Simulation of tungsten erosion and edge-to-core transport in neon-seeded JET plasmas

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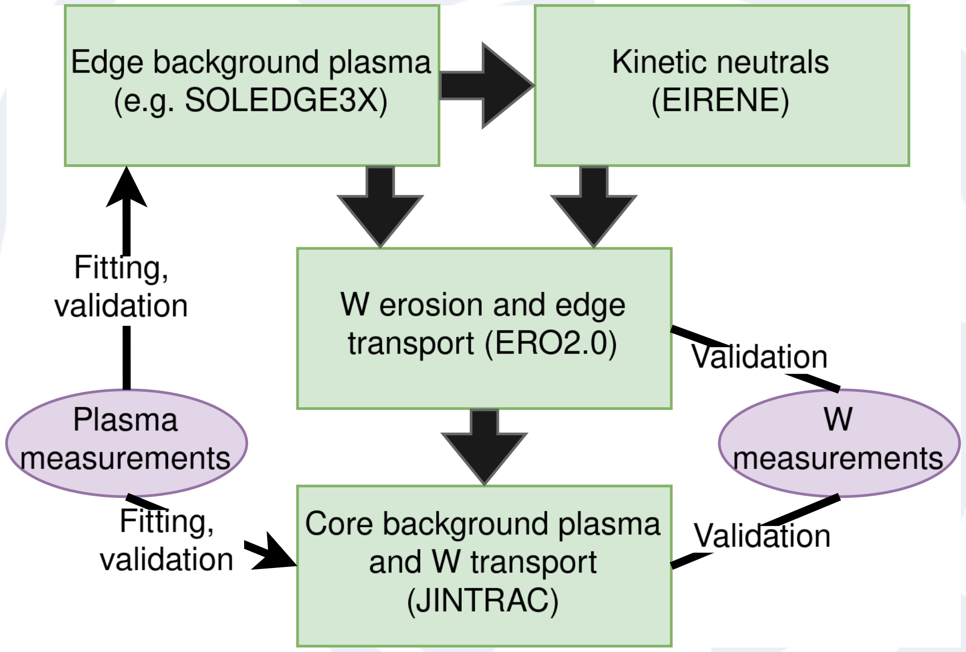
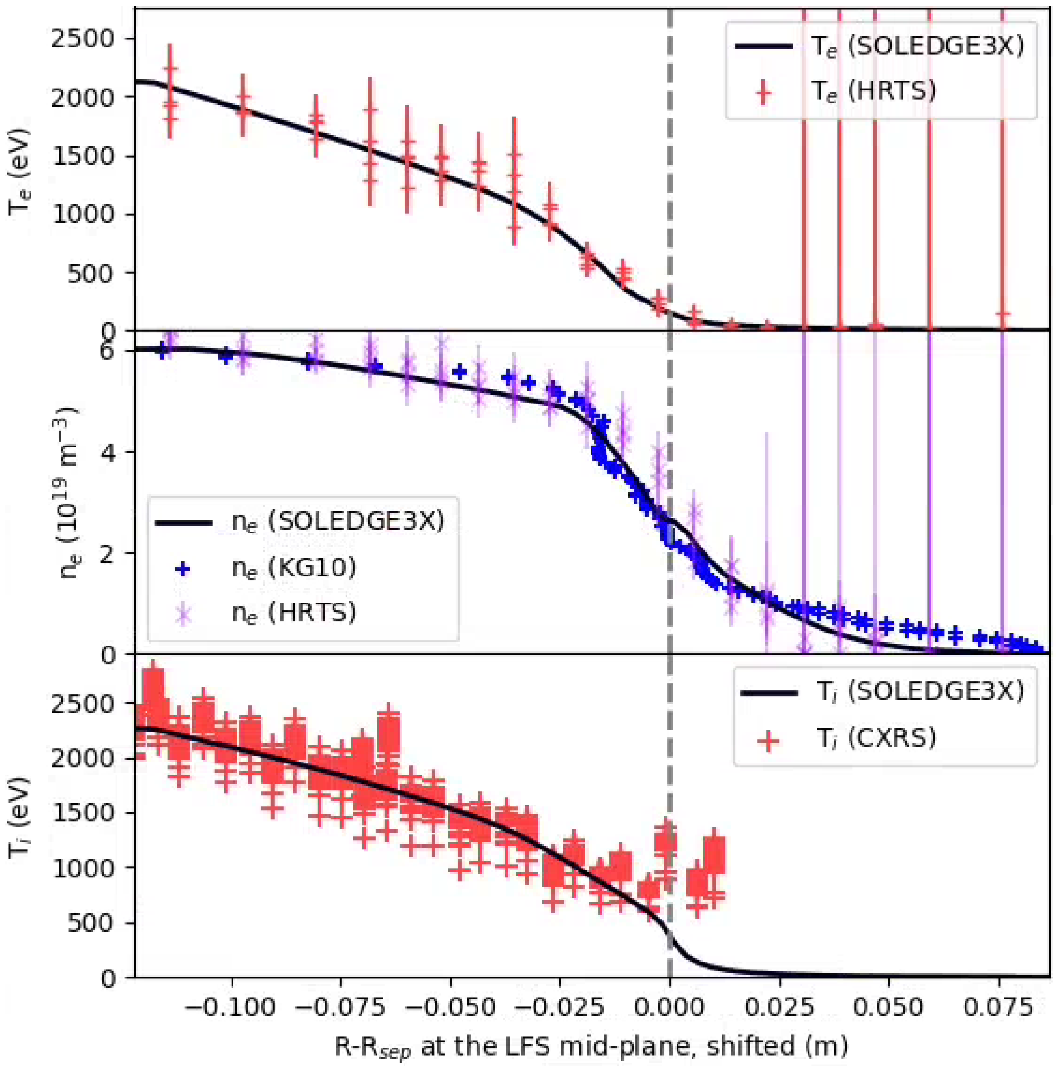
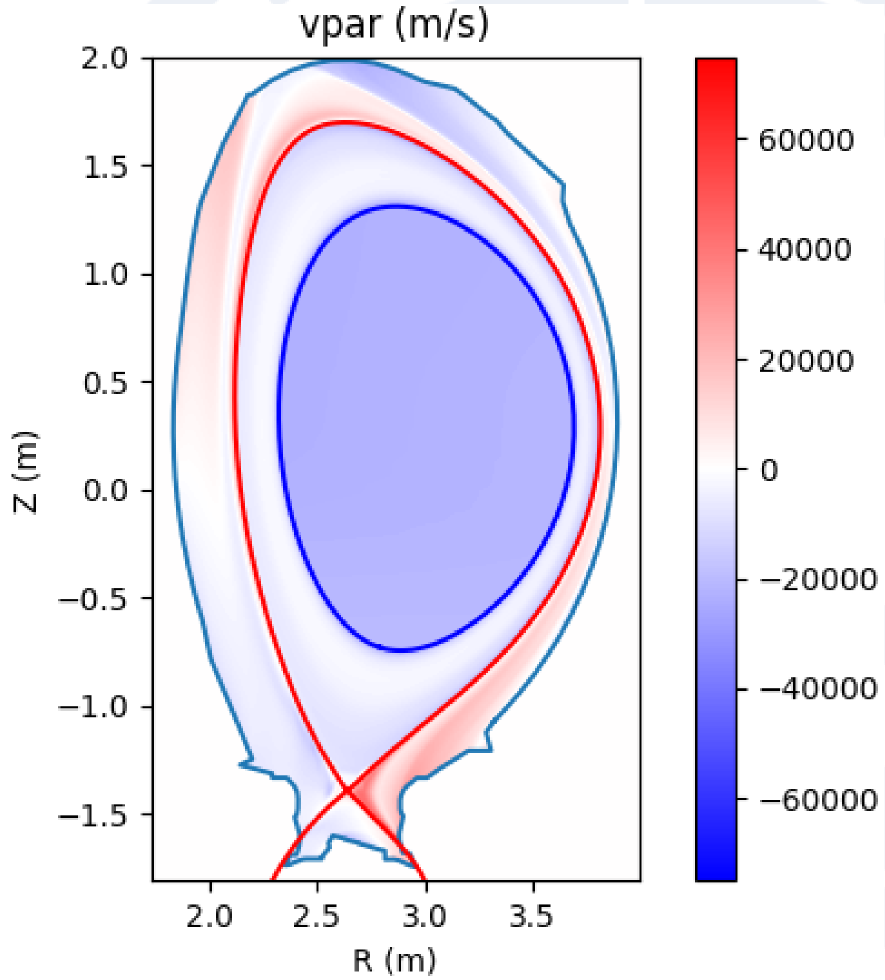
Goal: assess the ability of simulation codes to predict W erosion and transport

- Plasma: **Ne-seeded JET ITER-baseline** scenario #97490 (see C. Giroud et al. this conference)
  - Given a set of background plasma profiles, predict W
- **SOLEDGE3X** wide-grid plasma background solution including drifts
  Compared with SOLEDGE2D, no drifts
- **EIRENE** modelling of energy- and angle-resolved atomic flux at walls
- **ERO2.0** simulations for W erosion and edge transport
- **Validation of simulated W erosion (ERO2.0):**
  Predicted vs. measured W I line emission (400.9 nm) in the divertor
- **Validation of simulated W edge and core transport (ERO2.0 & JINTRAC):**
  Predicted vs. measured W density in the core, JINTRAC boundary condition for W taken from ERO2.0

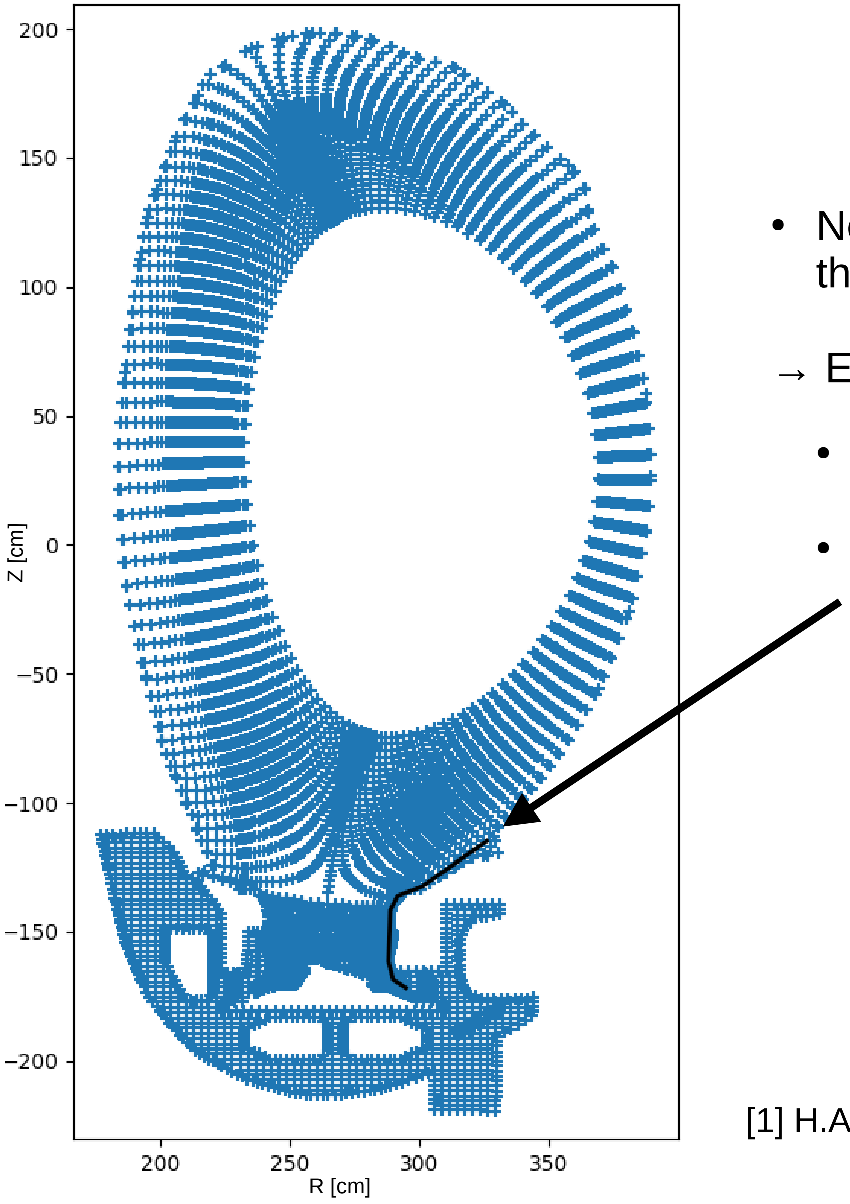


Plasma profiles from SOLEDGE3X with drifts (P. Innocente)





Atomic wall fluxes from EIRENE



- Need more detailed data on atomic flux and the impact energy & angle distributions than what is available from the coupled SOLEDGE3X-EIRENE simulation

→ EIRENE post-processing simulation on converged SOLEDGE3X solution

- Particle histories increased by factor 100
- Added diagnostic surfaces for tallying bivariate energy-angular distributions [1] at the most important wall locations

