Gyrokinetic modeling of tungsten transport and radiation in WEST and ASDEX Upgrade: towards the kinetic modeling of ITER physics

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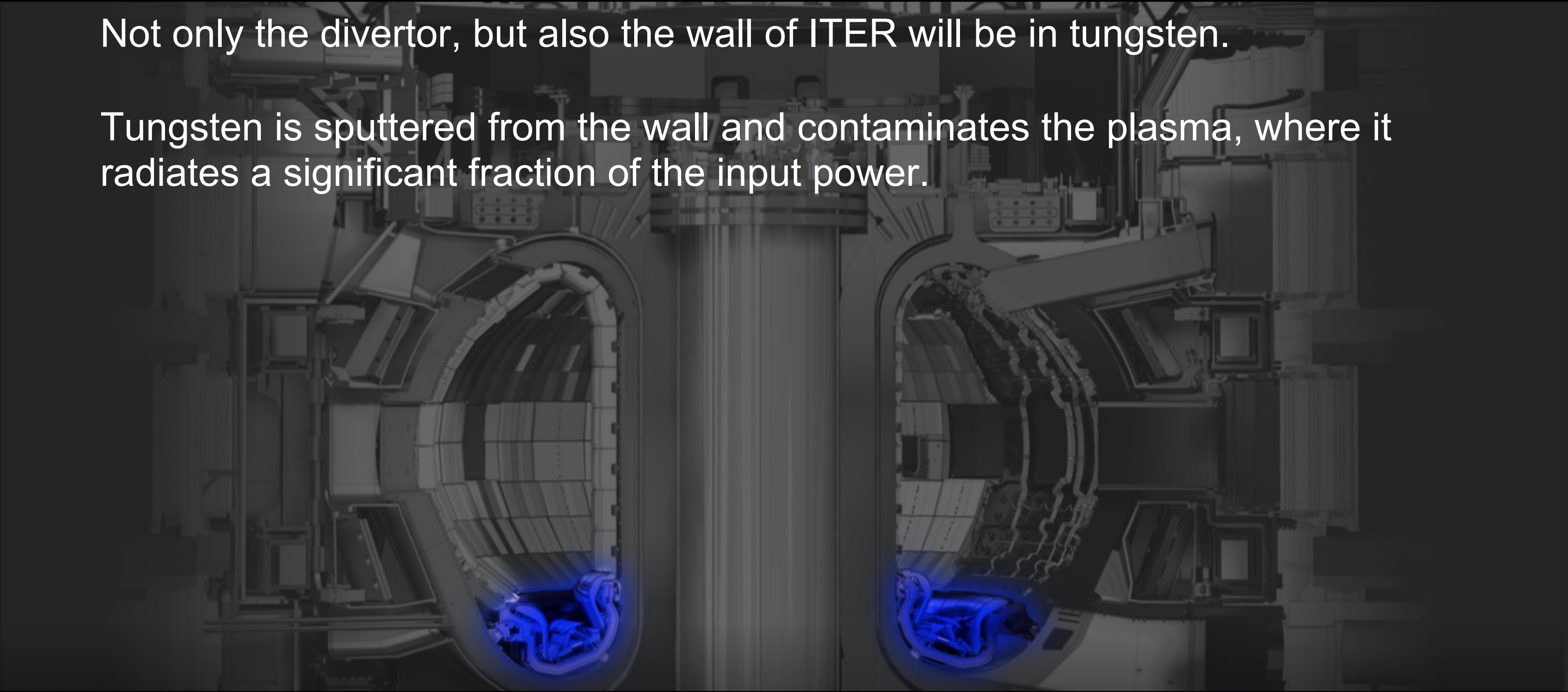
IPP Garching and U. Seville	A Kallenbach, T Putterich, E Viezzer, and AUG team

Theory seminar, Jun 20th 2024, PPPL

Motivation

Not only the divertor, but also the wall of ITER will be in tungsten.

Tungsten is sputtered from the wall and contaminates the plasma, where it radiates a significant fraction of the input power.



Motivation

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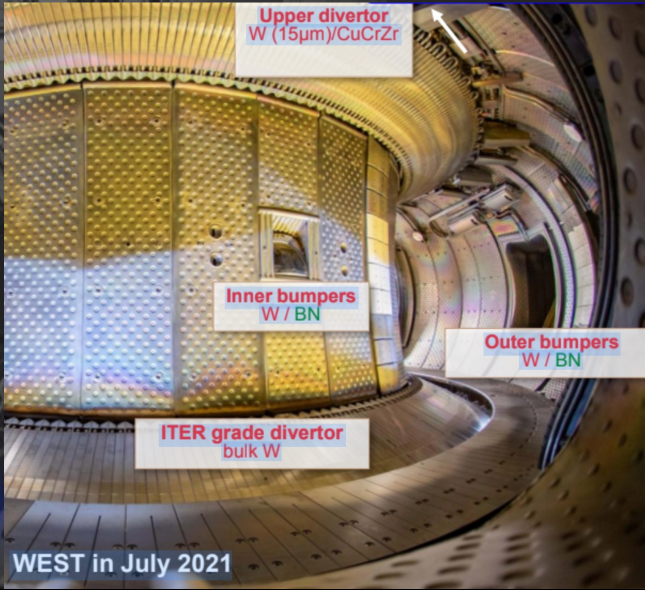
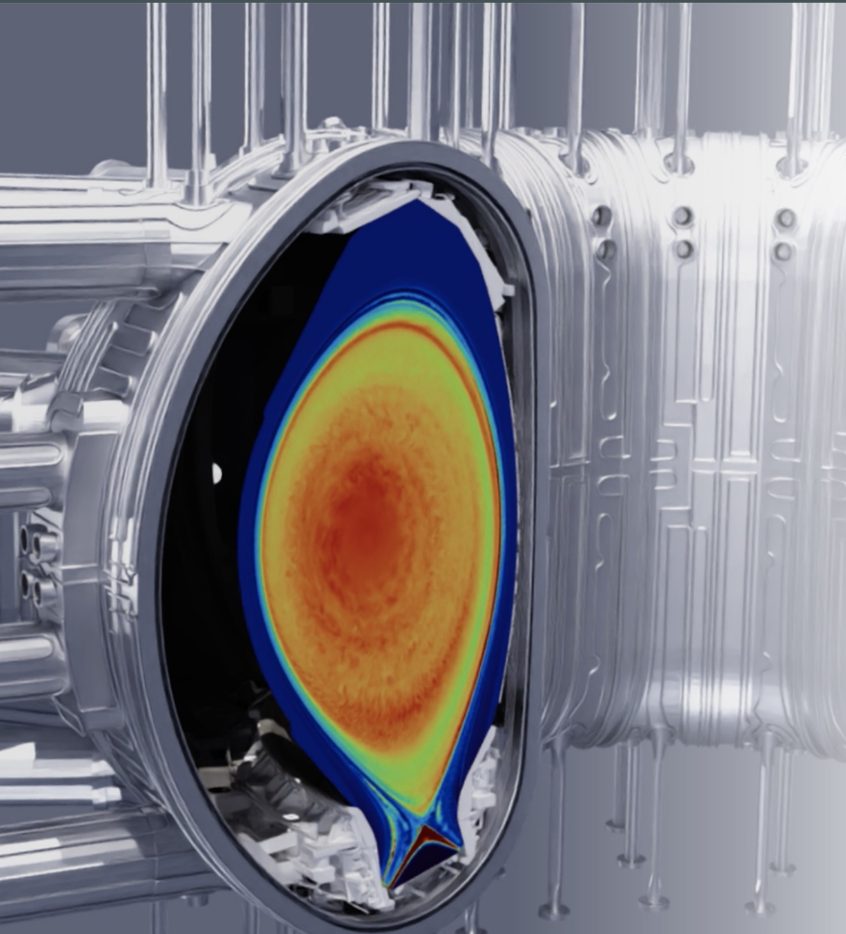
WEST is a test bed for ITER (divertor and wall)

