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Tungsten Sources and Core Contamination in WEST Plasmas: From Experiments to Simulations



DE LA RECHERCHE À L'INDUSTRIE

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EUROfusion



Institut
Sciences de la Fusion et
de l'Instrumentation en
Environnements Nucléaires
Aix-Marseille Université



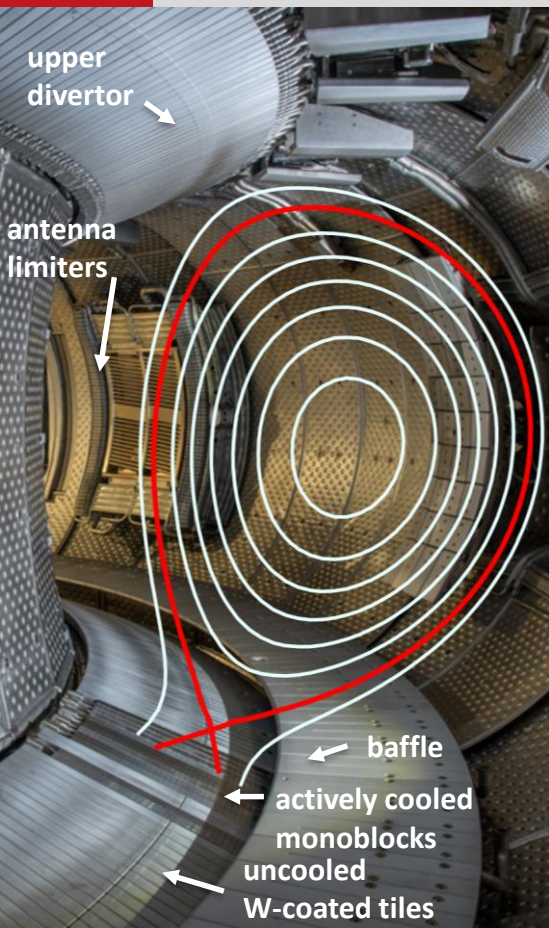


Overview of the *Phase 1* divertor operation

Experimental assessment of tungsten sources & core contamination

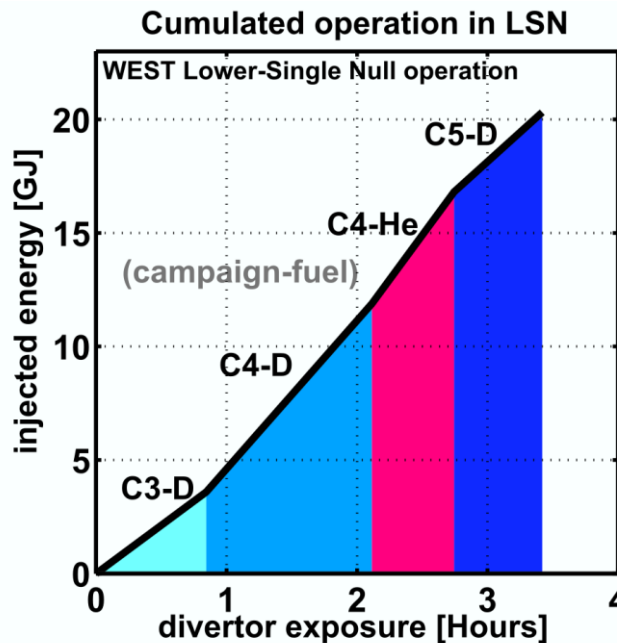
Numerical modelling of tungsten sources and transport with transport codes: status & developments

Divertor phase 1: Lower single null operation with *uncooled* divertor



W-coated graphite tiles + actively cooled ITER-like monoblocks

→ Exposed to ~3.5 hours of plasma & 20 GJ of injected energy



Lower hybrid current drive +

Ion cyclotron resonance heating

Up to 8.8MW coupled

Up to 40s steady-state operation in LSN

Divertor heat loads $q_{dep} \leq 6\text{MW.m}^{-2}$ [1]

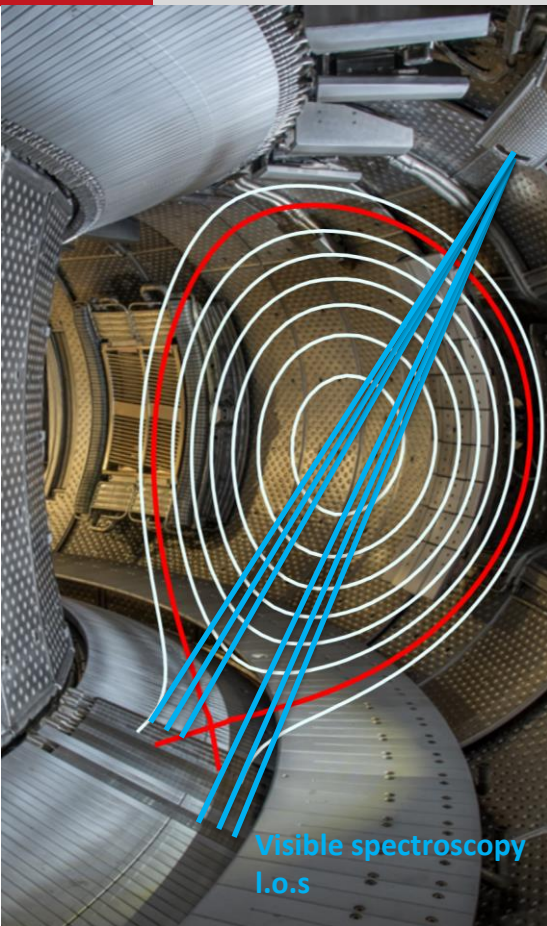
L-mode operation (limited by radiation)