[1] H.A. Kumpulainen et al. PPCF 2025

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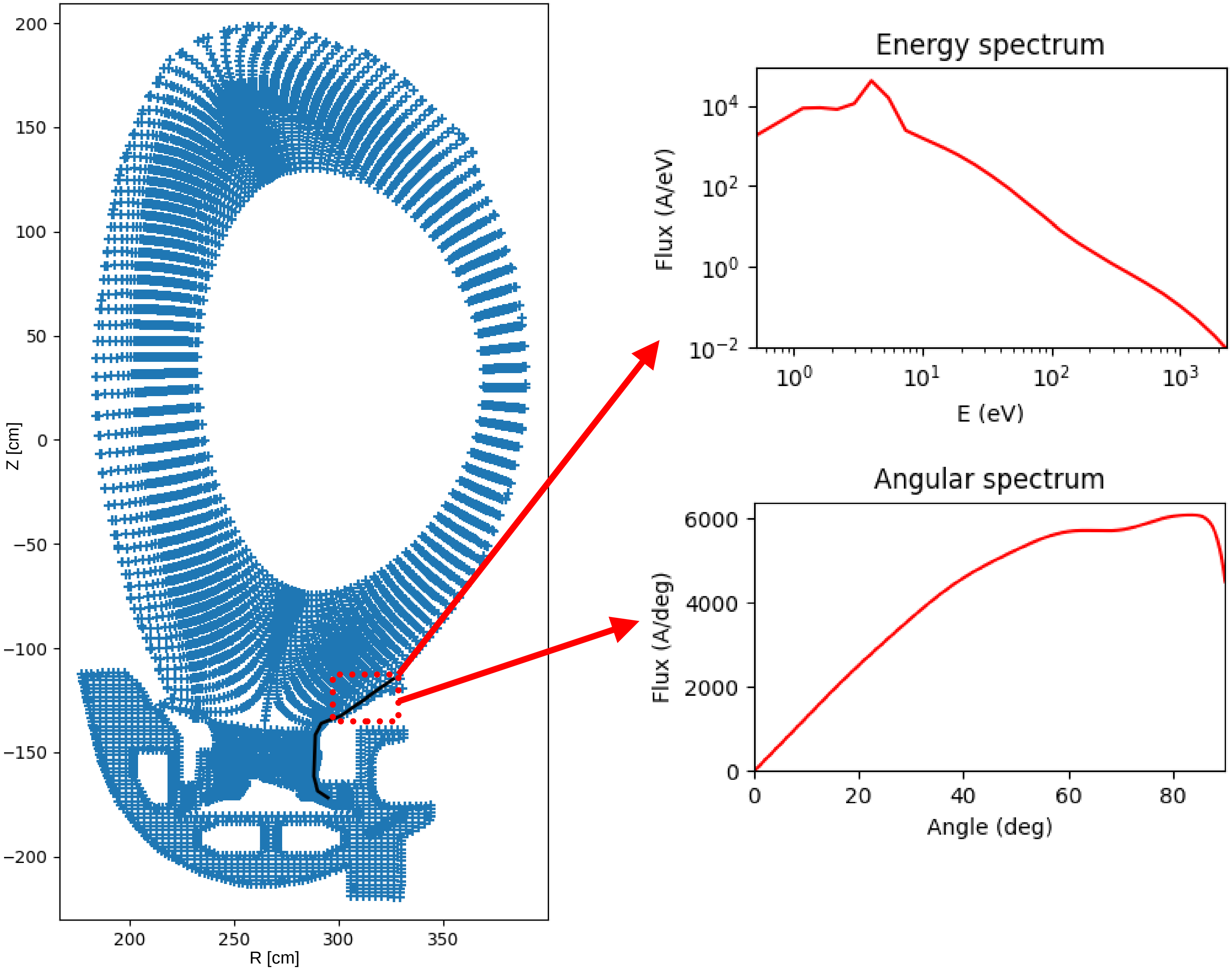

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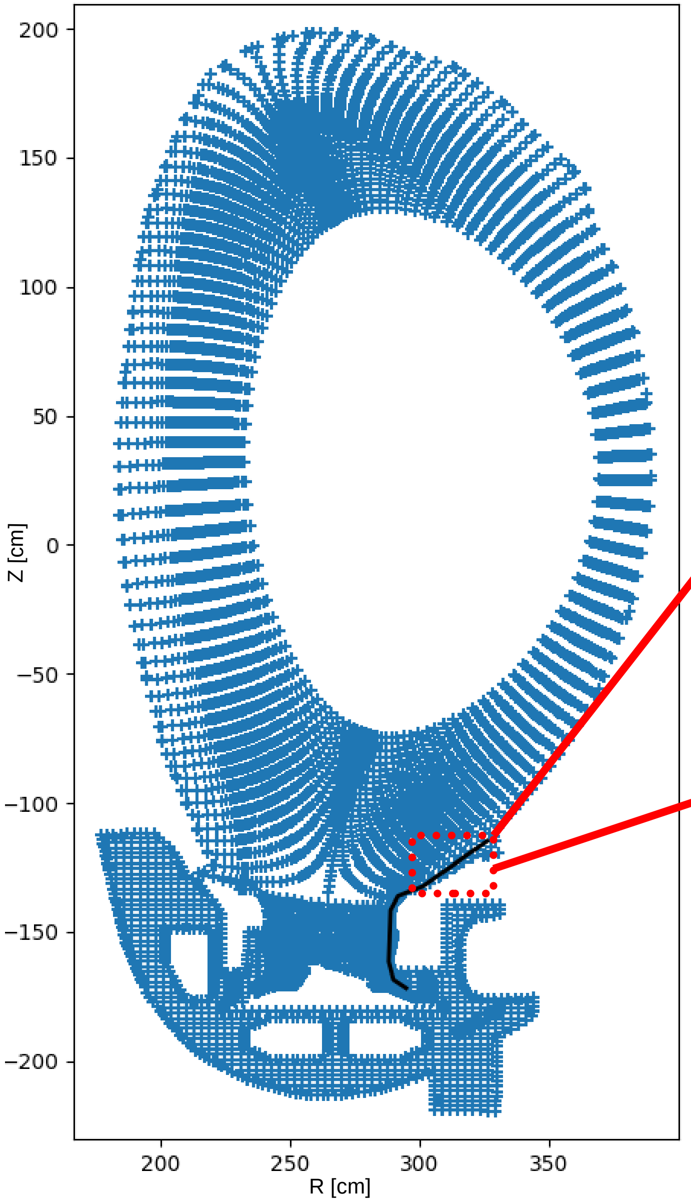
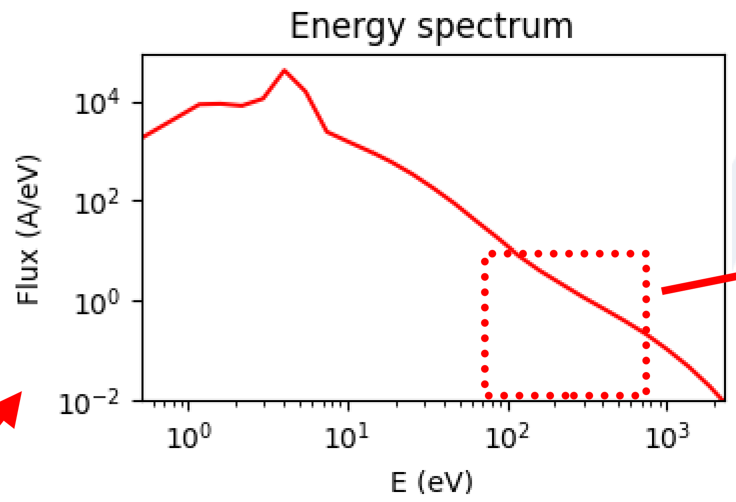
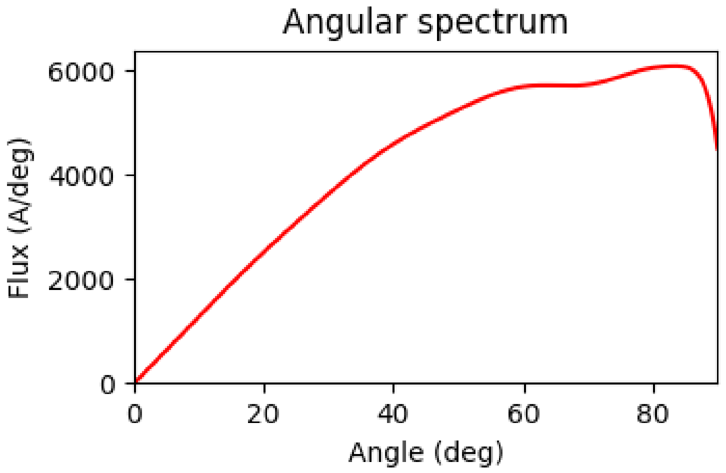
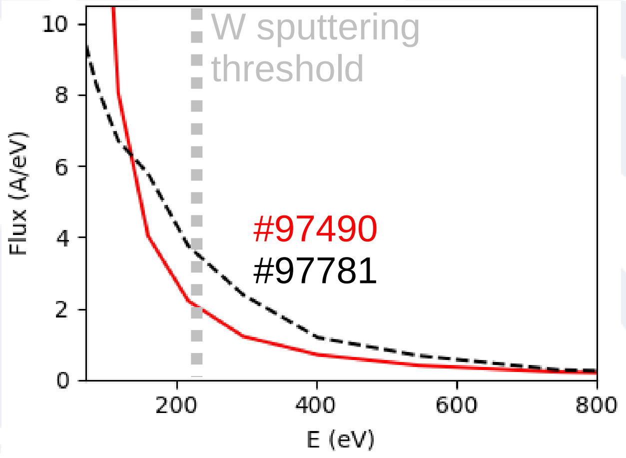


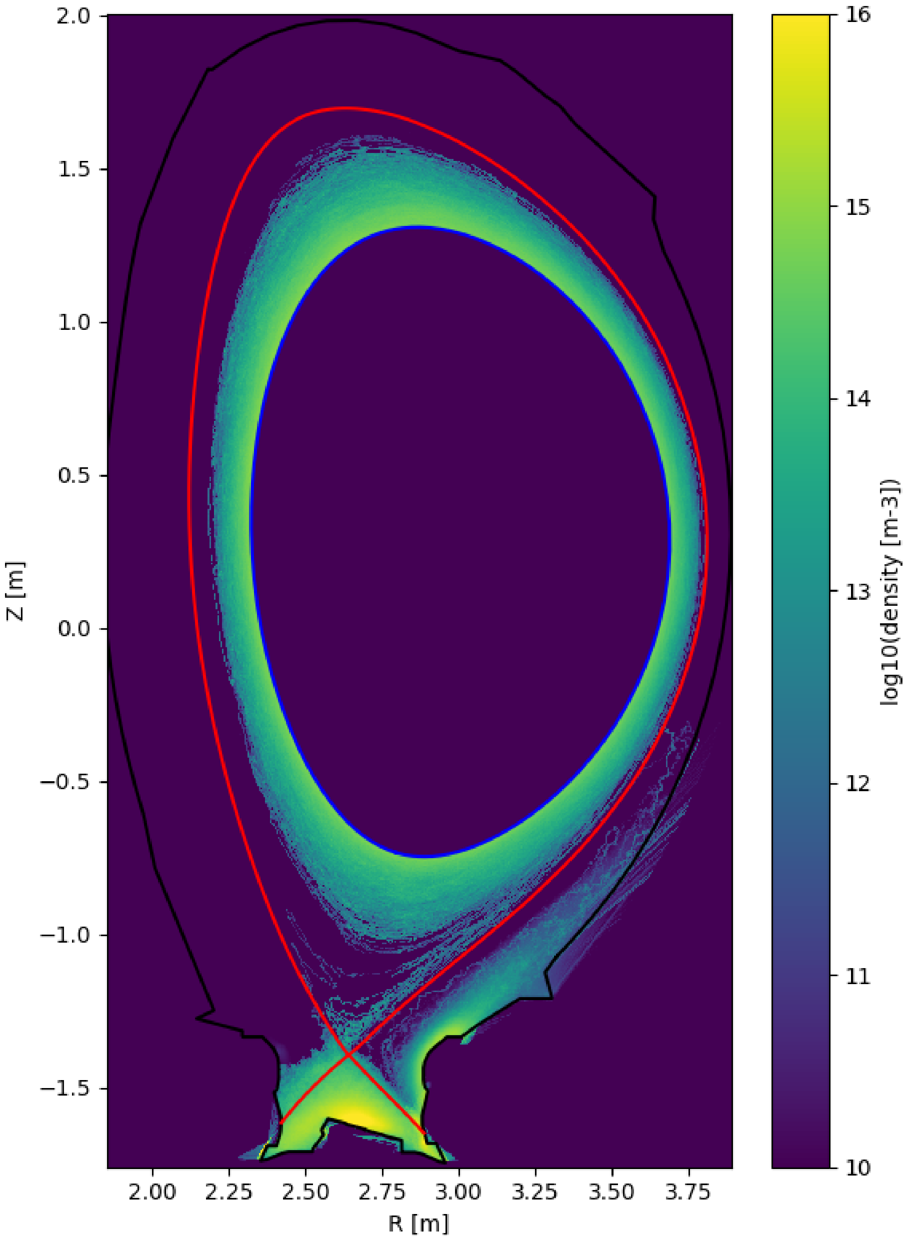






#97490: $n_{e,LCFS} = 2.7 \cdot 10^{-19}\ m^{-3}$, P = 34 MW
Denser SOL → energetic CXN flux attenuated
#97781: $n_{e,LCFS} = 1.9 \cdot 10^{-19}\ m^{-3}$, P = 34 MW
More energetic CXN from the pedestal

W erosion and transport predicted by ERO2.0



- ERO2.0 trace-impurity Monte Carlo simulation with a 3D wall
- Cross-field W transport coefficients:
  - Neoclassical $D_\perp$, $V_\perp$ profiles from NEO (D. Fajardo)
  - Anomalous $D_\perp$ profile based on SOLEDGE3X (P. Innocente)
- Electromagnetic drifts included (ExB, grad-B, curvature etc.)
- Fokker-Planck collisions and thermal forces included
- Plasma toroidal rotation included
- Charge-state resolved Ne density profiles from SOLEDGE3X
  → wall fluxes and m_{eff}, Z_{eff} profiles
- Adaptive GCA: full-orbit resolution near walls (prompt redeposition), guiding-center tracking elsewhere