- Ramp-up phase has no temperature screening and a large cooling rate (cold and hot branches)
- Light impurity seeding (N) helps passing the tungsten radiation peak
- Boron reduces tungsten sputtering (GDB & IPD)
- Radiative collapse
- …



XGC – The X-point Gyrokinetic Code



A multi-species total-f gyrokinetic code covering the whole volume with X-point

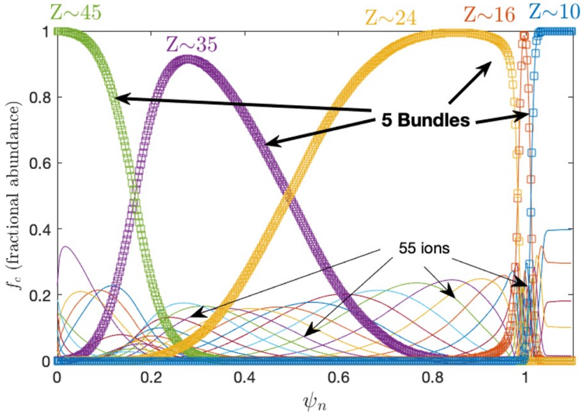
- Optimized for edge diverted geometry
- **Total-f gyrokinetic model** over the whole volume
- Nonlinear Fokker-Planck collision operator
- **Multi-impurities, bundles of tungsten**
- Neutral recycling, rotation, heat/torque sources
- Electromagnetic RMP model
- **Exascale-ready and portable**

General XGC references:
S. Ku et al., Phys. Plasmas (2018)
J. Dominski et al., *J. Plasma Phys.* (2019)
R. Hager et al., Phys. Plasmas (2022)
https://xgc.pppl.gov

Plan

1. Gyrokinetic bundles of tungsten
2. Tungsten asymmetries and flux in a JET H-mode plasma
3. Influence of nitrogen on the tungsten accumulation near the axis of **WEST**
4. Tungsten penetration at the separatrix of turbulent H-mode plasma of ASDEX-U
5. Conclusion

Collaboration with M. O'Mullane (UKAEA) and the ADAS group.



- The many charge states of tungsten ions are modeled with a few **gyrokinetic bundles**

  Fractional abundance is computed from atomic balance between ionization and recombination using **ADAS rates**.

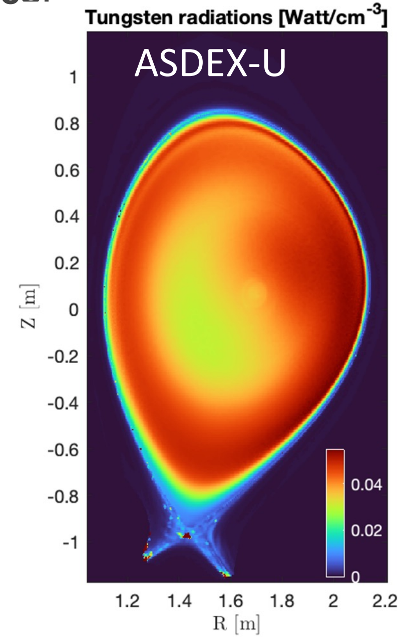
$$\frac{dn_i}{dt} = \sigma_{i-1}n_{i-1} - (\sigma_i + \alpha_i)n_i + \alpha_{i+1}n_{i+1}$$

- **Tungsten radiations** are also computed with **ADAS rates**.

