A+M data for validation of tungsten erosion and transport simulations: current status and prospects

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Decennial IAEA Technical Meeting on Atomic, Molecular and Plasma-Material Interaction Data for Fusion Science and Technology (AMPMI 2024)
18 July 2024

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.

Outline

- Predictive modelling of W erosion and edge+core transport in JET, L-mode and ELMy H-mode
- Role of atomic and PWI data in W transport simulations
- Comparison of simulations and W spectroscopy in the JET divertor
- Predicted and measured core plasma W density and radiated power
- Prospects for further studies

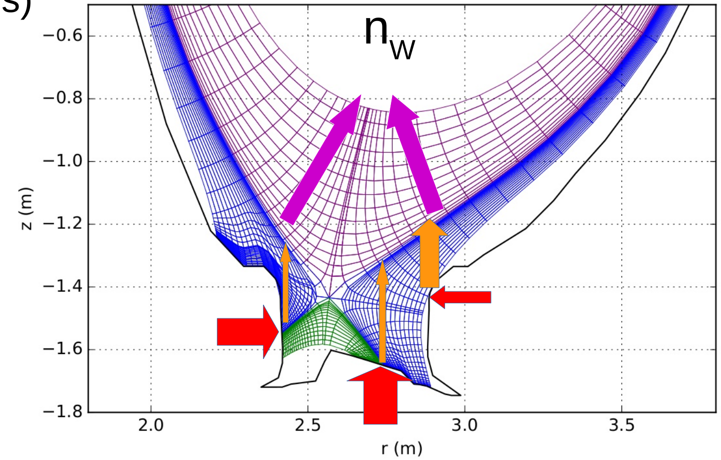
Motivation: understand and predict W erosion and transport by studying a set of JET-ILW plasmas

- How accurate is the predicted W density in the core plasma, if the plasma conditions are known with some uncertainty?

  → Separate the accuracy of the W transport model from uncertainties in the background (BG) plasma

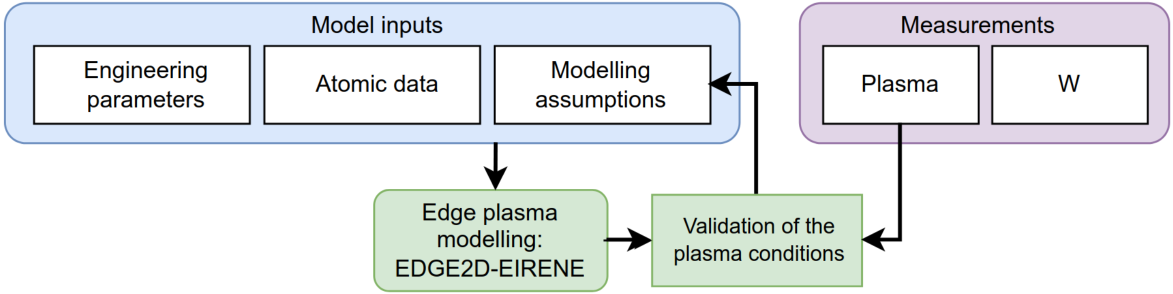
- When BG plasma measurements are available, the predicted W density is affected by:
  - **BG plasma conditions** (measurement coverage & uncertainties)
  - **W erosion** and **edge transport** (here, ERO2.0 in 3D)
  - **W core transport** (here, JINTRAC)

- In future machines or unexplored plasma scenarios, significantly higher uncertainty is expected for the W density due to uncertain predicted plasma conditions



While the plasma conditions are fitted to experiment, W transport is predictive

- The plasma conditions are simulated in EDGE2D-EIRENE [1] (JINTRAC [2]) by adjusting uncertain parameters to optimise agreement with measurements



Model inputs

Engineering parameters

Atomic data

Modelling assumptions

Measurements

Plasma

W

Edge plasma modelling: EDGE2D-EIRENE

Validation of the plasma conditions

[1] R. Simonini et al., CPP 34 368-373 (1994)
[2] M. Romanelli et al., Plasma Fusion Res. 9 3403023 (2014)
[3] J. Romazanov et al., NME 18 331-338 (2019)
[4] F. Casson et al., NF 60 066029 (2020)
[5] H. Kumpulainen et al., NME 33 101264 (2022)

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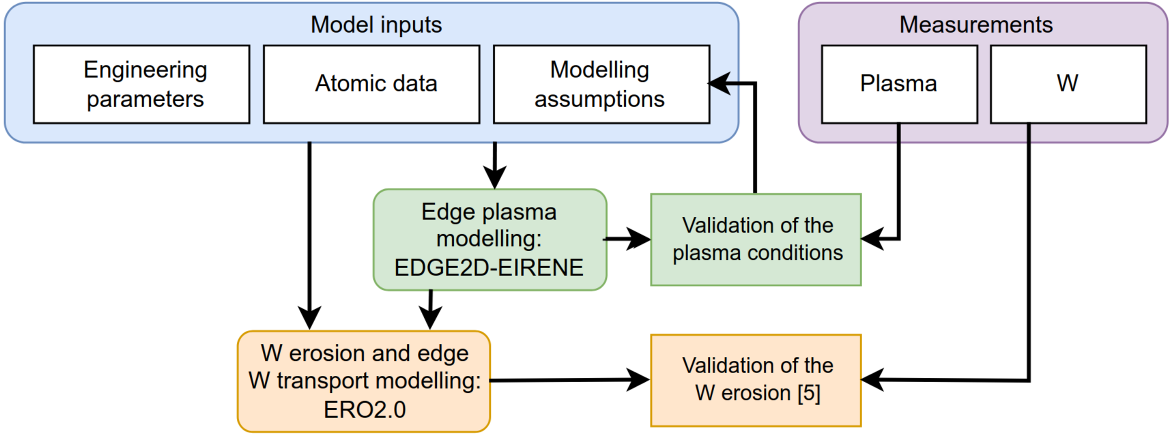

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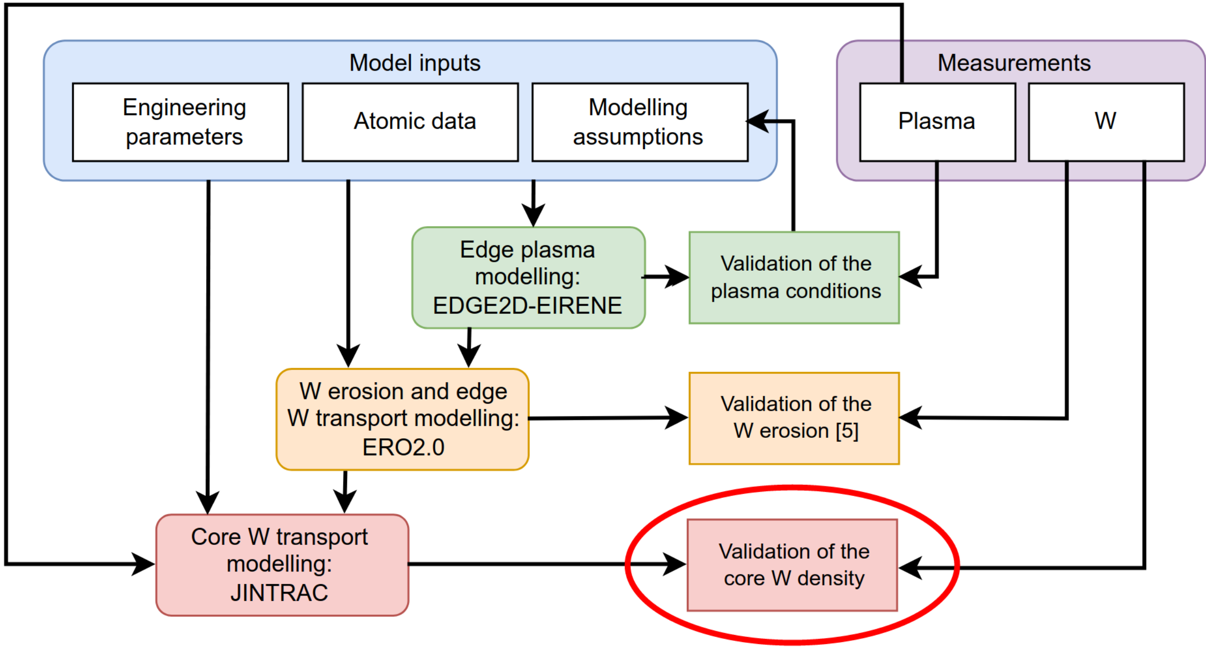
- W erosion and edge transport is predicted using ERO2.0 [3]

- The predicted W density at the pedestal top (ρ = 0.9) is used as the boundary condition for predictive W core transport simulations using JINTRAC

  → Earlier validation of JINTRAC W core transport [4] extended to cover the SOL and W erosion from ERO2.0

- No information from W diagnostics is used to fit the predictive W simulations



H. Kumpulainen et al. PPCF 2024

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[4] F. Casson et al., NF 60 066029 (2020)
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What kinds of A&M and PWI data are applied in this work?

- JINTRAC setup:
  - Background plasma diagnostics (Langmuir probes, divertor IR cameras, CXRS etc.)
  - Several atomic, molecular and PWI databases in EIRENE (D. Borodin et al. this meeting)

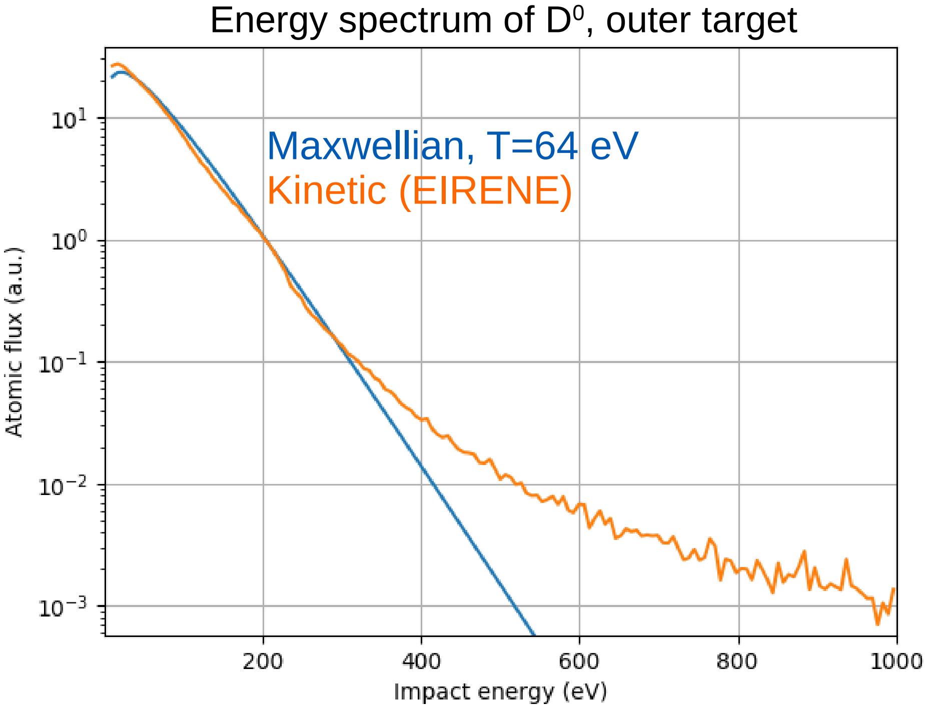
- ERO2.0 setup:
  - Effective ionisation, recombination, and photon emissivity rate coefficients from ADAS
  - Sputtering and reflection yields, and the distributions of sputtered/reflected particles from SDTrimSP
  - Surface concentration of Be at W divertor targets adjusted to match the measured Be II line emission
  - **Work in progress**: SDTrimSP database of mixed-material sputtering yields to replace interpolation of pure yields

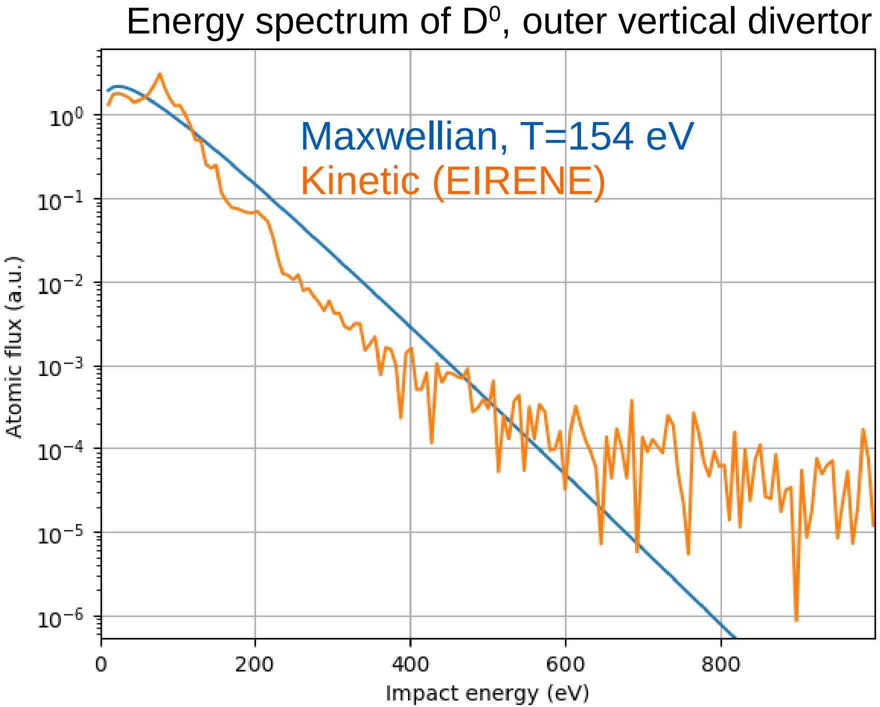
- Validation of W predictions:
  - W I & W II visible divertor spectroscopy
  - Soft X-ray and vacuum-ultraviolet W spectroscopy in the core plasma, integrated with bolometry and Z_{eff} measurements to reconstruct 2D poloidal W density profiles

