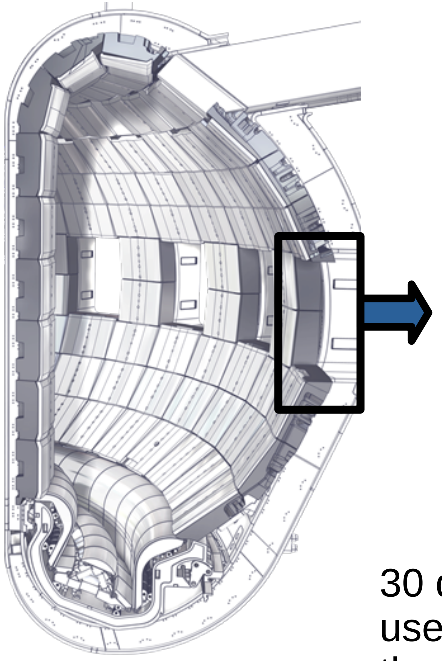


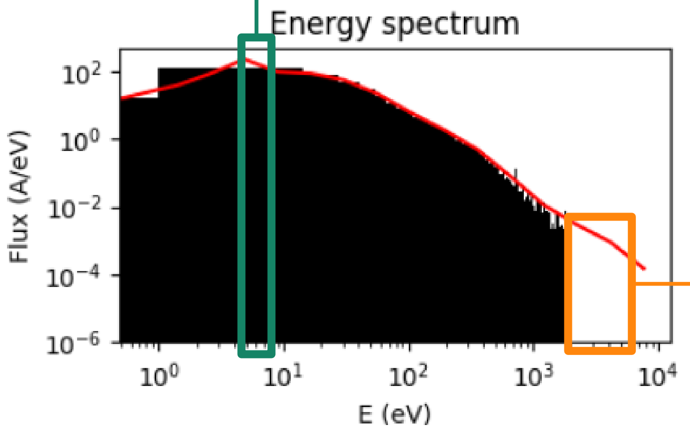
- W from main chamber flows to outer divertor
- near-perfect screening for W eroded from targets (despite thermal force)
- next steps: improved D-CXN data from EIRENE; transport coefficients from JINTRAC

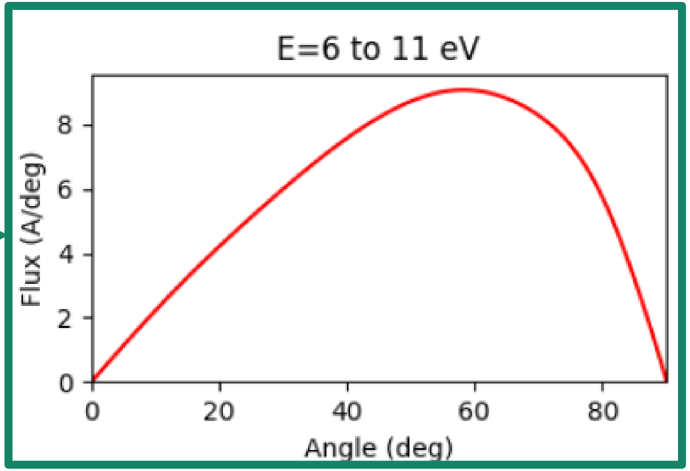
ITER: D-CXN spectra (work in progress)

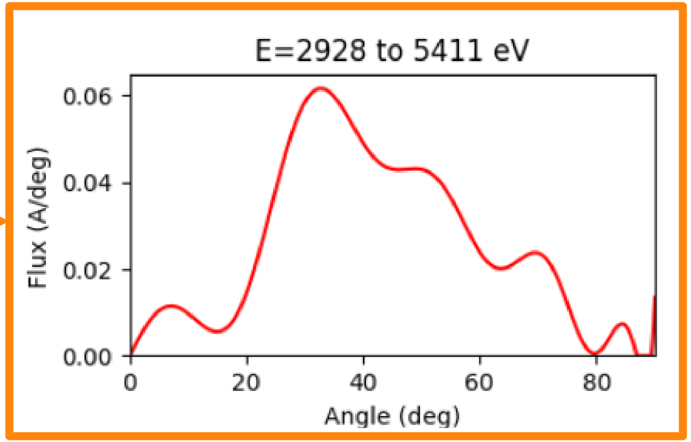
bivariate D-CXN spectra from EIRENE using functional expansion tallies [1]

Kumpulainen, submitted PPCF 2025







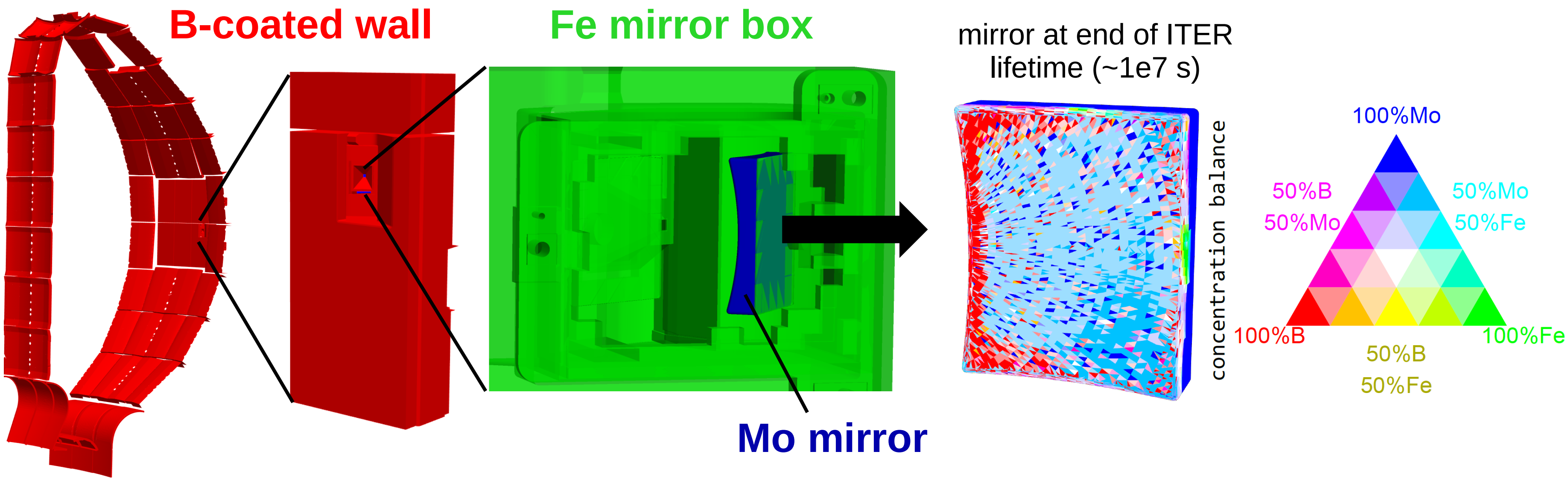


30 diagnostic surfaces were used for poloidally resolving the spectra

ITER: Simulation of mirror systems with boronization

Rode, PhD thesis (2024, HHU Düsseldorf)

