Tungsten sources and core contamination in WEST plasmas: from experiments to simulations

N Fedorczak, S Di Genova, C Guillemaut, R Guirlet, L Cappelli, A Gallo, L Colas, J Romazanov, S Brezinsek, Y Marandet, et al.

FI22

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

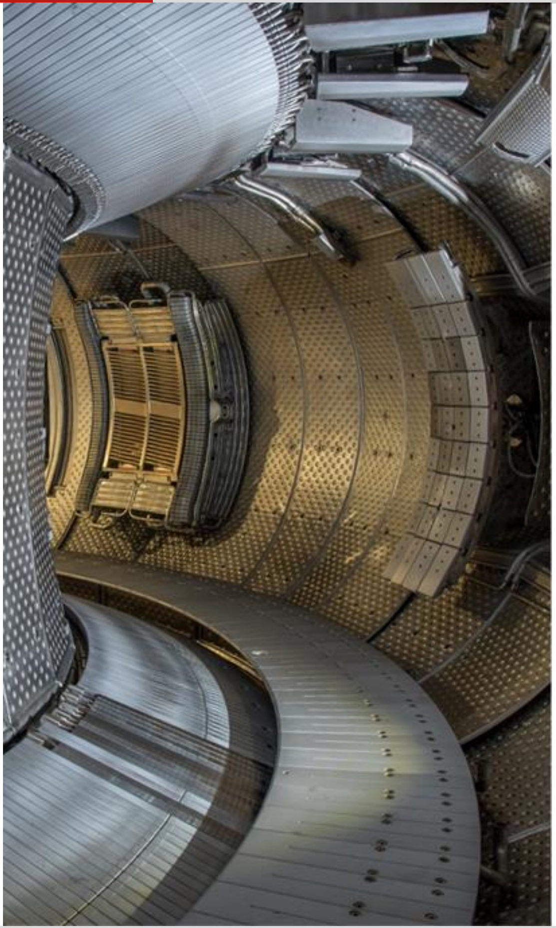
N Fedorczak[1], S. Di Genova[2], C. Guillemaut[1], R. Guirlet[1], L. Cappelli[2], A. Gallo[1],L. Colas[1], J. Romazanov[3], S. Brezinsek[3], Y. Marandet[4], H. Bufferand[1], H. Yang[1], G. Ciraolo[1], E. Serre[2], E.A. Unterberg[5], C.C. Klepper[5], C.A. Johnson[5], D.C. Donovan[6], S. Kosslow[6], J. Maker[6], A. Grosjean[6], E. Tsitrone[1], J. Bucalossi[1], and the WEST team[6]

DE LA RECHERCHE À L'INDUSTRIE

1 IRFM, CEA-Cadarache, 13108 Saint-Paul-lez-Durance, France
2 M2P2, Aix-Marseille Univ, CNRS, Centrale Marseille, 13013 Marseille, France
3 Forschungszentrum Jülich, 52425 Jülich, Germany
4 PIIM, Aix-Marseille Univ, CNRS, 13013 Marseille, France
5 Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA
6 Department of Nuclear Engineering, University of Tennessee-Knoxville, Knoxville, Tennessee 37916, USA
6 http://west.cea.fr/WESTteam

