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D Mazon, J Colnel, D Guibert, V Gerenton, M Chernyshova, K Malinowski, T Czarski, M Jagielski, G H Verdoolaege, A Wu, et al.

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Developing numerical tools for tungsten profile measurement from X-ray diagnostics in WEST plasmas

presented by D. Mazon

On behalf of :

- IRFM CEA:** Y. Peysson, J. Colnel, D. Guibert
- ENSICAEN:** V. Gerenton
- IPPLM:** M. Chernyshova, K. Malinowski, T. Czarski, M. Jagielski
- Ghent University:** G. Verdoolaedge, H. Wu
- WUT:** A. Wojeński, G. Kasprowicz, K. Poźniak, P. Linczuk,
- IFJ PAN:** A. Jardin, K. Król,
- ITER:** M. Walsh, D. Colette, R. Tieulent

And the WEST Team <http://west.cea.fr/WESTteam>

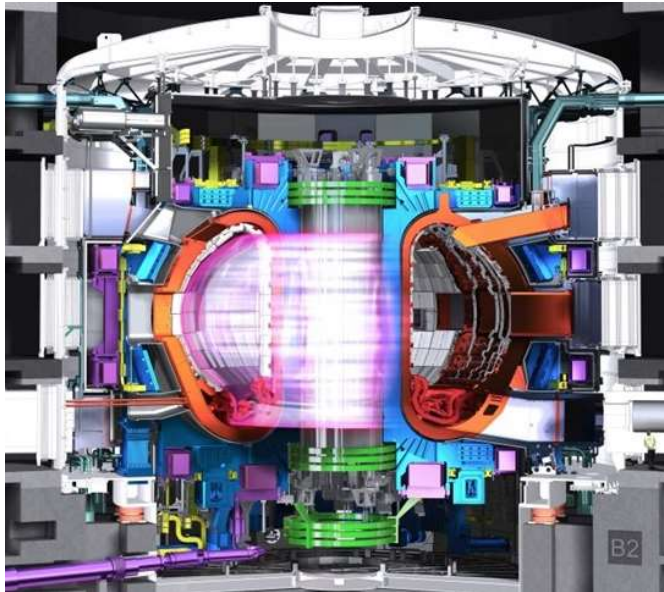


OUTLINE OF MY TALK

- Introduction about the WEST Tokamak
- Radiation emission in Tokamaks and Tungsten
- How to measure radiation and get local emissivity?
- 6 different techniques to reconstruct W concentration
- Conclusions and perspectives



The ITER Tokamak



Major radius	6,2 m
Minor radius	2,0 m
Plasma volume	837 m ³
Core T_e	Up to 40 keV
Plasma facing components	W , SS

ITER goals:

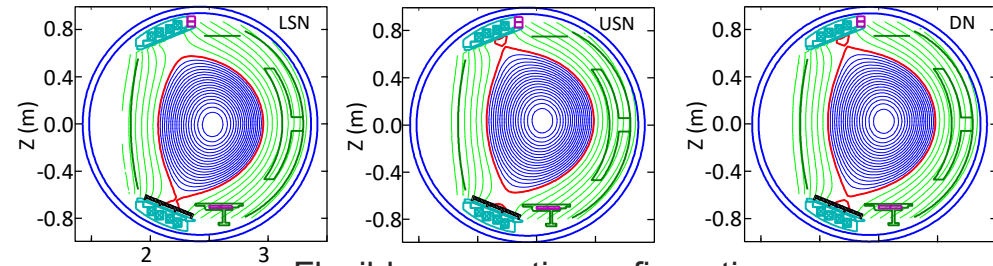
- Demonstrate the experimental feasibility of a nuclear fusion reactor
- $P_{fusion} = 500MW$, $P_{heating} = 50MW$ for 400 to 600 seconds
- Achieve $Q \geq 10$



WEST : a superconducting MA class full W tokamak



B	I_p	R	A	V_p	κ / δ	P_{RF}	Magnetic conf.
3.7 T	1 MA	2.5 m	5-6	15 m ³	1.4 / 0.5	16 MW	LSN, USN, DN