Regular boronisations, moderate gain

(radiation recovery after 5-10 pulses)

[1] J. Gaspar et al 2021 Nucl. Fusion 61

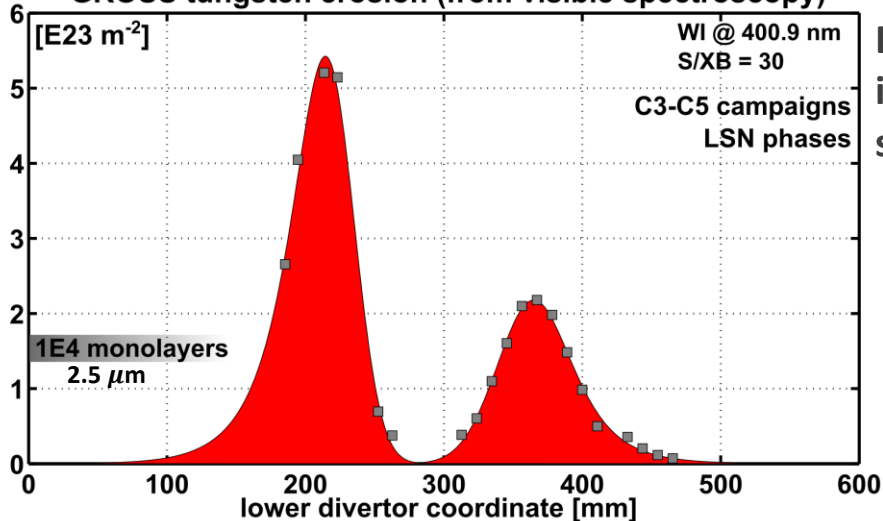
Divertor phase 1: significant surface bombardment



W-coated graphite tiles + actively cooled ITER-like monoblocks

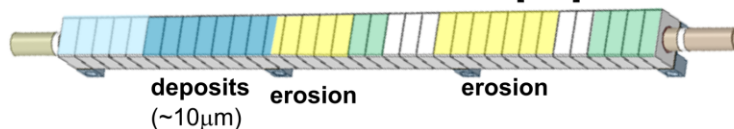
- Exposed to ~3.5 hours of plasma & 20 GJ of injected energy
- Deuterium fluency $E26 \sim 27 \text{ m}^{-2}$ (wetted area $\sim 1 \text{ m}^2$)
- Gross tungsten erosion \sim few μm + co-deposition

GROSS tungsten erosion (from visible spectroscopy)