PSI 2022

Outline

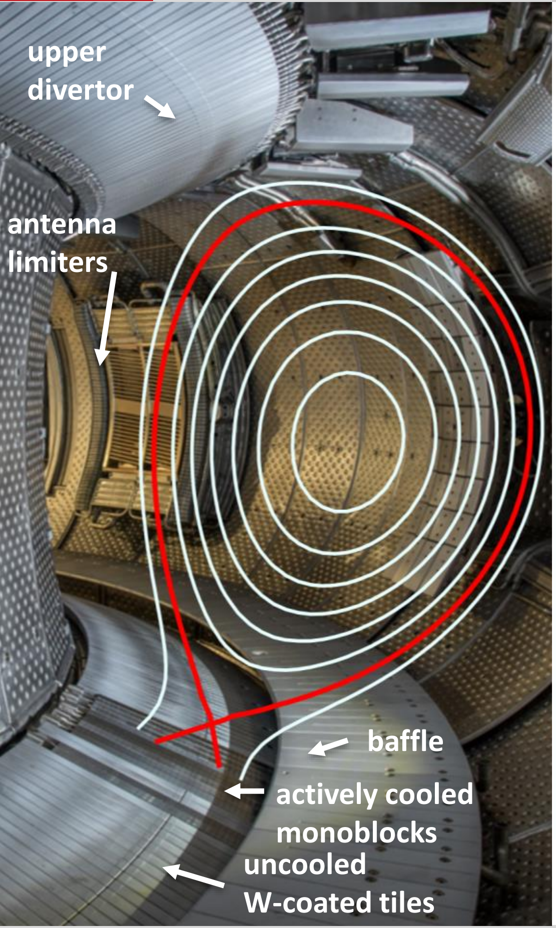


Overview of the *Phase 1* divertor operation

Experimental assessment of tungsten sources & core contamination

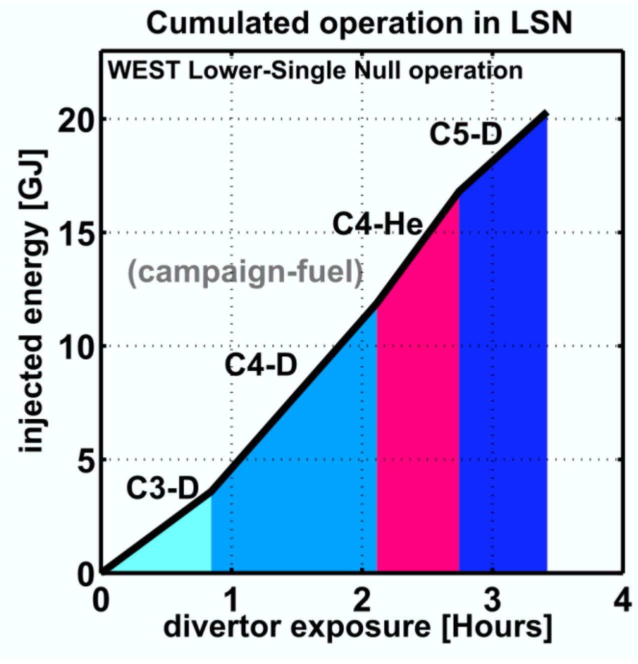
Numerical modelling of tungsten sources and transport with transport codes: status & developments

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

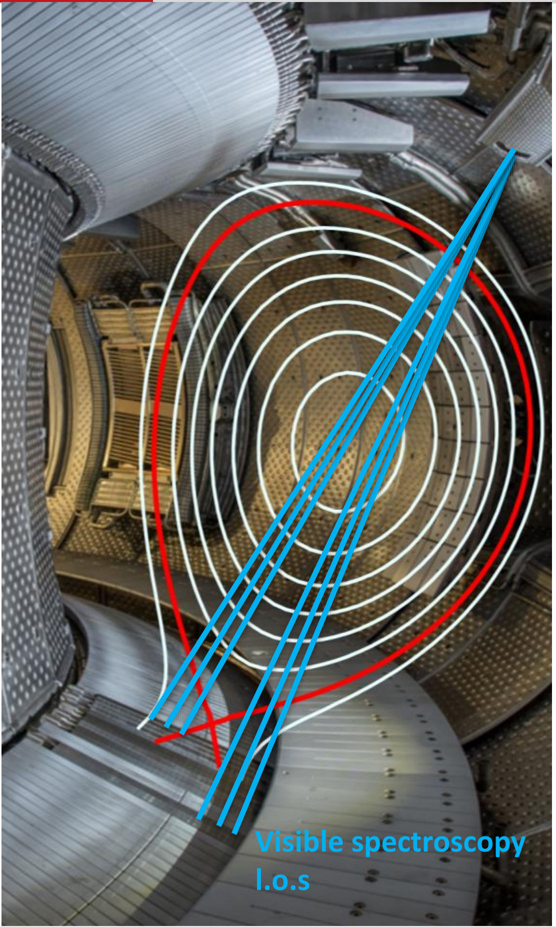
L-mode operation (limited by radiation)