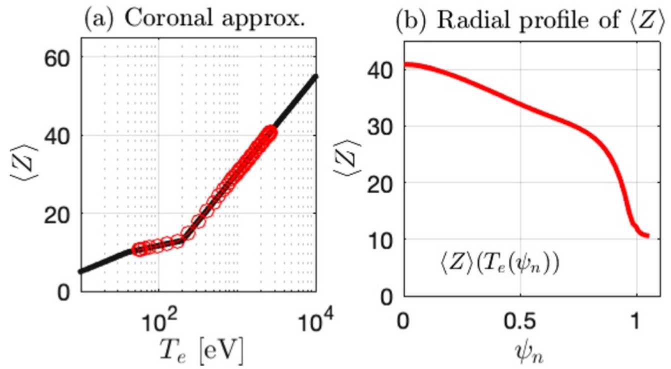
$$P_{\rm rad} = n_e n_{\rm w}\ L_{\rm cool}$$

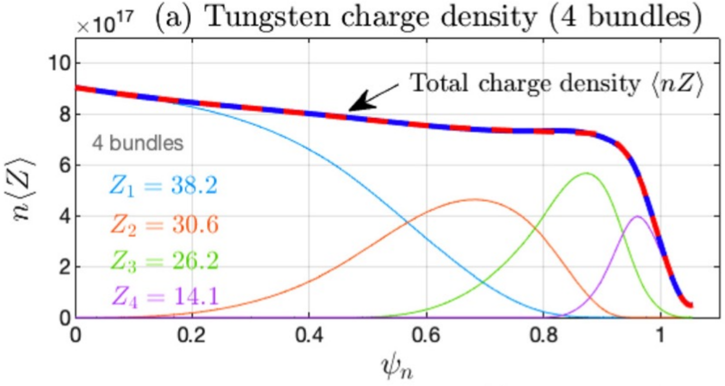
The cooling factor is consistently modeled with all ionization states.

Opportunity to validate the charge states emissions measured by the new multi-energy x-ray diagnostic in WEST.



1. Gyrokinetic bundles modeled with finite elements, and a Coronal approximation (Without ADAS rates)





- A Coronal approximation is used to determine <Z> as a function of T_e. **It was before I use ADAS atomic physics.**
- The density and charge are represented with finite elements (bsplines).

$$n(\psi_n) = \sum_i c_i \Lambda_i(\psi_n)$$

$$\langle nZ \rangle(\psi_n) = \sum_i c_i Z_i \Lambda_i(\psi_n)$$

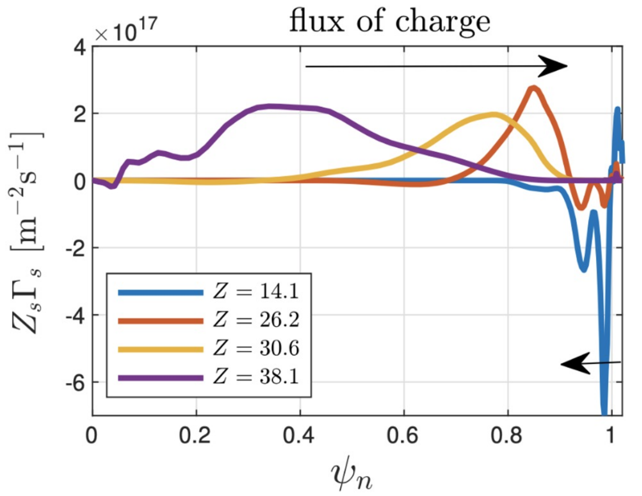
- The system is solved with a weak formulation.

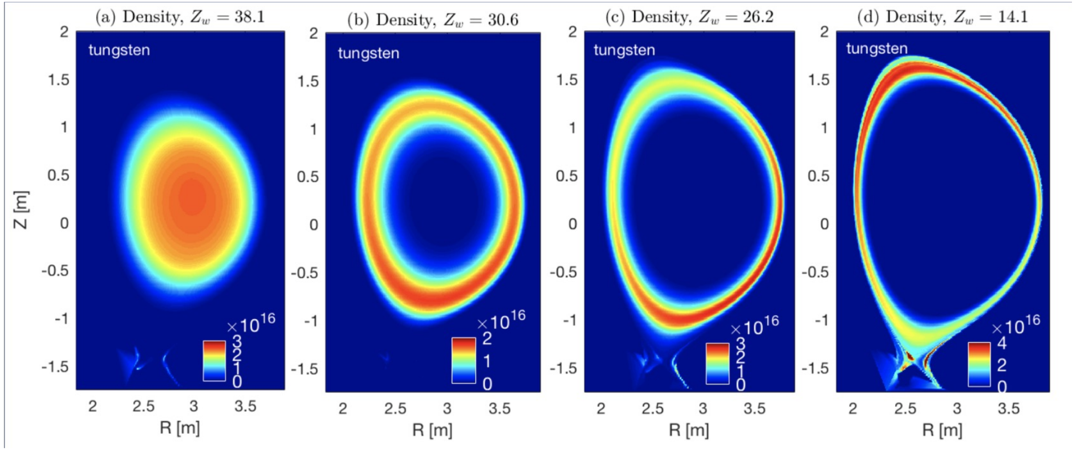
$$\begin{cases} c_i = (M^{-1})_{ij} \int d\psi\, \Lambda_j(\psi) \dfrac{\langle nZ \rangle(\psi)}{\langle Z \rangle(\psi)}, \\ c_i Z_i = (M^{-1})_{ij} \int d\psi\, \Lambda_j(\psi) \langle nZ \rangle(\psi), \end{cases}$$

$$M_{ij} = \int d\psi\, \Lambda_i(\psi) \Lambda_j(\psi)$$

Dominski et al. *Phys. Plasmas* (2024)

- Recent study of tungsten collisional transport using **4 bundles of tungsten**
- Influence of **large asymmetries** on the **collisional transport in the edge**
  - Reversal of the asymmetry in the edge caused by ion orbit-loss effects and $E_{||}$
  - Reversal of flux → accumulation in the pedestal top