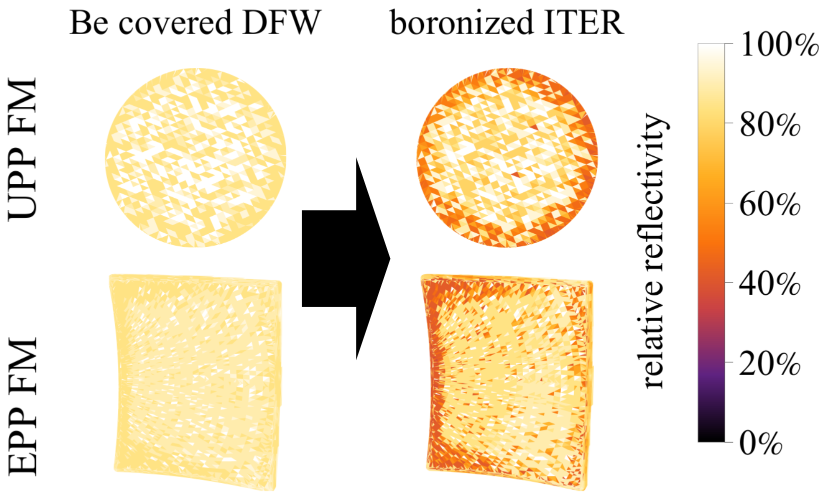
- **Setup:**
  - old ITER baseline OEDGE plasma backgrounds
  - 3-step ERO2.0 simulation approach to simulate far recessed areas in ITER mirror systems
  - **boronized (B)** first wall, but clean **iron (Fe)** mirror box around **molybdenum (Mo)** mirror



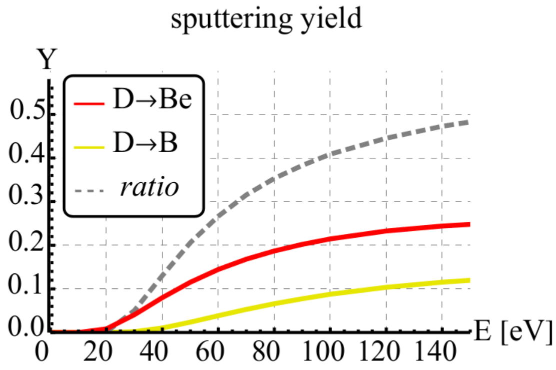
ITER: Simulation of mirror systems with boronization

Rode, PhD thesis (2024, HHU Düsseldorf)

- **Results:**
  - lower deposition for B compared to Be due to lower sputtering yields
  - despite this, B has stronger effect on mirror degradation due to worse reflectivity compared to Be (w.r.t. H_α line)



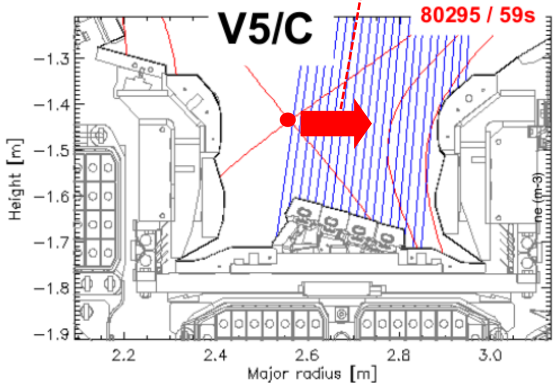
element	total reflectivity R_i
Be	0.54
B	0.25



JET: W erosion & prompt redeposition experiments

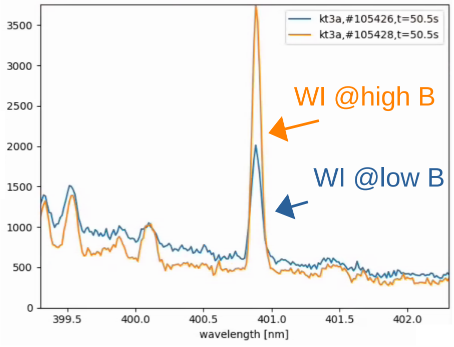
- **Experiment goals (D_2 plasma, L- & H-mode):**
  1) W source by D ions + D-CXN impact
  ⇨ **X-point position scan** to vary ratio of CXN to ions fluxes to hor. target + baffles
  2) W prompt redeposition
  ⇨ **B-field scan** to study Larmor radius effect

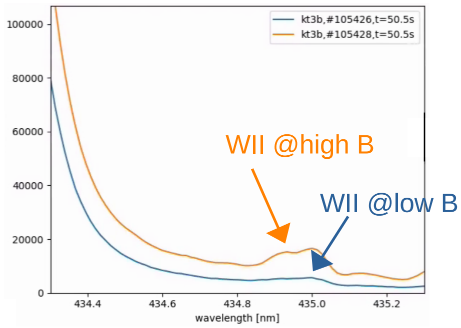
x-point position scan



+ B-field scan

- **Analysis & Modelling:**
  - Spectroscopy analysis for W I and W II ongoing
    - initial analysis seems to confirm relative WII reduction at low B-field (high r_g)
  - JINTRAC plasma background modelling complete (next slides)
  - ERO local modelling complete; ERO2.0 global modelling this year