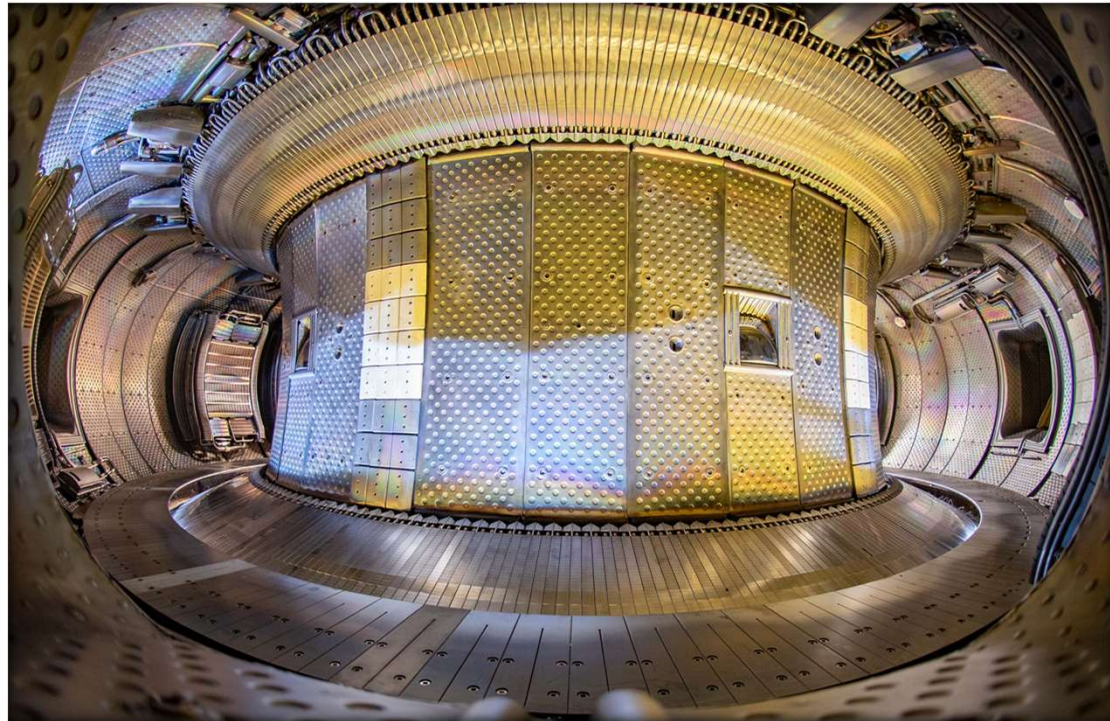
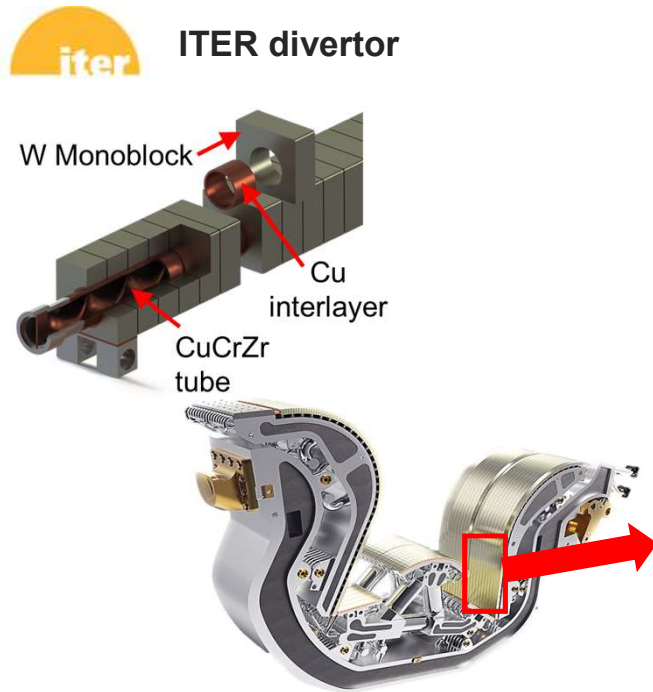
Flexible magnetic configuration

- ▶ Superconducting tokamak
- ▶ Actively cooled Plasma Facing Components
- ▶ Steady state heating / fuelling / pumping / diags systems
- ▶ Large current drive capability (LHCD),
- ▶ ECRH/ECCD in preparation
- ▶ ICRH (large heating power ...)
- ▶ Dominant e- heating, no external torque → relevant for transport studies
- ▶ Compact divertor with good diagnostic access → test bed for plasma edge modelling

Long pulse operation → 1000 s



Inside WEST : a full W environment



- ▶ Full W environment (W coatings on CuCrZr/CFC, W bulk)
- ▶ ITER grade divertor prototypes tested on the lower divertor (same monoblock geometry, same thermohydraulic conditions)



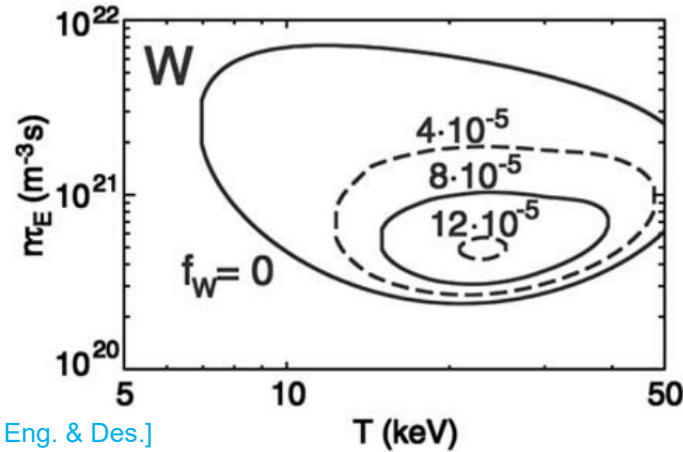
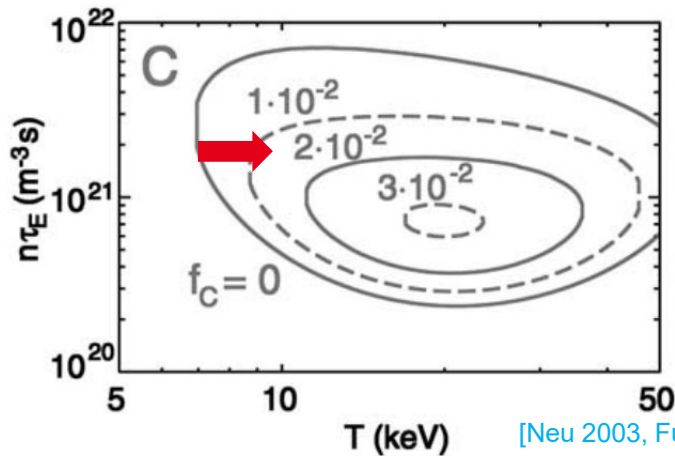
Why W is chosen?