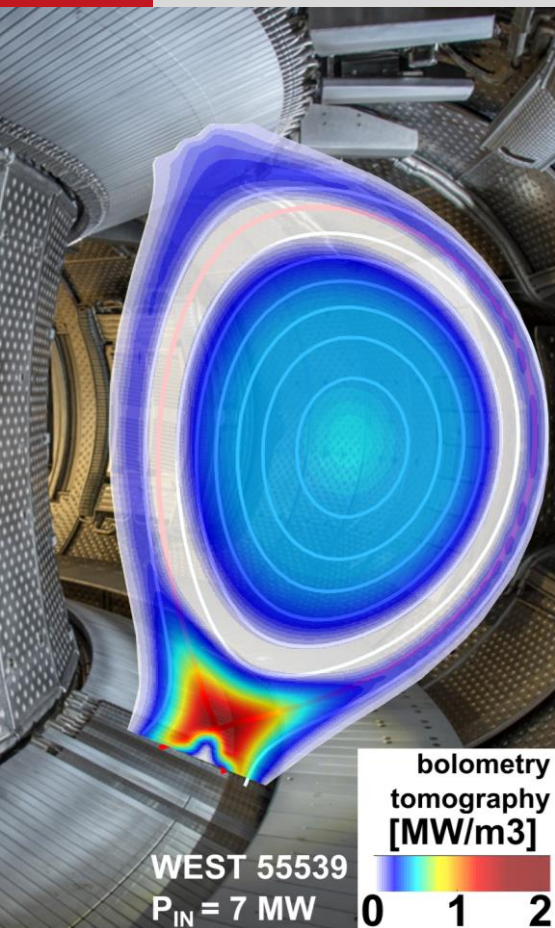


Deposition/erosion:
impact on infra-red
surface emissivity

J. Gaspar P003



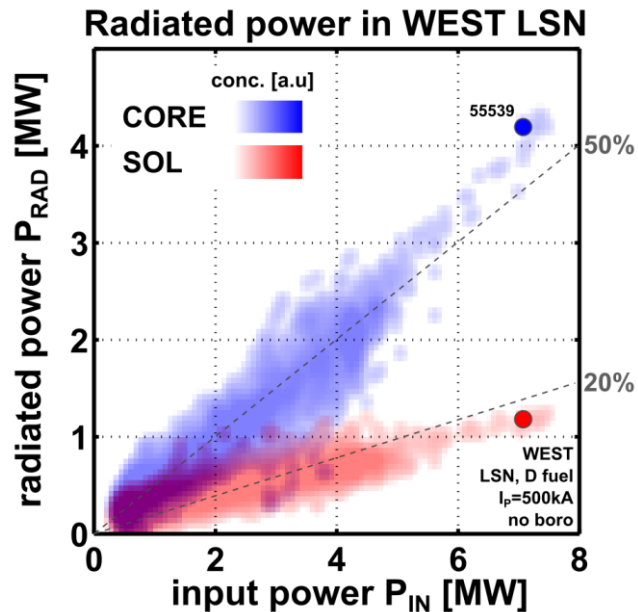
M. Diez T107 (Tuesday)



Standard scenario: LSN, $B_T = 3.7 \text{ T}$, $q_{95} = 4.5$, w/o boronisation

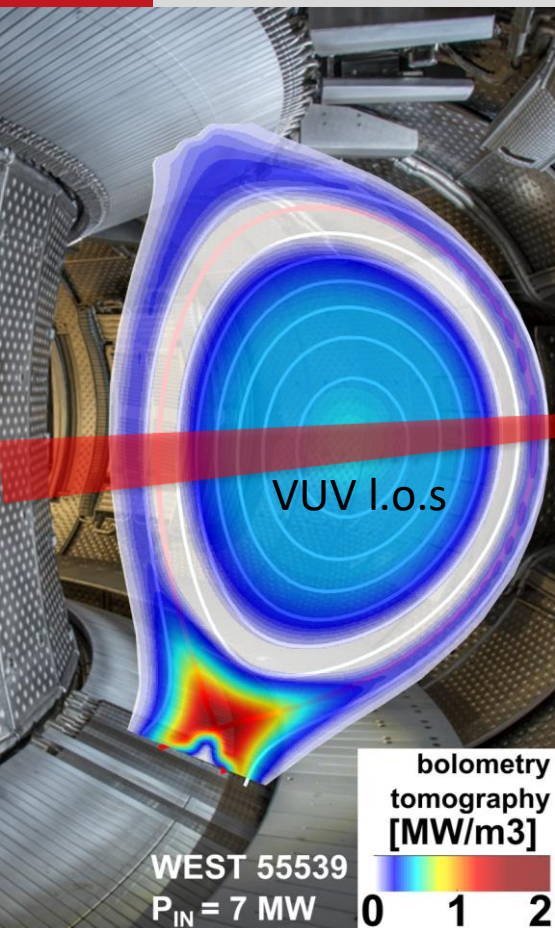
- line averaged density from 2 to 6 10^{19} m^{-3}
- total input power from 0.5 to 8 MW

→ “Stiff” radiated fraction: no dependence with plasma density
weak with input power



$$c_W \approx 10^{-4}$$

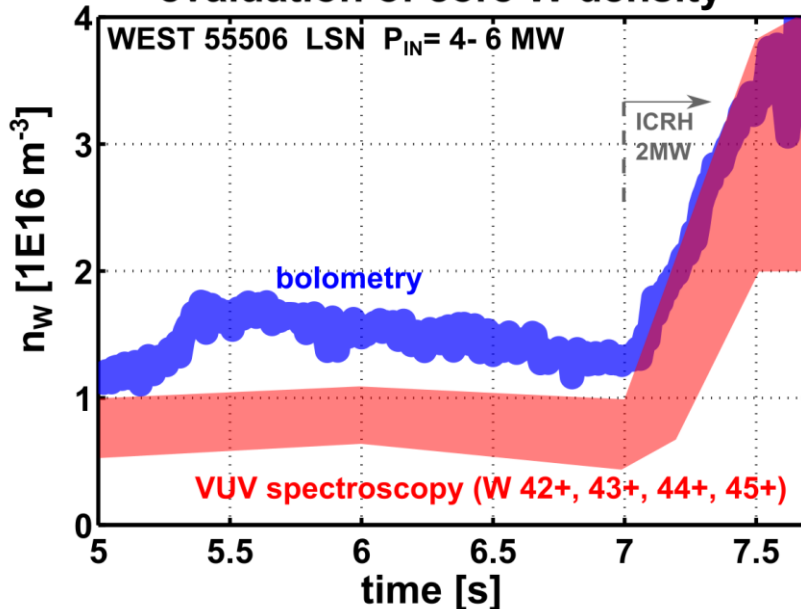
$$c_{lowZ} \approx 10^{-2}$$



Central tungsten density estimated with:

- Absolutely calibrated VUV spectrometer Γ_{ph}^{WX+} ($T_e \geq 3 \text{ keV}$) [1]
- Bolometry tomography + ADAS cooling rate ([2])
(soft X-rays treatment ongoing)