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

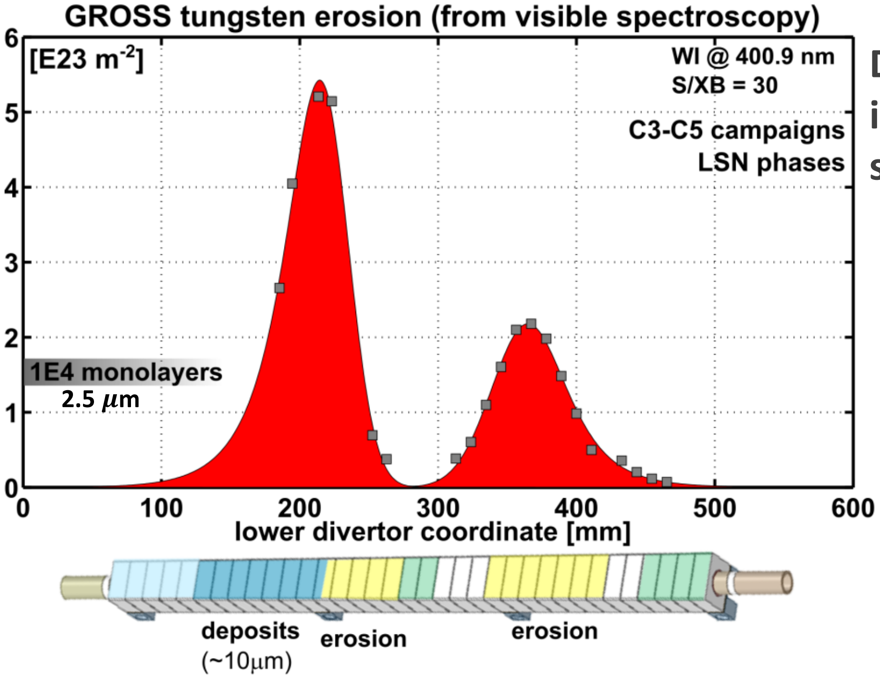


W-coated graphite tiles + actively cooled ITER-like monoblocks

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

→ Deuterium fluency E26~27 m^{-2} (wetted area ~ 1 m^2)

→ Gross tungsten erosion ~ few μm + co-deposition

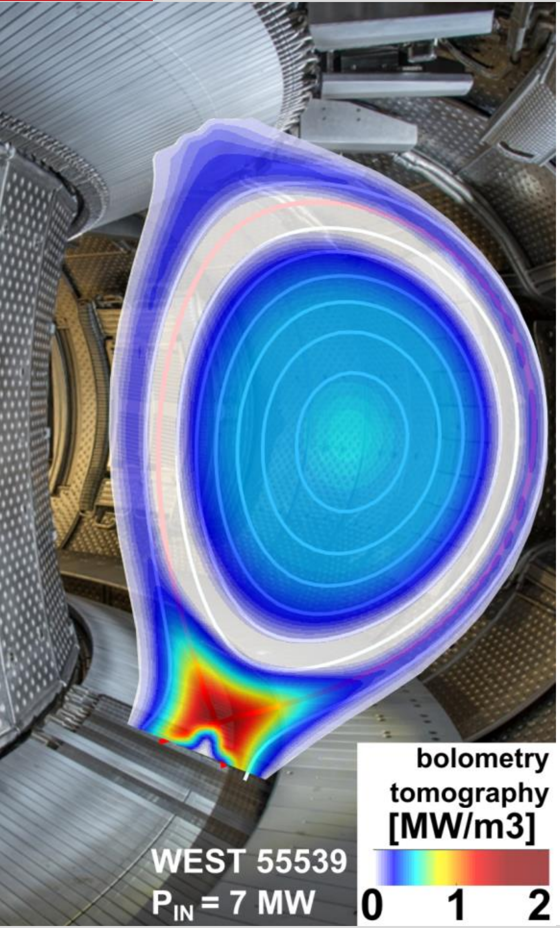


Deposition/erosion: impact on infra-red surface emissivity

J. Gaspar P003

M. Diez TI07 (Tuesday)

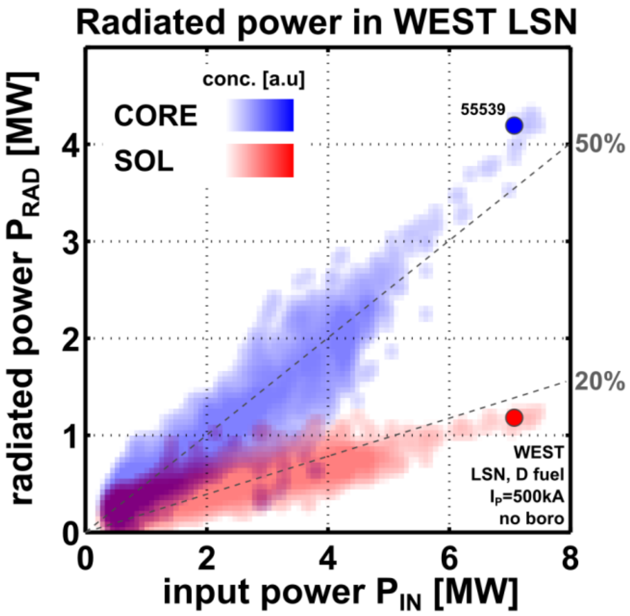
Radiated fraction (~60%) weakly impacted by plasma scenario



Standard scenario: LSN, $B_T = 3.7T, q_{95} = 4.5$, 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