Advantages of W (tungsten) over C (carbon):

- Higher heat flux resilience
- Lower neutron activation
- Lower tritium retention
- Lower erosion

Main drawback of W over C:

Plasma ignition domains for various impurity concentrations :

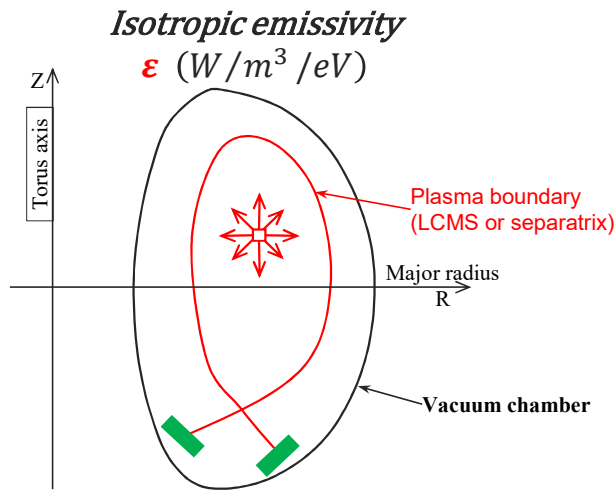


[Neu 2003, Fus. Eng. & Des.]

Significant radiation in the plasma core, in the soft X-ray (SXR) range, $c_W \sim 10^{-4}$ sufficient to decrease significantly ITER fusion performances, n_W must be measured and monitored



Radiation emission in Tokamaks

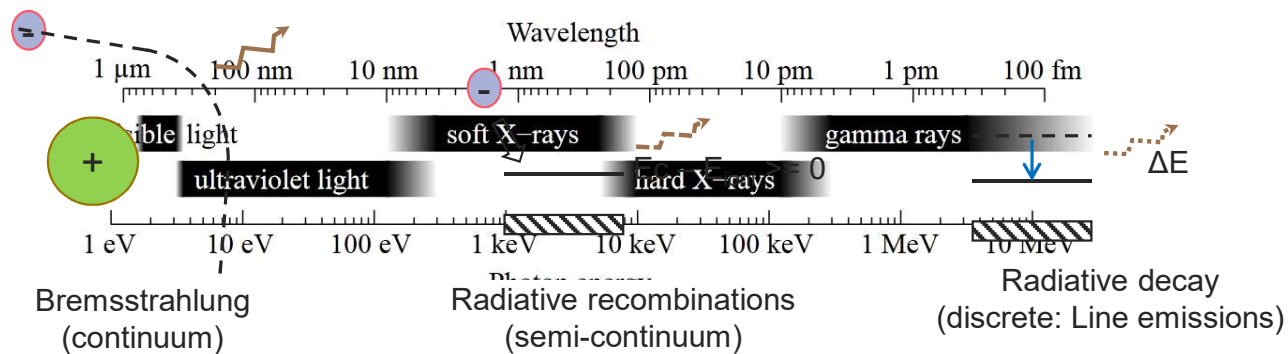


Electromagnetic radiation: Soft X-Rays (SXR)

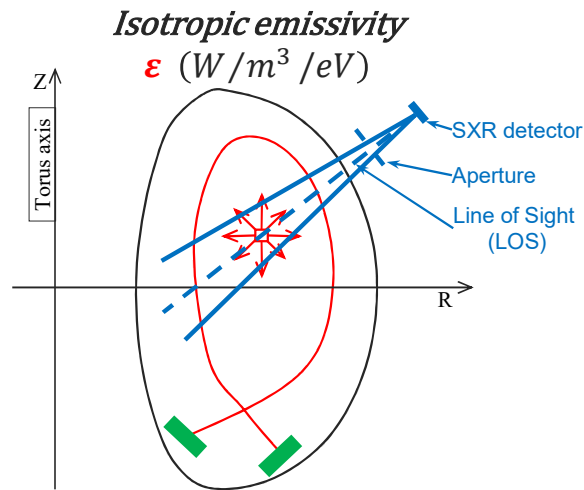
Low-energy X-Rays \neq « Hard » X-Rays
 $\approx 1 \text{ keV} - 15 \text{ keV}$

SXR stem from electron-ion interactions:

- Free-free interactions (Bremsstrahlung)
- Free-bound interactions (recombinations)
- Bound-bound interactions (line emission)



How to measure radiation and get local emissivity?



Electromagnetic radiation: Soft X-Rays (SXR)

$$\epsilon = \sum_S \epsilon_S = n_e \sum_S n_S L_S = f(T_e, n_e, n_{S,q})$$

The SXR emissivity conveys a lot of information:

- Electron temperature and density
- Impurity distributions (transport...)