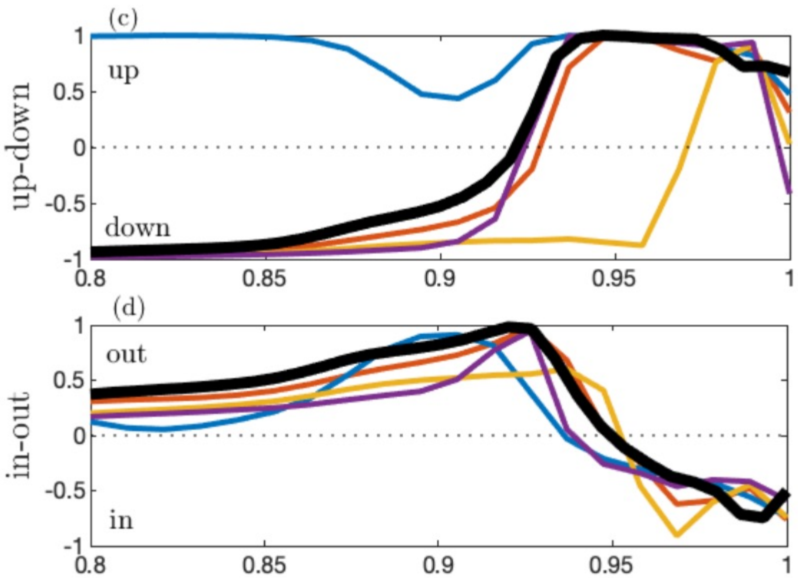




Dominski et al. *Phys. Plasmas* (2024)

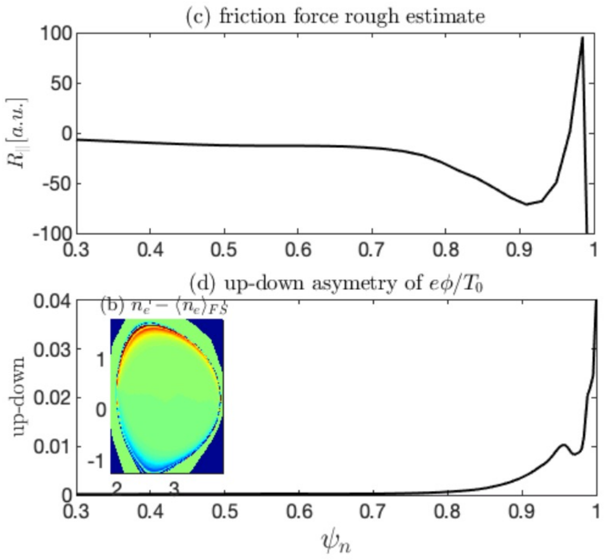
2. Asymmetries and friction force modulation

When the dominant up-down asymmetry cancels, the in-out asymmetry rise.



Reversal of the asymmetry in the edge is caused by ion orbit loss and $E_{||}$

$$\nabla_{\parallel} \ln n_w \simeq \frac{eZ}{T_w} E_{\parallel} + \frac{1}{n_w T_w} R_{\parallel,w}$$



Dominski et al. *Phys. Plasmas* (2024)

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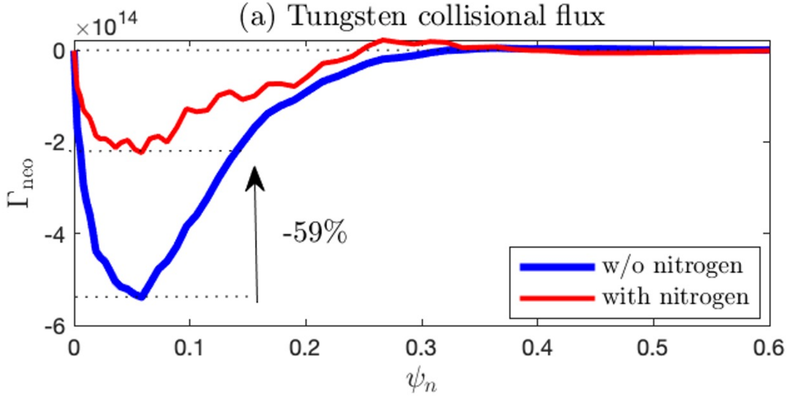
Collaboration with P Maget and P Manas, WEST team CEA

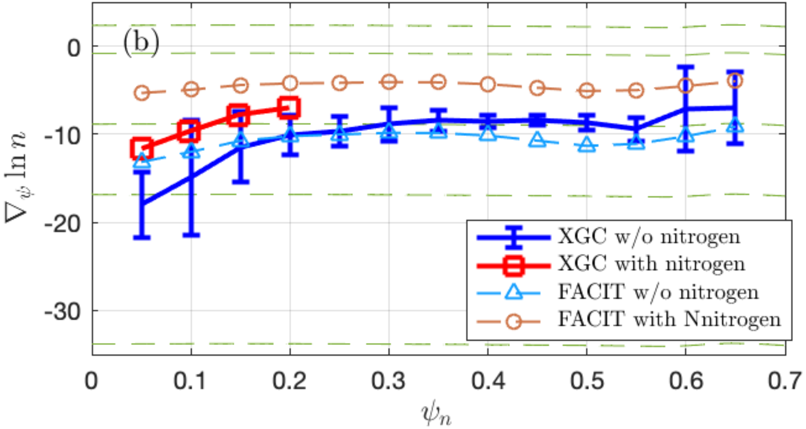
Collisional tungsten W^{25+} transport in the core is altered by nitrogen N^{7+}

(a) Reduction of the tungsten penetration in presence of N^{7+} (ohmic and heated plasmas)



(b) XGC simulations predict a ~60% reduction of the neoclassical peaking in presence of 2.5% of nitrogen.

>> We scan many radial profiles of density gradient (green dashed lines) and we interpolate the density gradient giving a zero particle-flux



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FACIT code: [Maget 2020 PPCF **62** 105001] [Fajardo 2022 *PPCF* **64** 055017]

Tungsten asymmetries are also reduced by ~60%.