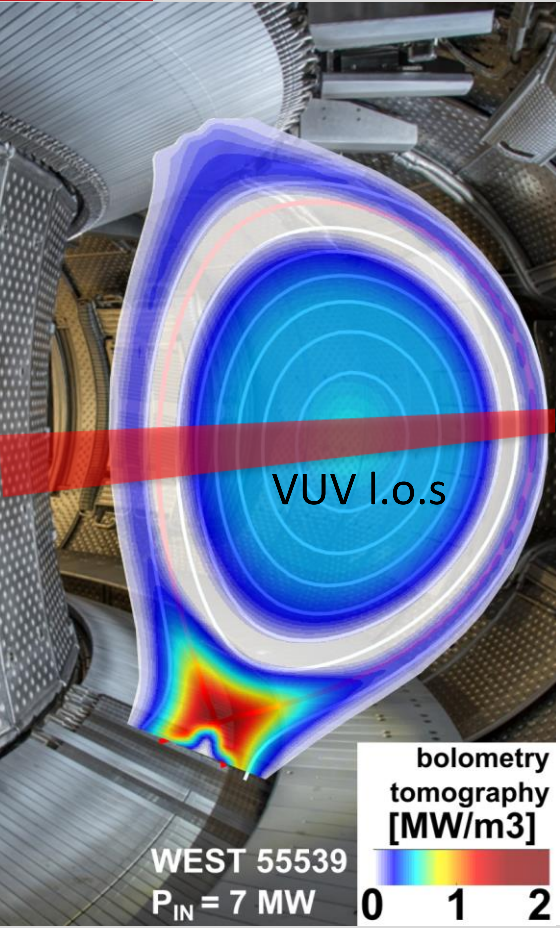
$c_W \approx 10^{-4}$

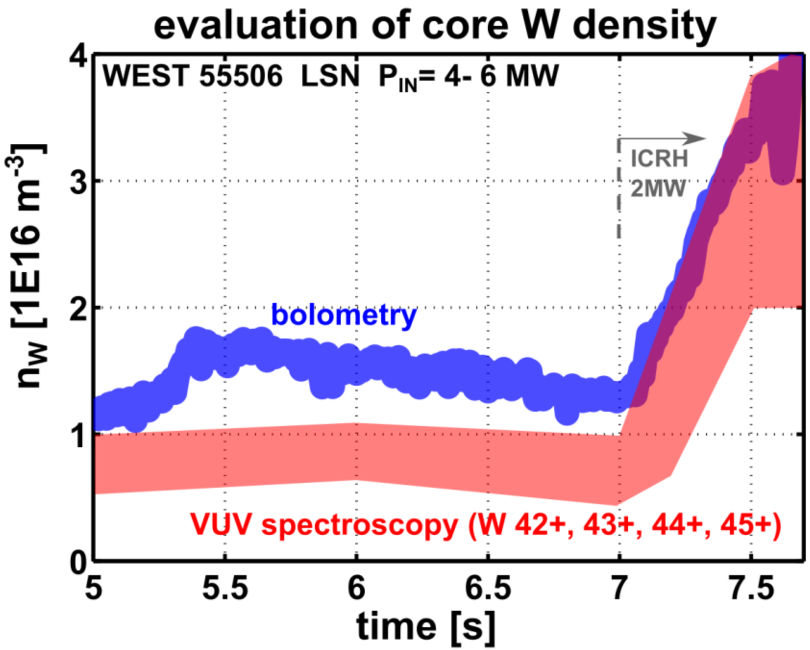
$c_{lowZ} \approx 10^{-2}$

Central tungsten density estimated with:

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

(soft X-rays treatment ongoing)



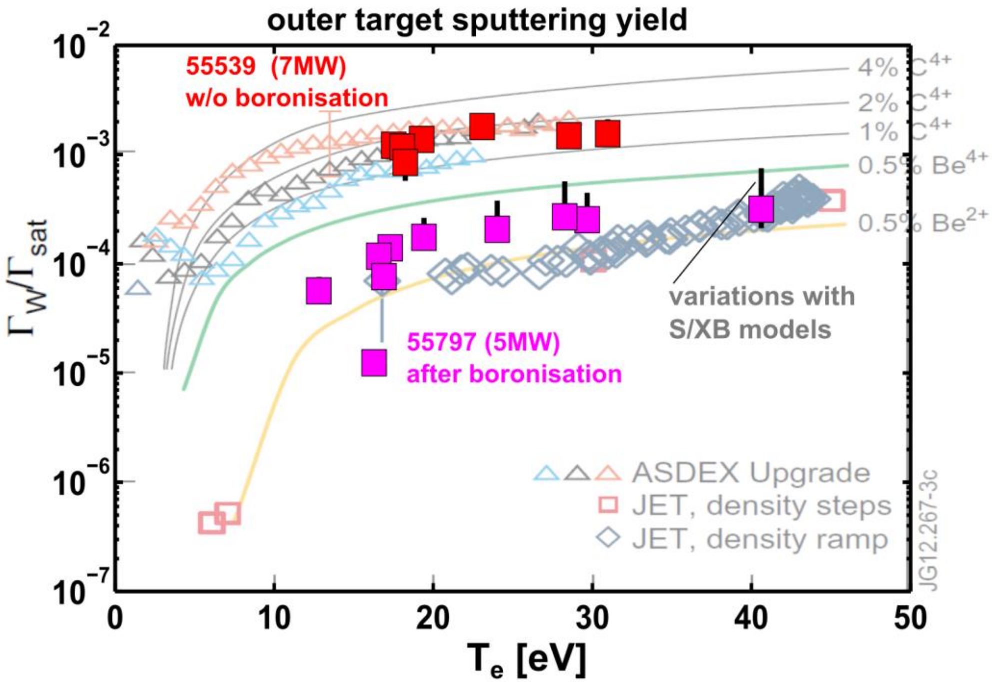


15% of scenarios impacted by tungsten accumulation or radiative collapses [3]