The plasma is optically thin to SXR:

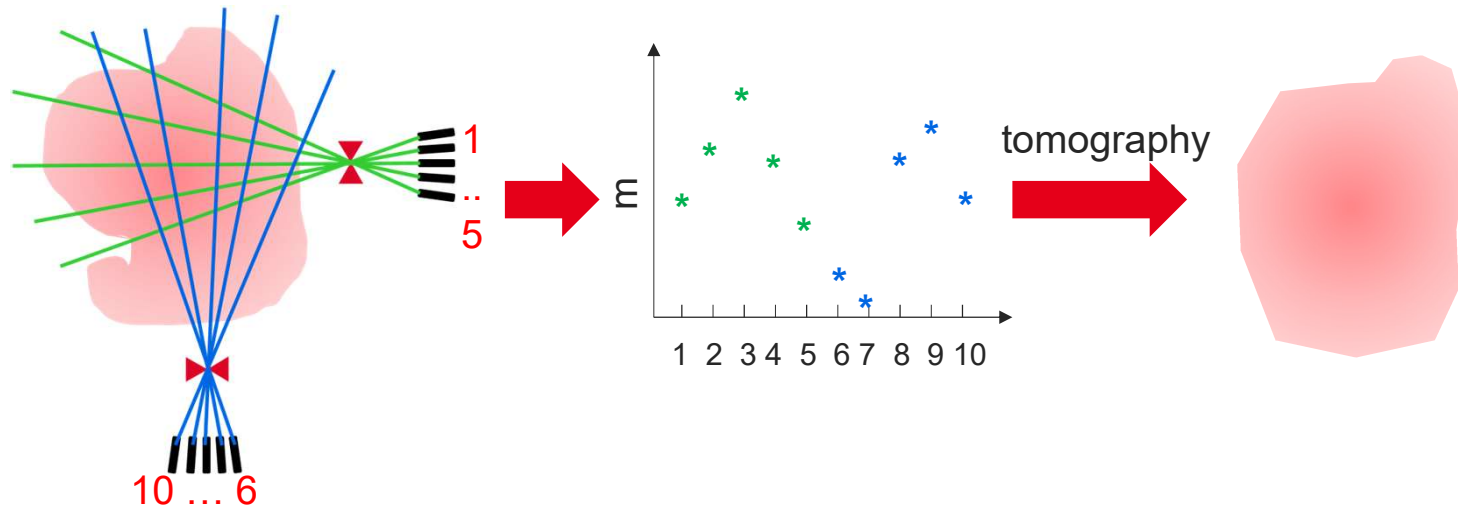
- ⇒ No re-absorption
- ⇒ Straightforward and non-intrusive measurements

Measurements: $m_i = \iiint_{V_i} \int_0^\infty \epsilon \times \eta d(h\nu) dV = \iiint_{V_i} \epsilon^\eta dV$

But the measurements are:

- Spatially integrated
- Spectrally integrated
- Summation of all contributions of all species (and ions) in the plasma
- Summation of 3 different contributions (ff, fb & bb) for each ion

How to get the emissivity?



Tomographic algorithm:

Finds the solution which fits best the measurement while retaining some physical sense. Example with Tikhonov regularization:

$$\varepsilon_{rec} = \underset{\varepsilon}{\operatorname{argmin}} (|m - f(\varepsilon)|^2 + \lambda R(\varepsilon))$$

Regularization using the Minimum Fisher Information:

Minimizes

$$I_F = \int \frac{1}{\varepsilon(r)} \left(\frac{d\varepsilon(r)}{dr} \right)^2 dr$$

[D. Mazon et al. RSI 2012]

[M. Anton PPCF 1996]

Which type of detectors?

Semiconductor detectors

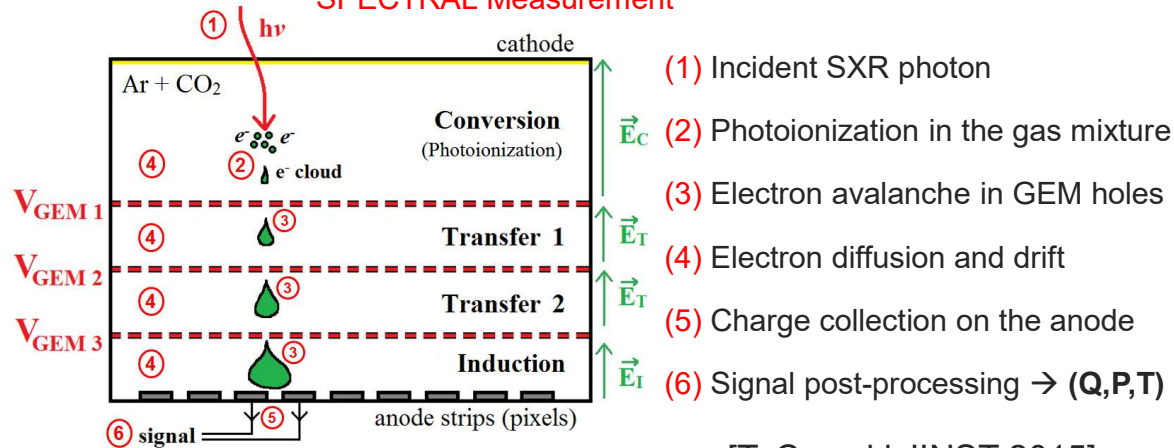
Gas detectors

Si & CdTe photodiodes	Current mode
SC diode arrays/matrices	Current mode with spectral information
Gas Electron Multiplier	Photon counting mode
Ionization chambers	Current mode

Principle of the triple-GEM (Gas Electron Multiplier):

In photon-counting mode (spectral resolution)

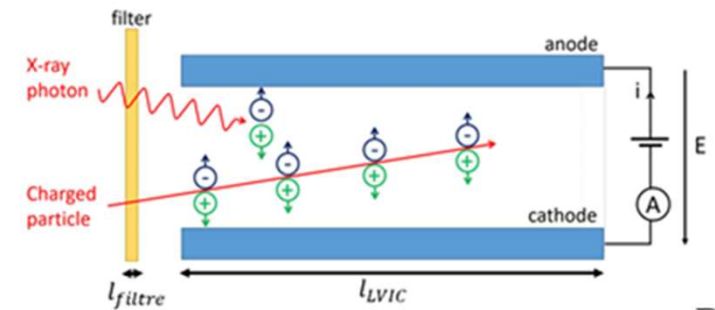
SPECTRAL Measurement



[T. Czarski JINST 2015]