Kinetic D atom impact energy spectra are calculated in EIRENE for each W surface

JPN 81472 (L-mode)

- Non-Maxwellian high-energy tail due to charge-exchange atoms causes W erosion on non-plasma-wetted surfaces
- Recently implemented EIRENE option to output bivariate energy-angular CXN distributions (ERO2.0 studies in progress)





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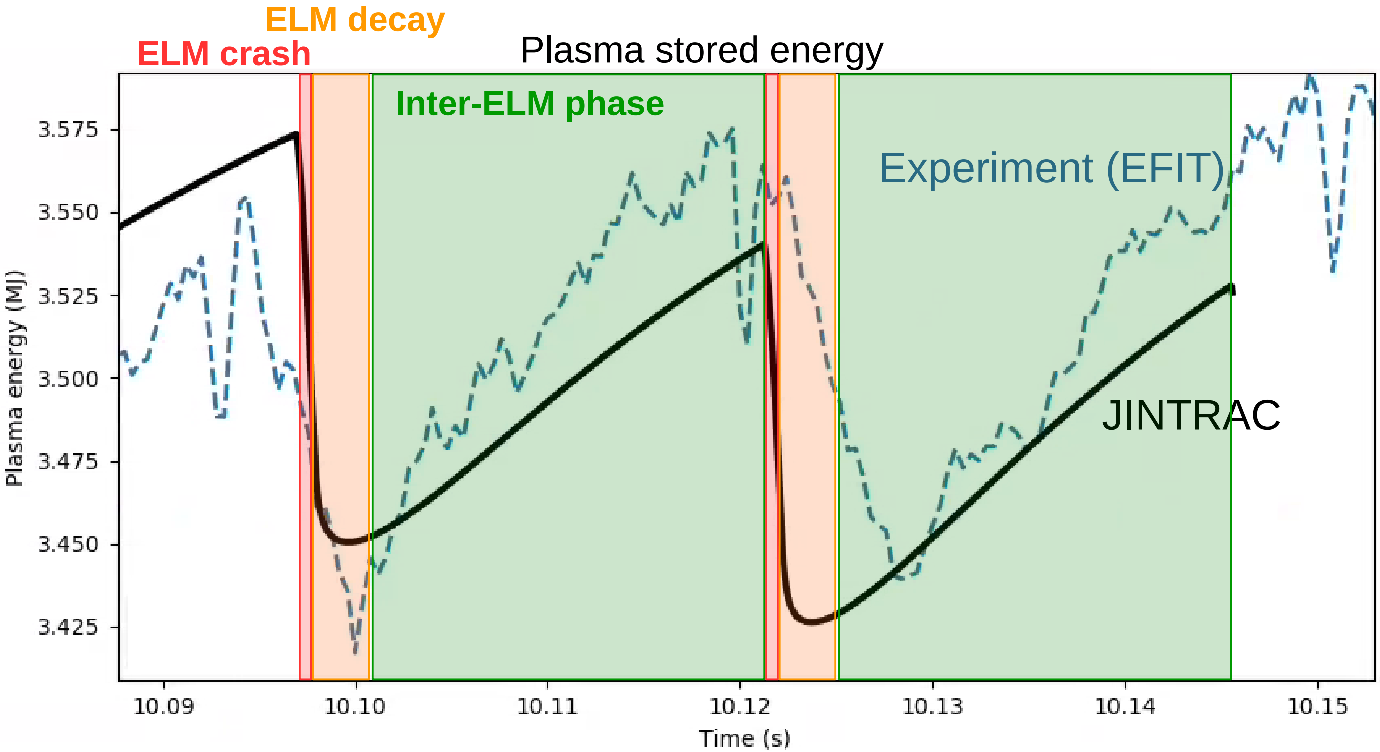
Time evolution during ELMs is modelled using a sequence of JINTRAC plasmas

JPN 94605 (P_{aux} = 18 MW)



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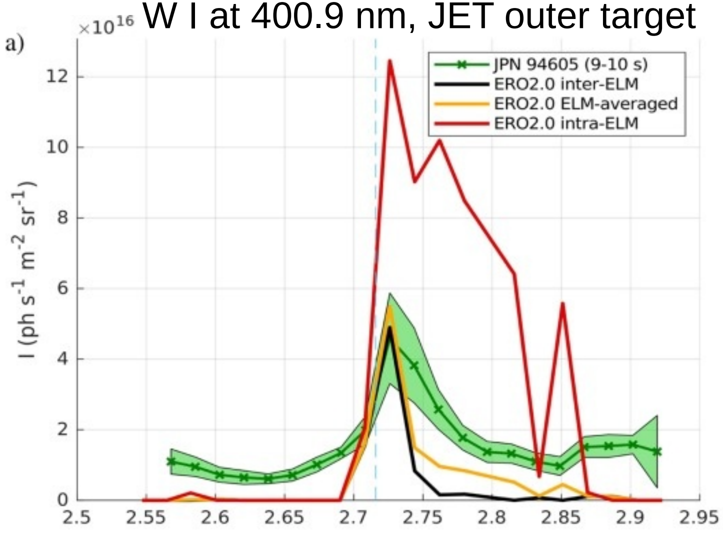
ERO2.0 reproduces the measured W I, but not W II, emission at the strike line

JPN 94605 (P_{aux} = 18 MW)

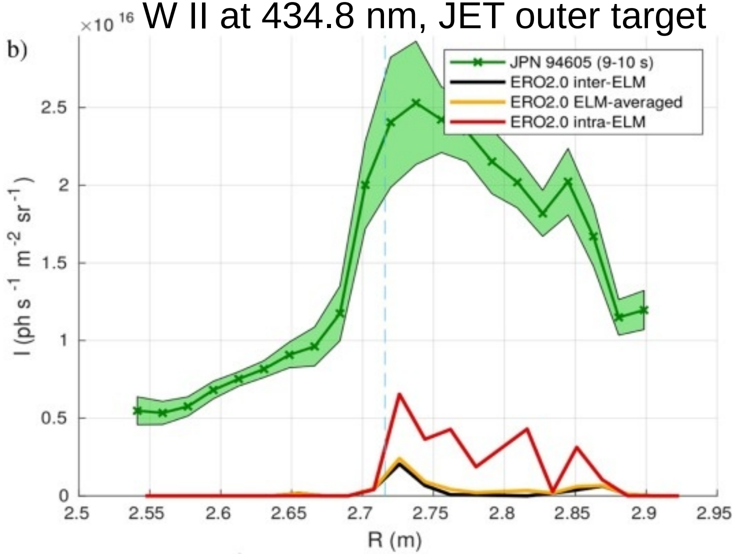
- Possible reasons for the W II discrepancy:
  - Uncertain W ionisation and photoemission rate coefficients
  - Simple description of the plasma sheath (changes proposed by S. Di Genova et al. NME 2023)
  - Accuracy of the simulated electric field, electron density, ion and electron temperature profiles
  - Uncertainties in the analysis and interpretation of the W II measurements

- Uncertainty of W atomic data can be assessed by benchmarking with experiments

W I at 400.9 nm, JET outer target



W II at 434.8 nm, JET outer target



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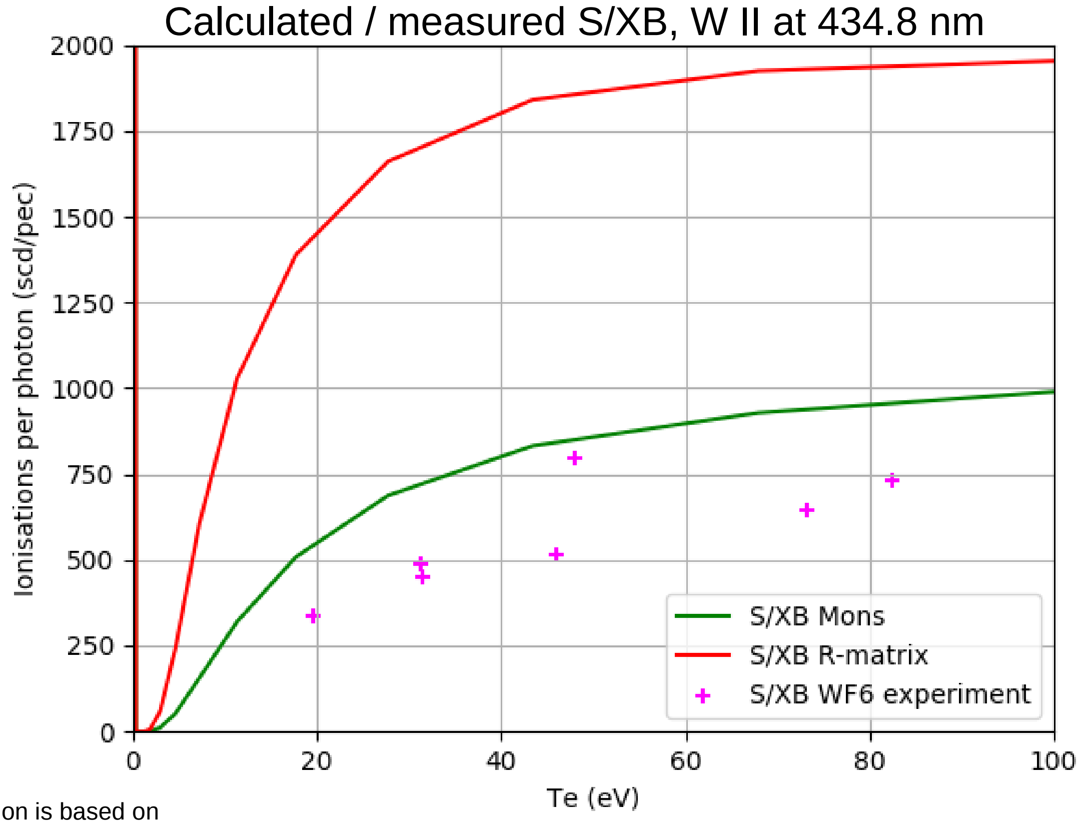
S/XB benchmark indicates that W data may partially explain the W II discrepancy

- Discrepancy on the 434.8 nm W II emission would be reduced to a factor of 5 if the photon emissivity was based on S/XB measurements from TEXTOR WF6 injection experiments, instead of ADF15 Mons or R-matrix calculations



W ionisation is based on ADF11 year 50

ERO2.0 predicts near-perfect divertor screening of W, except near the outer divertor entrance

JPN 81472 (L-mode)