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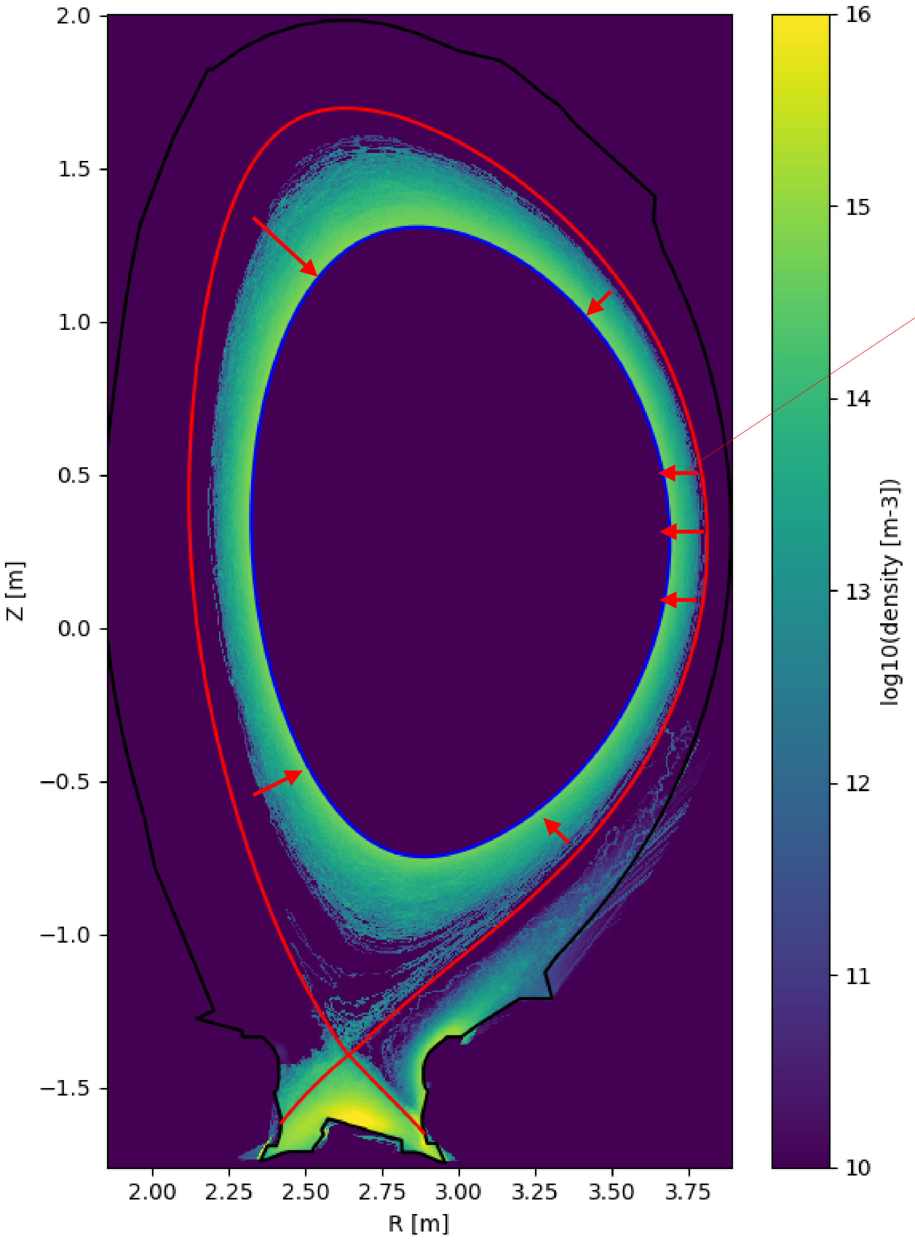
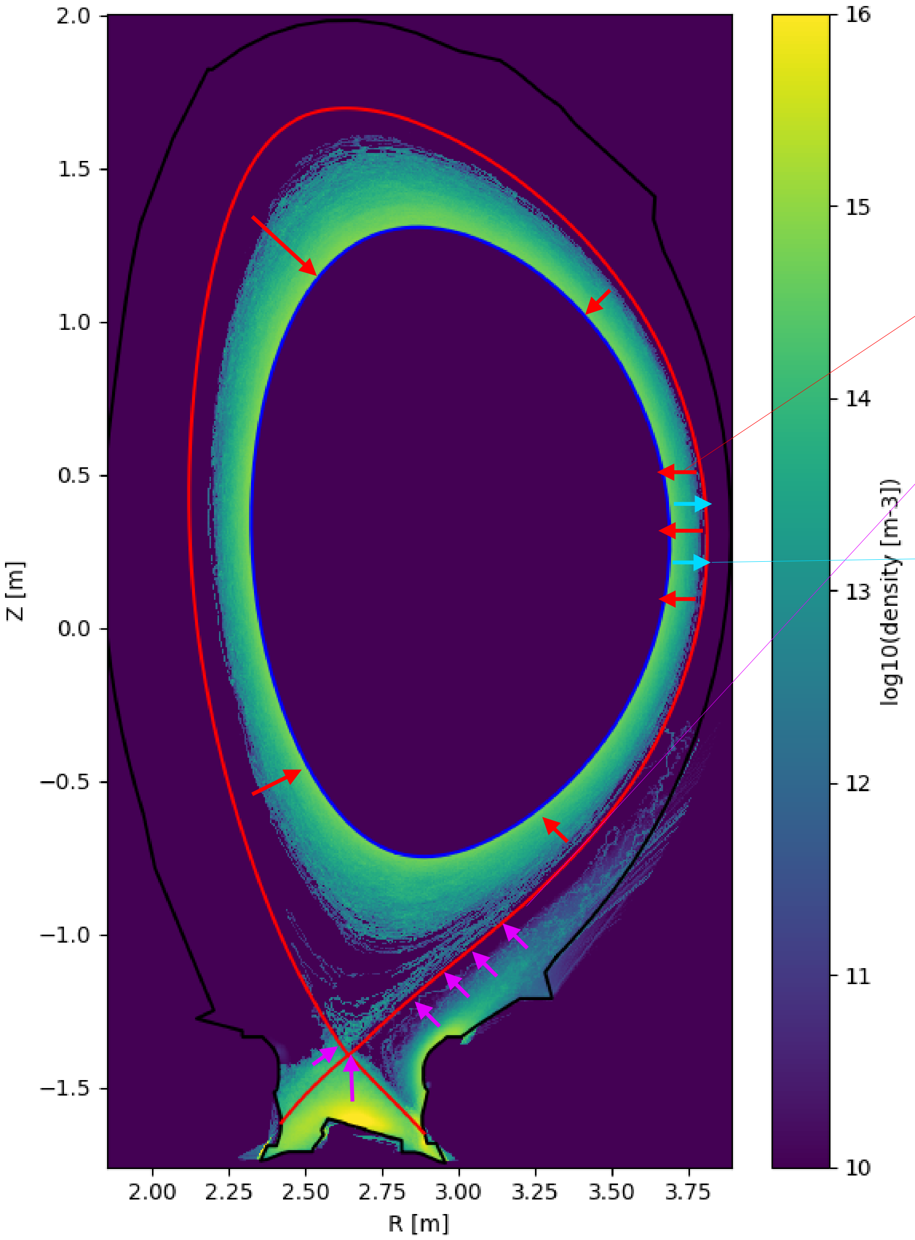


Inward neoclassical pinch (∇n_i)

W erosion and transport predicted by ERO2.0

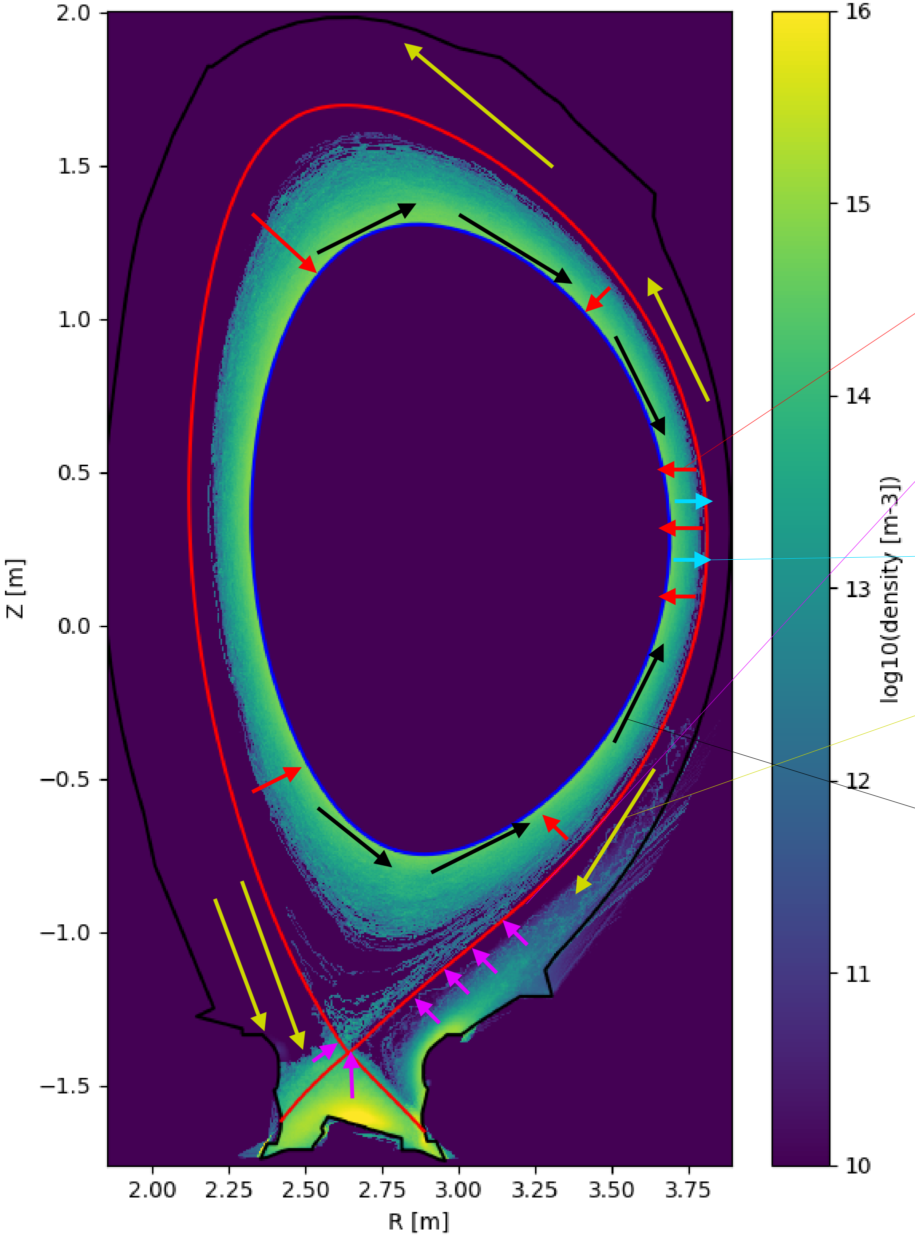


Inward neoclassical pinch (∇n_i)

Inward diffusion (∇n_W)

Outward diffusion (∇n_W)

W erosion and transport predicted by ERO2.0



Inward neoclassical pinch (∇n_i)

Inward diffusion (∇n_W)

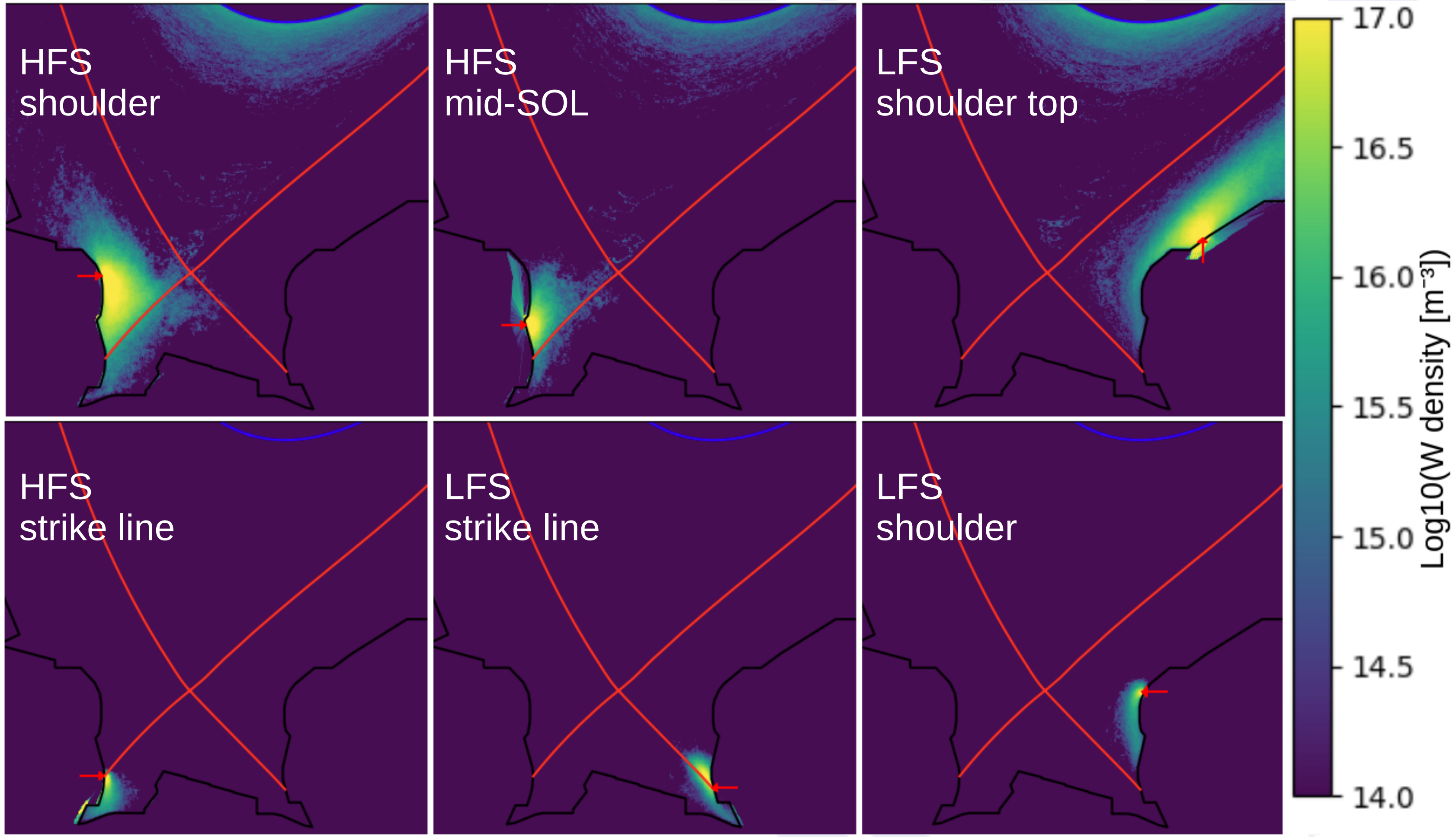
Outward diffusion (∇n_W)

Parallel-B friction (v_{par})

Centrifugal effect (rotation)

Excellent screening of W sources in the divertor

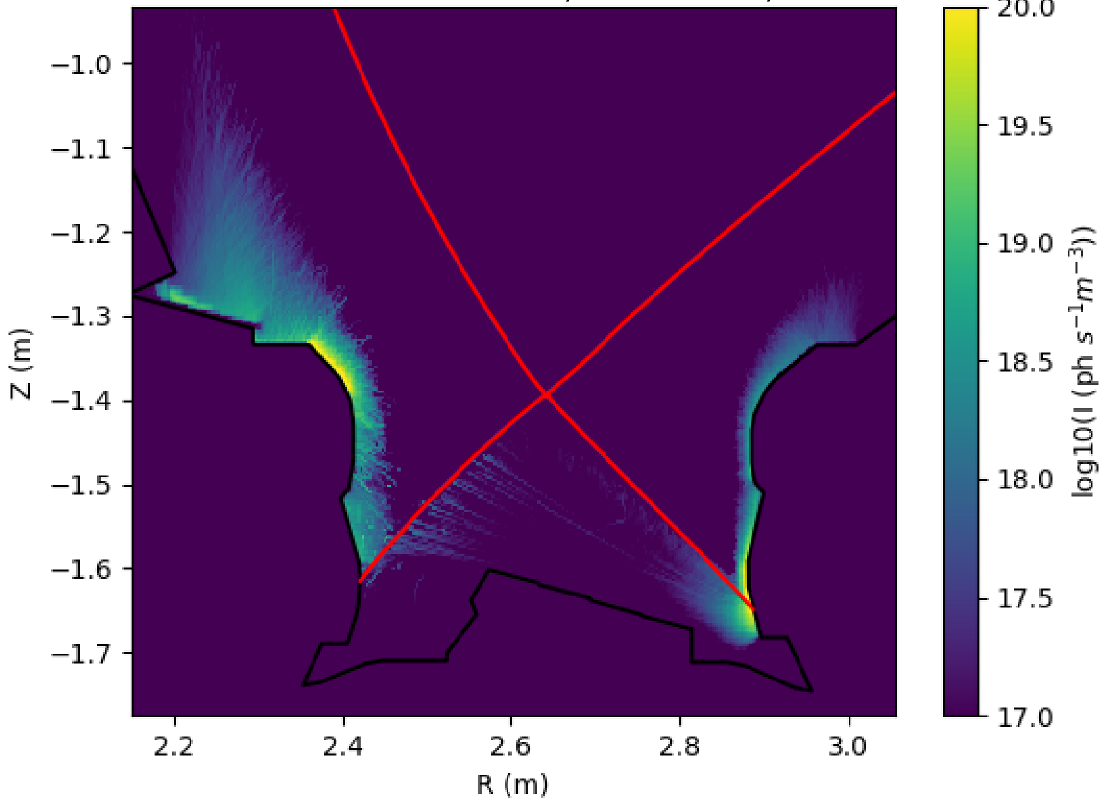
- ERO2.0 simulation study:
  erosion replaced by W point sources
  at different wall locations
- Both strike lines fully screened due to friction with main ion flow
- Weakest W screening above the divertor shoulders, esp. on the LFS (low n_e & T_e, long W^0 mean free path)
- Placing the W source at the mid-plane separatrix causes factor of > 2000 higher core W density than the divertor locations