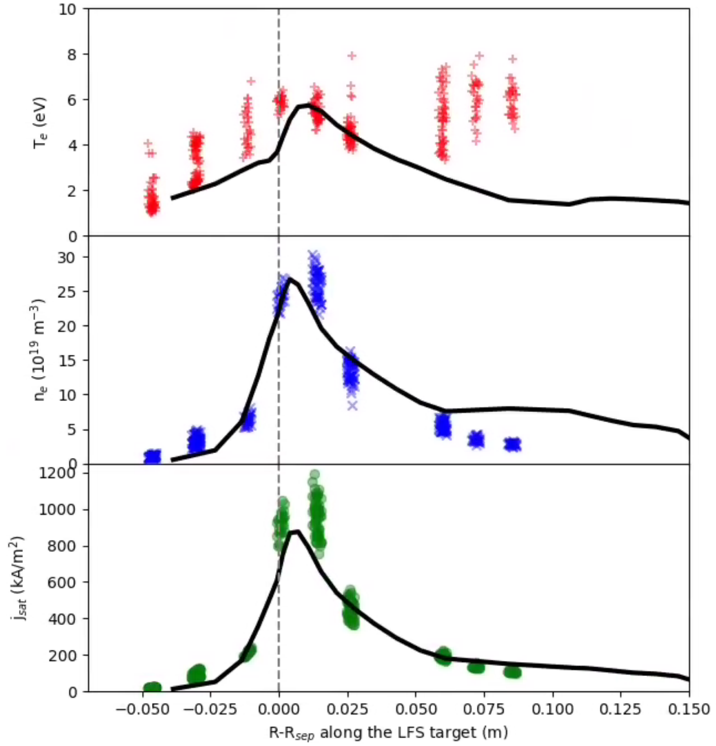


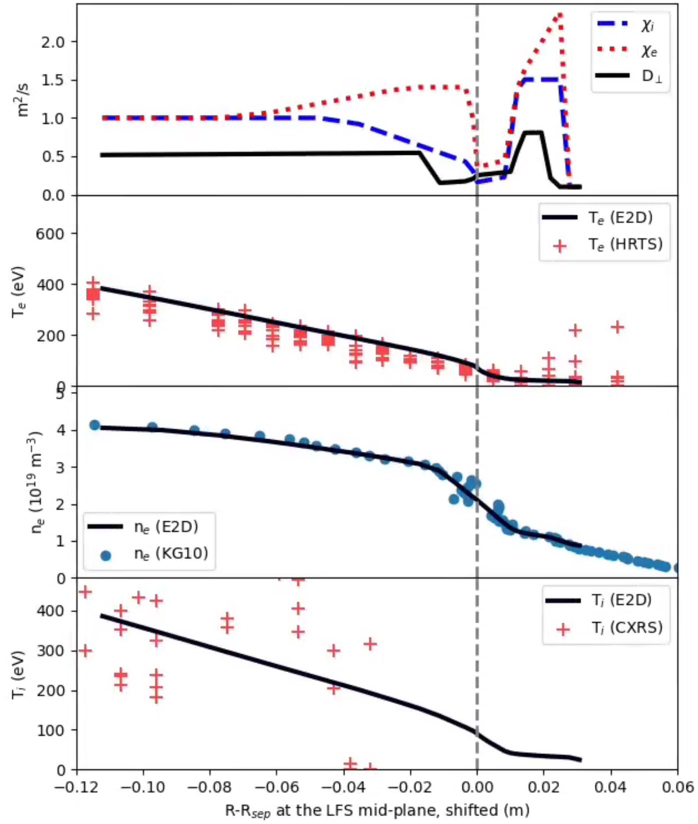


JET: JINTRAC simulations of plasma background

H. Kumpulainen

First simultaneous agreement on target Te, ne, jsat and upstream profiles in a high-recycling plasma





Key parameters: $D_\perp$, χ_i, χ_e, “main ion SOL wall decay length” = 8 cm

JET: ERO simulations of W prompt redeposition

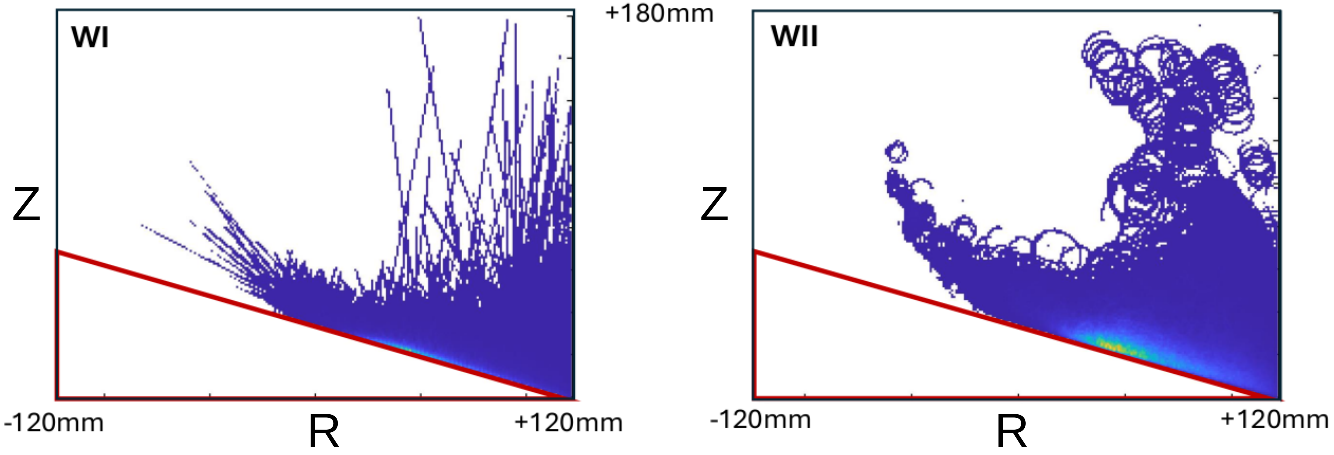
A. Kirschner

Experiment at JET with varying magnetic field B: #102560 with B = 1.8 T
#102558 with B = 2.5 T
#102563 with B = 3.0 T

Plasma parameter deduced from Langmuir probes at tile 5, $D_{perp} \equiv 0.2\ m^2/s$

Aims: - estimate amount of prompt redeposition in dependence on magnetic field
- compare modelled line emission (WI, WII) with experimental data