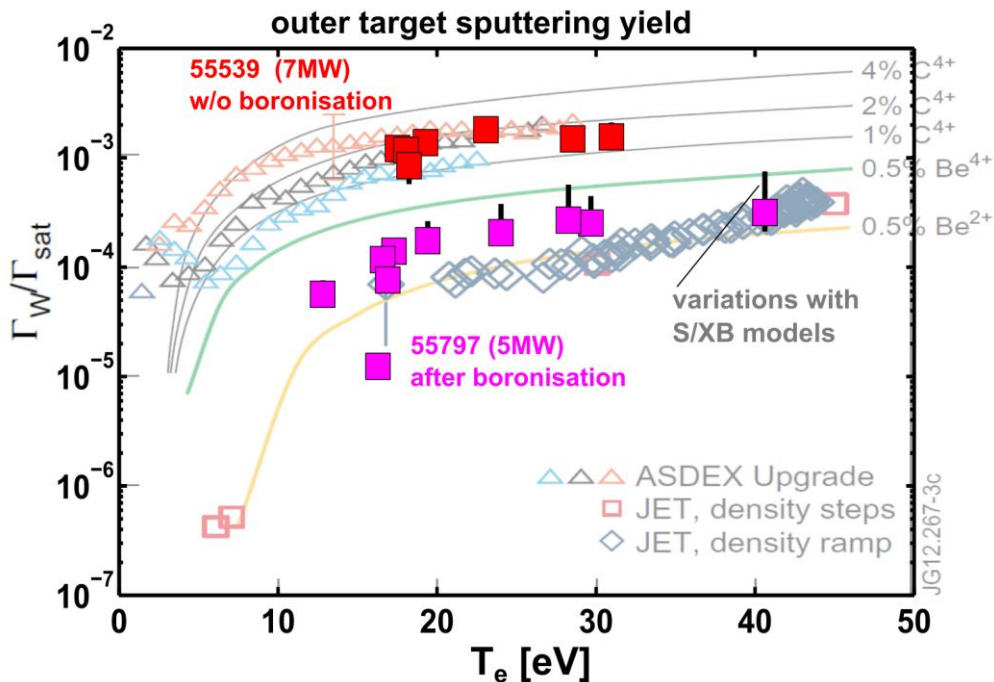
evaluation of core W density



15% of scenarios impacted by tungsten accumulation or radiative collapses [3]

Core tungsten density profiles weakly peaked

- [1] R. Guirlet submitted 2022
 [2] T. Pütterich Nucl. Fusion 2010
 [3] V. Ostuni, submitted 2022



Langmuir probes : $\Gamma_{\text{sat}}, n_e, T_e$, [1]

Visible spectroscopy : $\Gamma_{\text{ph}}^{WI\ 400.9\text{nm}}$ [2]

$$\Gamma_W \equiv \frac{S}{XB} (n_e, T_e) \times \Gamma_{\text{ph}}^{WI\ 400.9\text{nm}} \quad [3]$$

→ **uncertainties from atomic models
(meta-stables + sheath profiles)**

Large variability from experiment, but
effective sputtering yield coherent with
~ 0.1 - 1% light impurity concentration
(B,C,O,N)

A. Grosjean P184

**Note: Core radiation not correlated with
divertor sources**

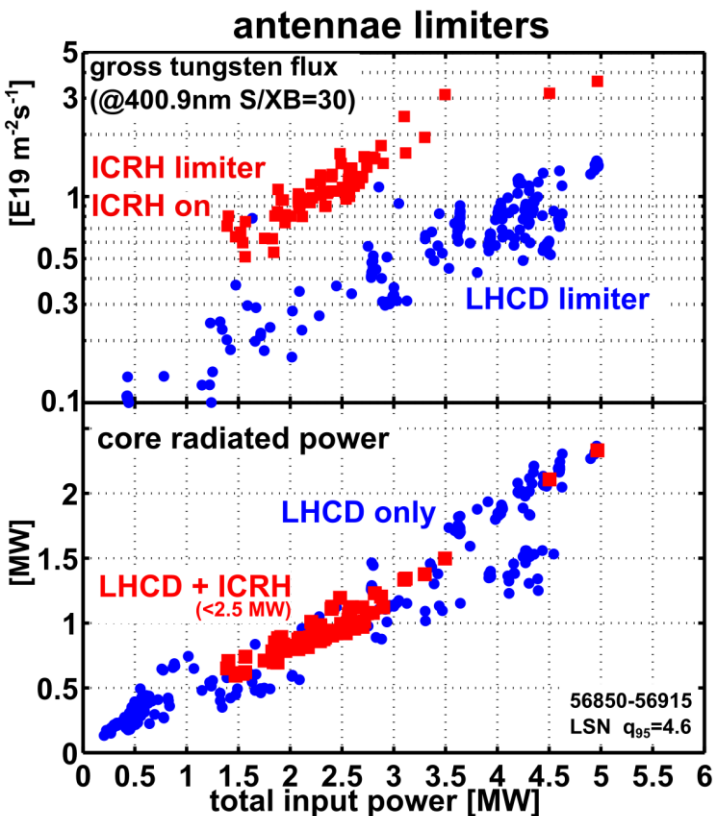
[1] R. Dejarnac et al *Fus.Eng.Des* (2020)