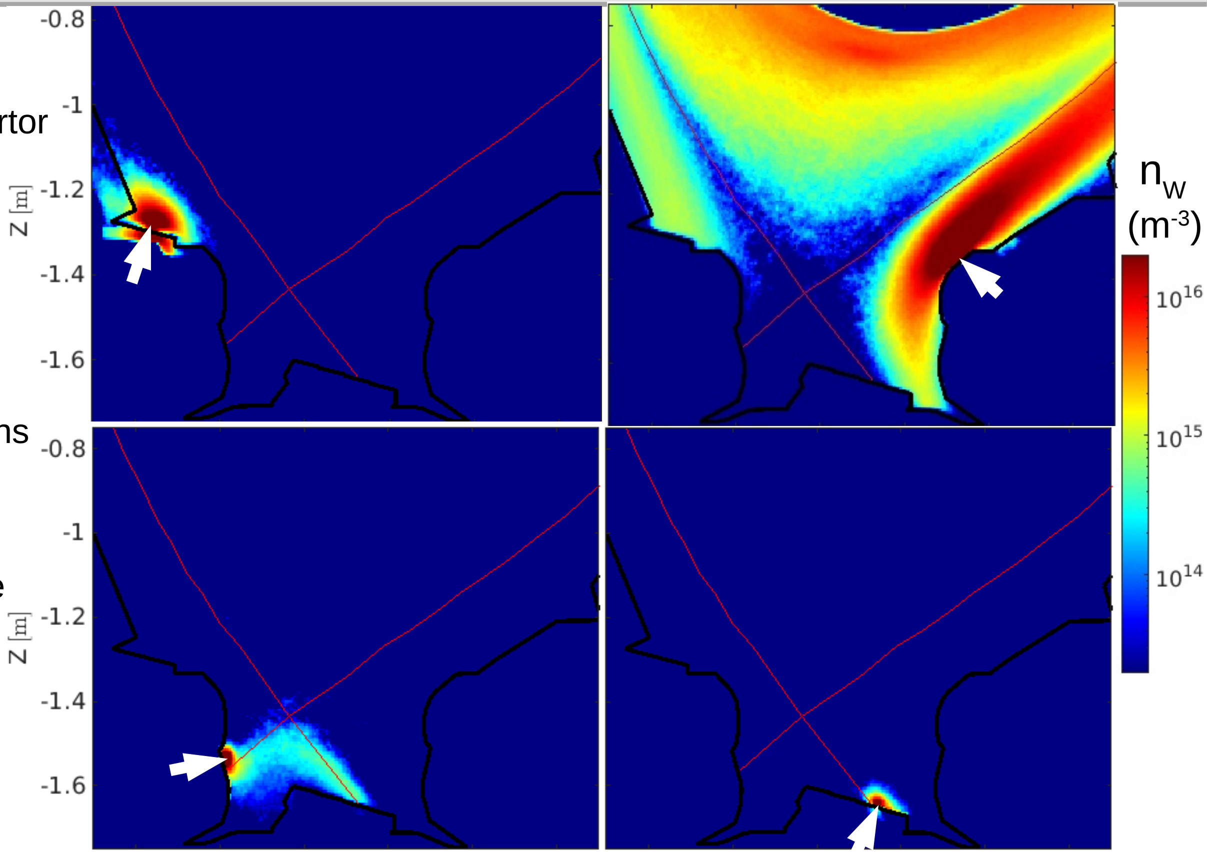
- Modelling a hypothetical experiment:
  W injection sources placed in the JET divertor to assess W screening of different source locations

- Same W source in each location:
  10^{20} W atoms/second, initial energy 10 eV

- At the divertor targets, SOL plasma flows efficiently screen the small fraction of W ions which is not promptly redeposited

- Strong W accumulation in the core from W sources near the outer divertor entrance (such as sputtering by CX atoms)

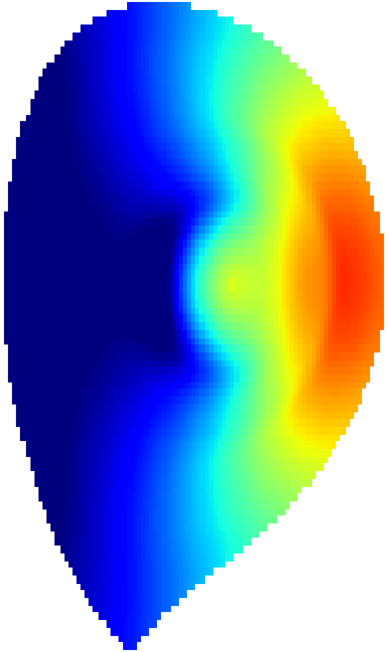
  → W II at the outer target does not affect the predicted core W density



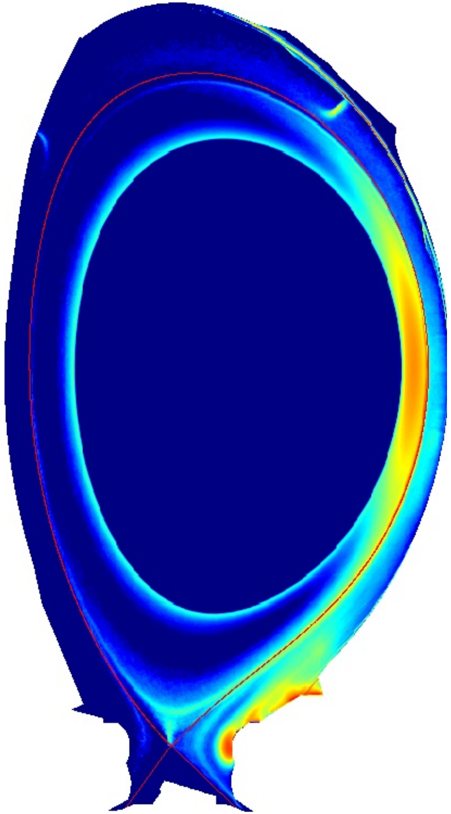
The predicted 2D W density profile is within a factor of 2-3 of the measured W density

JPN 97781 (P_{aux} = 34 MW)

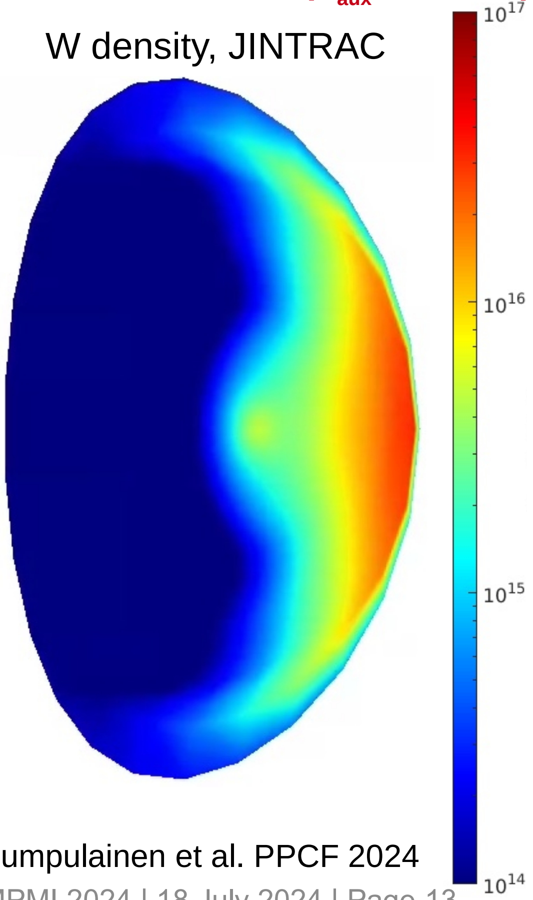
W density, experiment [1]



W density, ERO2.0, ELM-averaged



W density, JINTRAC



H. Kumpulainen et al. PPCF 2024

[1] M. Sertoli et al., J. Plasma Phys. (2019) 85 90585050

JINTRAC core transport simulations with the W boundary condition from ERO2.0 predict the core W density within a factor of 2-3

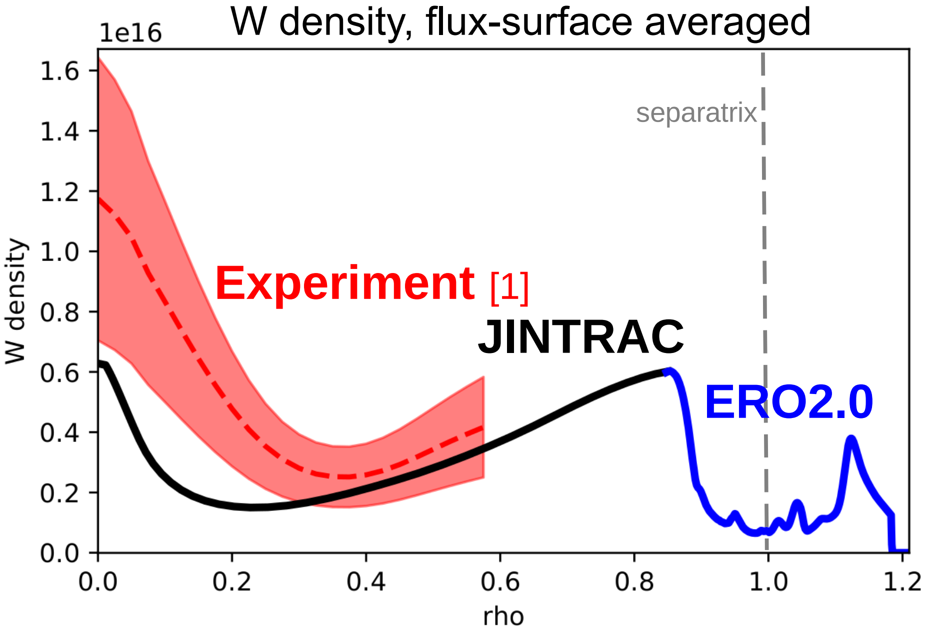
JPN 97781 (P_{aux} = 34 MW)

- Boundary condition: Flux-surface averaged W density at pedestal top (rho=0.9) from ERO2.0 predictions

- Propagating the estimated uncertainties of each BG plasma parameter, the predictive uncertainty of W in the core is roughly +200% / -70% (ELMy H-mode)

  → Consistent with the observed level of agreement

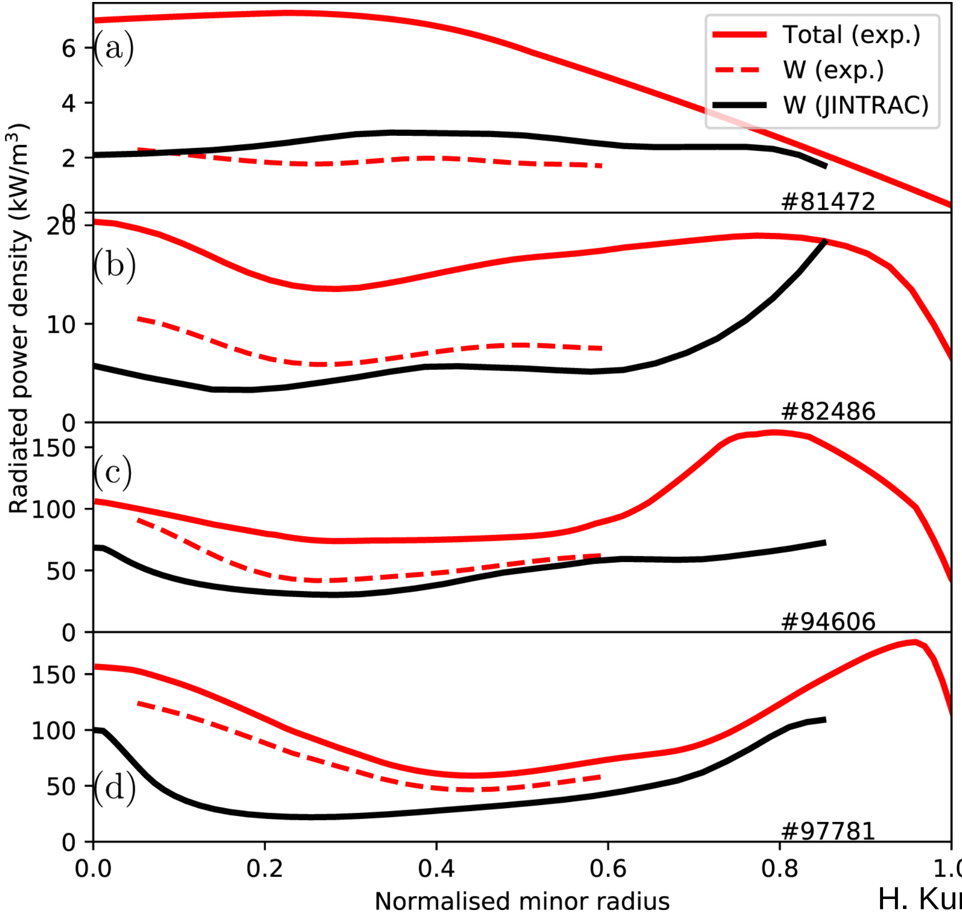
  → Description of the BG plasma most likely a larger source of uncertainty than the transport models



H. Kumpulainen et al. PPCF 2024

[1] M. Sertoli et al., J. Plasma Phys. (2019) 85 90585050

JINTRAC matches the observed W radiation within the modelling uncertainties



L-mode
B = 2.5 T
P_{aux} = 1 MW

ELMy H-mode
B = 2.0 T
P_{aux} = 10 MW

ELMy H-mode
B = 2.5 T
P_{aux} = 18 MW

ELMy H-mode
B = 3.45 T
P_{aux} = 35 MW

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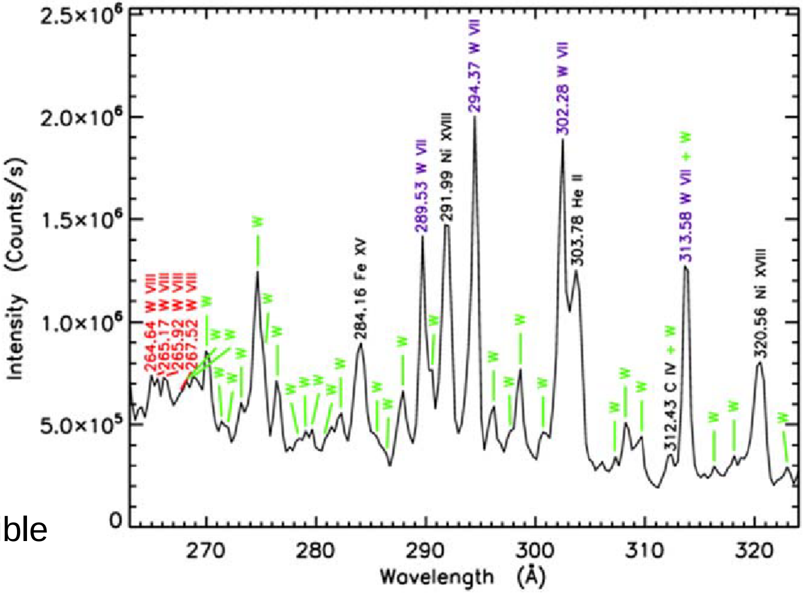
VUV W emission from the divertor could help validate SOL W transport models