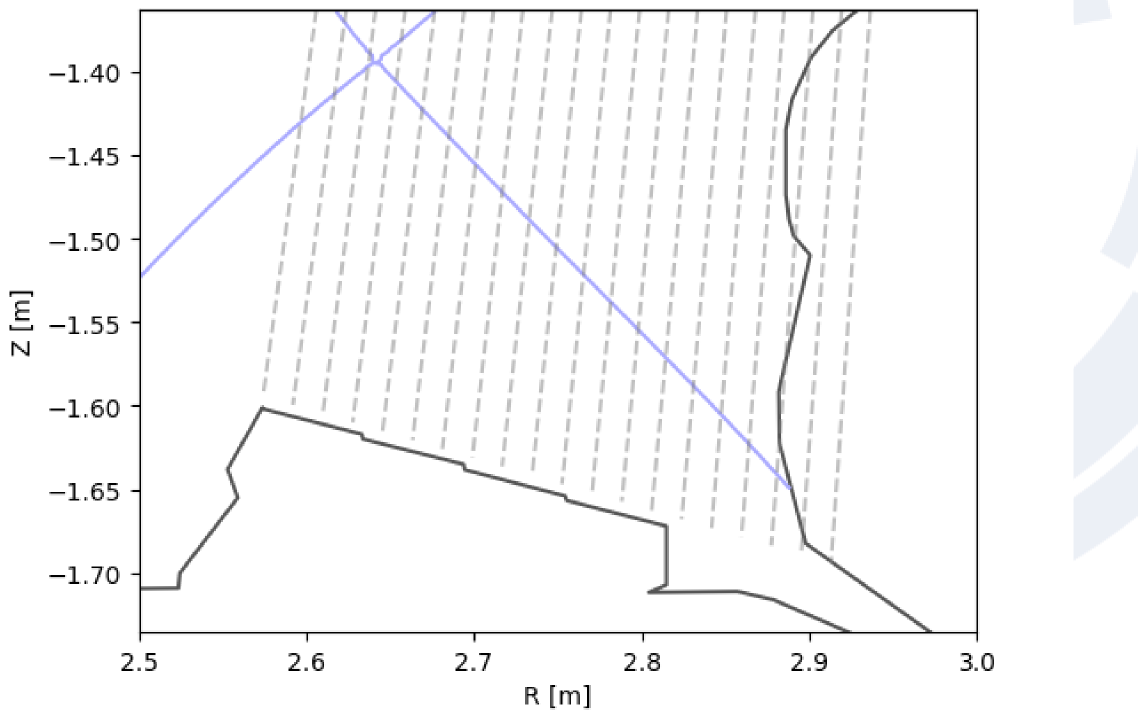
Validation of ERO2.0 W erosion sources (W I emission)

- ERO2.0 calculates emission profiles and synthetic spectrometer data from neutral W trajectories
- Spectrometer view of LFS strike point obstructed by divertor shoulder → measured W I light mostly reflections

W I line emission, 400.9 nm, ERO2.0



LOS-integrated W I emission, no photon reflections in ERO2.0



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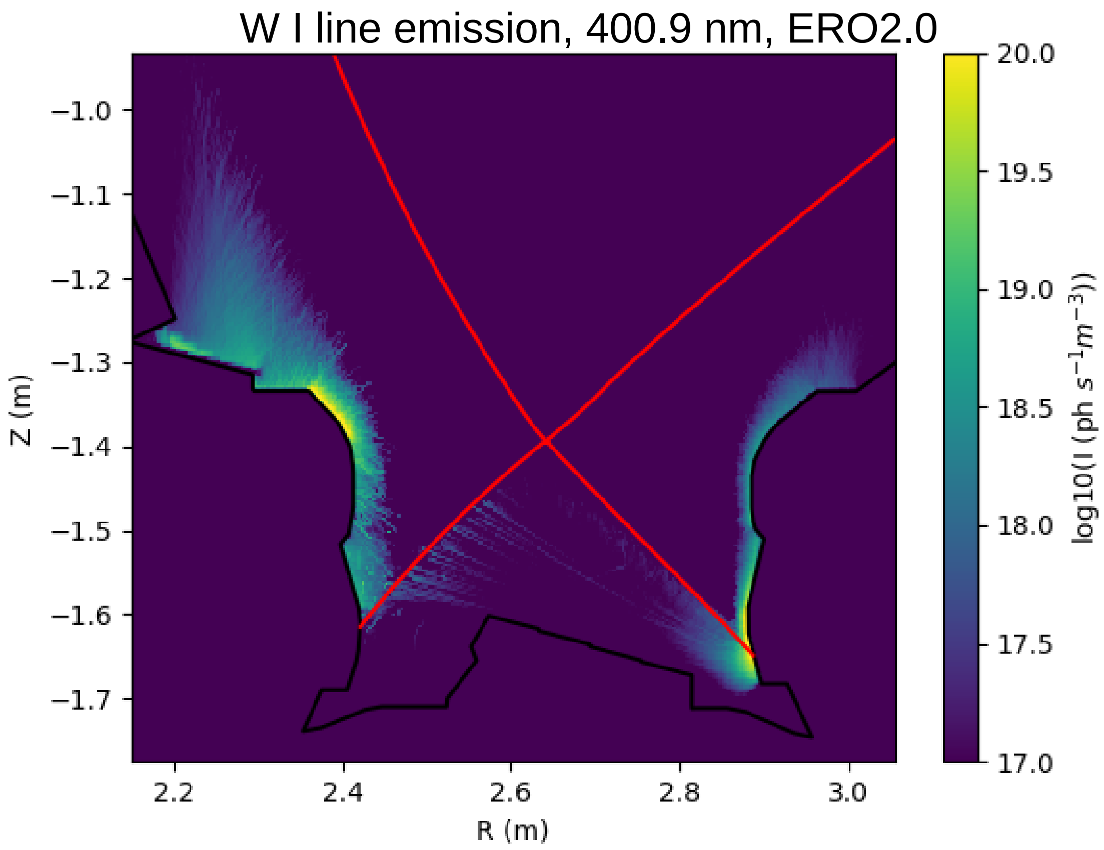

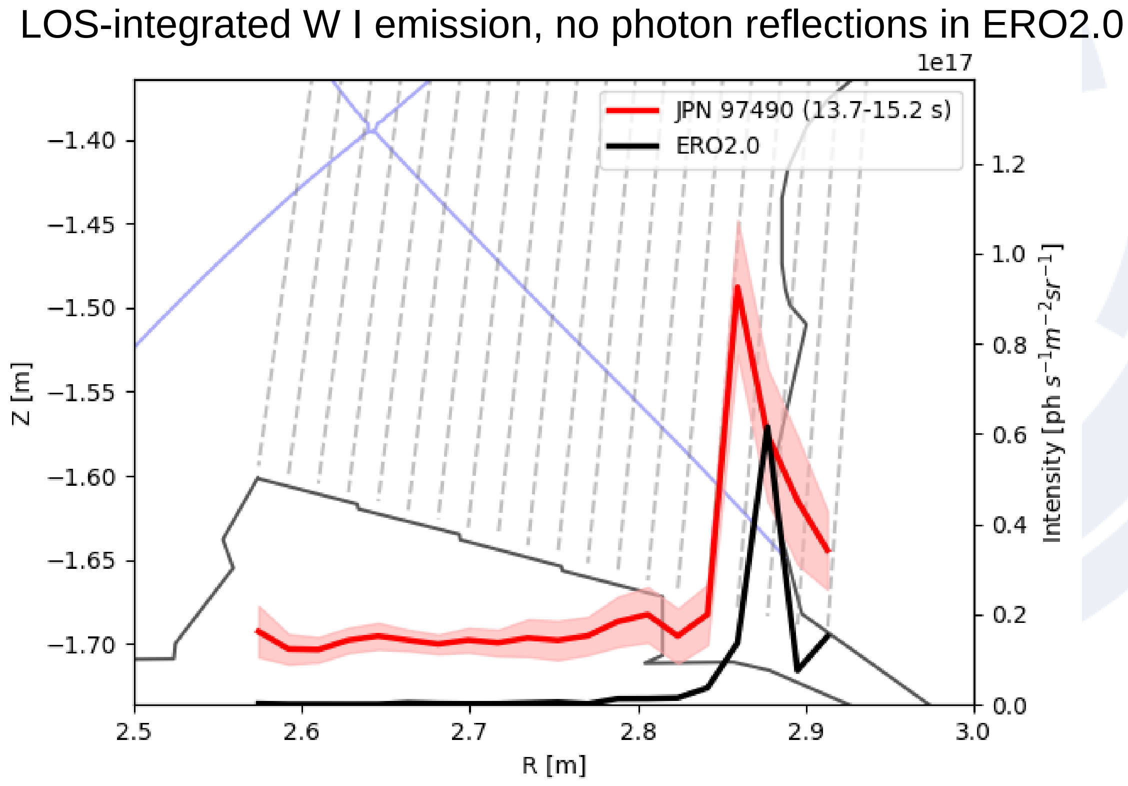

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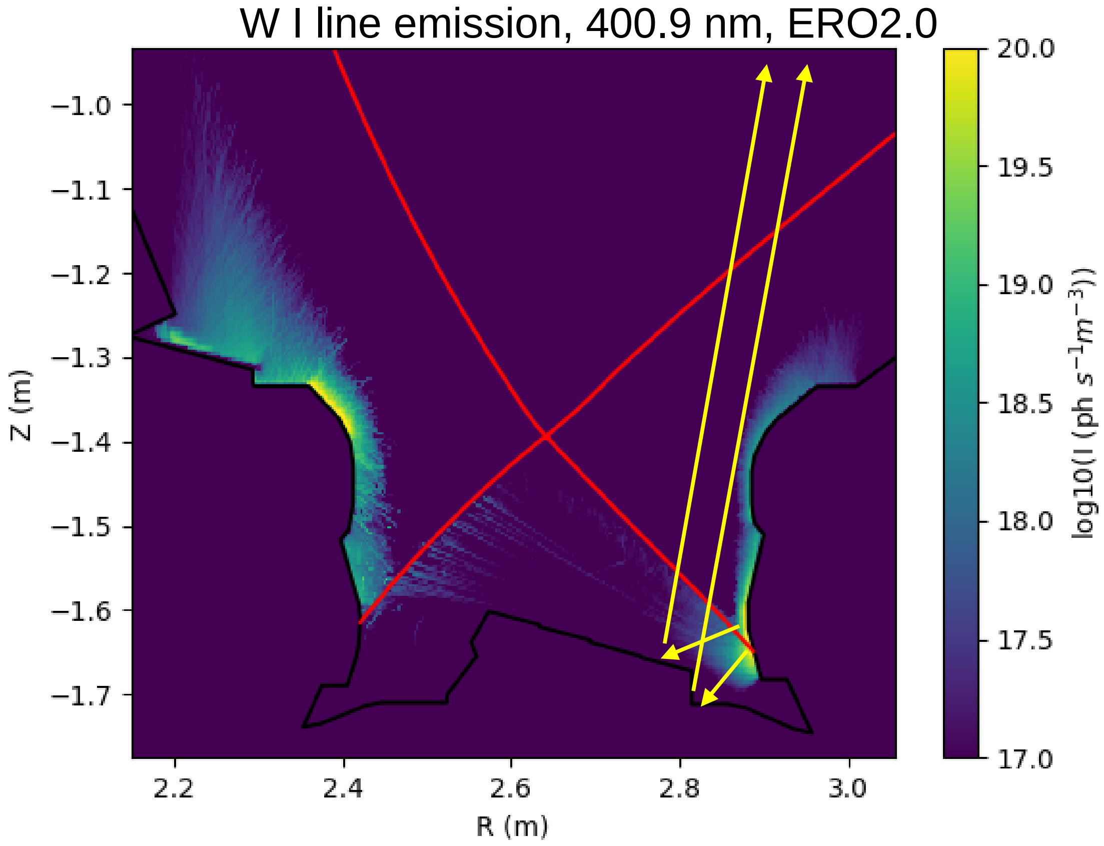
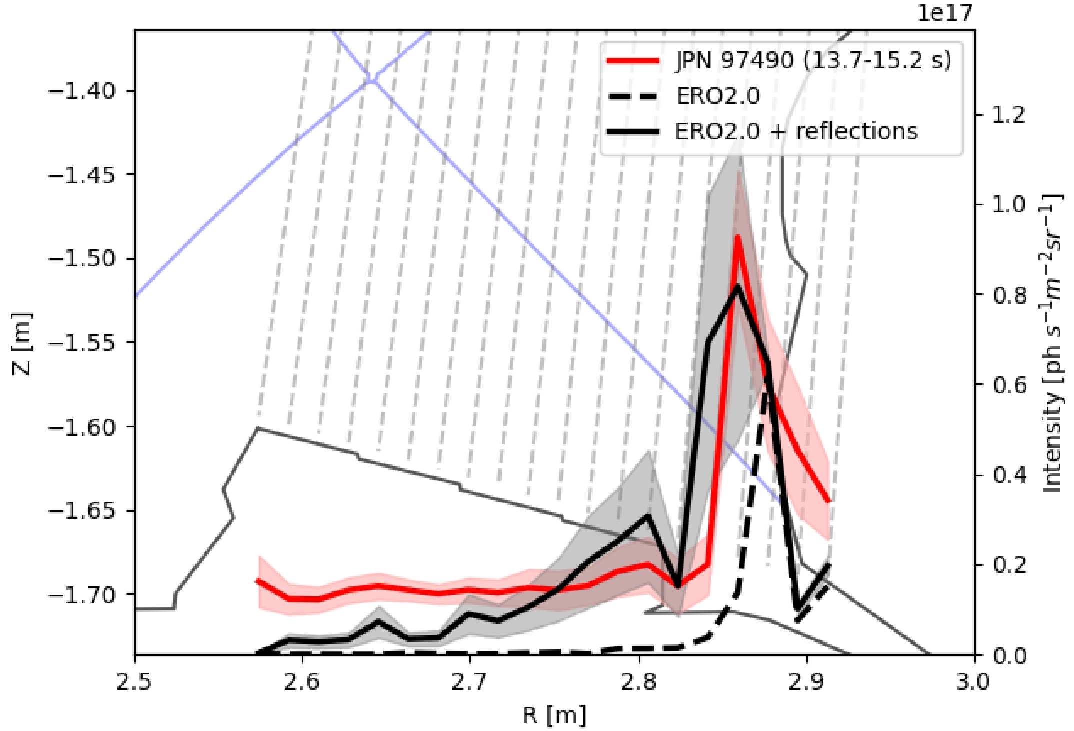
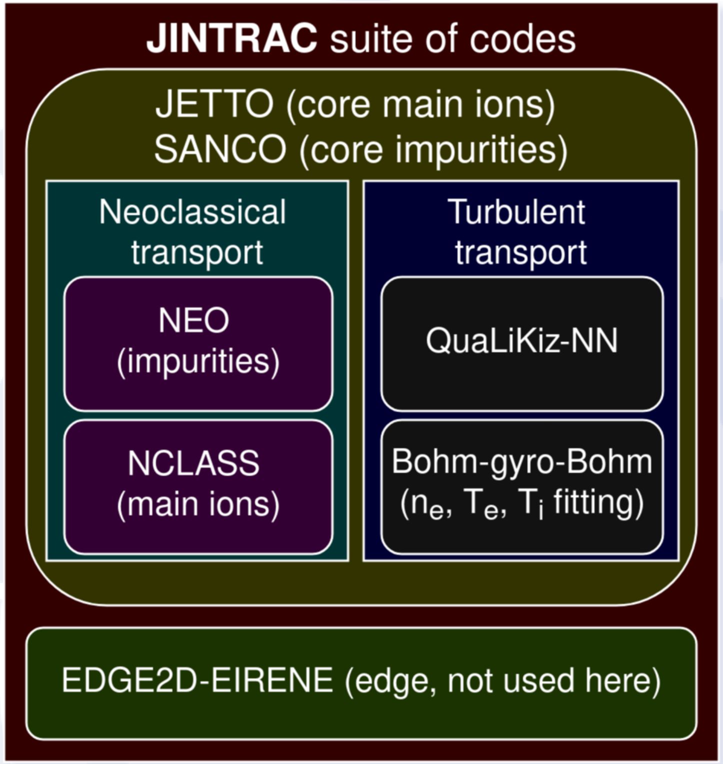