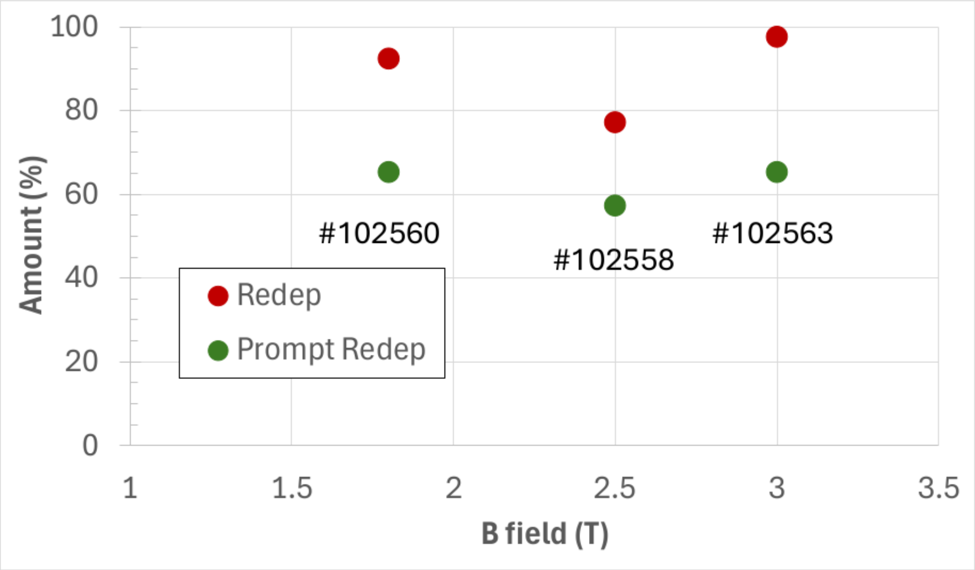
Example: simulated WI and WII for 2.5 T pulse



JET: ERO simulations of W prompt redeposition

A. Kirschner

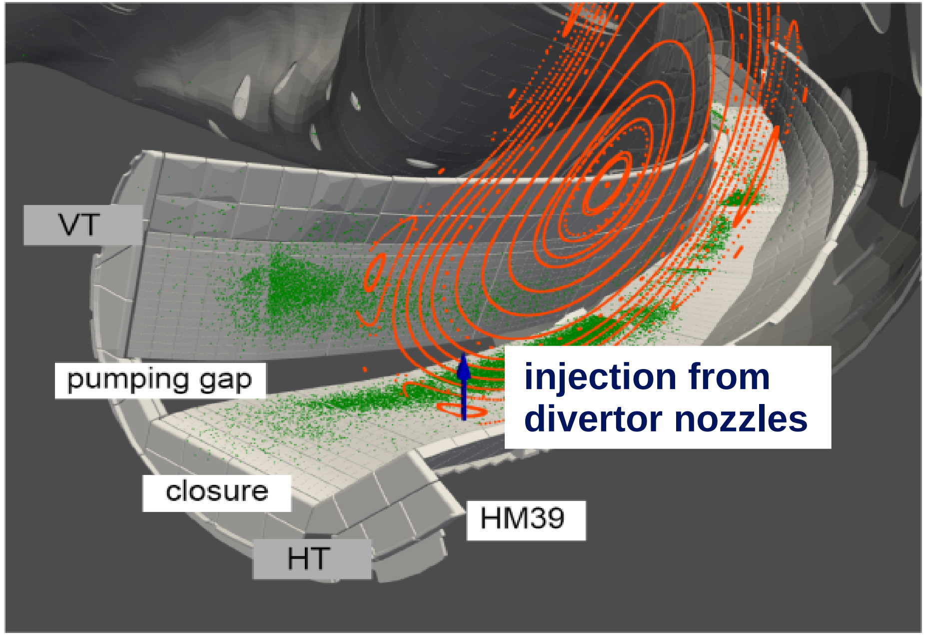
Amount of simulated overall redeposition and prompt redeposition

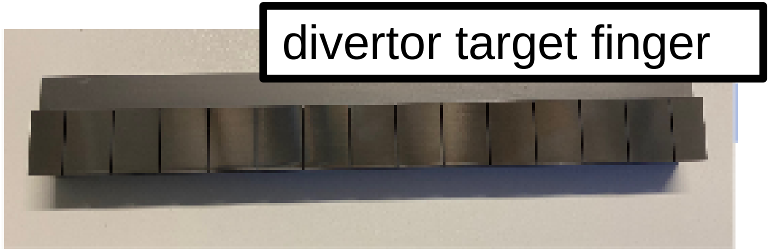


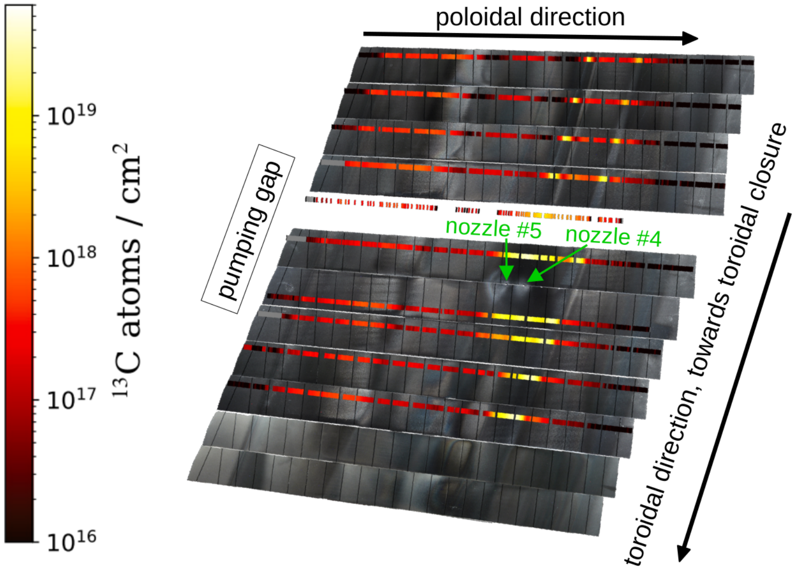
- **No clear dependence on B field strength**
- **WI/WII ratio: almost constant ...** comparison with experiment to be done ...
- **Reason: pulses with different B also have different plasma conditions**
- **Remark:** simulations with fixed plasma show clear decrease of prompt redeposition with increasing B