Principle of the LVIC (Low Voltage Ionisation Chamber):

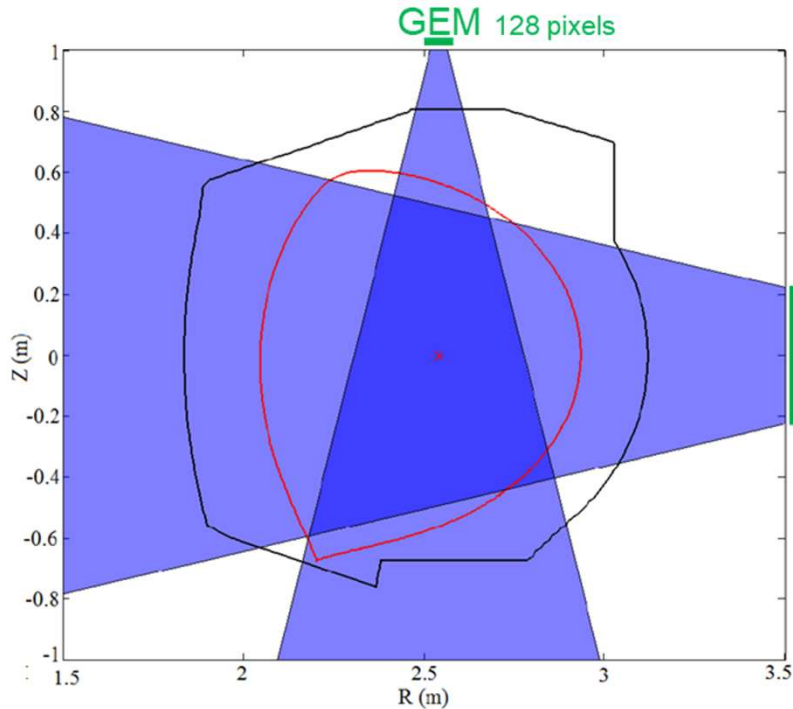
In current mode



D. Mazon Rev. Sci. Instrum. 93, (2022)



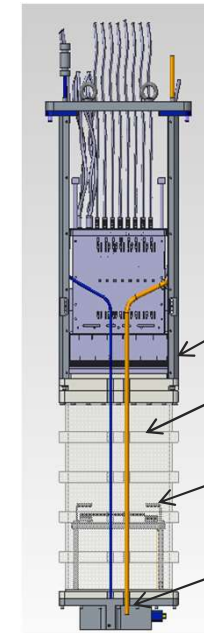
GEM application at WEST tokamak



DTOMOX (SBD)
45 lines of of sights

Collaboration: CEA (France), IPPLM/WUT (Poland)

Vertical Camera



[D. Mazon et al., JINST 2017]

GEM detector

He Buffer

Fe⁵⁵ source

Be pinhole

SBD Diodes for the horizontal camera (DTOMOX)
used for validation



Only one GEM camera (vertical) is presently installed



1 ■ Use of tomographic inversion



First Method to monitor W distribution: use of tomographic inversion

$$\varepsilon_S(h\nu, T_e, n_e, \vec{I}_{S,q}) = n_e n_S \sum_{i=0}^{Z_S} f_{S,q}(T_e, \vec{I}_{S,q}) \cdot [\varepsilon_{S,i}^{f-f}(T_e, h\nu) + \varepsilon_{S,i}^{f-b}(T_e, h\nu) + \varepsilon_{S,i}^{b-b}(T_e, h\nu)]$$

Fractional abundance
Free-free emissivity (Bremsstrahlung)
Free-bound emissivity (recombination)
Bound-bound emissivity (line emission)