Core tungsten density profiles weakly peaked

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

Outer strike point sputtering in the range of multi-machine observations



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

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

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

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

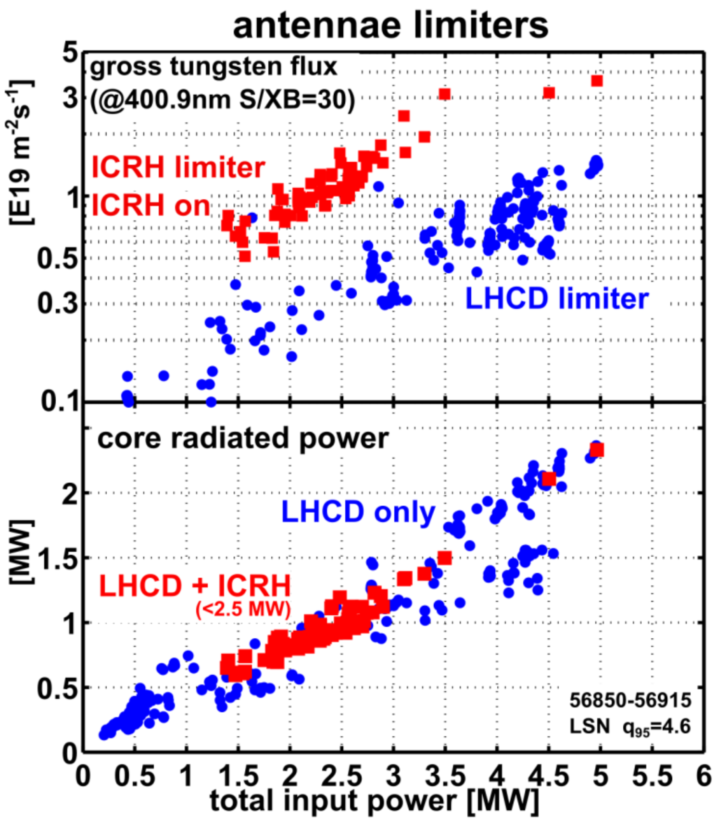
Large variability from experiment, but effective sputtering yield coherent with ~ 0.1 - 1% light impurity concentration (B,C,O,N)

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

Sources from RF antennae limiters *might* dominate core contamination



LHCD & ICRH antennae equipped with tungsten limiters

(total limiters surface ~1m^2)

WEST ICRH antenna

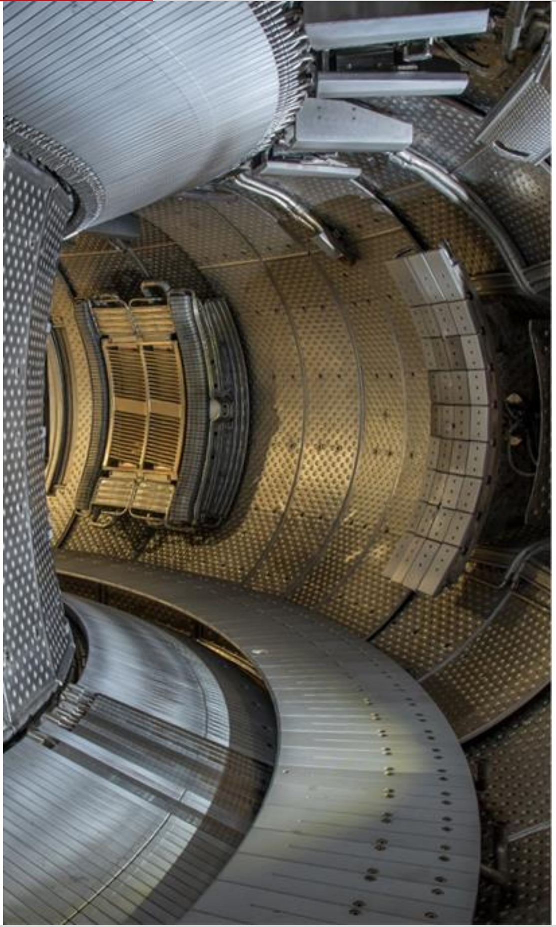
Main trends concerning gross tungsten fluxes:

- 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**

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



Overview of the *Phase 1* divertor operation

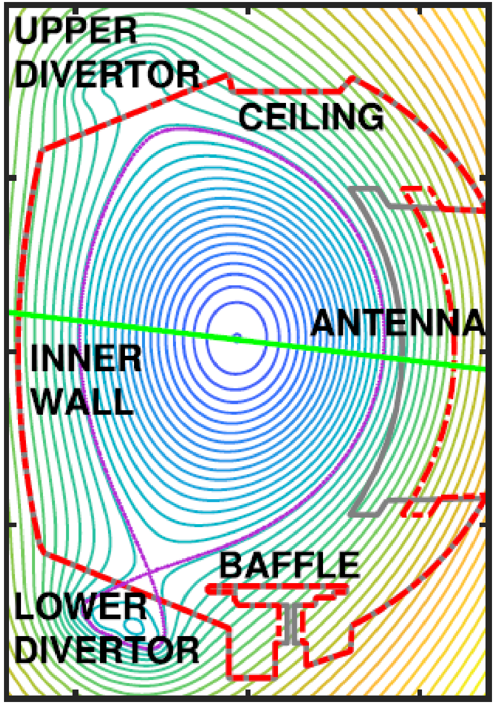
Experimental assessment of tungsten sources & core contamination

- Sputtering yields coherent with 0.1-1% low-Z conc.
- Core radiation (tungsten) ~ 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

Modelling objectives & workflow



Curtesy S. Digenova Nucl. Fus. 2021

Validate modelling tools against L-mode WEST experiments:

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

WEST data → (Outer target T_e, separatrix n_e) → SOLEDGE-EIRENE [1] → (Plasma background) → ERO2.0 [2]

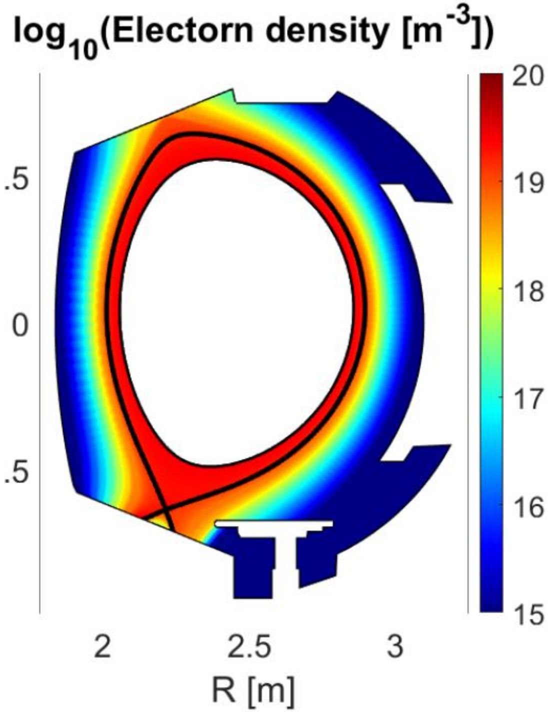
J. Maker P181 — OEDGE : OSM + EIRENE → DIVIMP [3]

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

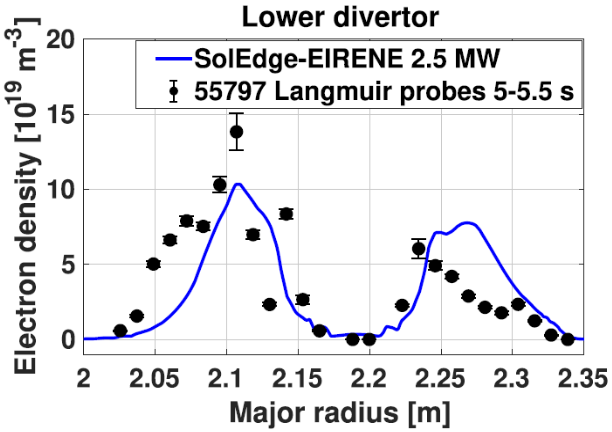
SOLEDGE-EIRENE background coherent with experimental conditions

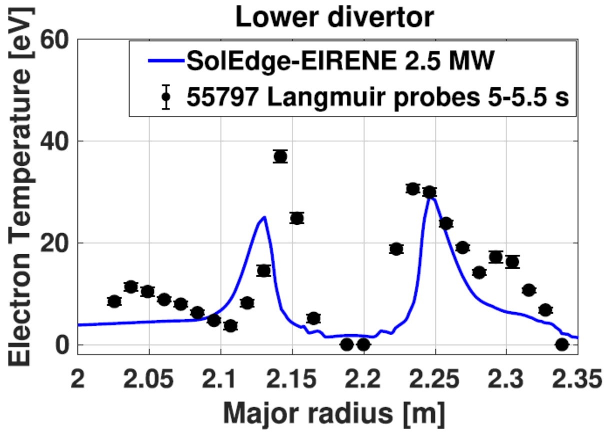
S. Di Genova et al. Nucl. Fus 2021



- WEST scenario $P_{SEP} \approx 2.5$ MW, $n_{sep} \approx 2$ E19m^{-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>20eV)