W7-X: ^{13}C injection from divertor nozzles

Kawan, NME 2024
Romazanov, submitted NF 2025





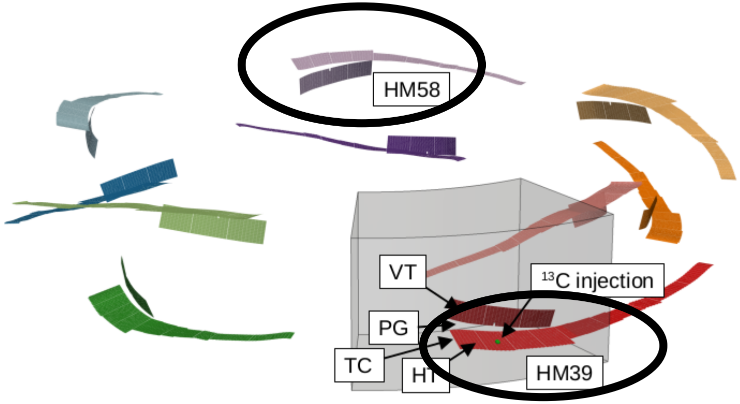


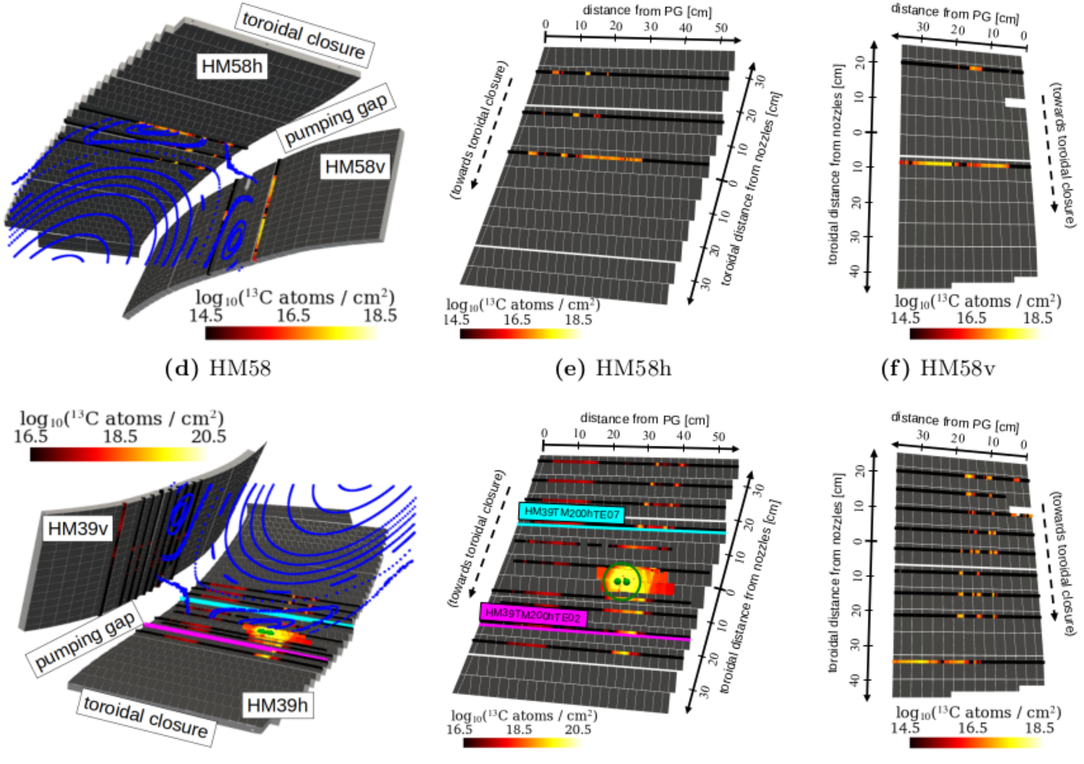
large amounts of ^{13}C-marked methane were puffed into magnetic island O-point and then measured by ion beam analysis (IBA)

W7-X: ^{13}C injection from divertor nozzles

Kawan, NME 2024
Romazanov, submitted NF 2025

IBA measurements peformed from target elements close and far from the injection location