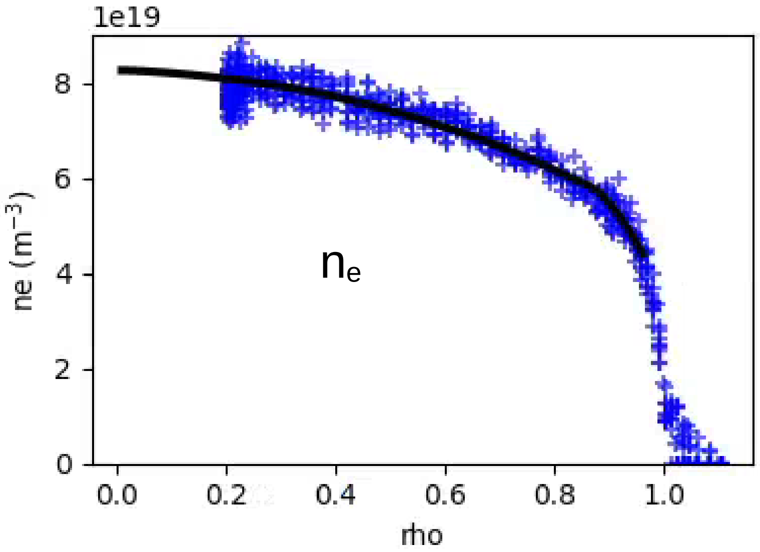


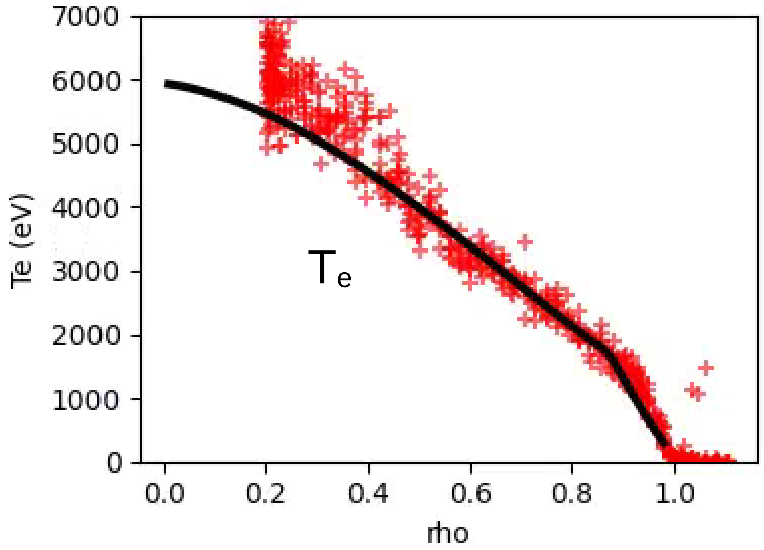
Assumed 400.9 nm reflectance at W surfaces: 0.4 +/- 0.2

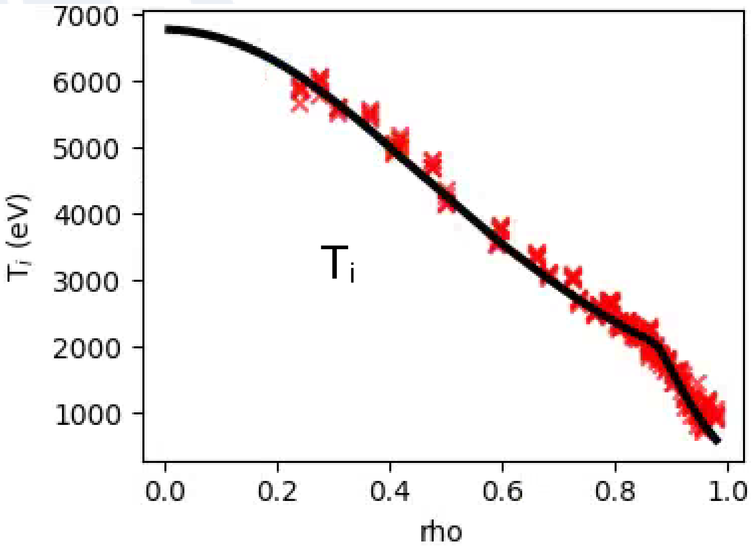
Validation of ERO2.0 + JINTRAC W transport

- JINTRAC core transport (JETTO) with Ne, Ni, W impurities (SANCO)
- Boundary condition for W to match ERO2.0 W density at the pedestal top
- n_e, T_e, T_i profiles and Ne, Ni concentrations fitted to experiment, W predicted
- Heating, radiation, current, rotation, fuelling prescribed
- Neoclassical transport (NEO / NCLASS)
- Turbulent transport (QLK-NN + ad-hoc Bohm-gyro-Bohm to match n_e, T_e, T_i)









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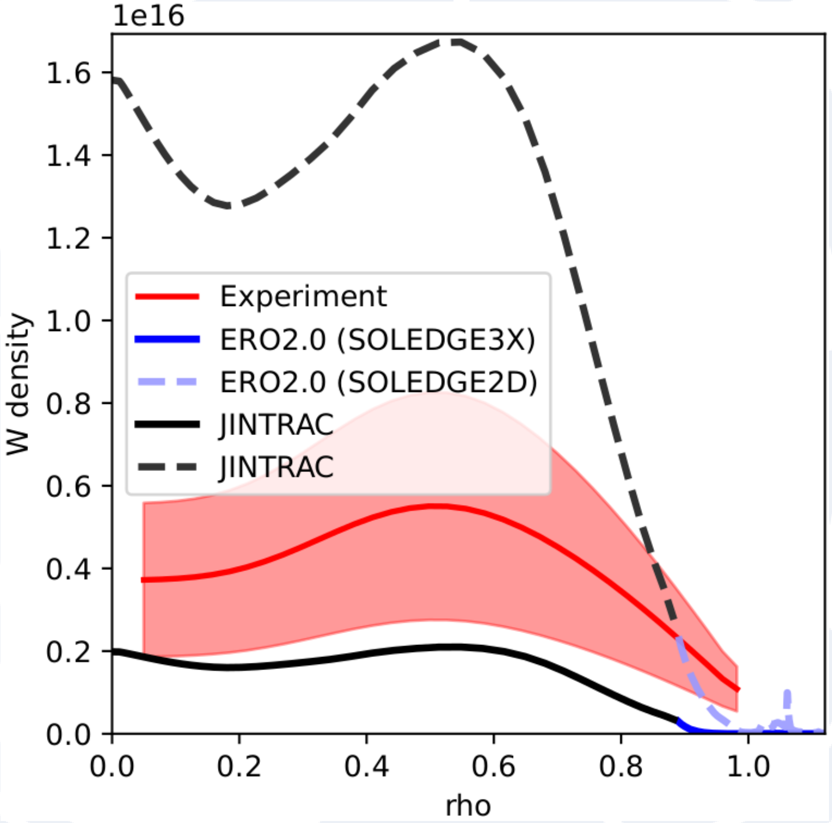
- Turbulent transport (QLK-NN + ad-hoc Bohm-gyro-Bohm to match n_e, T_e, T_i)

- W density profile more accurate with a SOLEDGE3X background (drifts) than with SOLEDGE2D (no drifts)
- W transport very sensitive to plasma profiles → uncertainty > factor of 3

W density profile, flux-surface averaged



Conclusions

- First application of ERO2.0 + JINTRAC W erosion and transport workflow to JET Ne-seeded ELM-free H-mode → W I line emission and core W density predicted within a factor of ~3

- Including photon reflections is necessary to match W I emission if coverage of main W erosion source is obstructed

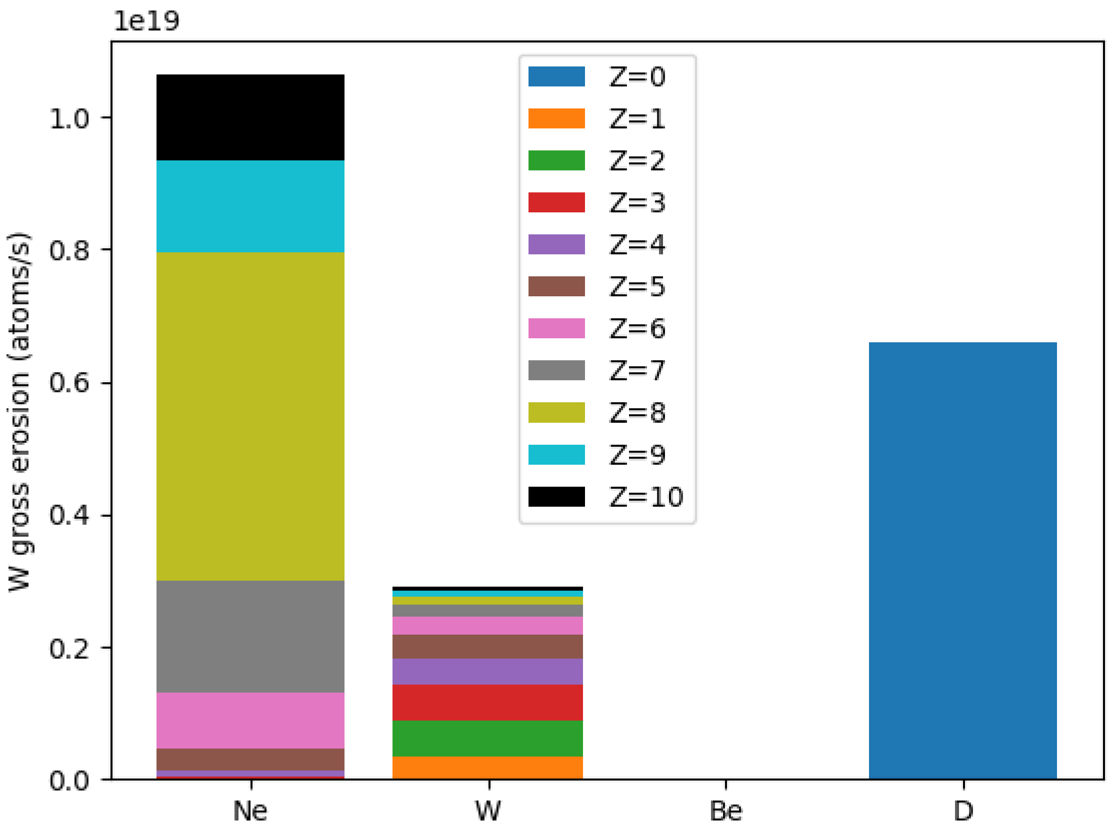
- Analysis of experiments and simulations reveals effective W accumulation control strategies:
    - Excellent divertor screening of W sputtered by Ne ions (main ion flow)
    - Wide high-density SOL → CXN attenuation → reduced W erosion by atoms
    - No W flushing by type-I ELMs required
    - W screening in the SOL vs. main plasma: contrast with JET hybrid scenario