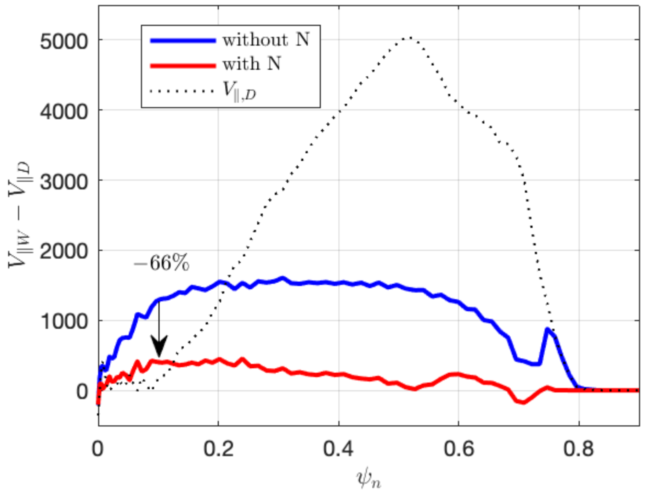
This is explained by a reduction of the friction force related to a reduction of the parallel flow of tungsten.

$$R_{\|\mathrm{w}} = -m_z n_z \nu_{\mathrm{wd}} \left(V_{\|\mathrm{w}} - V_{\|\mathrm{d}} - \frac{3}{5} \frac{q_{\|\mathrm{d}}}{n_{\mathrm{d}} T_{\mathrm{d}}} \right)$$

- Main ion flow does not change (doted black line). It is almost negligible near axis. Similar for $q_{||} \sim \nu \nabla_{||} \ln T$ (temperature asymmetry is very weak 10^{-4}).

- Tungsten flow is reduced to the same level as nitrogen.

Parallel flow difference $V_{||w}$-$V_{||d}$



WEST – smaller asymmetry & damping rate w/ nitrogen

Figure on the right shows the evolution of the asymmetry of tungsten density with (red) and without (blue) nitrogen.

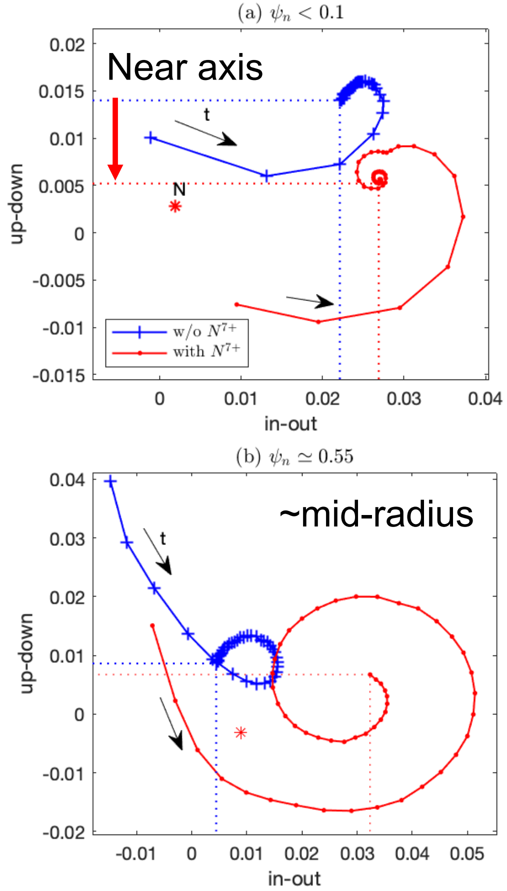
Asymmetry reduction by nitrogen:

Nitrogen reduces the up-down asymmetry near axis (a).

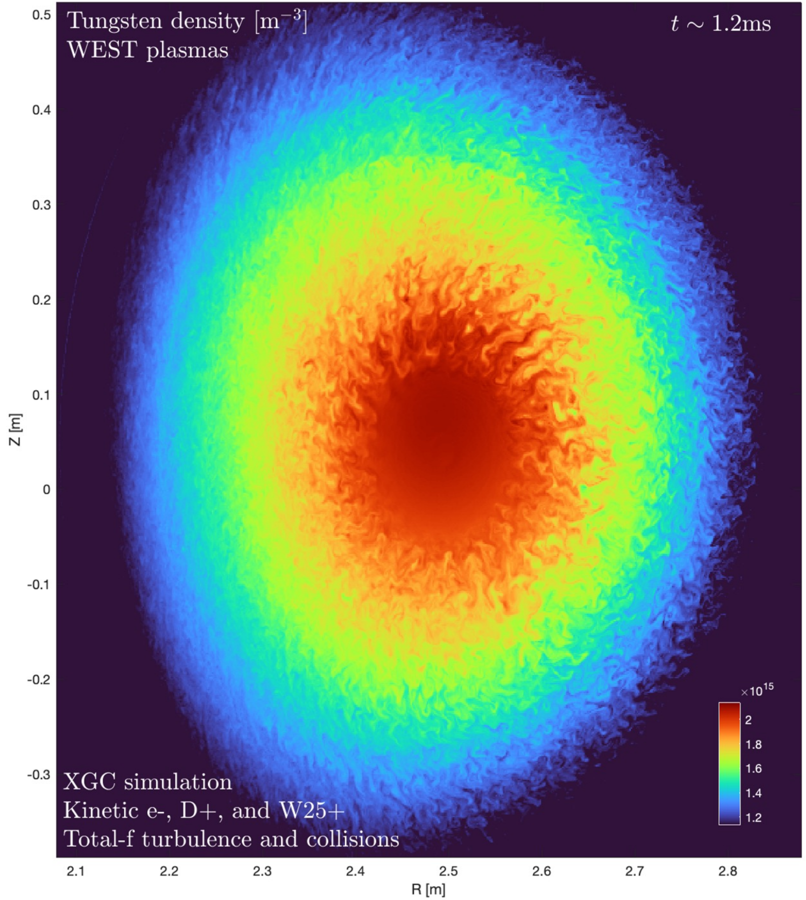
Damping rate reduction by nitrogen:

Without nitrogen (blue) the asymmetry converges rapidly.
With nitrogen (red) the asymmetry takes 3x longer to converge.

The damping of the tungsten m=1 oscillations is reduced by a factor 3x. No such effect on deuterium GAM oscillations.