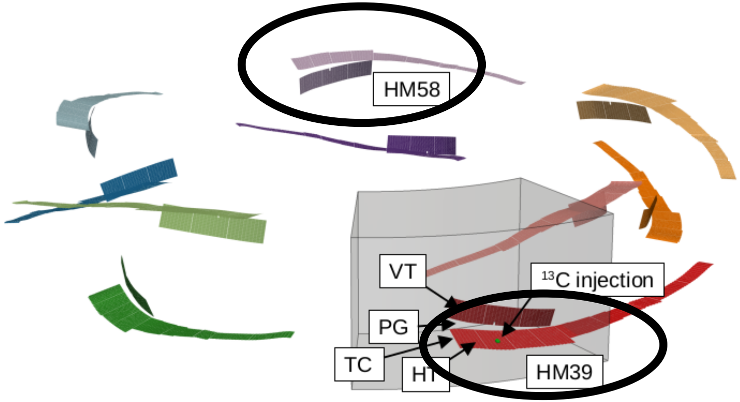
(d) HM58 (e) HM58h (f) HM58v

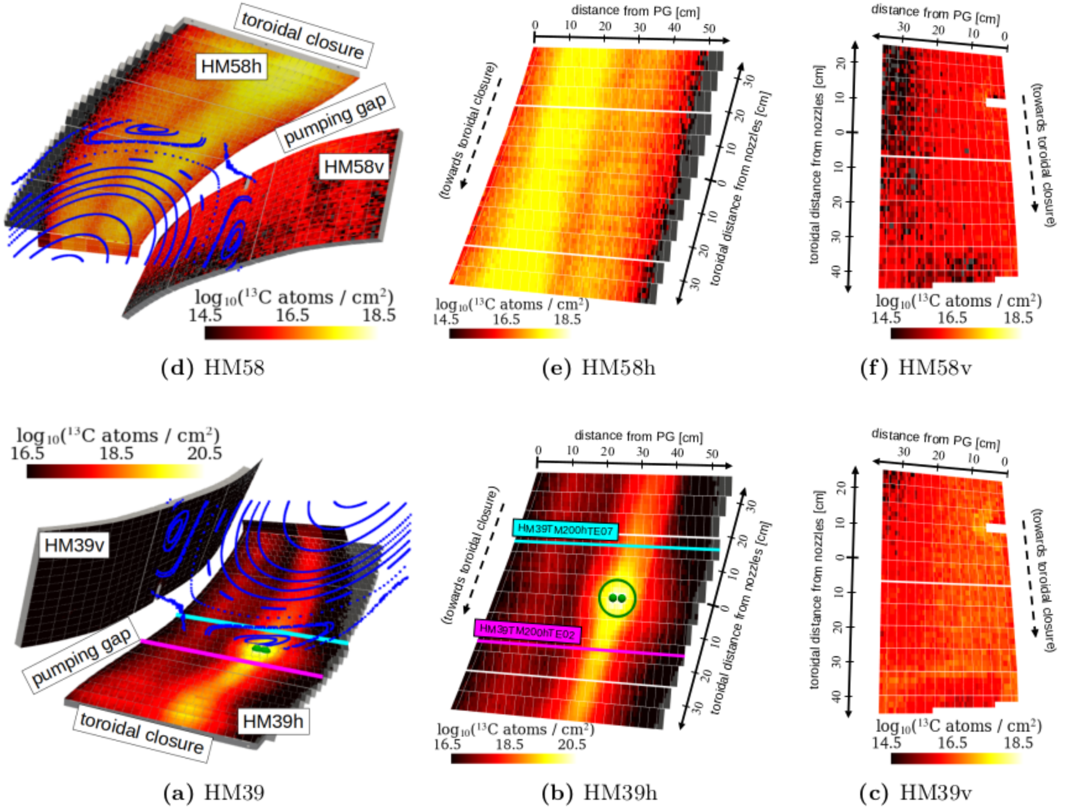
(a) HM39 (b) HM39h (c) HM39v

W7-X: ^{13}C injection from divertor nozzles

Kawan, NME 2024
Romazanov, submitted NF 2025

Matching ERO2.0 simulations covering all divertor areas

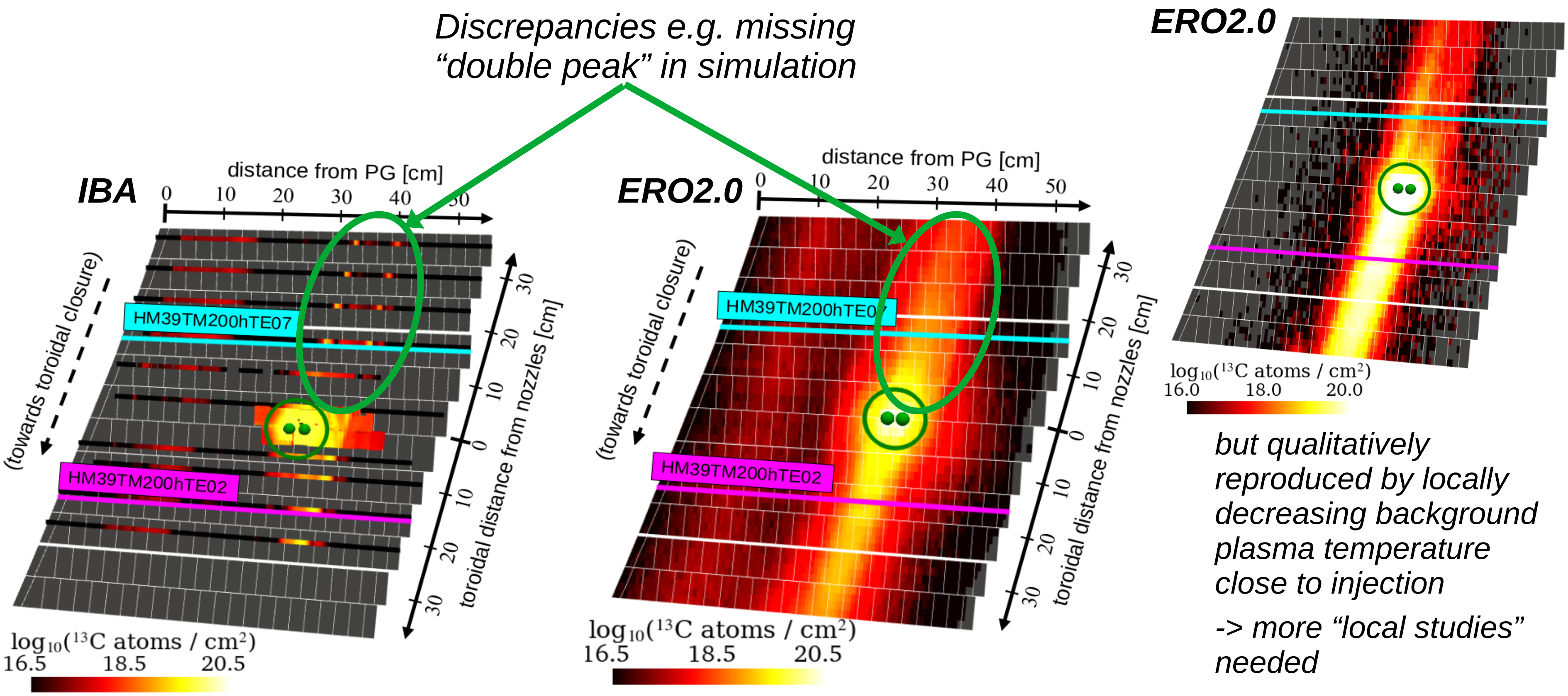




W7-X: ^{13}C injection from divertor nozzles

Kawan, NME 2024
Romazanov, submitted NF 2025

Discrepancies e.g. missing “double peak” in simulation



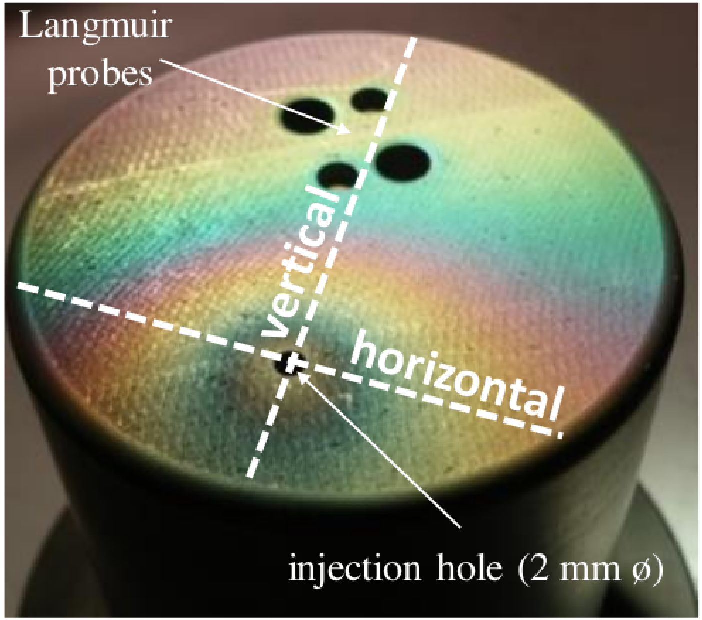
but qualitatively reproduced by locally decreasing background plasma temperature close to injection