Backup slides

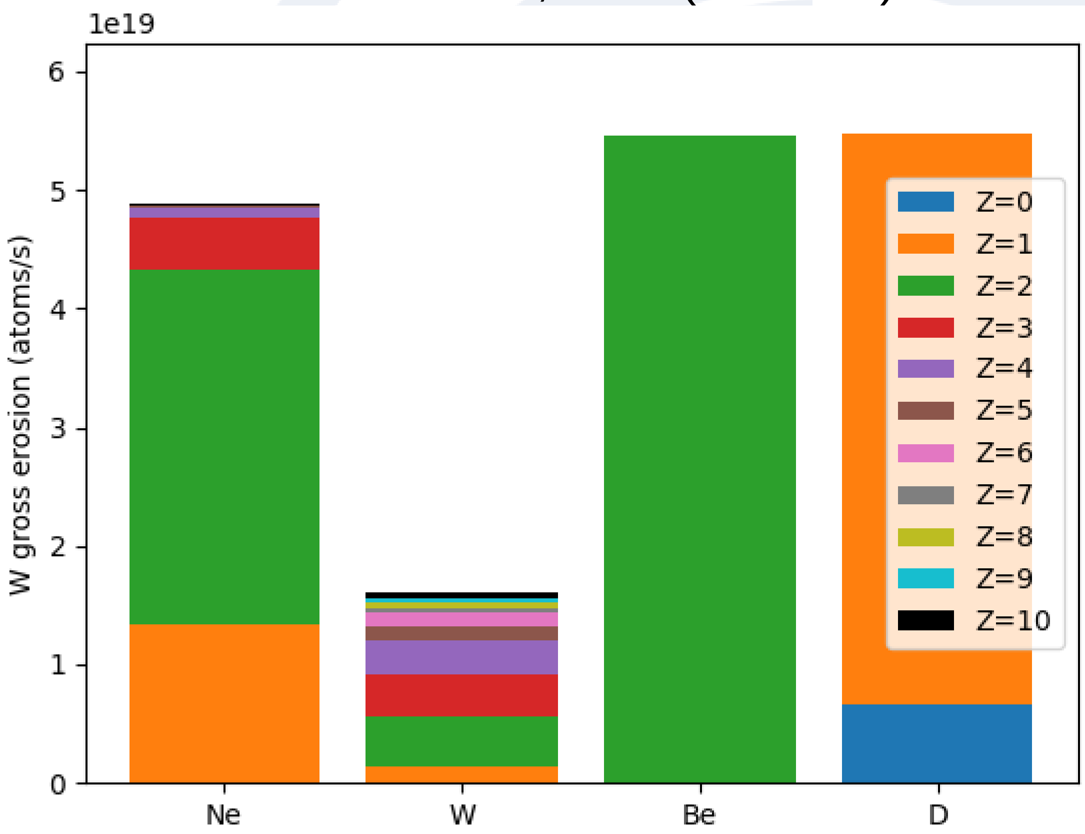
Backup slides

W sputtering rate by projectile species
ERO2.0

SOLEDGE2D, no drifts (semi-detached)

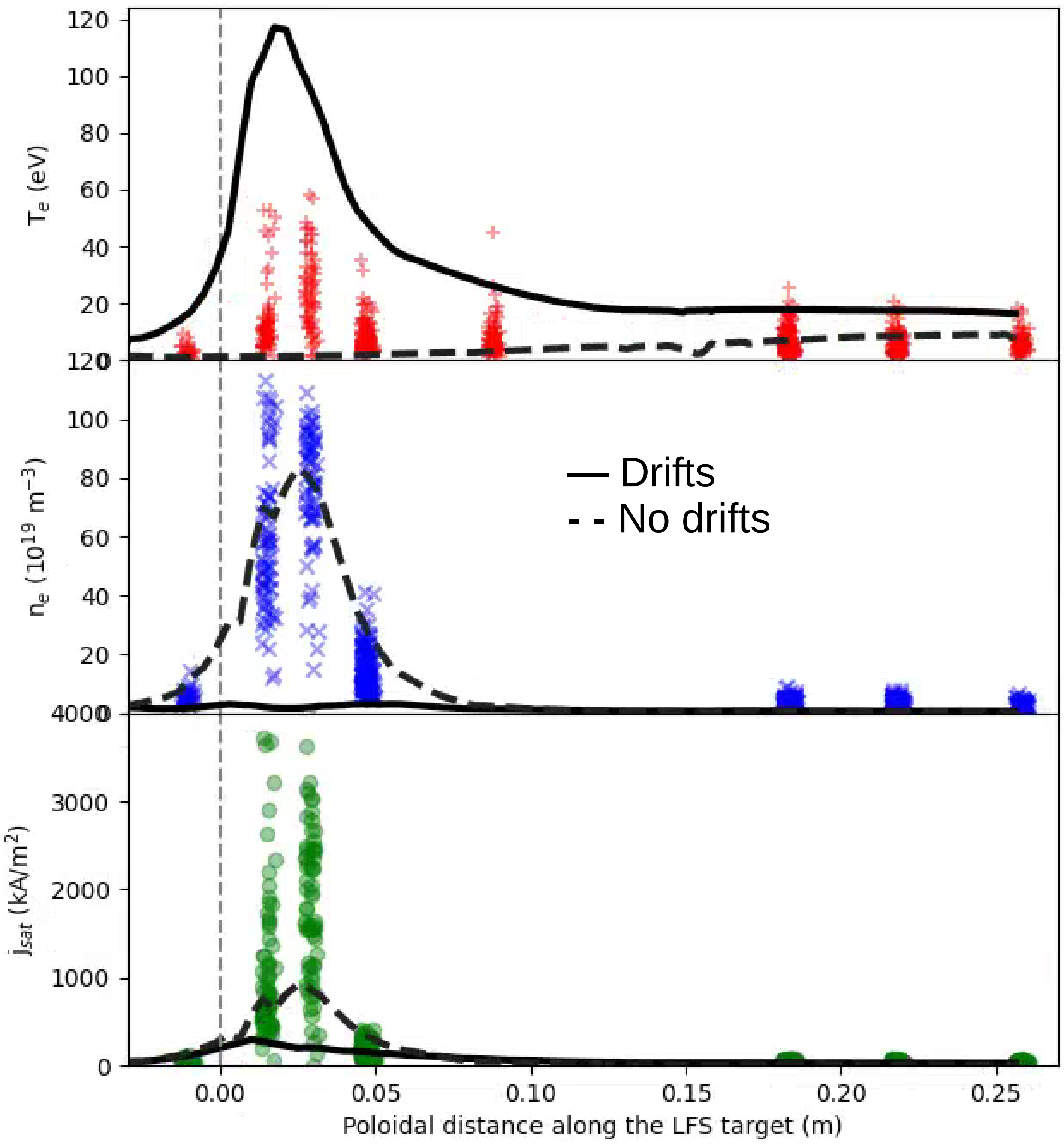


SOLEDGE3X, drifts (attached)



Assumptions:
0.5% Be^{2+}
Same Ne flux and charge in both cases

Backup slides



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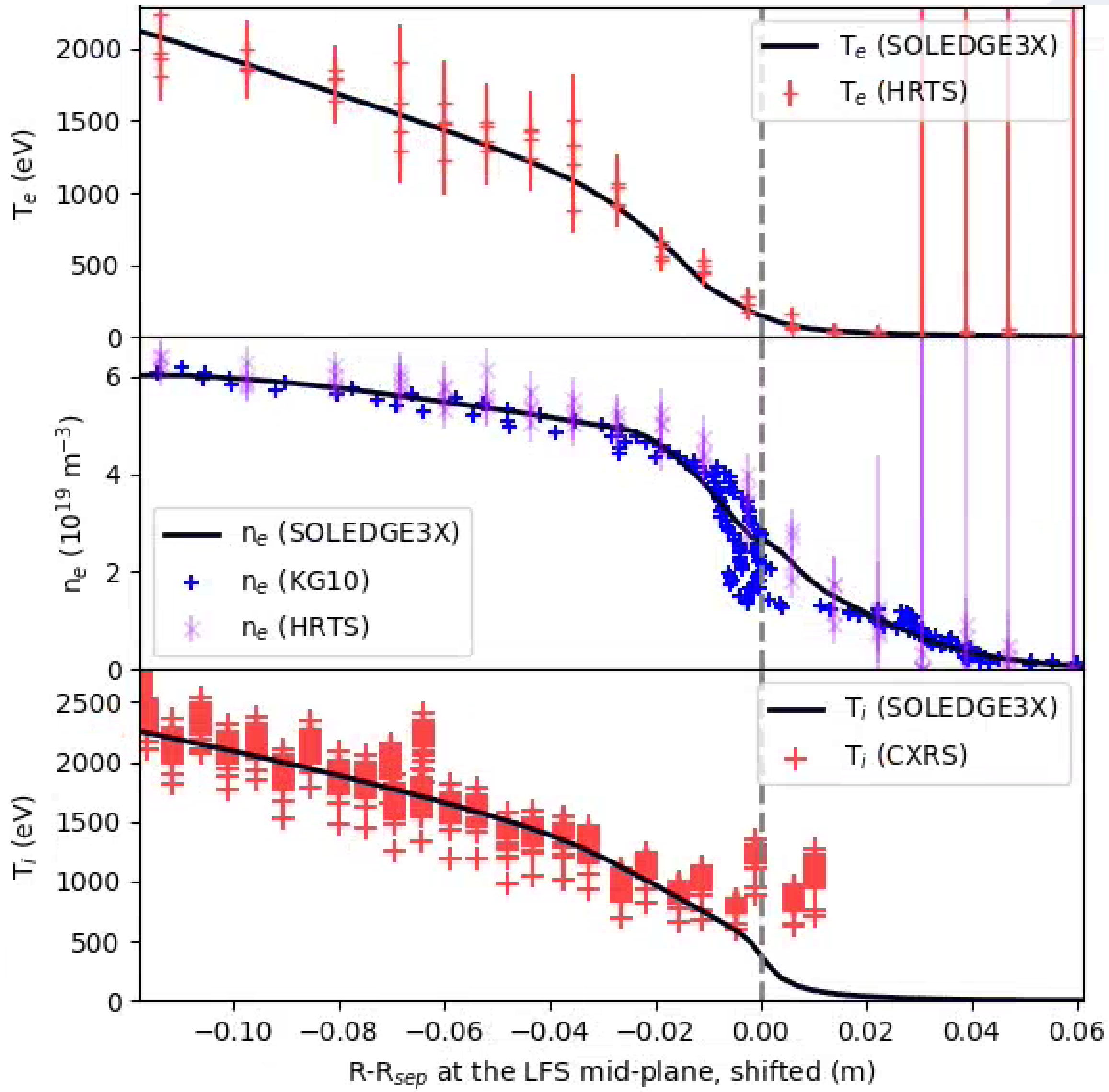

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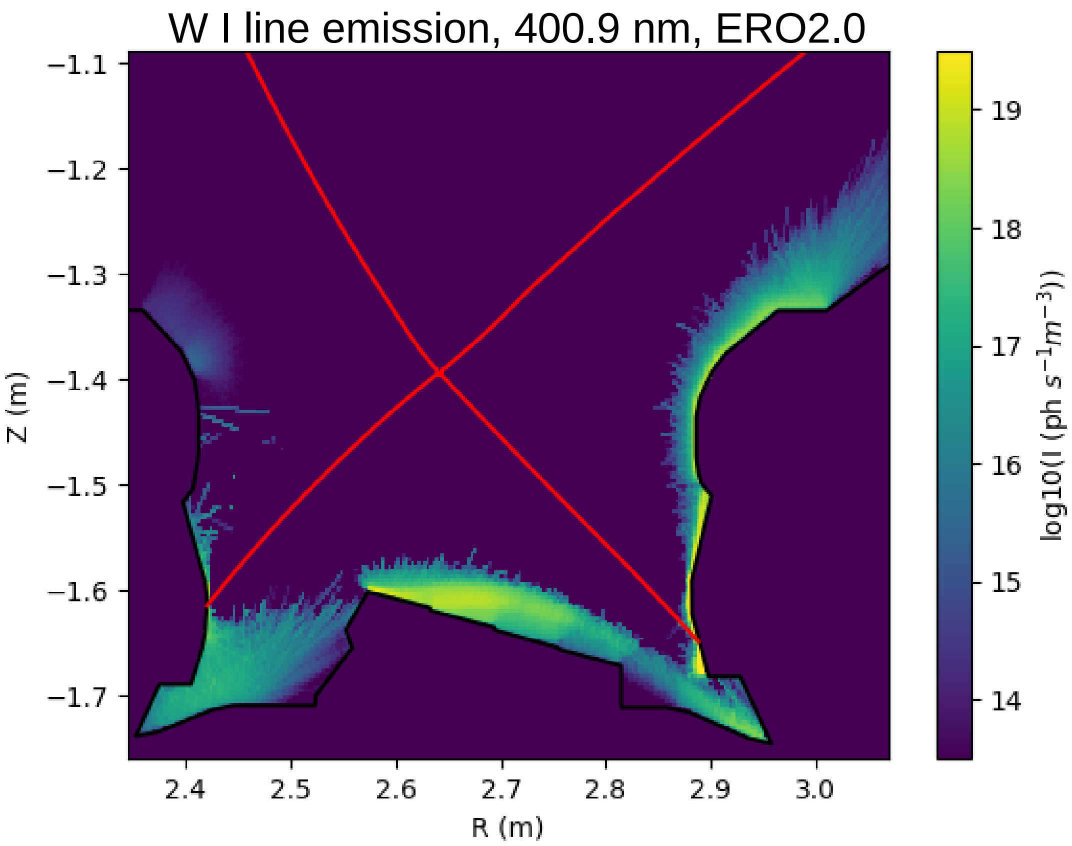