- So far, W ion transport in the SOL has only been validated indirectly by combining edge and core W transport simulations
- Several low-charge ionisation states of W were observed in the JET divertor after a change in the viewing geometry of a VUV spectrometer in May 2018 [1]
- What is needed:
  - Selection of well-diagnosed pulses for W modelling (eg. 94606)
  - Identification of strong isolated W lines
  - Absolute calibration for the line-integrated radiance
  - **ADF15 effective photon emissivity coefficients** for each line, ideally with benchmark experiments to evaluate accuracy if feasible

JPN 95012



K.D. Lawson et al., Phys. Scr. 2022

[1] K.D. Lawson et al., Phys. Scr. (2022) 97 055605

Conclusions

- Simulation workflow including ERO2.0 and JINTRAC developed for more accurate predictions of W erosion and transport in the edge and core plasma
- Precise description of the plasma conditions is critical to W prediction accuracy
- Code-experiment agreement on W I emission at the outer target, but low-ionised W is challenging
- Predicted main plasma W density profiles in all studied scenarios reproduce the experiment within the modelling uncertainty (factor of 2-3)
- Currently looking for photon emissivities for W lines in the scrape-off layer to validate W ion transport

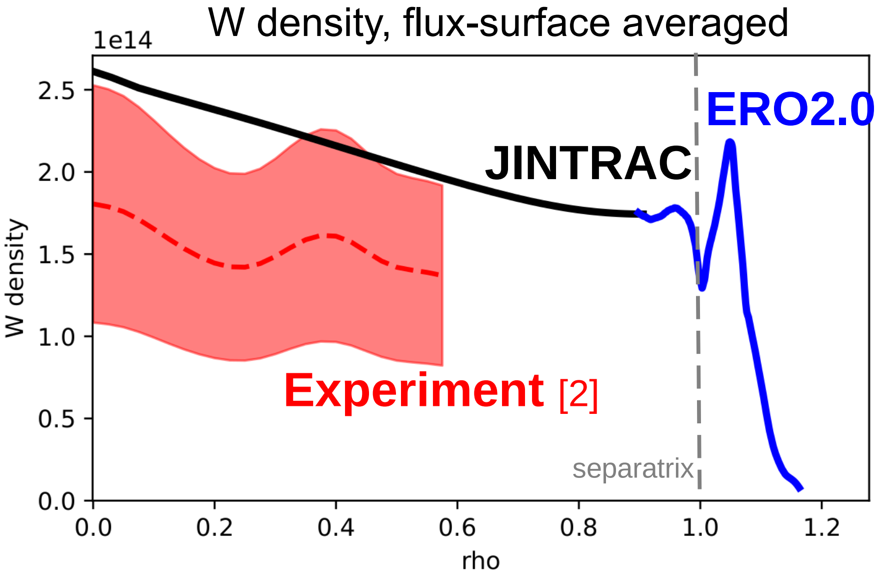
Backup slides

In L-mode, high-fidelity W transport models are less important than in H-mode

JPN 81472 (L-mode)

- The measured W density in L-mode was previously reproduced by core-edge integrated JINTRAC without ERO2.0 [1]
  → The benefits of the presented modelling approach are more evident in H-mode cases

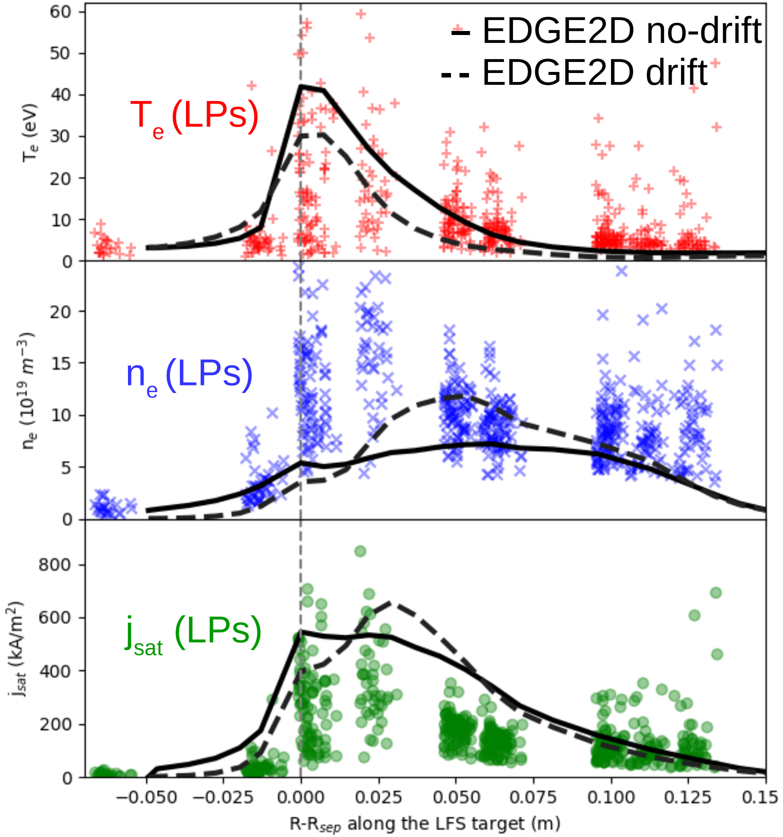
- Code benchmark of ERO2.0 vs. EDGE2D-EIRENE: agreement on W density within a factor of 1.5 (L-mode)



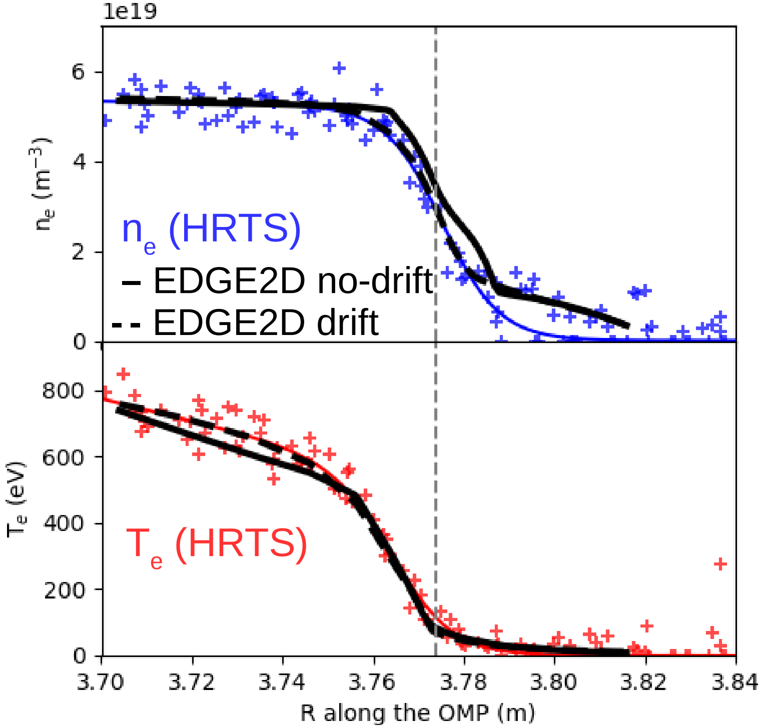
[1] H. Kumpulainen et al., NME 25 100866 (2020)
[2] M. Sertoli et al., J. Plasma Phys. (2019) 85 90585050

Validated inter-ELM H-mode plasmas were produced using EDGE2D-EIRENE with and without cross-field drifts and pinch velocity

JPN 94605 (P_{aux} = 18 MW)



- A pinch velocity (ad-hoc) is necessary with drifts to reproduce measured upstream and target profiles

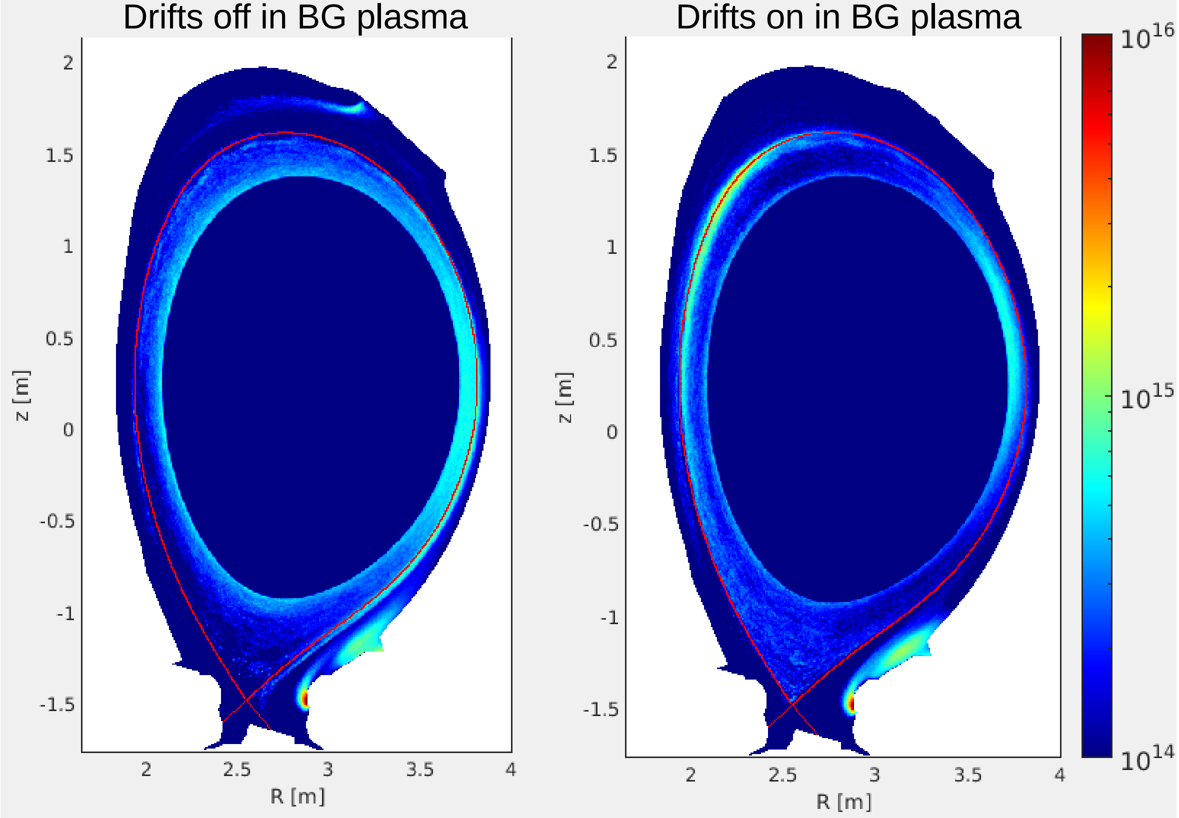


Drifts redistribute W near the separatrix, but minor impact <30% on core W density

JPN 94605 (P_{aux} = 18 MW)
Inter-ELM phase

- Both plasmas are fitted to upstream and target measurements
- The main benefit of drifts is a more realistic parallel-B flow profile in the SOL
- ELM phase with drifts not available → steady inter-ELM phase shown

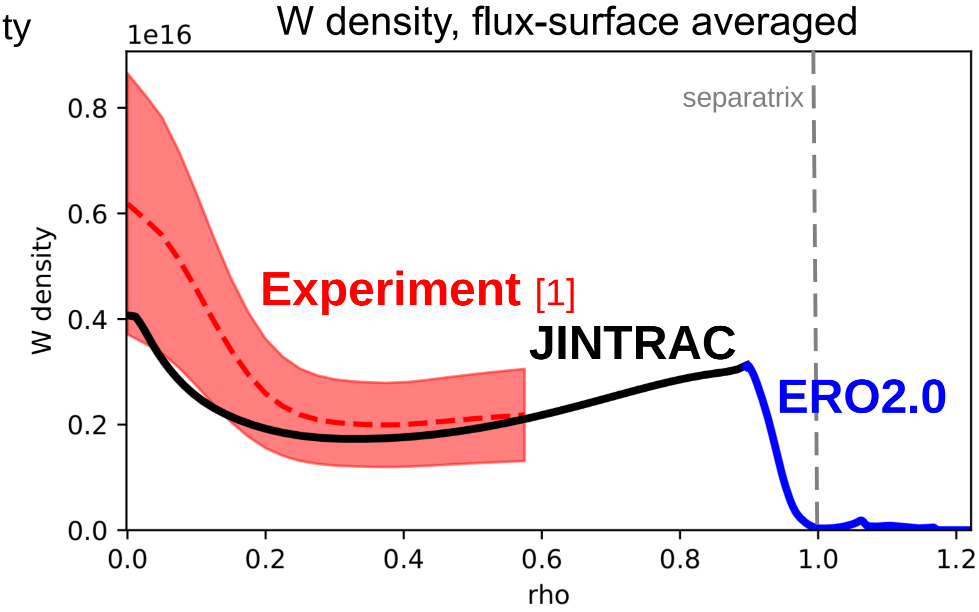
W density, ERO2.0



JINTRAC core transport simulations with the W boundary condition from ERO2.0 predict the core W density within a factor of 2