[2] O. Meyer et al *Rev. Sci. Instrum* (2018)

[3] S. Brezinsek et al *Phys. Scr.* (2017)

C. Johnson et al *Nuc. Mater. Energy* 2019

J. Guterl et al *Contrib. Plasma Phys.* 2020



LHCD & ICRH antennae equipped with tungsten limiters
(total limiters surface $\sim 1\text{m}^2$)

Main trends concerning gross tungsten fluxes:

- Increase with input power (or P_{SEP}) [1]
→ correlates with core radiated power
- Strong increase from active ICRH antennae
→ enhanced sputtering from rectified sheath potential [2,3]

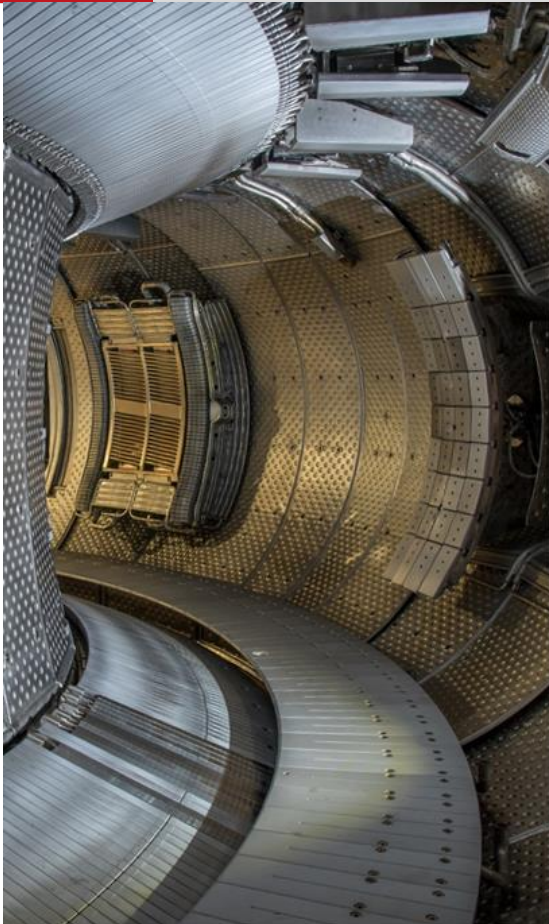
But:

- Similar radiated power with ICRH or LHCD
- Sources decrease with plasma/antennae gap, not the radiated power

WEST ICRH antenna



- [1] C.C. Klepper et al PPCF submitted
[2] L. Colas et al Nucl. Fusion 62 (2022)
[3] G. Urbanczyk et al Nucl. Fusion 2021



Overview of the *Phase 1* divertor operation

Experimental assessment of tungsten sources & core contamination

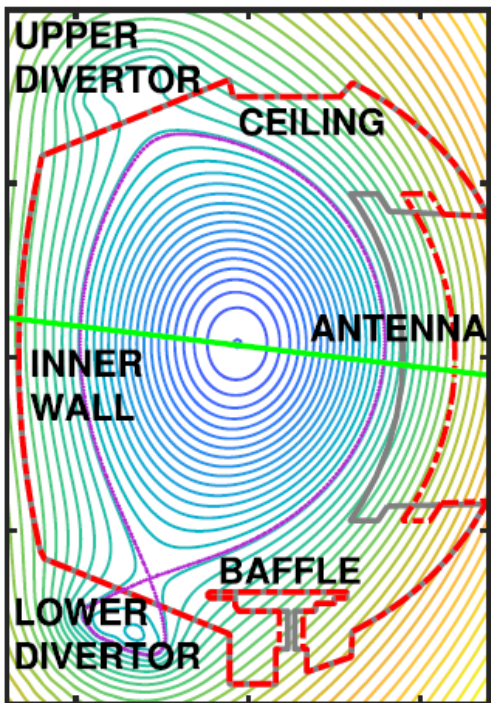
- Sputtering yields coherent with 0.1-1% low-Z conc.
- Core radiation (tungsten) $\sim 50\% P_{IN}$ in any scenario
- Core radiation weakly correlated to gross sources
→ sheath redeposition & transport are critical

Numerical modelling of tungsten sources and contamination with transport codes: status & ongoing developments