WEST – Turbulence simulations of tungsten transport



This is the **total tungsten density** (up to $\sqrt{\psi}\approx 0.9$)

- **Large turbulent fluctuation** ~30% of background
  W adiabatic response is $eZ\Phi/T_i$
- Near axis dominated by **collisional transport & peaking**
- **Mid-radius** dominated by turbulence that **flattens** the tungsten profile
- **Nitrogen stabilizes** the tungsten turbulence

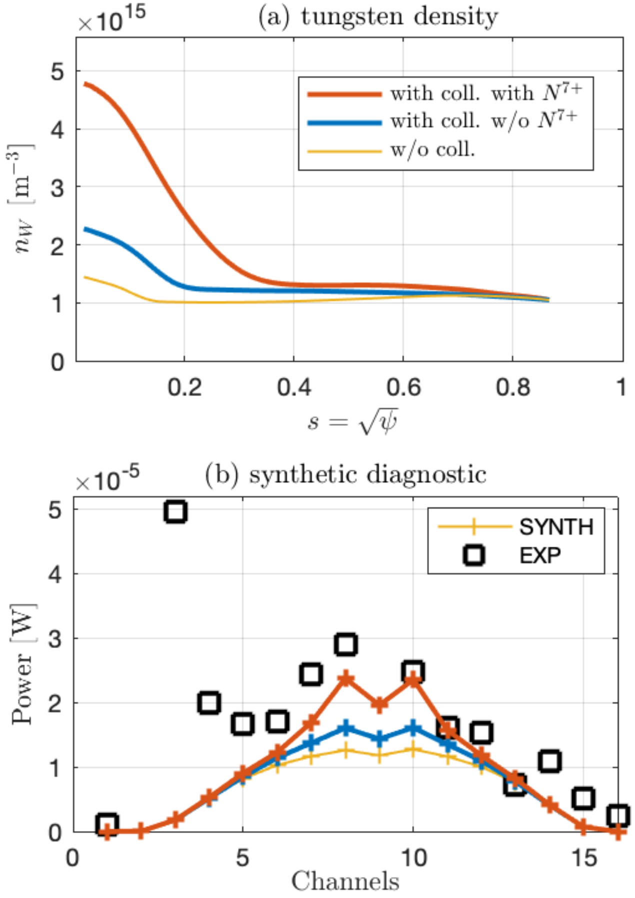
WEST – Prediction of tungsten accumulation in the core

Similarly to what was done for computing the neoclassical peaking factor, we look for the profile of tungsten gradient leading to a zero particle flux.

(a) We integrate it to obtain a profile of tungsten density.
(b) We use a synthetic diagnostic of radiation power measured by bolometers. [Devynck et al 2021 JPC]

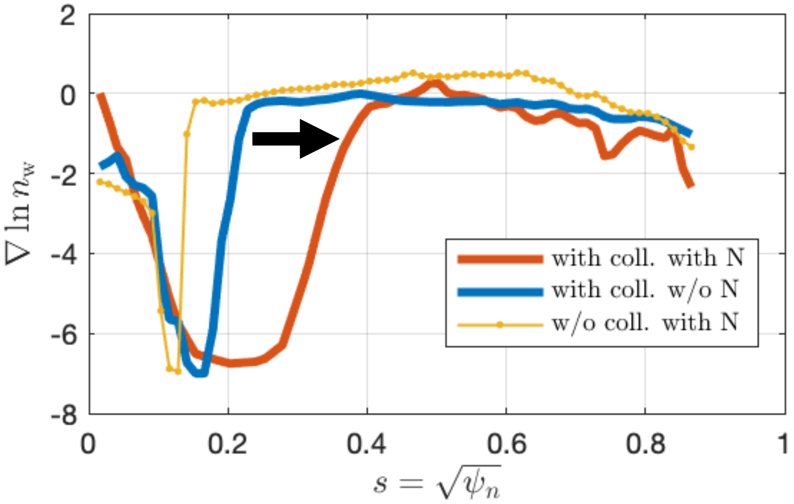
Including nitrogen is necessary for an accurate prediction.

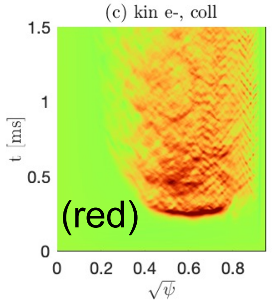
Nitrogen increases the tungsten accumulation on axis.

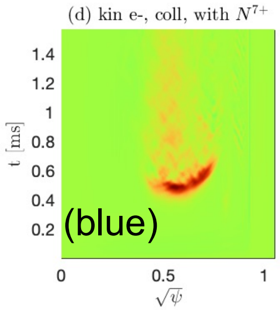


Collaboration with P Maget and P Manas, WEST team CEA

WEST – Tungsten peaking in turbulent simulations







Nitrogen stabilizes the turbulence and in turns reduces the associated screening of tungsten.

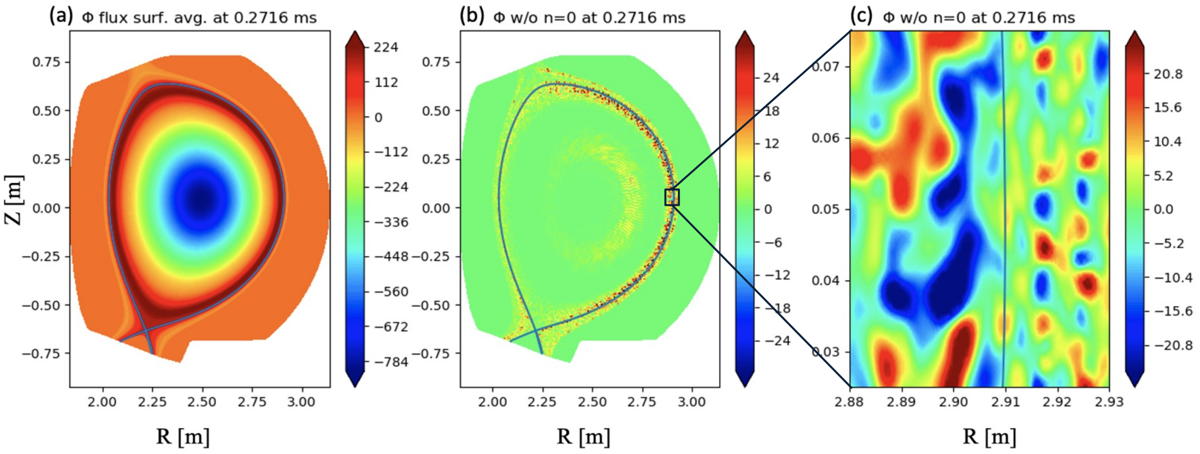
The interface between the region dominated by neoclassical transport and the one dominated by turbulent transport shifts outwardly in presence of nitrogen (red) compared to the simulation without nitrogen (blue).