JPN 94605 (P_{aux} = 18 MW)

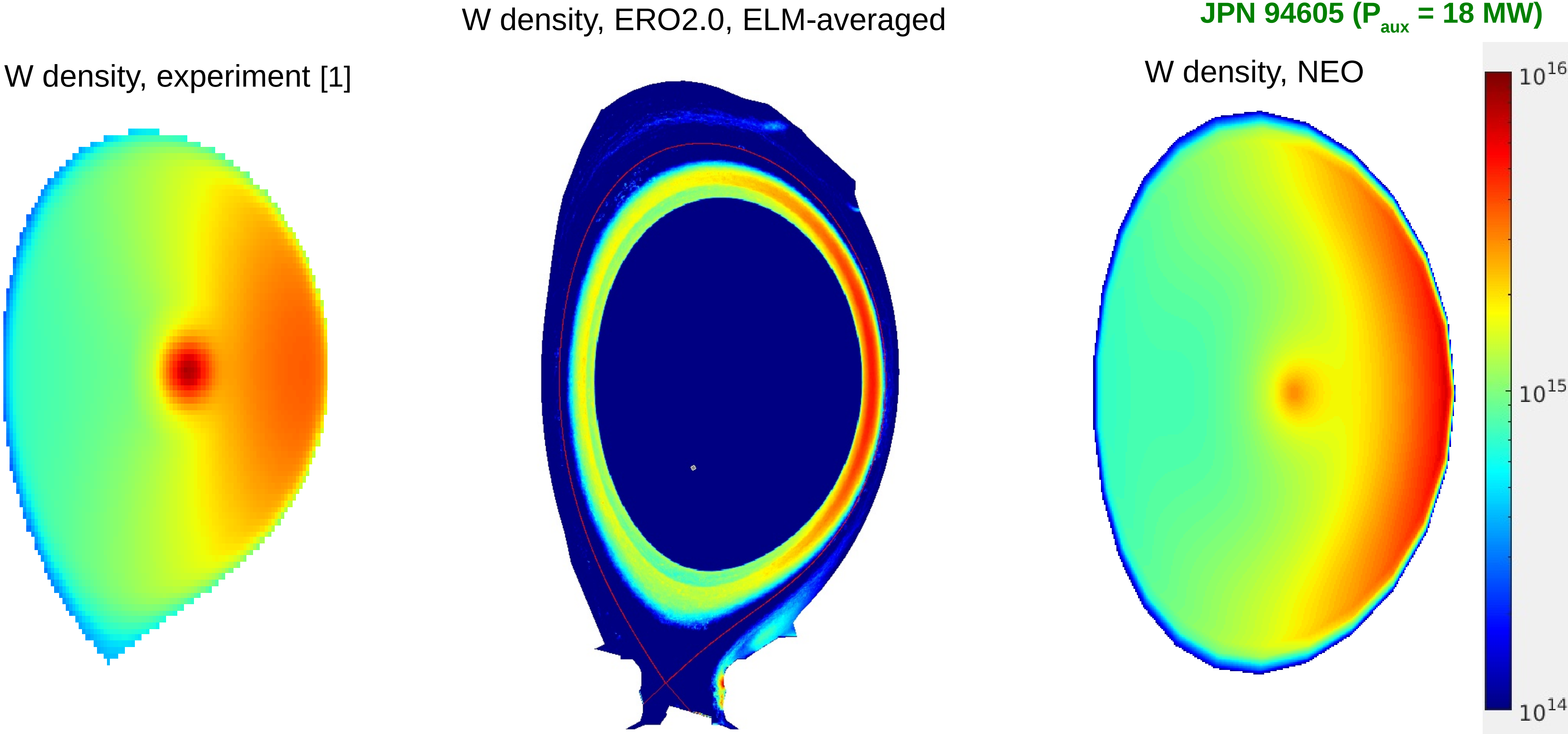
- Boundary condition: Flux-surface averaged W density at pedestal top (rho=0.9) from ERO2.0 predictions
- Neoclassical W core transport predicted using NEO



[1] M. Sertoli et al., J. Plasma Phys. (2019) 85 90585050

The predicted 2D W density profile is within a factor of 2 of the measured W density

JPN 94605 (P_{aux} = 18 MW)



W density, ERO2.0, ELM-averaged

W density, experiment [1]

W density, NEO

[1] M. Sertoli et al., J. Plasma Phys. (2019) 85 90585050

Fast core transport codes used for BG modelling, first-principles for predicting W

- The following models from the **JINTRAC** suite of codes are applied in this work:

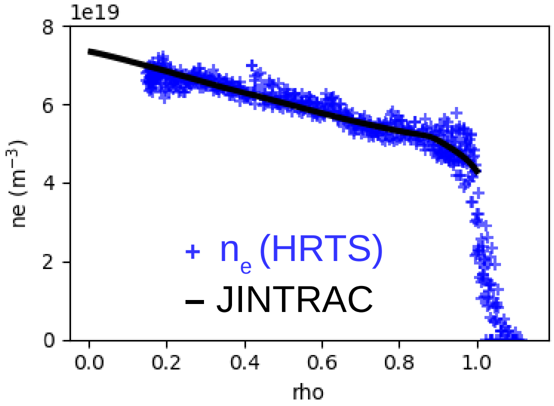
- Empirical **Bohm/gyro-Bohm** (BgB) [1] scaling for anomalous transport
  - Fast and versatile way to obtain plasma profiles consistent with experiments
  - Used for interpretive but self-consistent modelling of the BG plasma

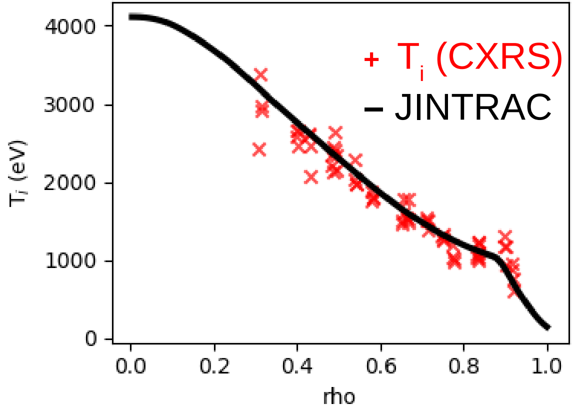
- **NCLASS** [2] is a fast 1D neoclassical transport model
  - Used in combination with BgB for BG plasma modelling

- **QuaLiKiz** [3] is a 3D quasilinear gyrokinetic code for turbulent transport
  - First-principles alternative to BgB
  - Faster approximate solutions available from a neural network [4] trained on a QuaLiKiz simulation database

- **NEO** [5] is a first-principles drift-kinetic neoclassical transport code
  - Includes the strong impact of rotation on neoclassical convection
  - Neoclassical convection in JET dominates high-Z core transport [6]

JPN 94605 (P_{aux} = 18 MW)





[1] M. Erba et al., PPCF 39 261 (1997)
[2] W.A. Houlberg et al., PoP 4 3230 (1997)
[3] C. Bourdelle et al. PoP 14 112501 (2007)
[4] A. Ho et al. PoP 28 032305 (2021)
[5] E.A. Belli et al., PPCF 50 095010 (2008)
[6] S. Breton et al., PoP 25 012303 (2018)

W density is sensitive to gradients, ELM properties, and SOL conditions

- Core W density is **very** sensitive to the T_i and n_e gradients and the rotation frequency

  → W predictions are within the uncertainty induced by measurement accuracy

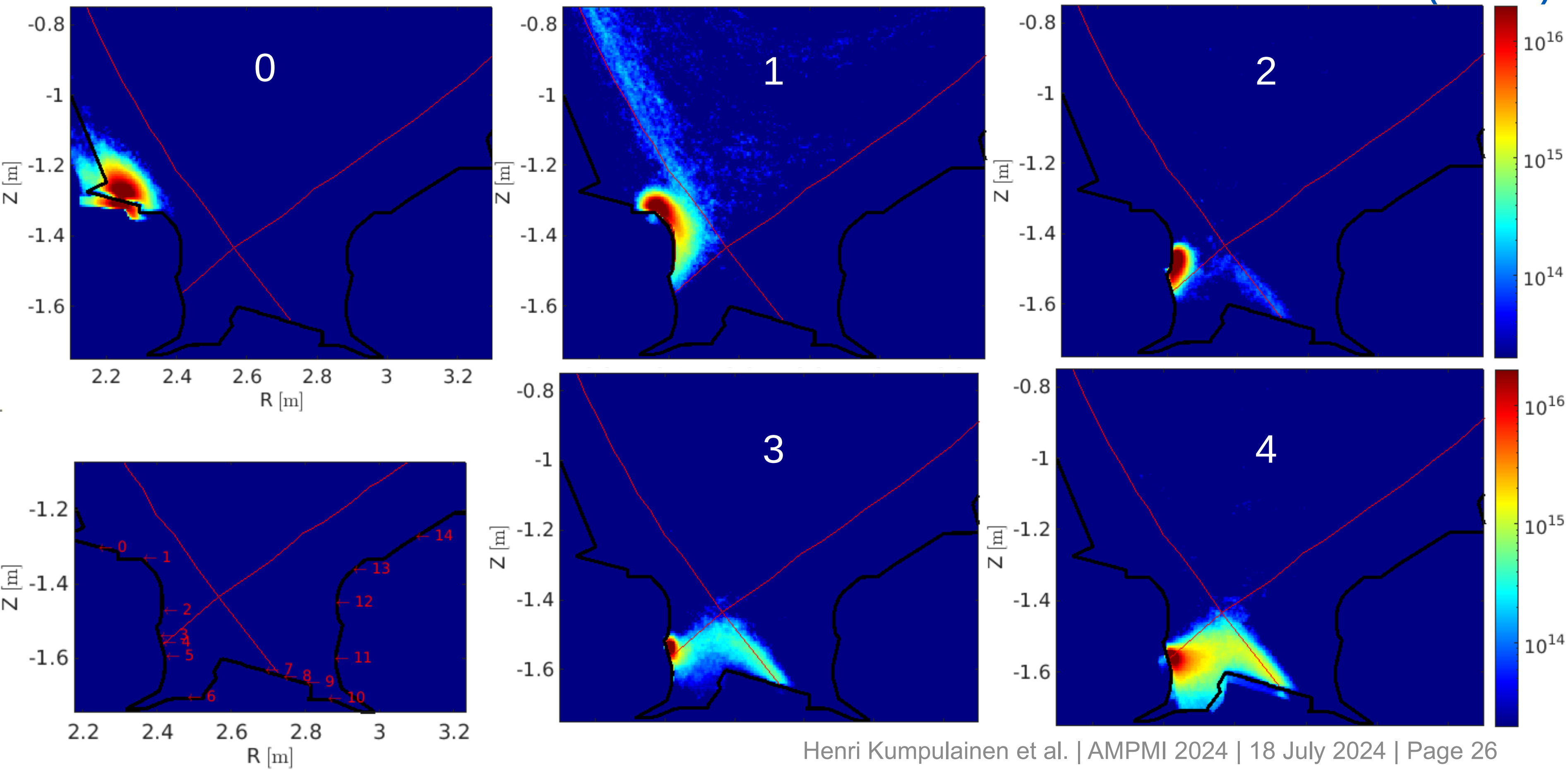
  → Fully predictive modelling of both the background and W a major challenge: Assuming 15-20% uncertainty in the gradients, W uncertainty ~ **factor of 5**

- What are the most critical parameters affecting the uncertainty of W predictions?