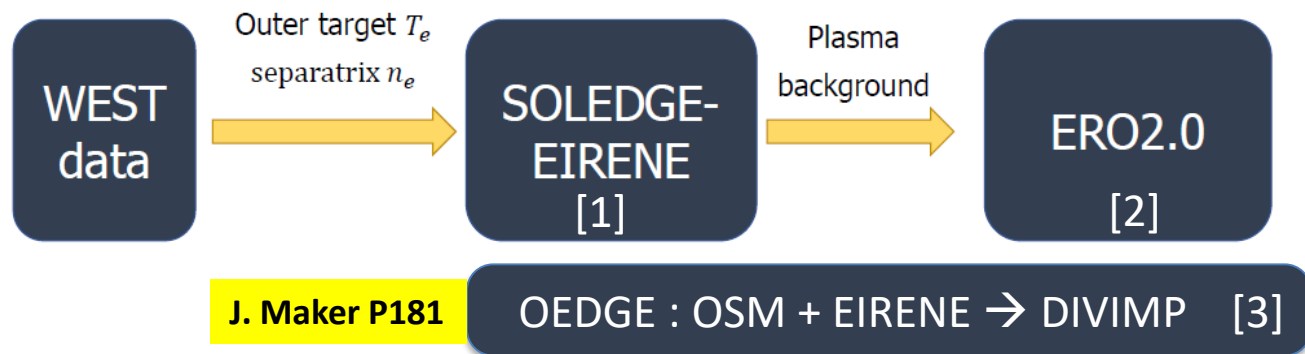


Validate modelling tools against L-mode WEST experiments:

- source strength & wall distribution (full W device)
- resulting core contamination (screening mechanisms)



Courtesy S. Digenova Nucl. Fus. 2021



Tungsten sputtering & transport: kinetic Monte-Carlo
+ Synthetic diagnostics for experimental comparison

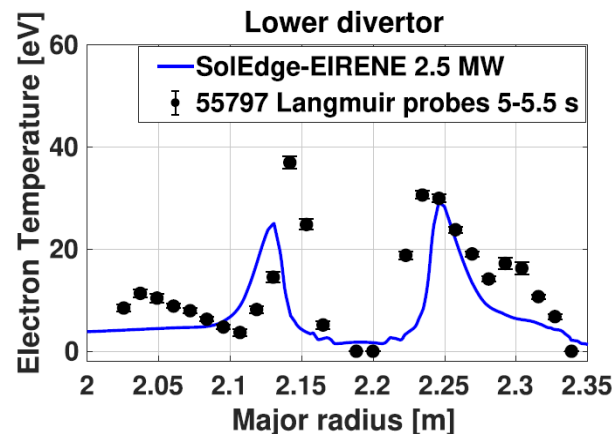
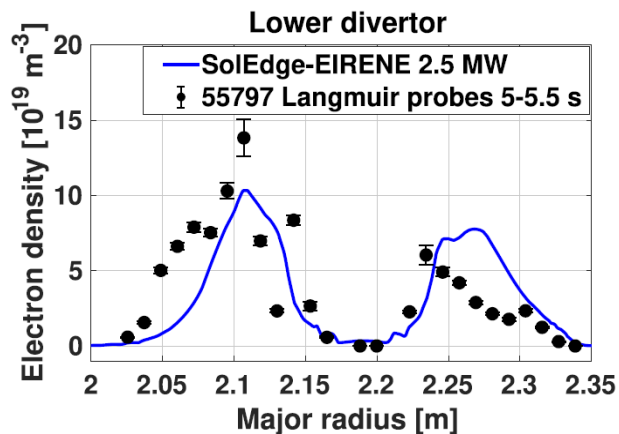
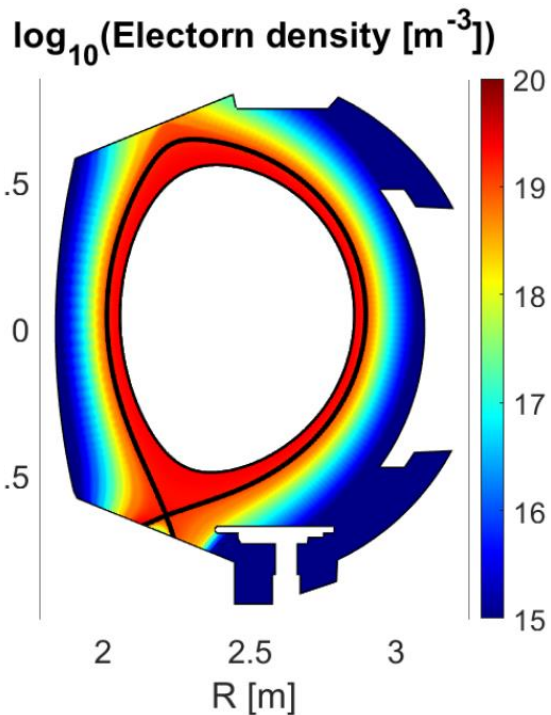
Note: no feedback (yet) of W radiation on background simulations