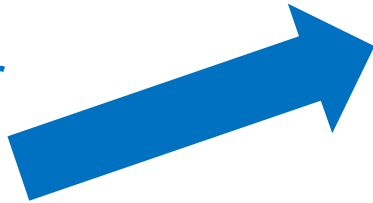
Cooling factor

$$L_S(h\nu, T_e, \vec{I}_{S,q})$$

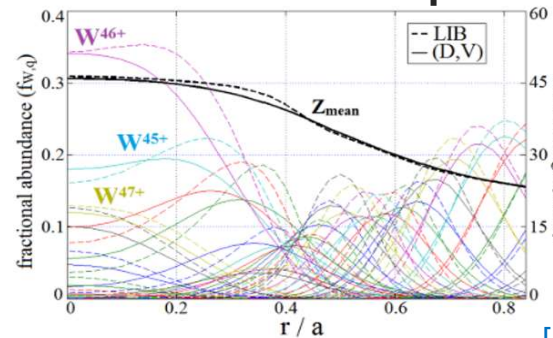
At High Te High Z

$$L_S(h\nu, T_e)$$

Can be Tabulated



With/without transport effect



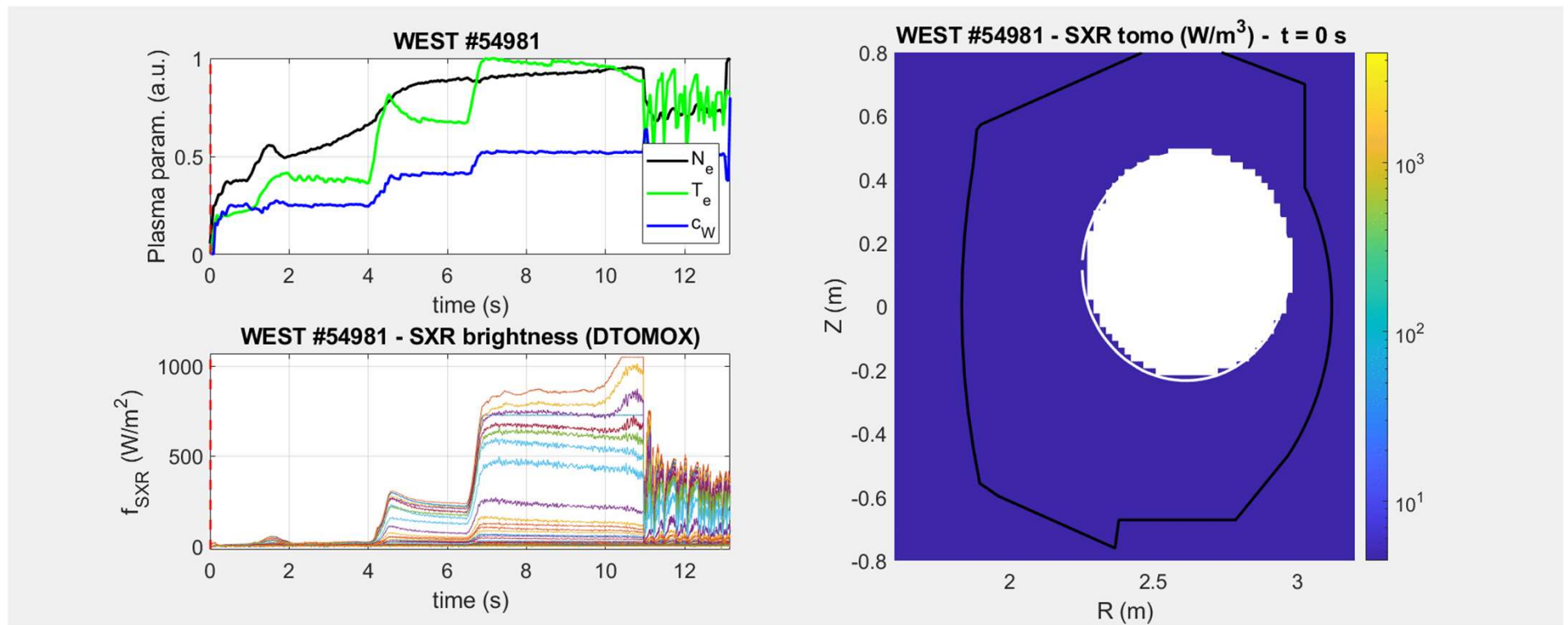
Tungsten density:

$$n_W \approx \frac{\varepsilon_{SXR} - n_e^2 \cdot L_H}{n_e \cdot L_W}$$

[A. Jardin et al, EPS 2018]
[D. Vezinet et al, NF 2014]

SXR tomography on WEST

- SXR tomography of WEST discharge #54981 with DTOMOX diagnostic:

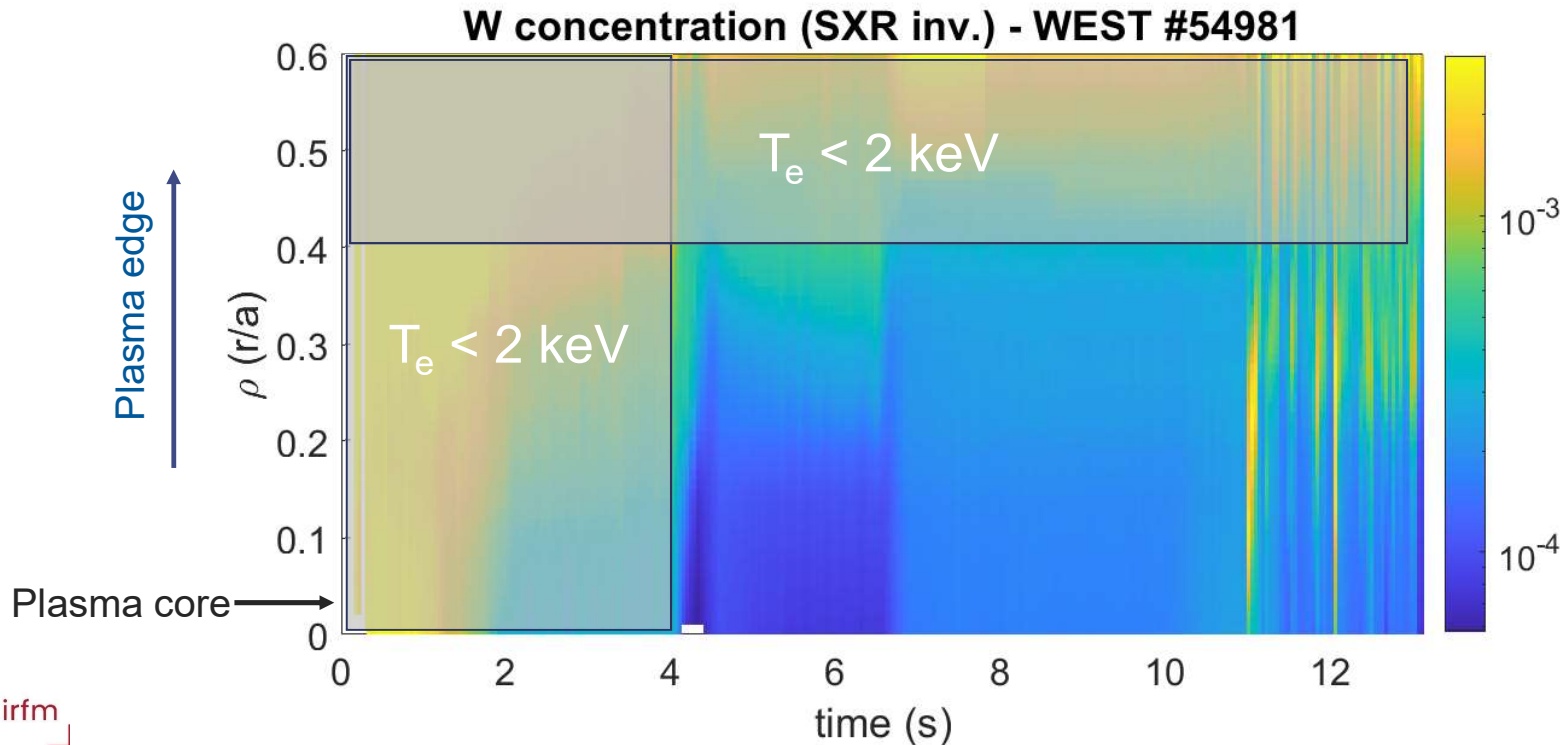


1st method: W reconstruction from SXR tomography

- SXR 2D tomography → ϵ_{SXR}
- radial + time evolution of W concentration
- Plasma parameters (n_e , T_e) from other diagnostics

Tungsten density:

$$n_W \approx \frac{\epsilon_{\text{SXR}} - n_e^2 \cdot L_H(T_e)}{n_e \cdot L_W(T_e)}$$





2 ■ Bayesian inference

2nd method: Bayesian inference



Bayes' theorem:

$$p(\vec{\theta}|\vec{d}) \propto p(\vec{d}|\vec{\theta})p(\vec{\theta})$$

- $\vec{\theta}$: unknown parameters
- \vec{d} : experimental data
- $p(\vec{d}|\vec{\theta})$: **likelihood**, related to χ^2
- $p(\vec{\theta})$: **prior distribution**, applying physical constraints and regularizations

SEE TALK HAO WU at 12h10 today!

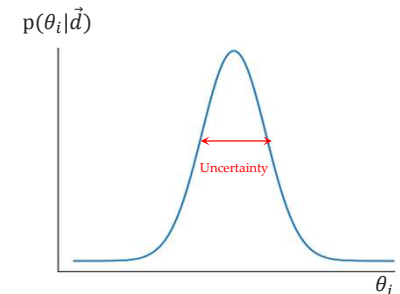
Point (Maximum a posteriori, MAP) estimate:

$$\vec{\theta}_{\text{MAP}} = \underset{\vec{\theta}}{\text{argmax}} p(\vec{\theta}|\vec{d}) \quad \Longrightarrow$$

Can be obtained using generic optimization algorithms.

Posterior distribution $p(\vec{\theta}|\vec{d})$:

- Natural uncertainty quantification (width of the posterior distribution)
- To explore the probability distribution Monte Carlo sampling is usually required
- Closed-form solutions are possible for special cases



Bayesian tomography with Gaussian process priors



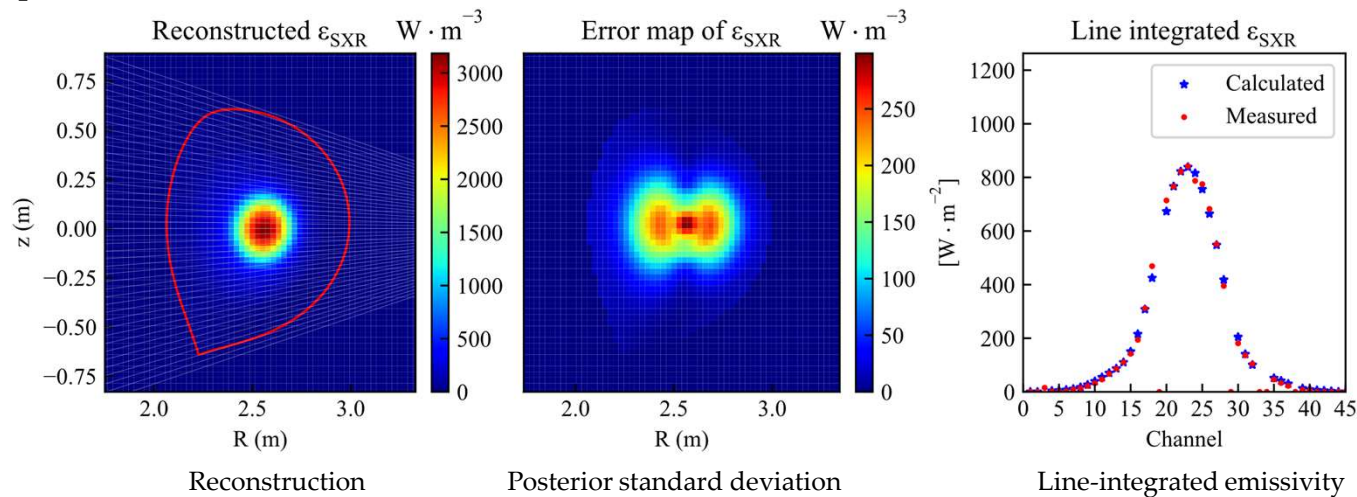
- Tomography: ill-posed problem, number of unknowns (pixels) \gg number of observations
- Gaussian processes: non-parametric model, capable of fitting almost all smooth functions
- Bayesian tomography with Gaussian process priors \rightarrow analytically tractable posterior distributions
- Magnetic equilibrium information can also be incorporated in the prior