  – **T_i and n_e** radial gradients and **rotation** on closed flux surfaces
  – **ELM** properties (heat and particle fluxes, duration, frequency)
  – **T_e and n_e** profiles and plasma **flow** patterns in the SOL
  – **Flux and energy spectrum of atoms** incident on non-plasma-wetted W surfaces

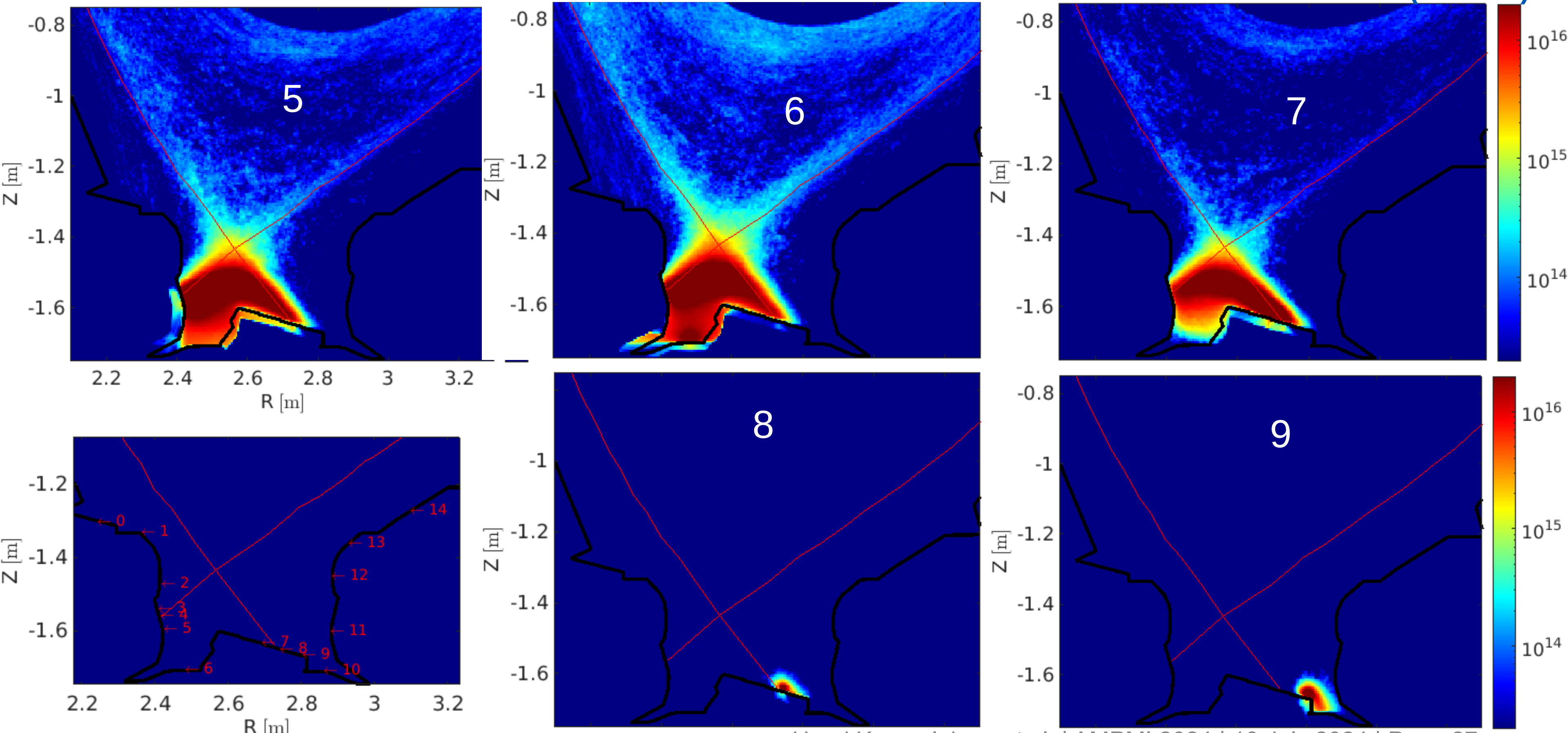
W sources in the high-field side SOL are efficiently screened

JPN 81472 (L-mode)



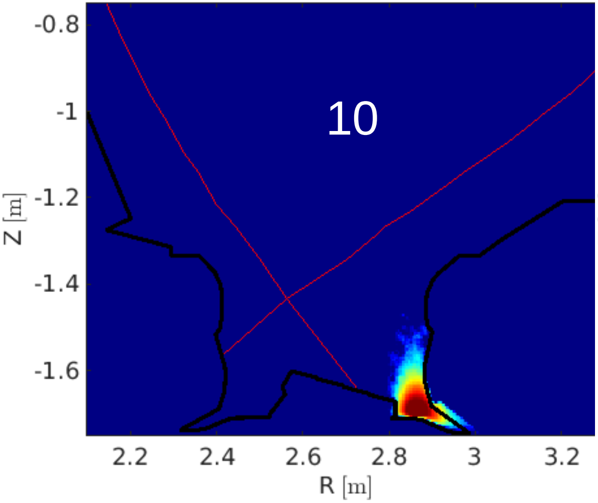
W sources in the PFR result in modest W influx; OT W sources are fully screened

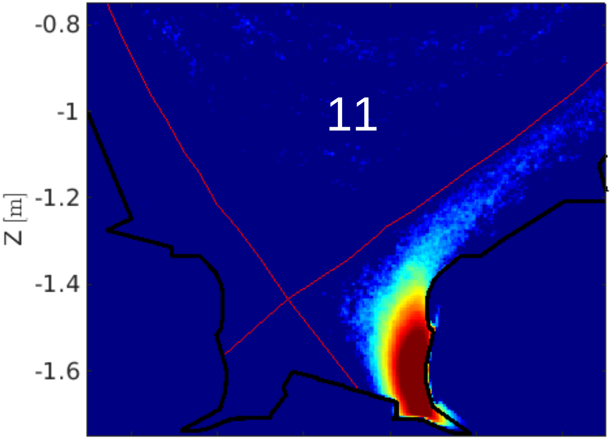
JPN 81472 (L-mode)

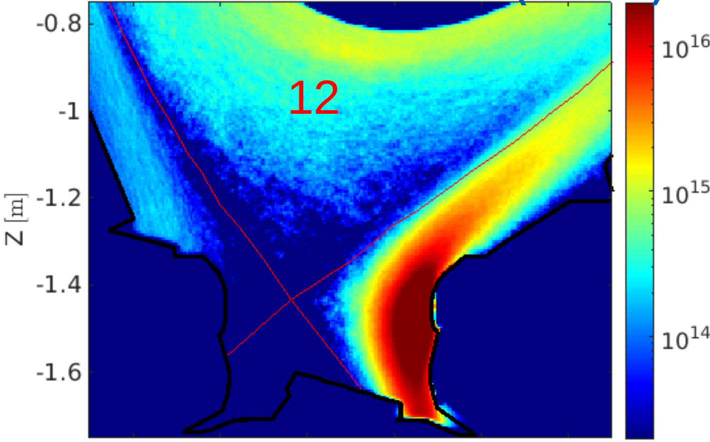


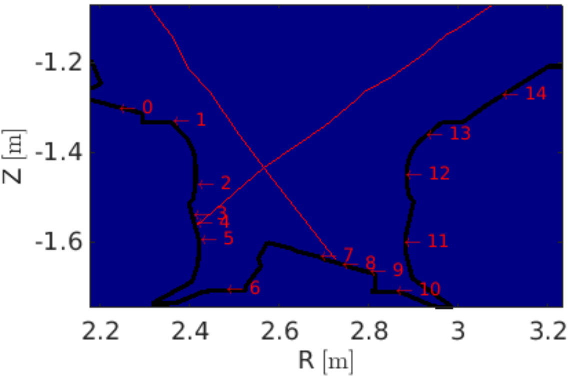
Tile 7 is well screened, but tiles 8 and B have very weak W screening ($n_{W,ped} > 10^{15}$ m^{-3})

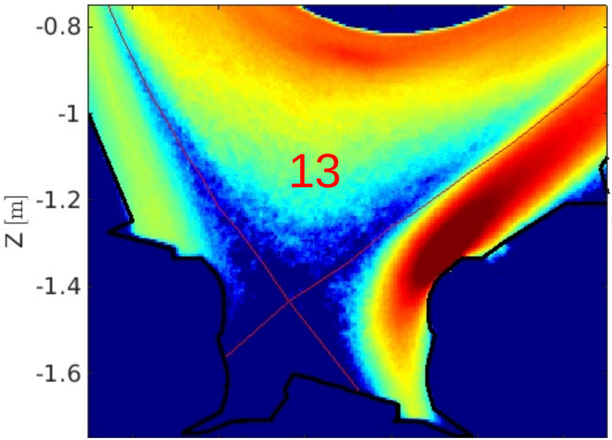
JPN 81472 (L-mode)

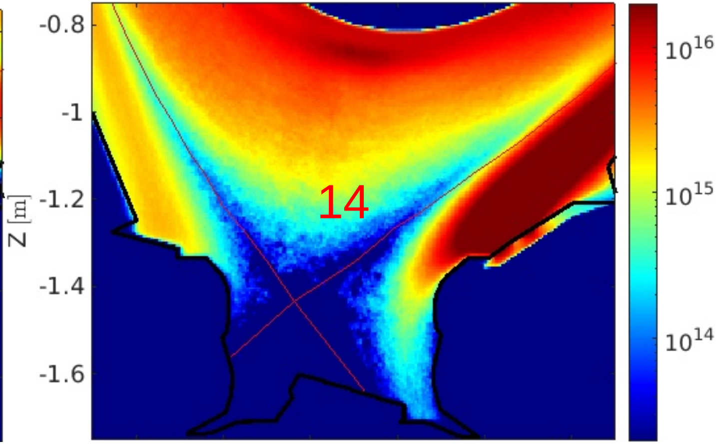






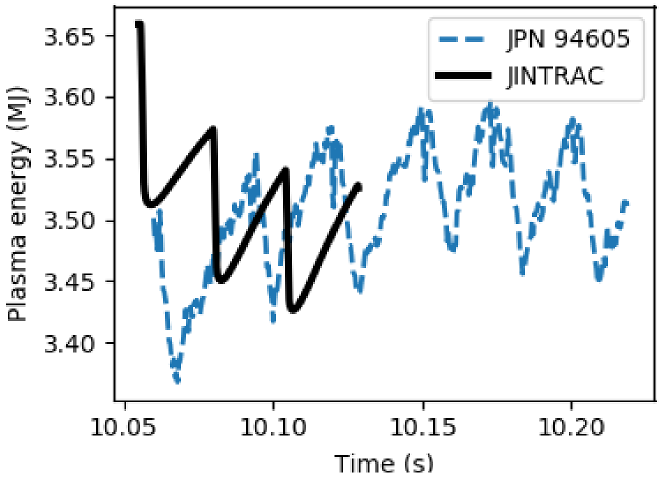


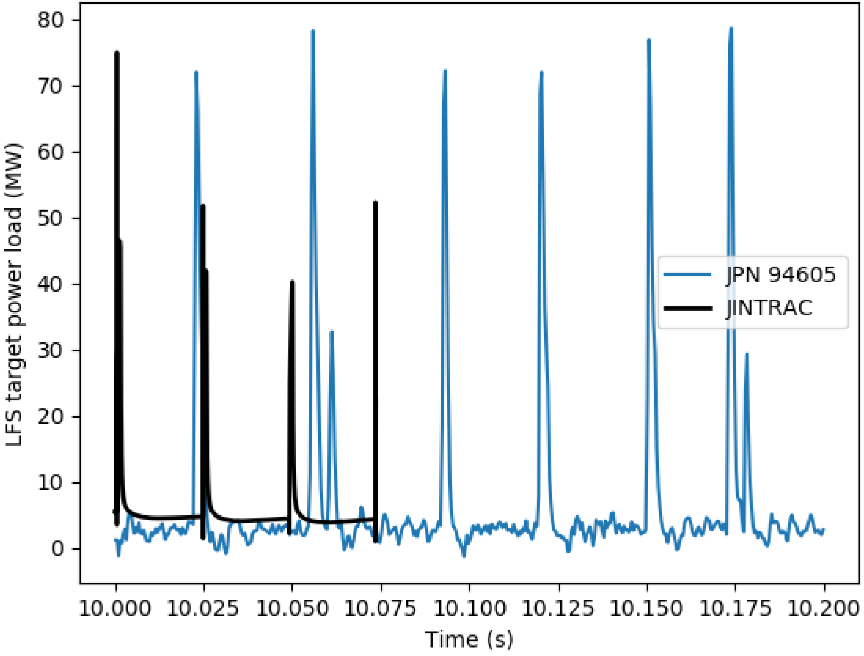


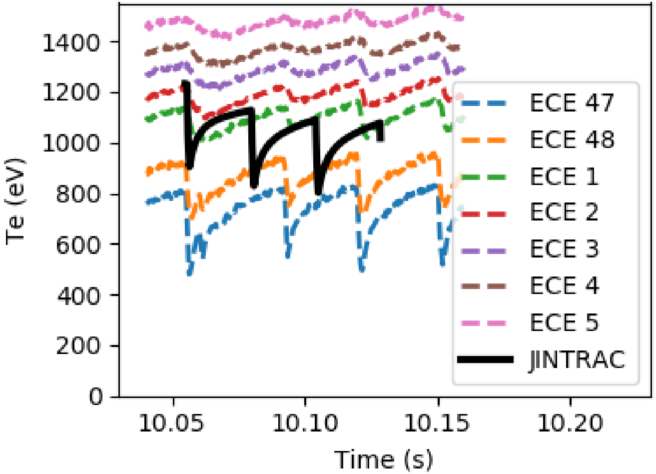


ELM energy losses and heat loads on the divertor targets are fitted to measurements

JPN 94605 (P_{aux} = 18 MW)