[1] H. Bufferand Nucl. Fus. 2015

[2] J. Romazanov et al Phys. Scr. 2017

[3] J.D. Elder et al Nuc. Mat. Energy 2017

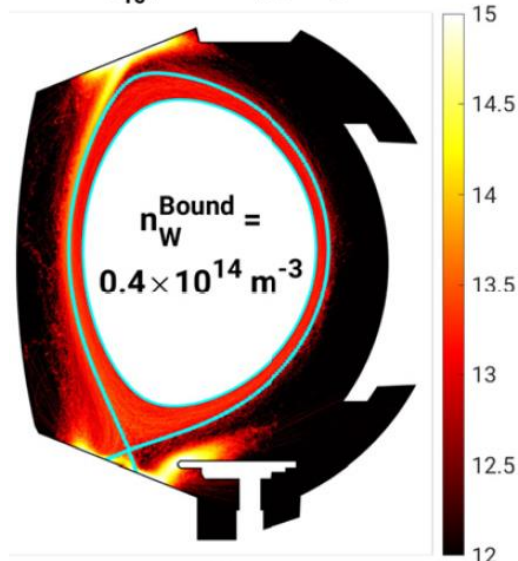
- WEST scenario $P_{SEP} \approx 2.5$ MW, $n_{sep} \approx 2 \text{ E}19\text{m}^{-3}$
- SOLEDGE transport tuned to “match” experimental profiles
- No drifts
- **Outer gap with antenna limiters LARGER than in experiment**
- both strike points in high recycling regime ($T_e > 20\text{eV}$)



Experiment:

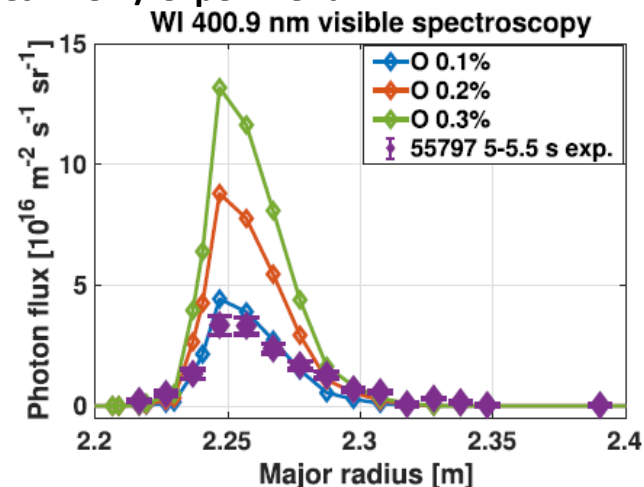
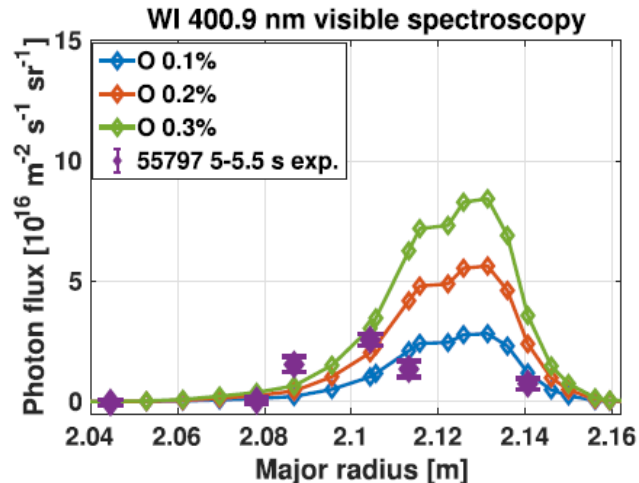
$$\langle n_W \rangle_{core} \approx 50 \times 10^{14} m^{-3}$$

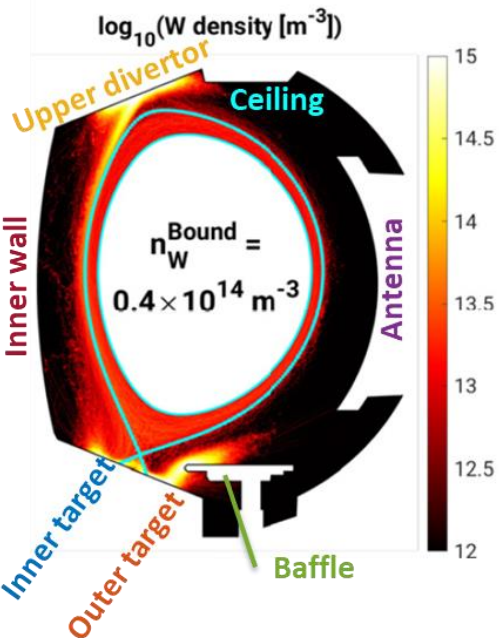
ERO2.0 result:

$$\log_{10}(W \text{ density } [m^{-3}])$$


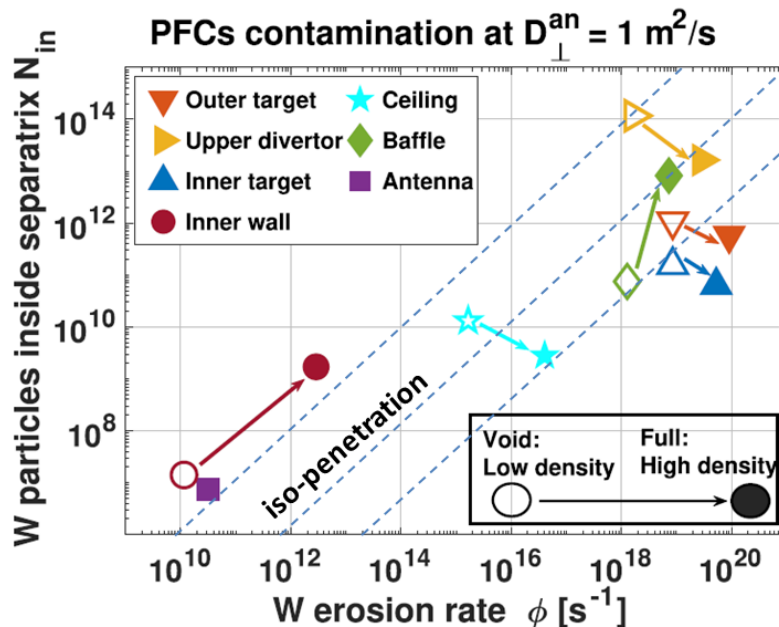
- Modelled divertor sources match experiment with 0.1% oxygen
- Core contamination:
 - Defined as averaged tungsten density inside separatrix
 - sources from all plasma facing components