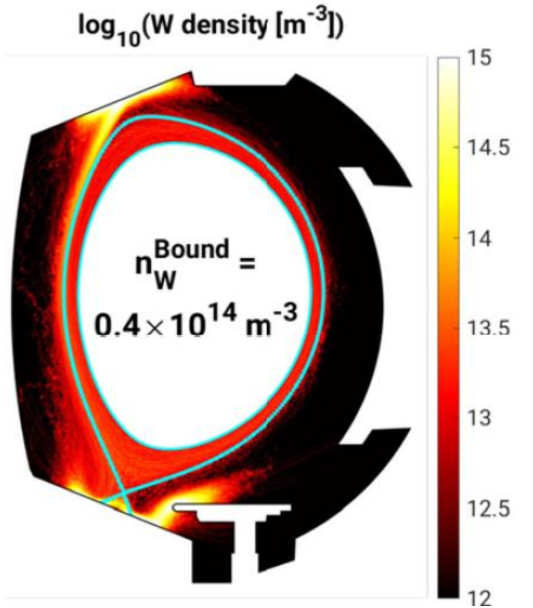
ERO2.0 generates W sources from deuterium + oxygen (low-Z proxy)

S. Di Genova et al. Nucl. Fus 2021

Experiment:

$< n_W >_{core} \approx 50 \times 10^{14} m^{-3}$

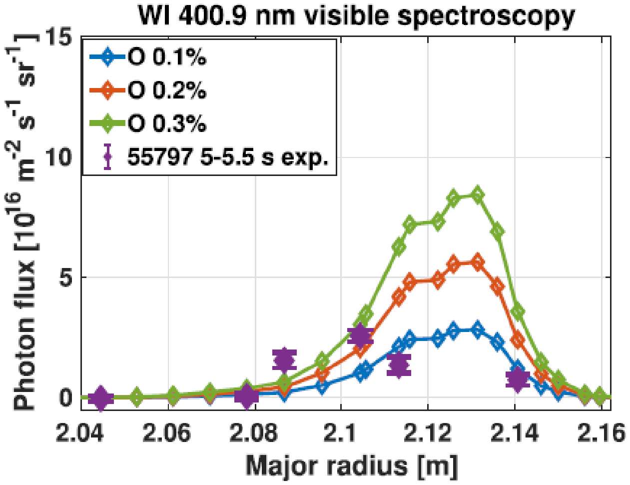
ERO2.0 result:

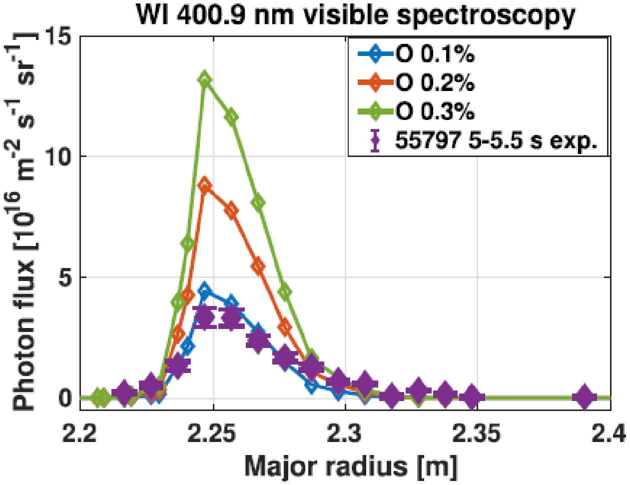


- Modelled divertor sources match experiment with 0.1% oxygen
- Core contamination:
  - Defined as averaged tungsten density inside separatrix
  - sources from all plasma facing components