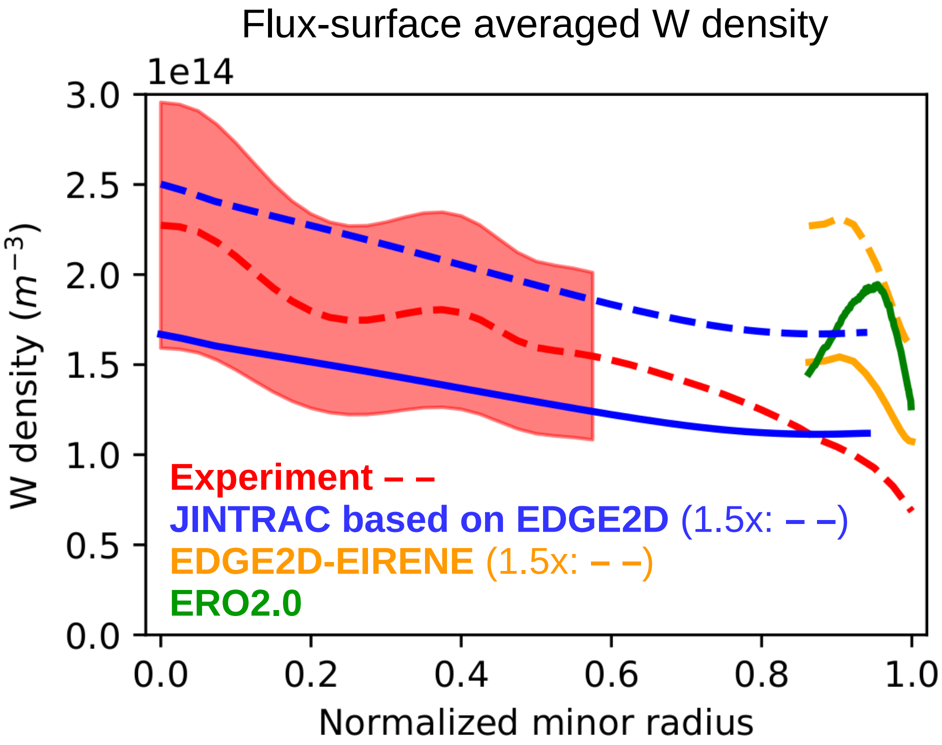






L-mode: EDGE2D and ERO2.0 match the observed W density in the main plasma

- It is known [1] that EDGE2D underestimates the W charge in the main chamber SOL due to the bundled fluid treatment of W ion states
- A correction factor of 1.5 can be applied to the EDGE2D main chamber W density to match fully charge-resolved predictions [1]
- Only minor differences between EDGE2D and ERO2.0 due to W erosion rate, rotation profile, fluid vs. kinetic transport etc.

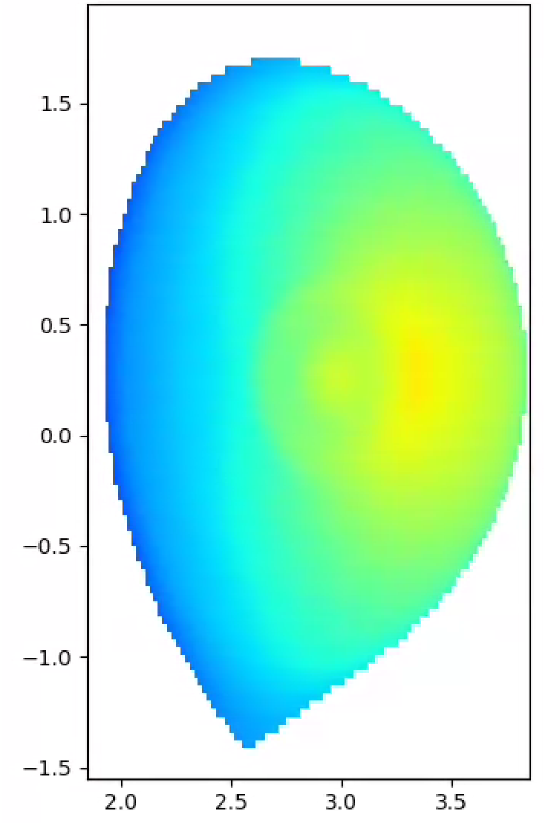


Experiment:	L-mode JPN 81472 at 9 s, msertoli/wsxp/hz01
JINTRAC run:	hkumpul/jet/81472/may2120/seq#1
EDGE2D-EIRENE run:	hkumpul/jet/81472/apr0120/seq#2
ERO2.0 run:	hkumpulainen/run36/seq01

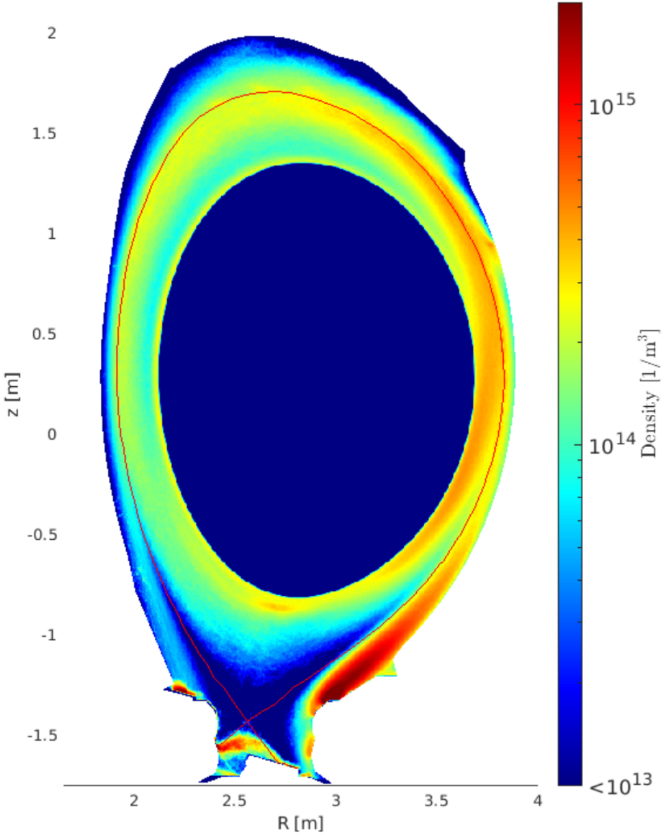
[1] H. Kumpulainen et al., NME 25 100784 (2020)

L-mode: ERO2.0 2D W main plasma density is consistent with experiment (factor of <2)

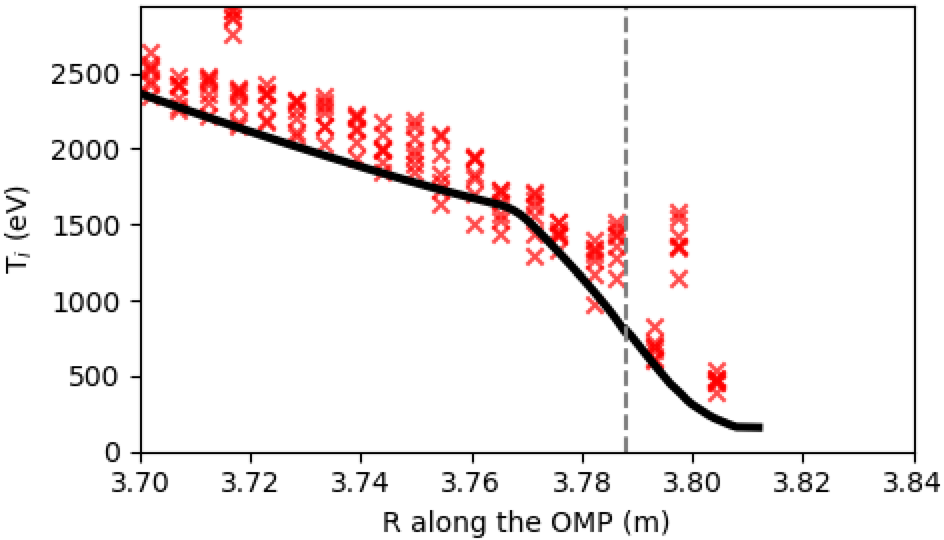
W density, JPN 81472 (9 s)