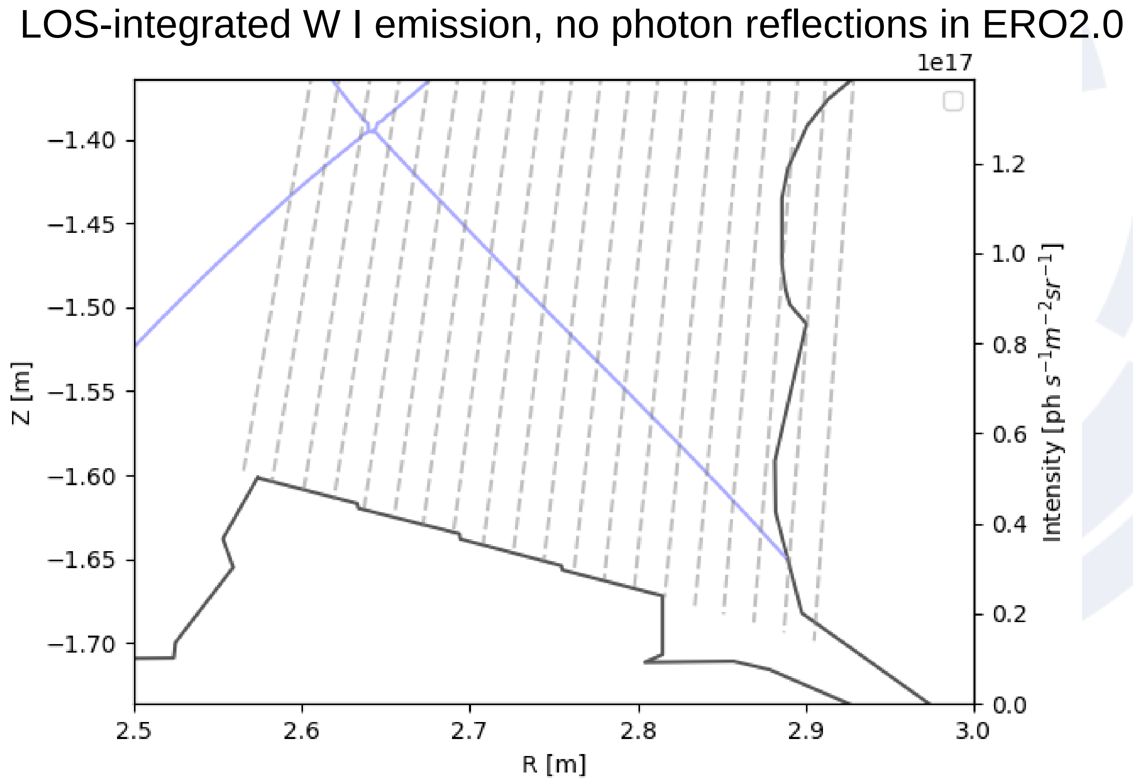

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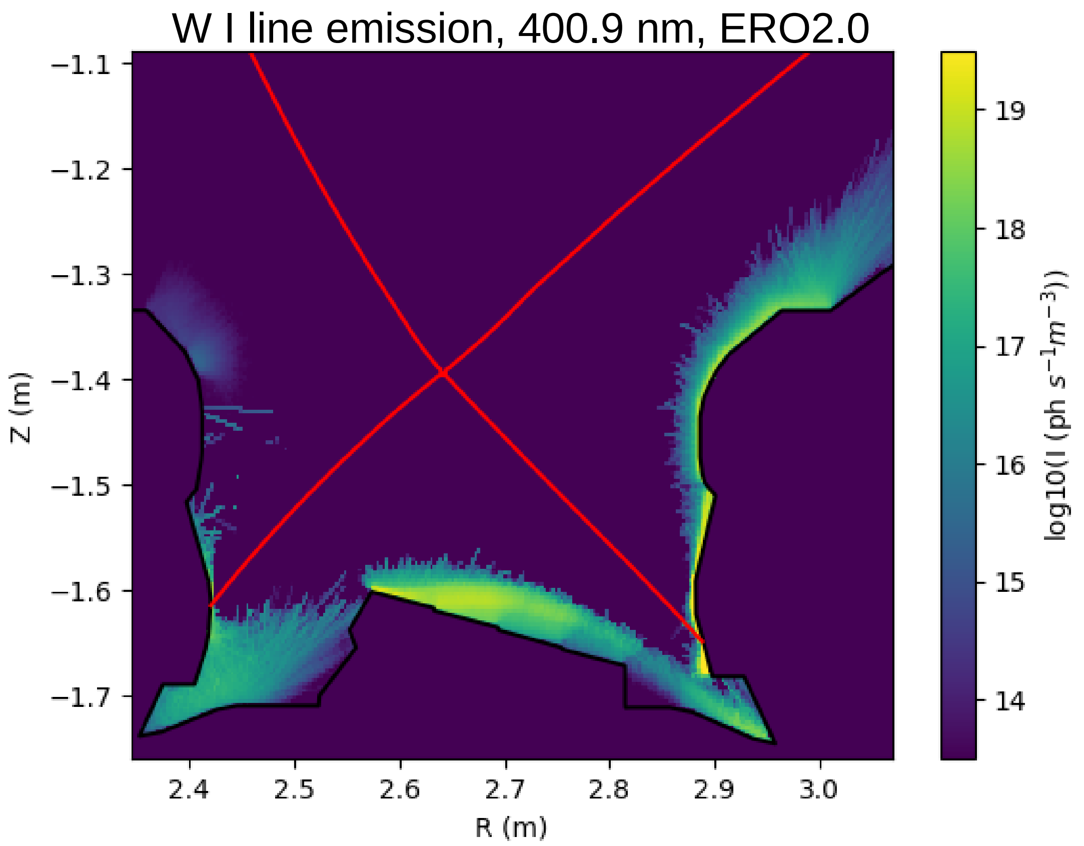

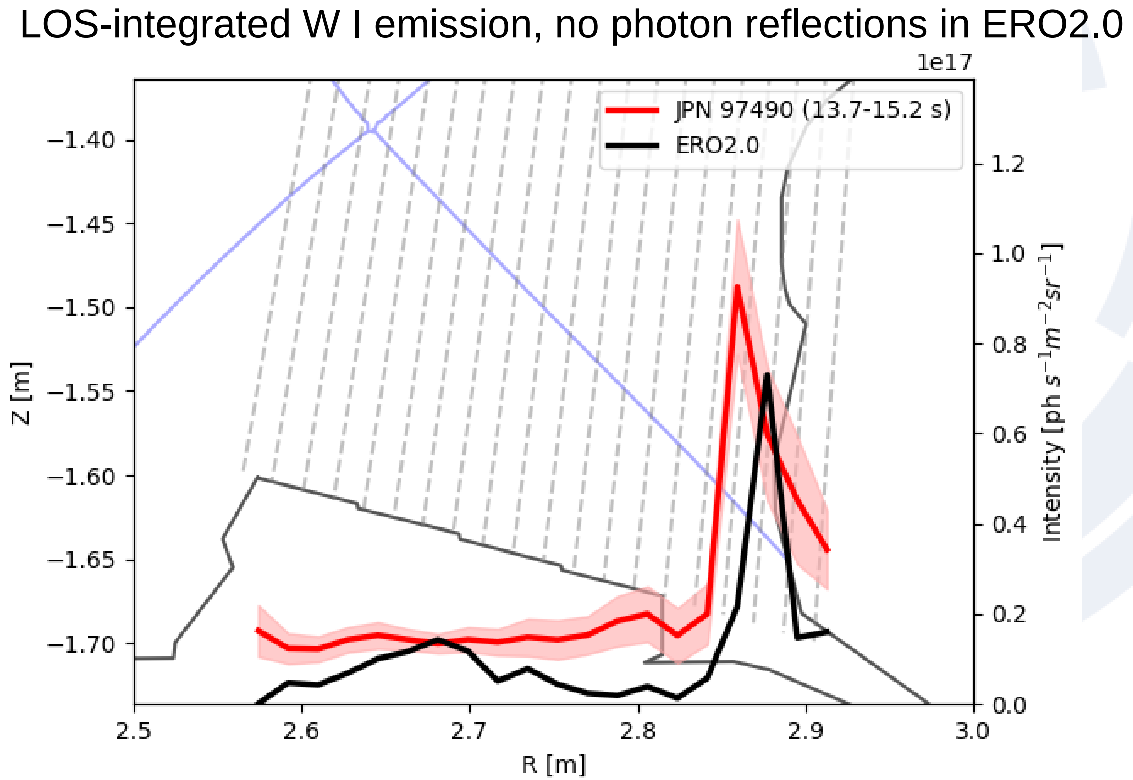

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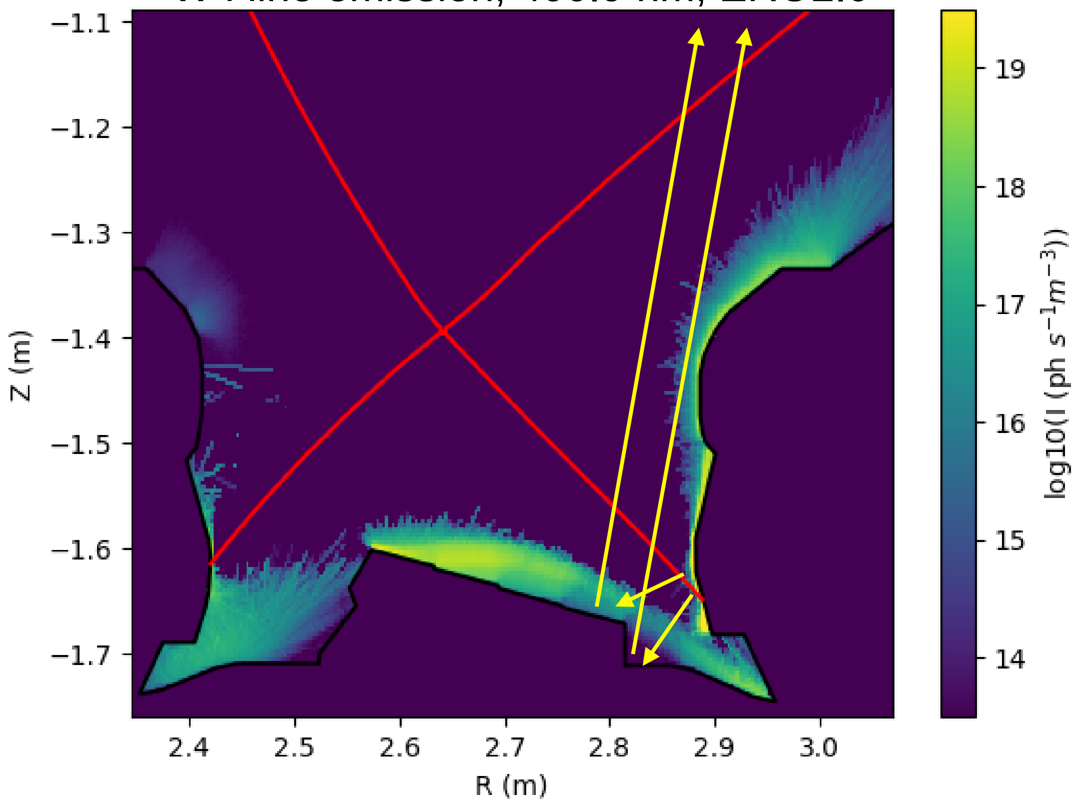
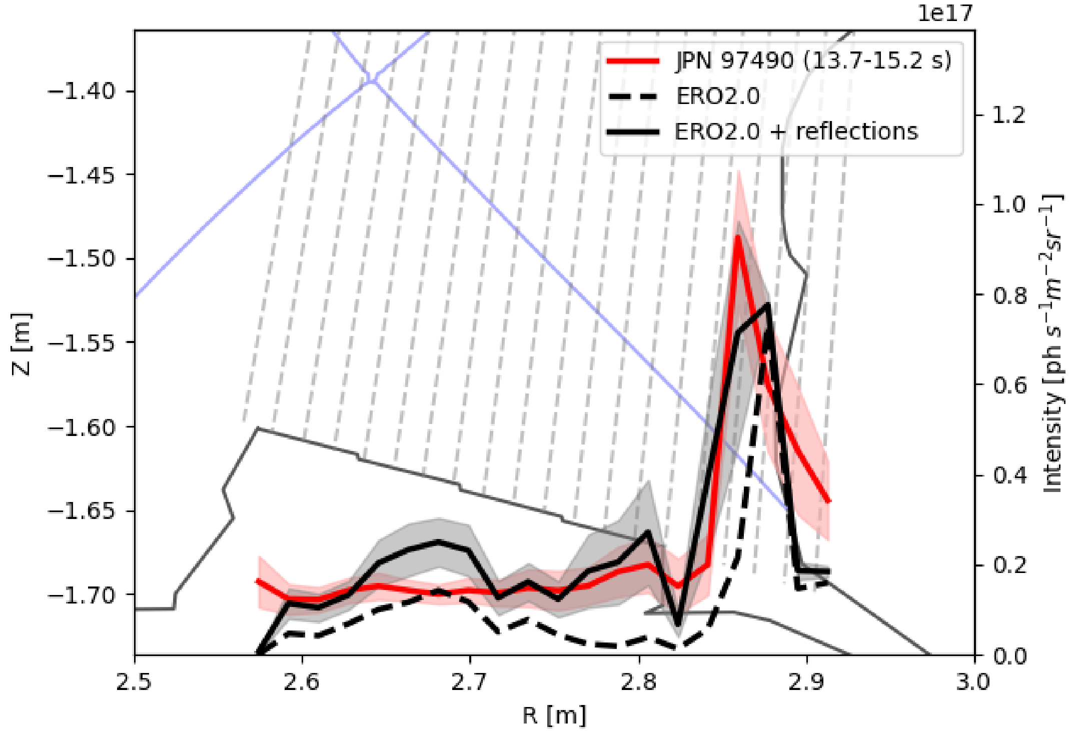
W I line emission, 400.9 nm, ERO2.0