→ **Simulated core contamination much lower than in experiment**

lower divertor sources ERO2 / experiment



- Lower divertor dominates the source, but low penetration
- **Upper divertor dominates core contamination, in LSN**
- Baffle sources potentially important (far SOL) **J. Maker P181**



Contamination highly sensitive to SOL regime & PFC/plasma gaps

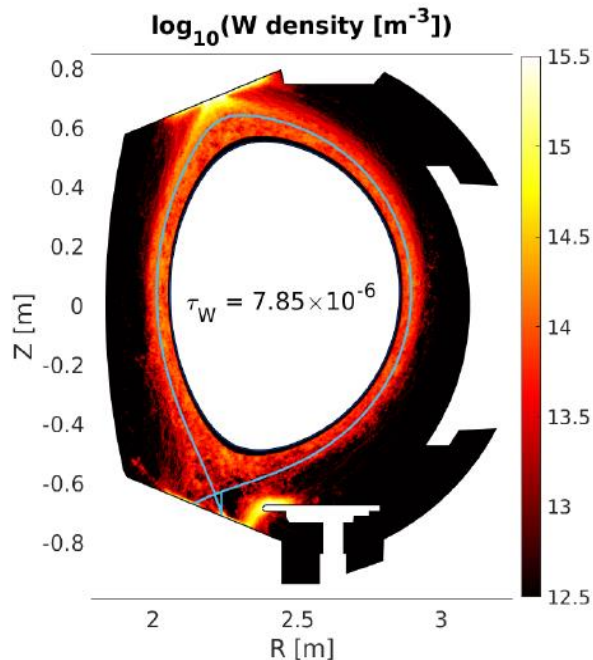
Accurate plasma & wall geometry necessary (3D antennae, etc)

S. Di Genova P129

ERO2.0 simulations (all PFCs) with same oxygen level but *different charge states*

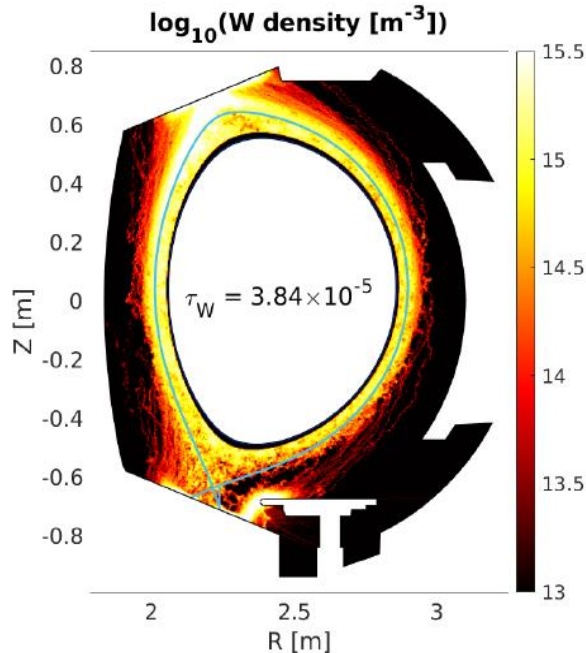
Case 1

75% O⁺¹ / 15% O⁺² / 10% O⁺³



Case 2

O⁺¹ → O⁺⁸ from SOLEDGE [1]



- Gross source larger in Case 2:
Impact $E_{inc} = 2T_i + 3ZT_e$
on sputtering yield
- **At equivalent source, core contamination 5X larger in the case 2**
- **Lower redeposited fraction**
- **Refined kinetic modelling needed**

[1] A. Gallo et al Nucl. Fus. 2020



- **Phase 1 divertor operation limited by tungsten core radiation**
 - Prevented routine H-mode access (P_{SEP} marginal \rightarrow ITER?)
 - DOMINANTE SOURCES NOT ELUCIDATED YET \rightarrow highly sensitive to transport
 - Significant L-mode database (IMAS format) for code validation
- **Simulation tools under validation, not yet quantitative:**
 - ERO2.0 improved with better description of sheath profiles & thermal forces
 - Redeposition physics (in grazing angles) highly sensitive to kinetic details
 - \rightarrow UV spectroscopic data needed from SOL region (W7+ etc)
 - 3D sources & transport from localized limiters *on going*
 - Modelling of rectified RF sheath & impact on W erosion & transport