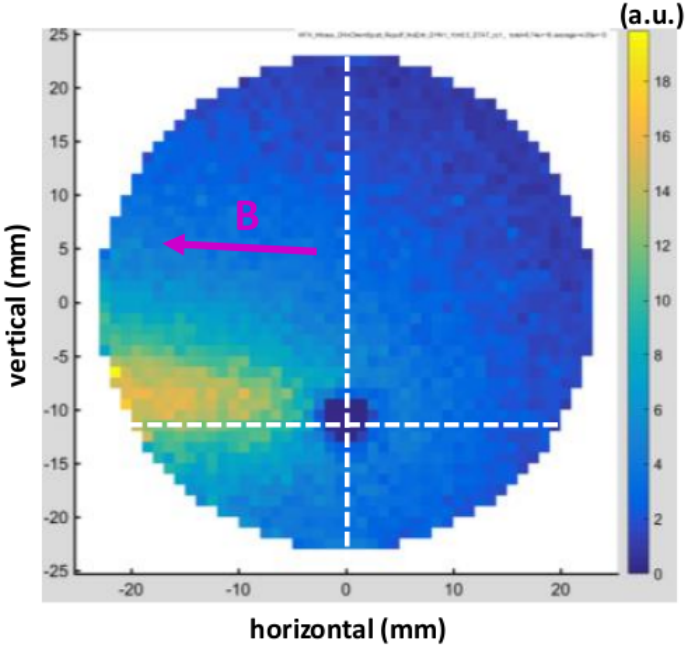
-> more “local studies” needed

W7-X: ^{13}C injection from multi-purpose manipulator (MPM)

Kirschner, EPS 2023

- ERO studies performed with scans of sticking coefficients, enhanced re-erosion, tracking of H from injected methane
- New ^{13}C MPM injection experiments with reduced puffing rate performed this month -> ERO modelling planned, investigate fluence dependence on enhanced re-erosion

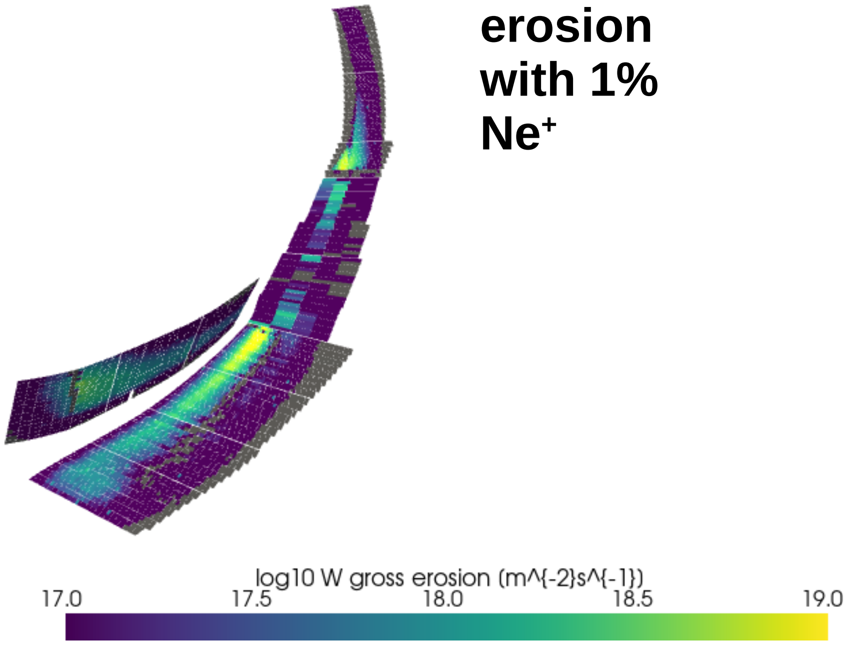




First proof-of-concept simulations for metallic wall W7-X

- Goal: first estimate of erosion in W7-X operation with full-W divertor
- Using TDU geometry from OP1.2, but replace C by W as material
- Plasma parameters: EMC3-EIRENE C-seeded solution, artificially added 1% neon (with Z=1)
- Next steps:
  - switch to detached Ne-seeded EMC3-EIRENE plasma solution
  - inclusion of D-CXN