LOS-integrated W I emission, photon reflections included



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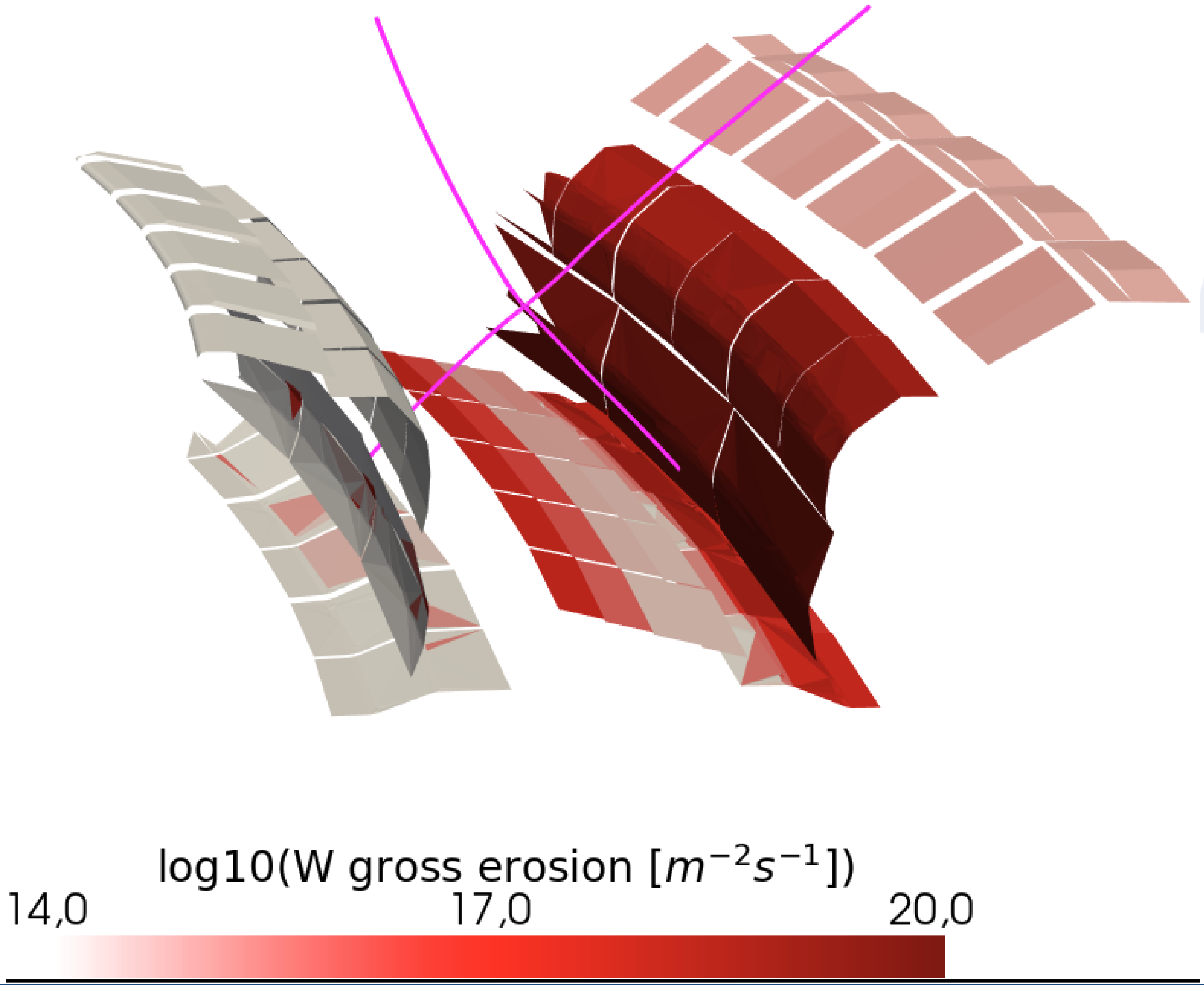
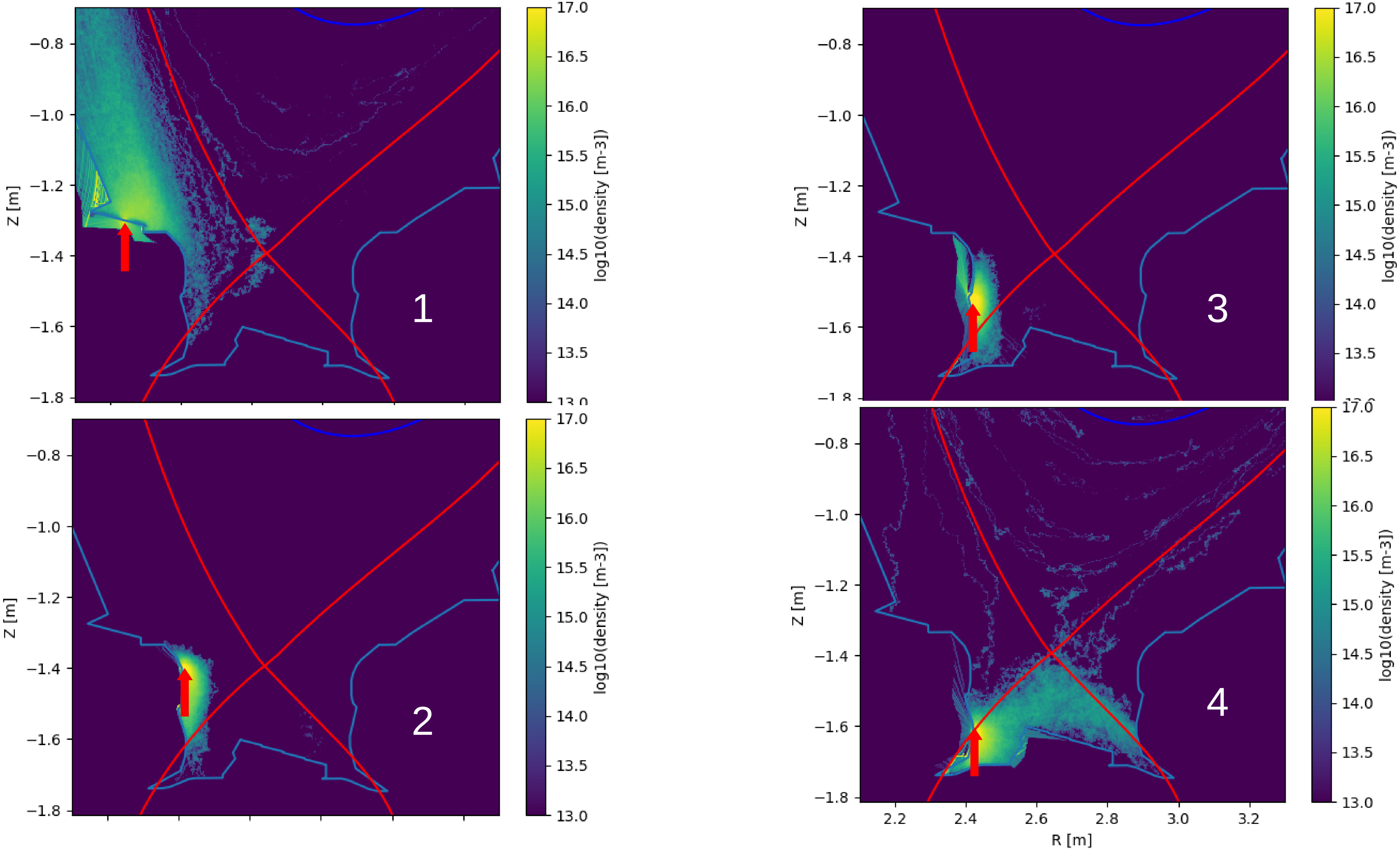
Backup slides



Contributions to W gross erosion:

Ne, Be, D ions: 87% ($1.5*10^{20}$/s)
W ions: 9% ($1.6*10^{19}$/s)
D atoms: 4% ($6.6*10^{18}$/s)



1
2
3
4
Z [m]
R [m]
log10(density [m-3])
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
2.2
2.4
2.6
2.8
3.0
3.2
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13.5
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15.5
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16.5
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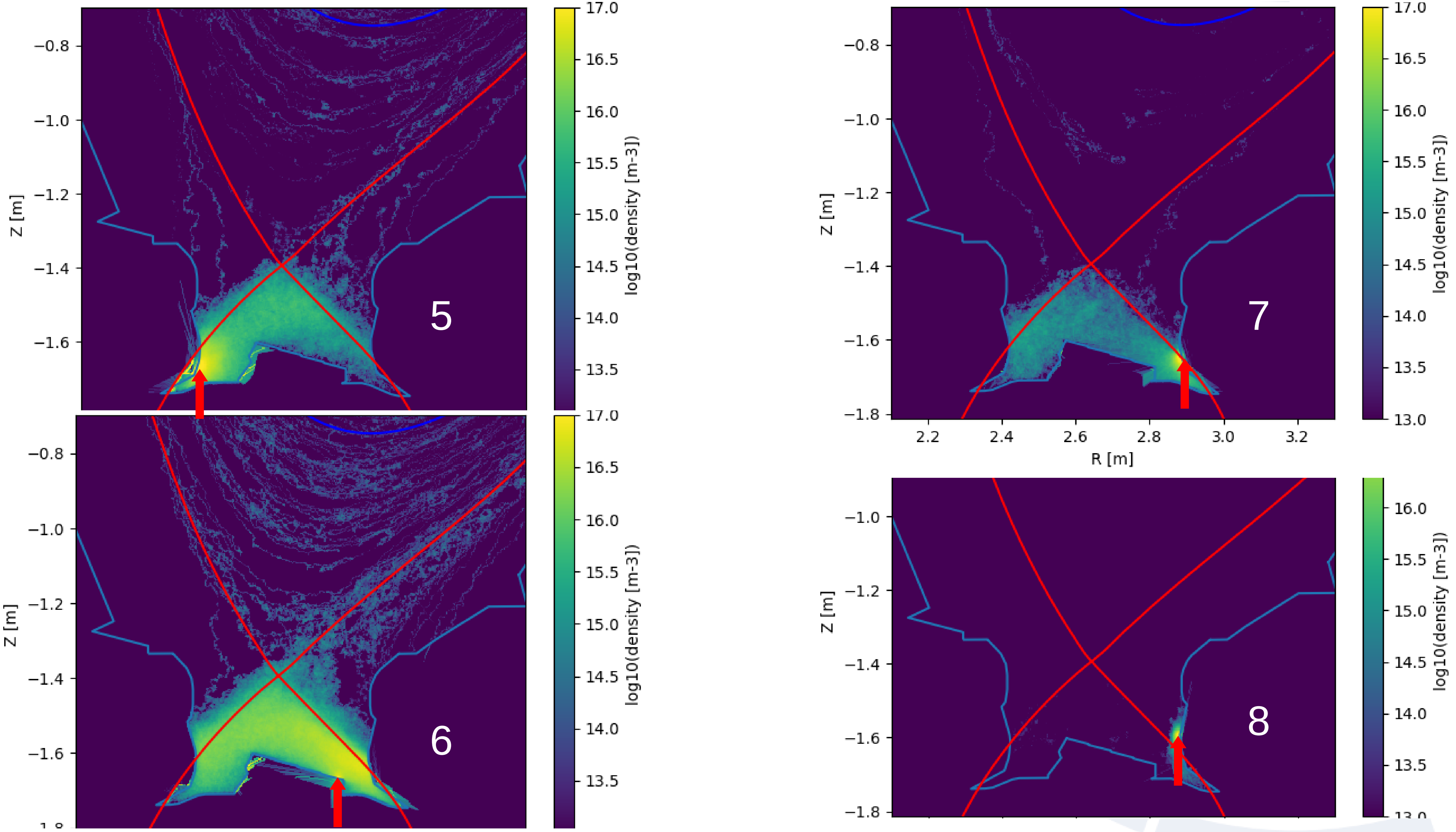
5
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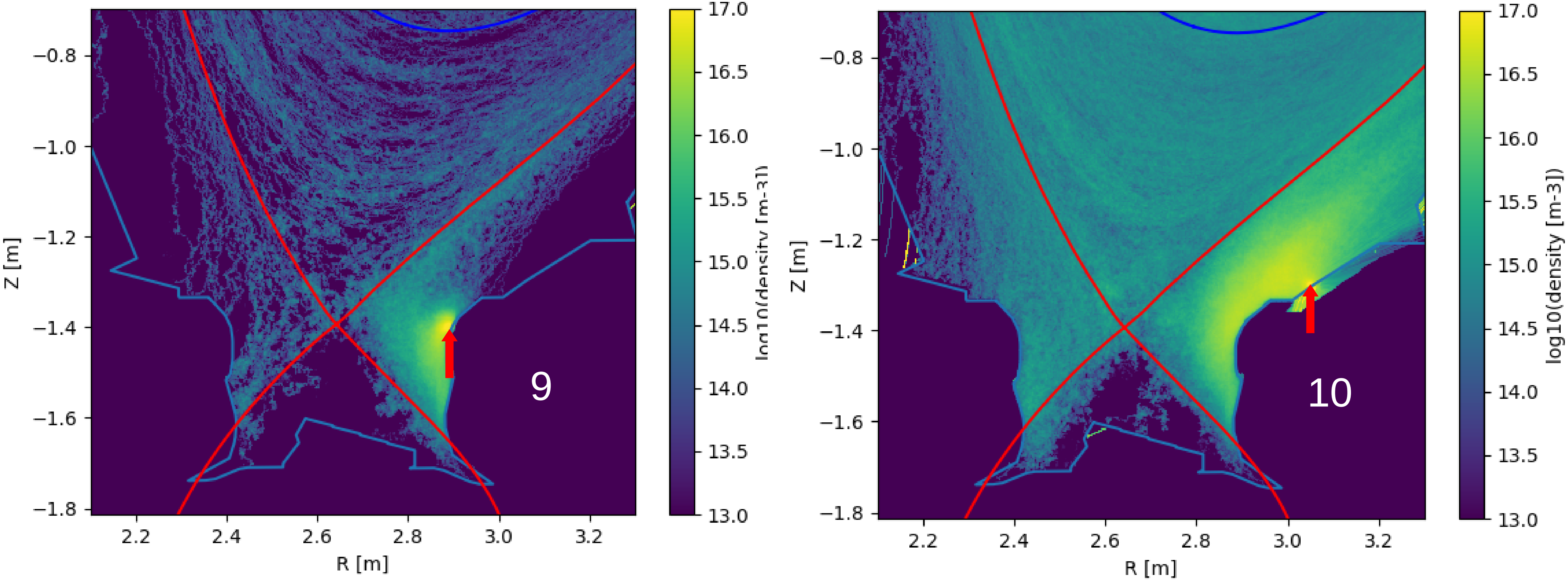
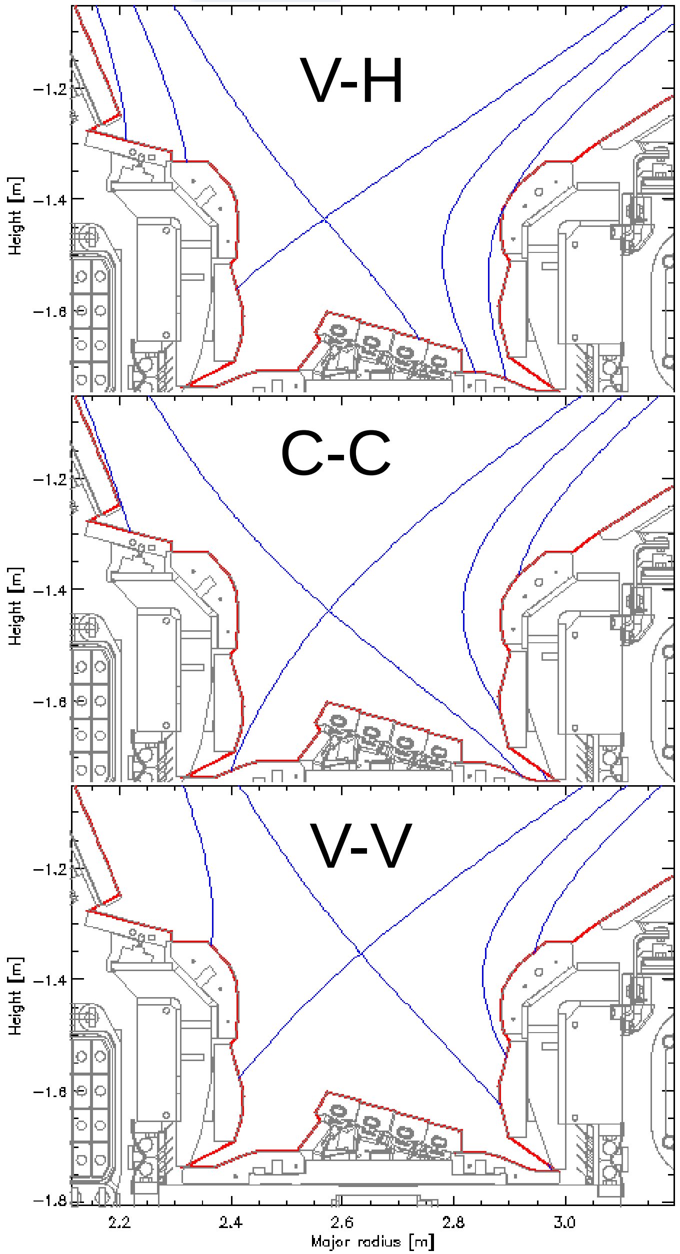
Backup slides



Backup slides

- Earlier JET studies validating ERO2.0 W erosion and transport simulations [1,2]:
  - L-mode #81472, P_{aux} = 1 MW, unseeded, V-H divertor targets
  - ELMy H-mode #82486, P_{aux} = 10 MW, unseeded, V-H
  - ELMy H-mode #94606, P_{aux} = 18 MW, unseeded, V-H
  - ELMy H-mode #97781, P_{aux} = 34 MW, trace Ne, C-C (JET hybrid scenario)
- Now: **H-mode #97490, no ELMs, P_{aux} = 34 MW, Ne seeding, V-V** (JET ITER baseline)



[1] H.A. Kumpulainen et al. NME 2022
[2] H.A. Kumpulainen et al. PPCF 2024