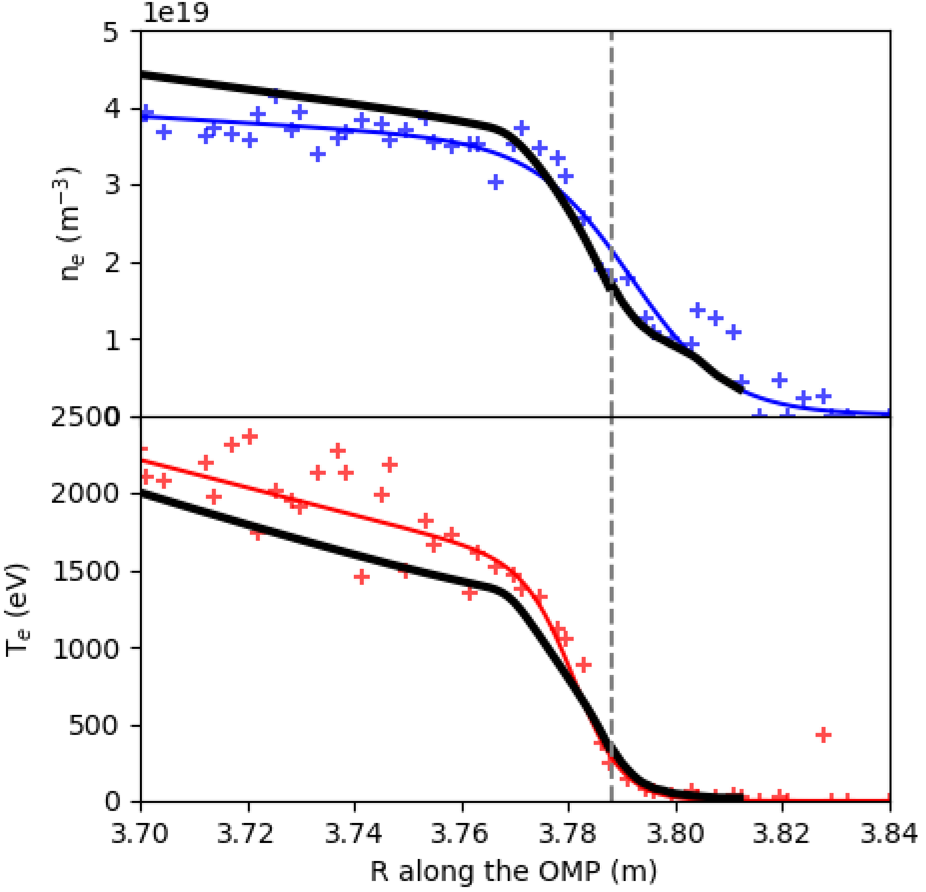


W density, ERO2.0

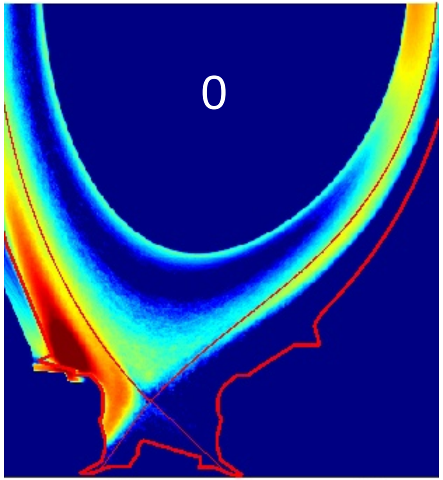


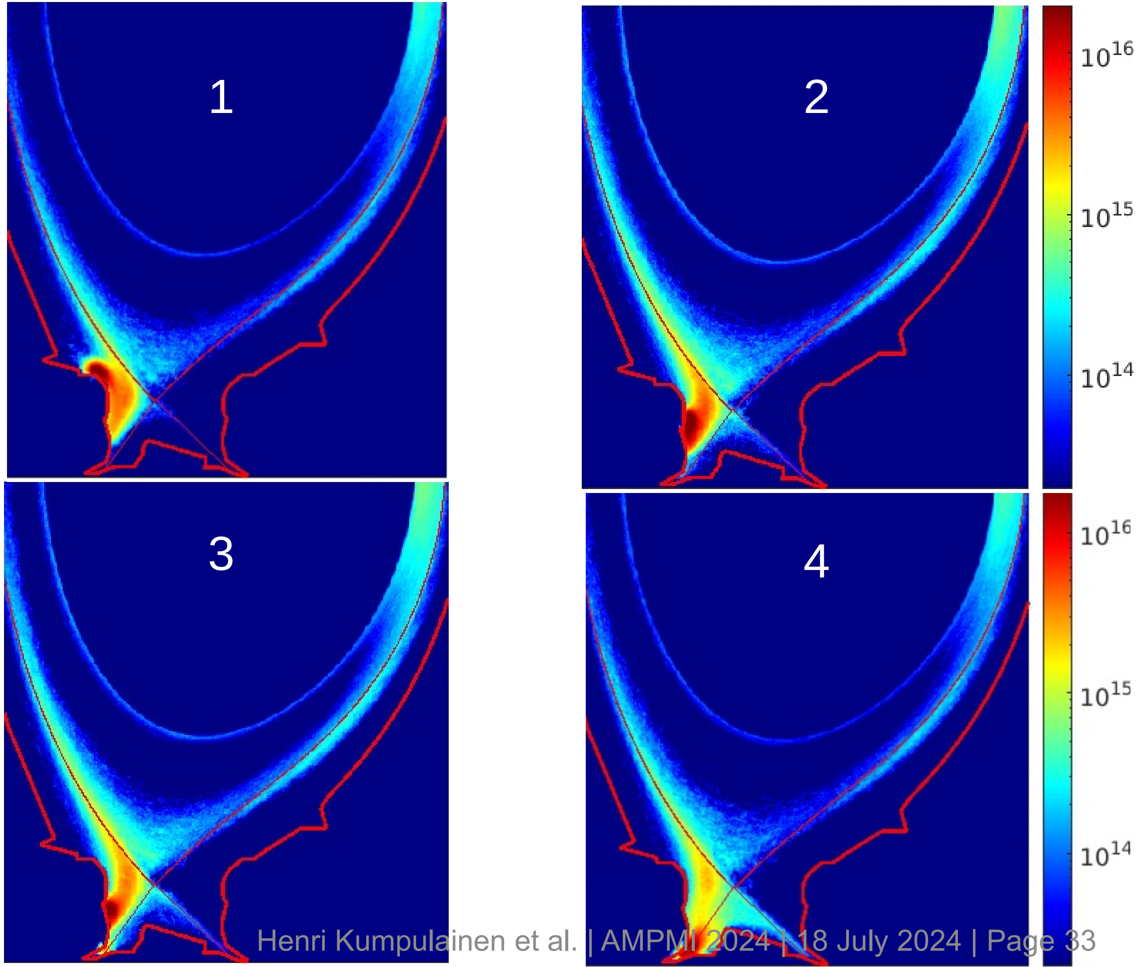
Edge plasma profiles, #97781 at 8 s, P_{aux} = 35 MW

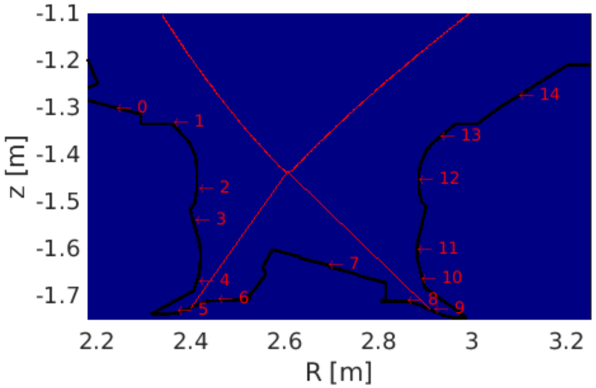




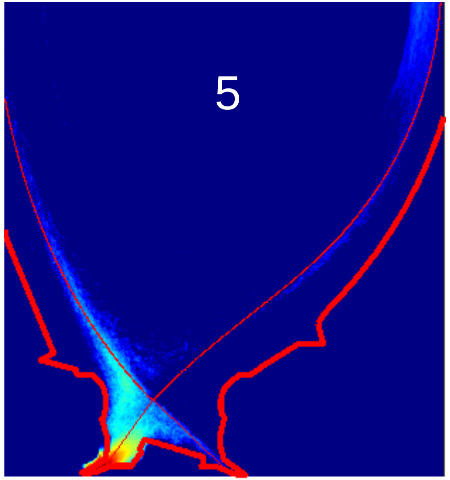
Tile 0 is imperfectly screened in the C-C configuration, unlike V5/C

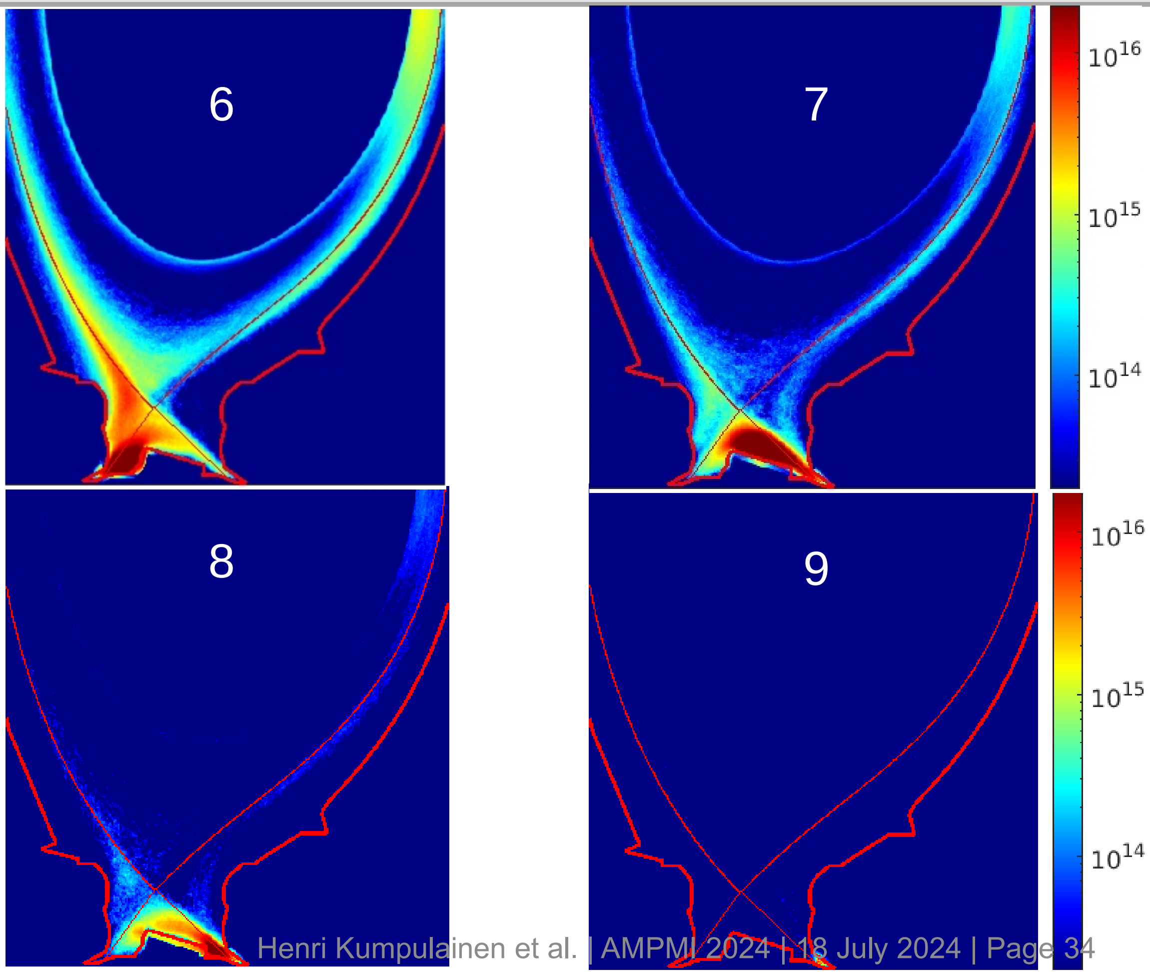


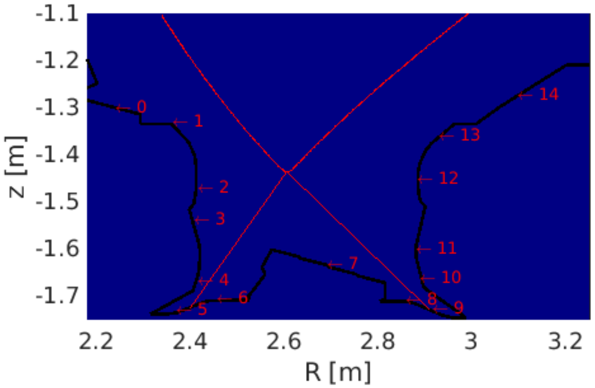




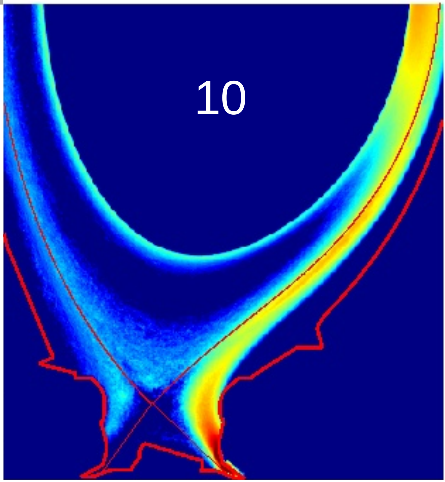
W sources in the divertor corners are almost fully screened

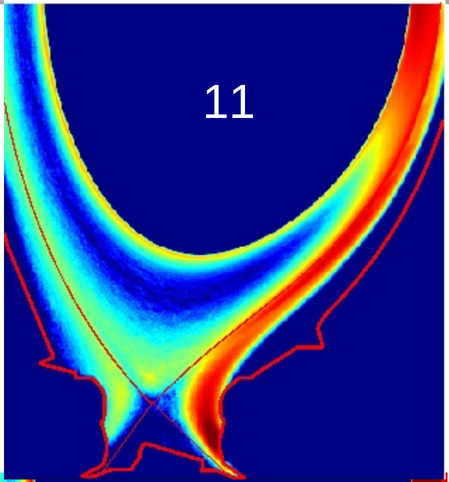


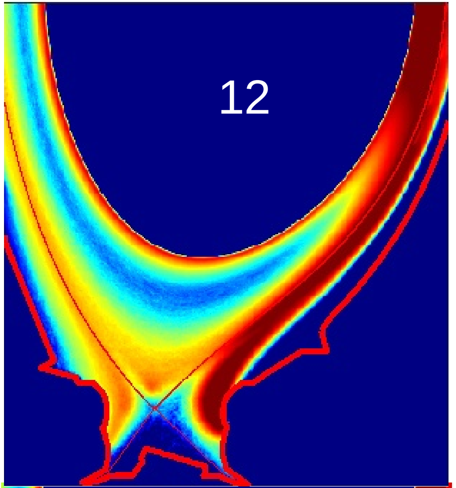


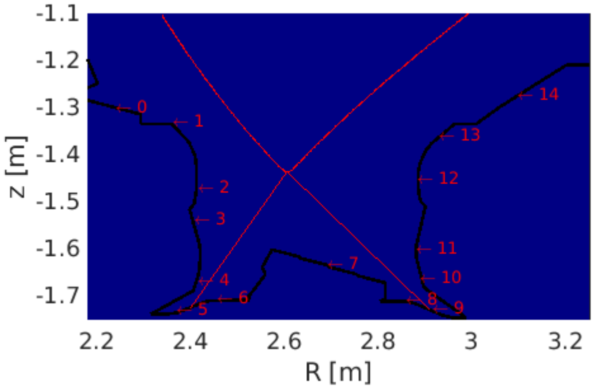


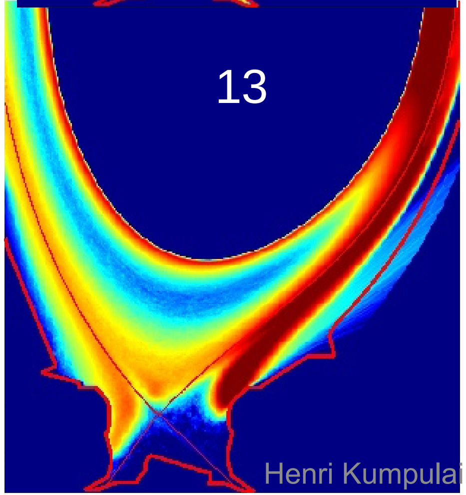
The upper part of tile 7 and 8, B, and C have weak W screening

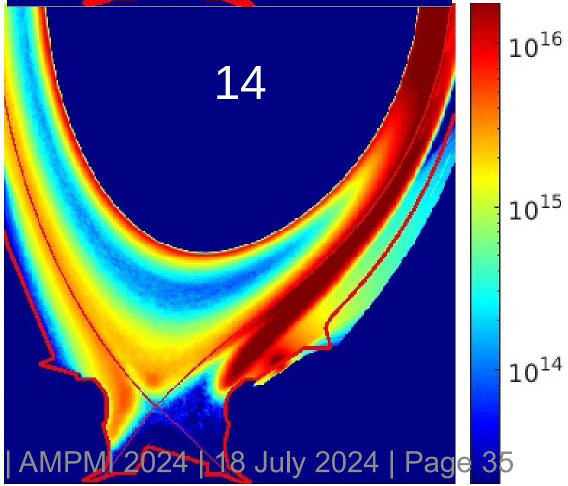












ELM phase W screening is weaker than intra-ELM on tile 7 but stronger on tile 8 (~2x)