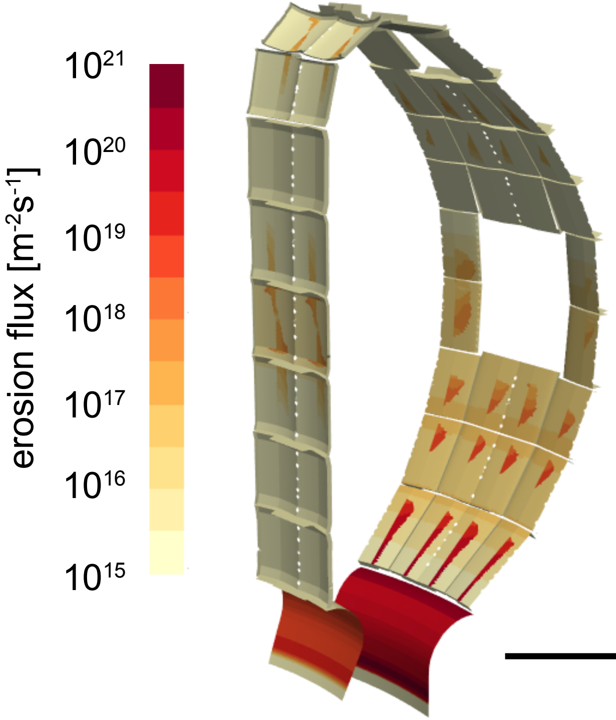
W gross erosion with 1% Ne^+



Summary

- focus of recent ERO/ERO2.0 studies for JET, ITER and W7-X in 2024/2025:
  - JET, ITER: studying W erosion and transport, role of different erosion and transport mechanisms, including prompt redeposition
  - W7-X: study of ^{13}C tracer impurity injection; initial predictions for W divertor upgrade
- further plans for 2025:
  - ITER: refinement of ERO/ERO2.0 simulations; potentially comparison of SOLPS-ITER solutions with others from SOLEDGE3X, EMC3-EIRENE
  - JET: comparison with W erosion experiments, also using ERO2.0 and using PIC input for refined sheath parameters
  - W7-X: use new Ne-seeded EMC3-EIRENE solutions once available for W divertor predictions

ITER: contributors to W source



$\Gamma_{ero} = 4.92 \times 10^{20}\ s^{-1}$ …

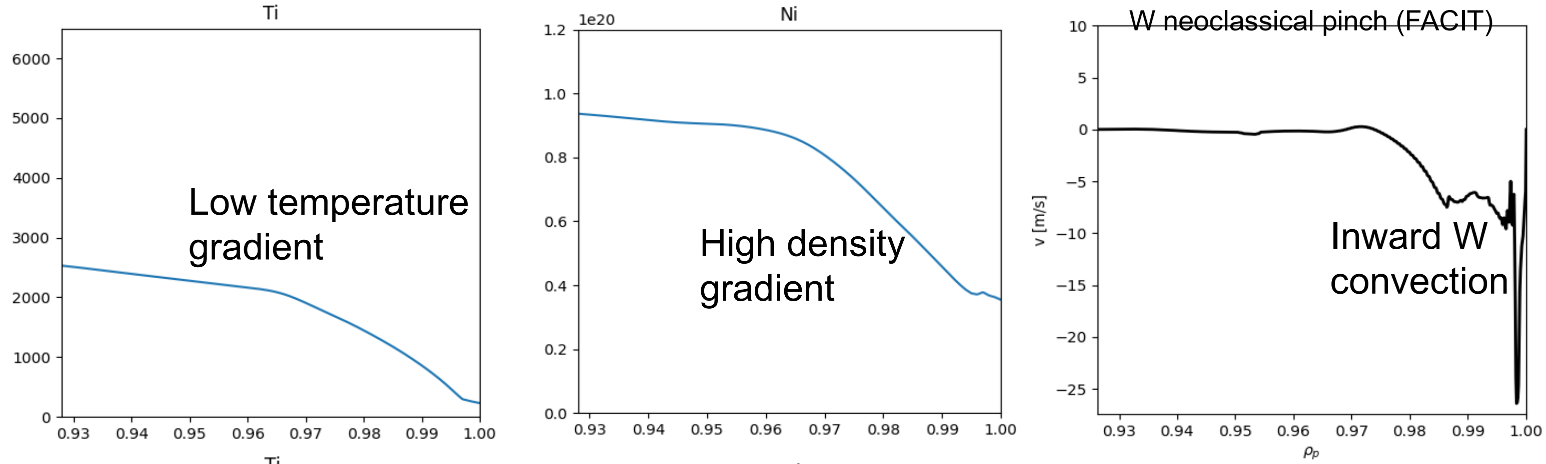
- 0.05 % by D
- 99.15 % by Ne
- 0.80 % by He

$\Gamma_{ero} = 6.85 \times 10^{21}\ s^{-1}$ …

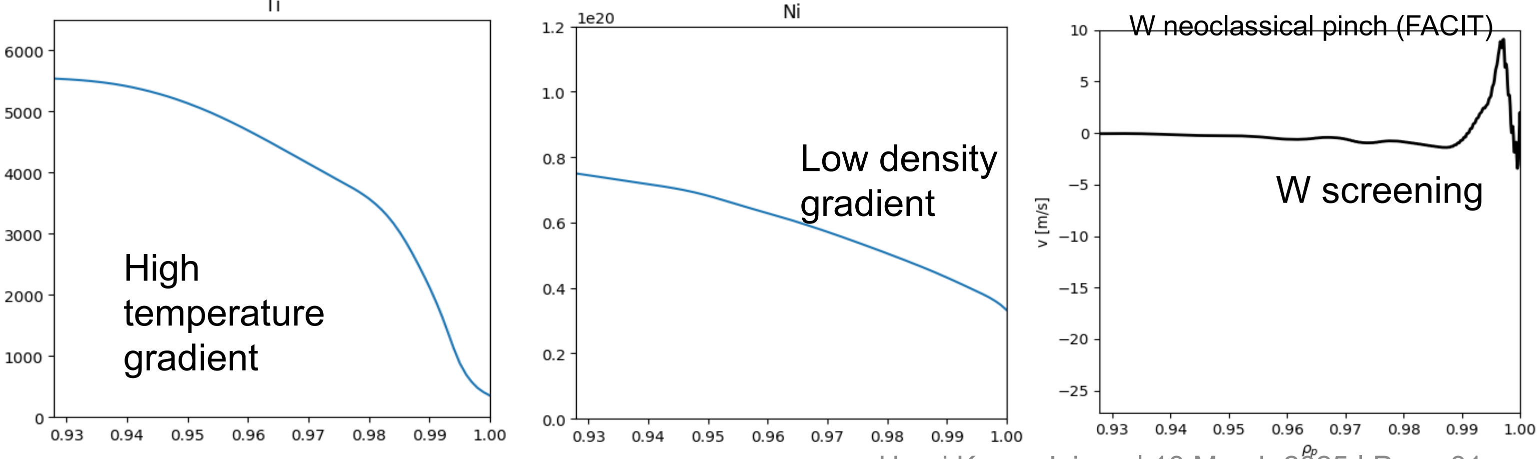
- 0.11 %
- 99.74 %
- 0.15 %

Should we expect adequate W screening with the provided SOLPS-ITER solution?

New wide-grid SOLPS-ITER 1233-61



Be ITER baseline i-wdn-0003-2481-01g-Ne



JET simulations of W prompt redeposition

Plasma parameter profiles along tile 5