→ Simulated core contamination much lower than in experiment

lower divertor sources ERO2 / experiment

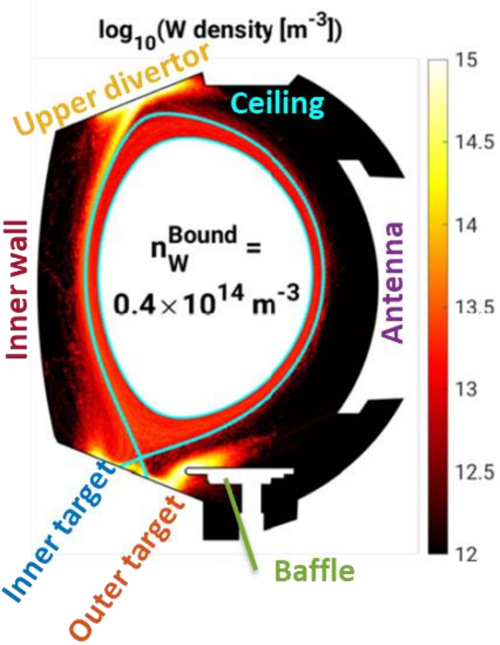


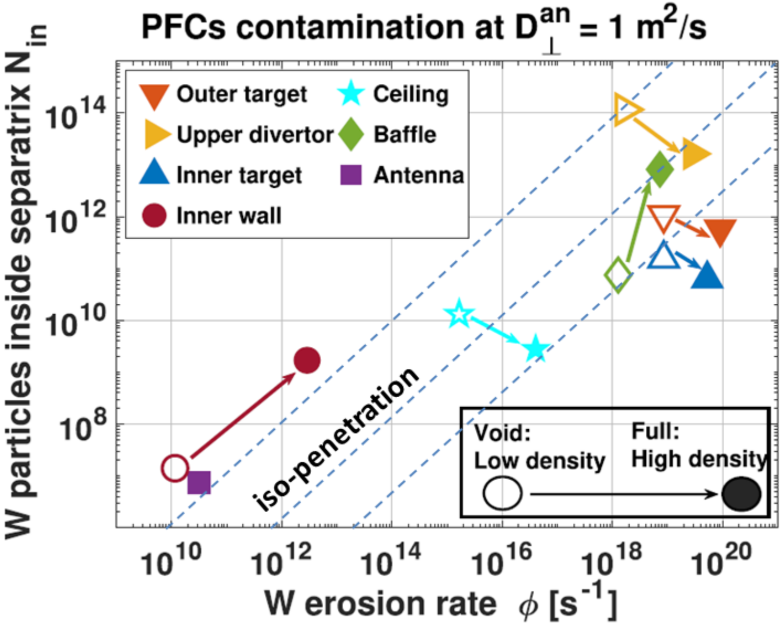


ERO2.0 simulations indicate the dominant role of secondary PFCs

S. DiGenova et al. Nucl. Fus 2021

- 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

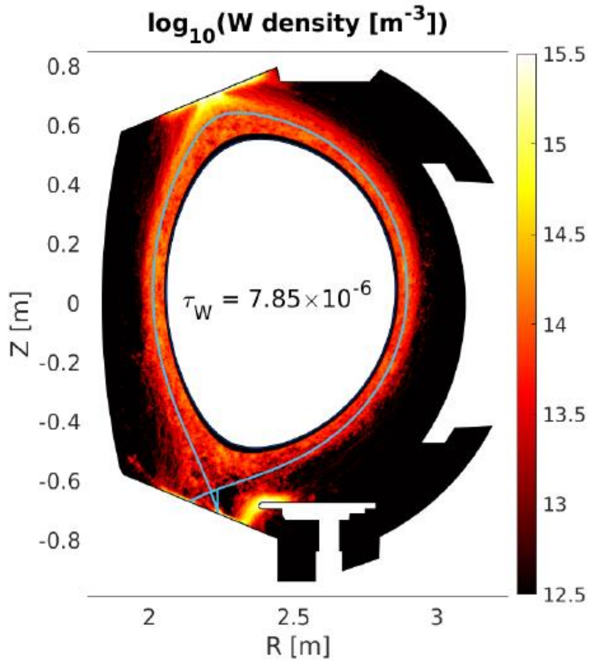
ERO2.0 highlights the importance of energetic Tungsten atoms

S. DiGenova

ER02.0 simulations (all PFCs) with same oxygen level but *different charge states*

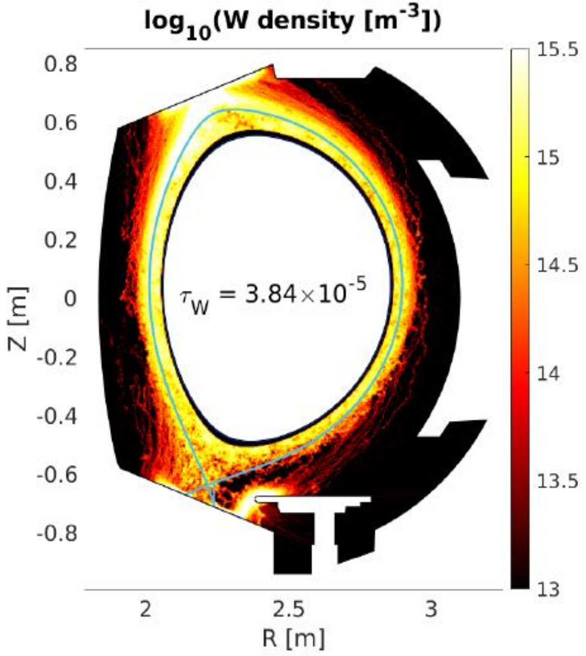
Case 1

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

Wrap-up & future plans

- **Phase 1 divertor operation limited by tungsten core radiation**
  - Prevented routine H-mode access (P_{SEP} marginal → ITER?)
  - DOMINANTE SOURCES NOT ELUCIDATED YET → 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

  → 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