Similarly, collisions reduce the non-adiabatic electrons and reduce the turbulence. With collision (blue) this interface shift outwardly compared to a collision-less turbulent simulation (yellow).

WEST - Edge simulation with turbulence and collisions

Total-f simulation of the edge of WEST with tungsten.

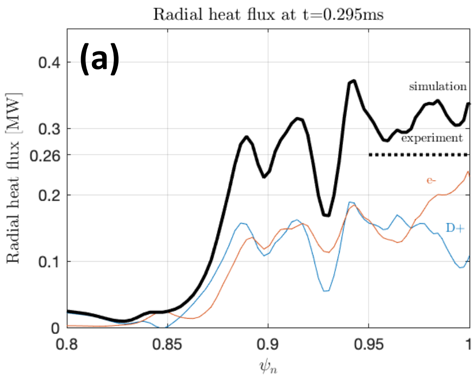
- High resolution (<1mm)
- Exascale run on Frontier (OLCF)
- Waiting simulation with N^{7+}

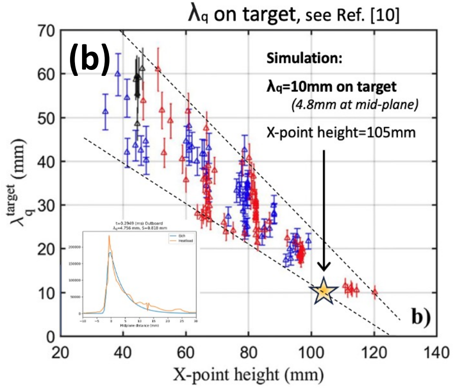


Validation of

a) heat flux at separatrix

b) heat load width on target





WEST – Intermediate conclusion

Collisional tungsten transport

- Tungsten peaking on axis verified against FACIT
- Reduction of asymmetries, tungsten flows, and damping, in presence of nitrogen

Total-f tungsten turbulence

- Tungsten accumulation prediction near axis
- Validation with a synthetic diagnostic
- Significant influence of nitrogen on tungsten

Edge transport validation

- Level of heat flux at separatrix
- Heat load width on target

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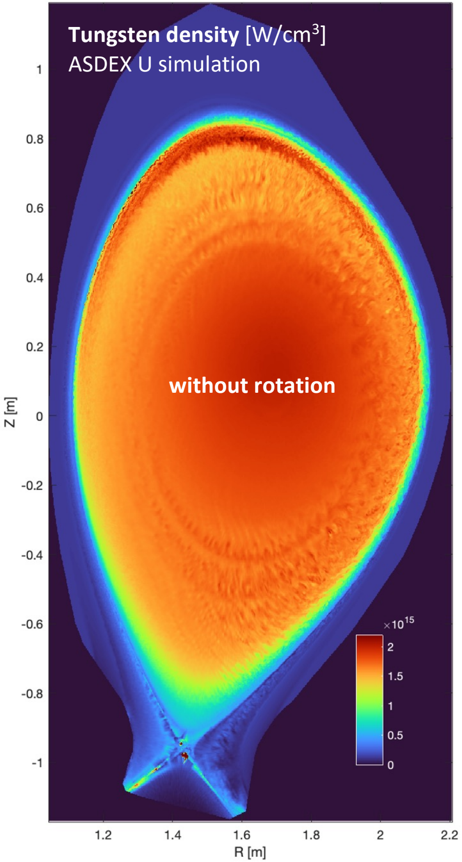
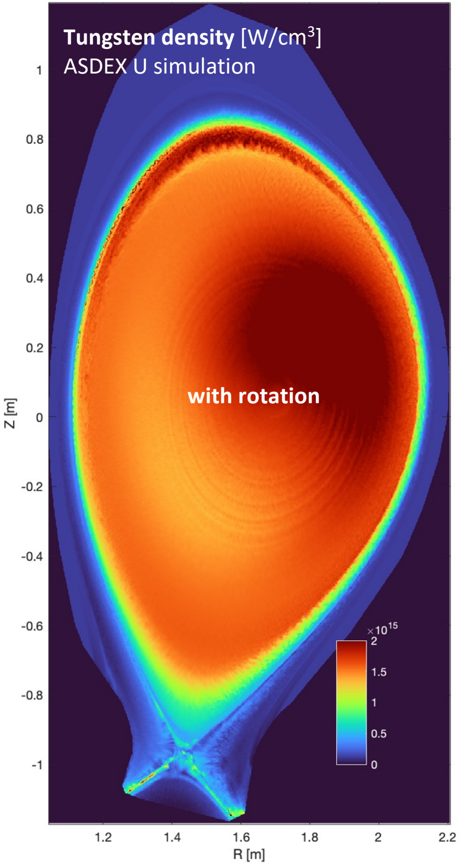
AUG - collision and turbulence simulations (short t~0.3ms)

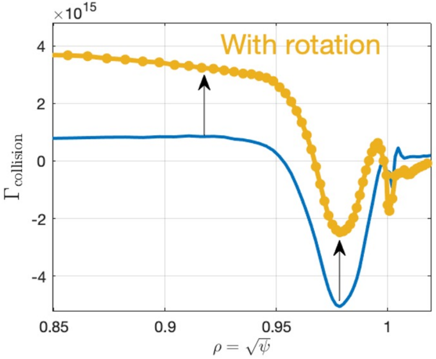




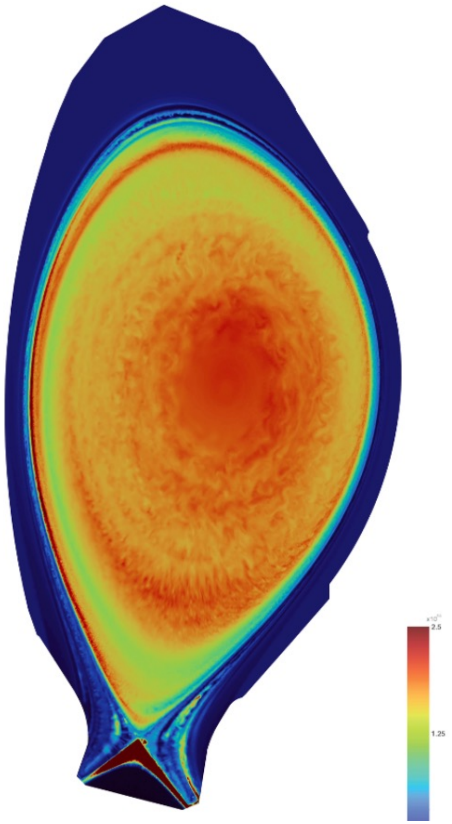
This is the **total tungsten density**

- **Rotation quenches** core tungsten **turbulence**
- Tungsten **accumulation at top** is still visible with rotation.
- Rotation enhances the tungsten accumulation at right leg

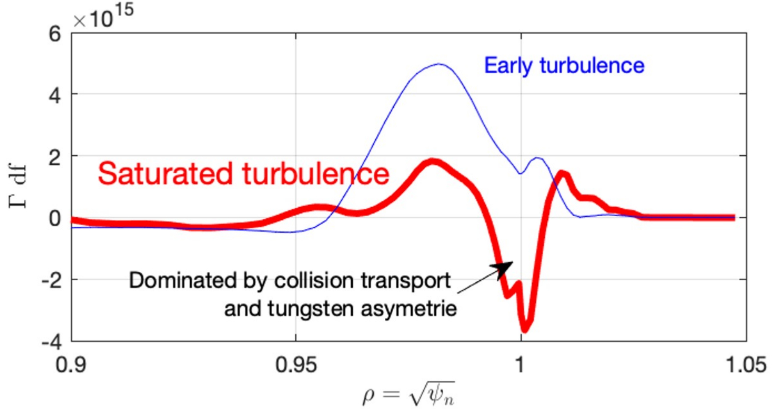
Collisional simulations show a reduction of the tungsten penetration with rotation



AUG - collision and turbulence simulations (t~1.5ms)



- Without rotation
- Transits into the H-mode regime
- Fully saturated turbulence (e,D,W)
- Tungsten penetrates at separatrix because of collisions and density asymmetry. Confirmed in simulation using 2 tungsten bundles.



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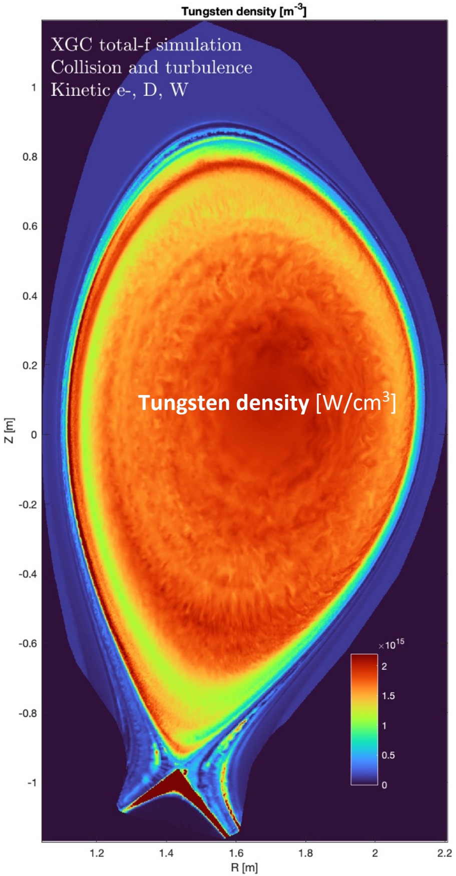

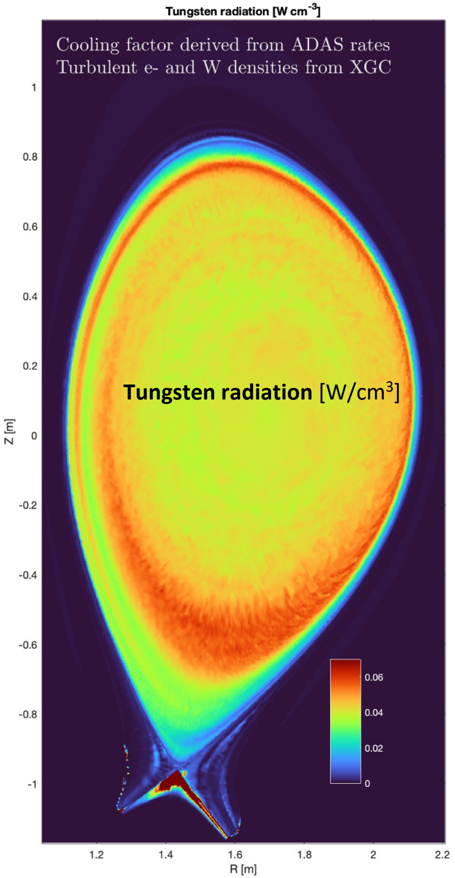

- Radiation calculation done with the ADAS rates
- Hollow tungsten radiations
- Tungsten organization not fully visible by radiation (triple product)

Improving and verifying the modeling.

5. Conclusions

- Collisional transport in a model JET-plasma with tungsten bundles in a coronal approximation
- Collisional and turbulent study of tungsten W^{25+} peaking on axis of WEST, in presence of nitrogen N^{7+} [to be submitted in NF]
  - Interface between neoclassic and turbulence transport is shifted by nitrogen
  - Validation with a synthetic diagnostic
- H-mode saturated turbulence in whole device of ASDEX-U
  - Interplay between collisional and turbulent transport
  - Penetration of tungsten at separatrix
- Complex tungsten physics is continuously improved
  - Implementation of electron cooling by tungsten radiation
  - Validation of bundle modeling with radiations
  - Tungsten sputtering from the wall
  - Validation of rotation of heavy tungsten

Backup slides