D. Li et al., *Rev. Sci. Instrum.* **84**, 083506 (2013)

T. Wang et al., *Rev. Sci. Instrum.* **89**, 10F103 (2018)

H. Wu et al., *J. Fusion Energy* **43**(1) (2024)

Example: WEST pulse #58089, $t = 1.4$ s



Integrated estimation of tungsten concentration profiles



- Integrated data analysis (IDA): coherent solution that is consistent with all diagnostics; no explicit error propagation needed

- Plasma emission diagnostics:

- SXR

$$\varepsilon_{\text{SXR}} = n_e^2 [L_{\text{H}}^{\text{SXR}}(T_e) + c_W \cdot L_{\text{W}}^{\text{SXR}}(T_e)]$$

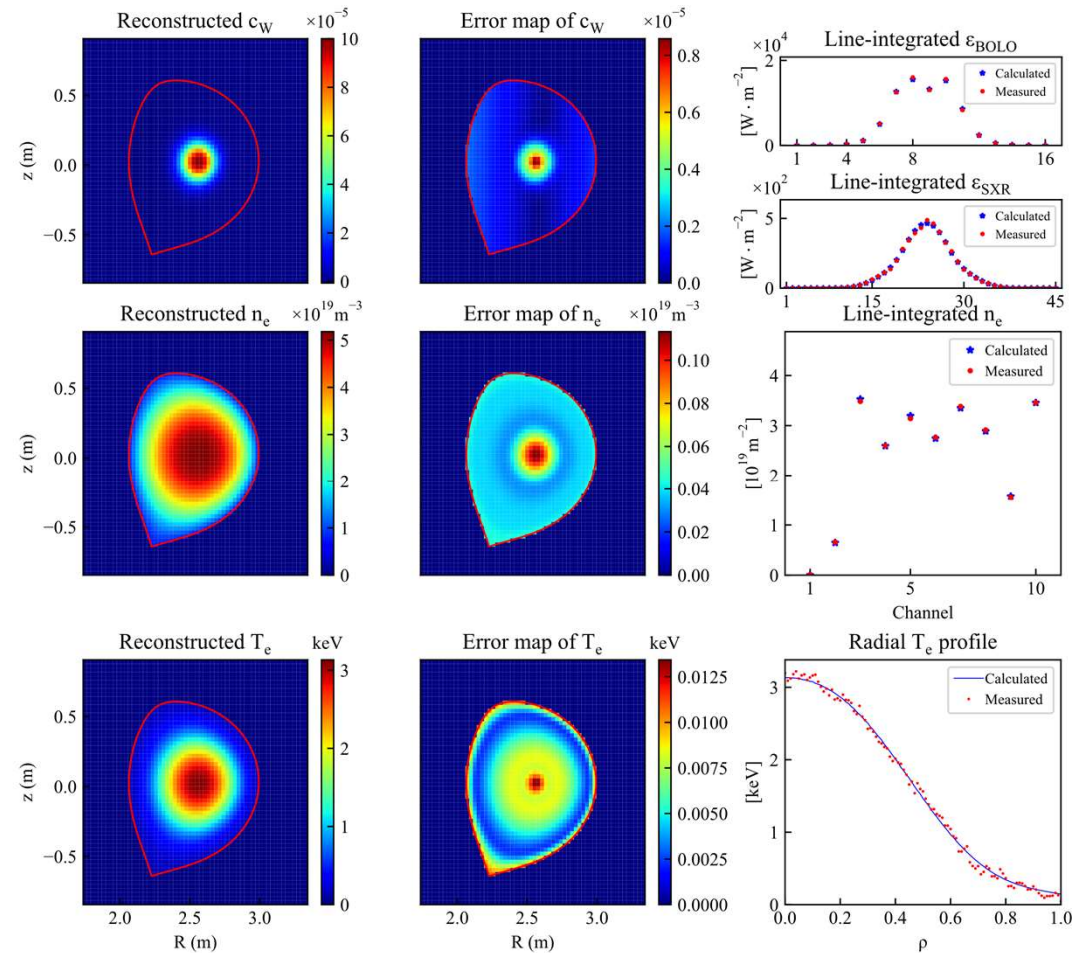
- Bolometer


$$\varepsilon_{\text{BOLO}} = n_e^2 [L_{\text{H}}^{\text{BOLO}}(T_e) + c_W \cdot L_{\text{W}}^{\text{BOLO}}(T_e)]$$

- Joint posterior distribution:

$$p(\vec{c}_W, \vec{n}_e, \vec{T}_e \mid \vec{d}_{\text{INT}}, \vec{d}_{\text{ECE}}, \vec{d}_{\text{SXR}}, \vec{d}_{\text{BOLO}}) \\ \propto p(\vec{d}_{\text{INT}} \mid \vec{n}_e) p(\vec{d}_{\text{ECE}} \mid \vec{T}_e) p(\vec{d}_{\text{SXR}} \mid \vec{n}_e, \vec{T}_e, \vec{c}_W) \\ p(\vec{d}_{\text{BOLO}} \mid \vec{n}_e, \vec{T}_e, \vec{c}_W) p(\vec{c}_W) p(\vec{n}_e) p(\vec{T}_e)$$

Phantom test with synthetic data:



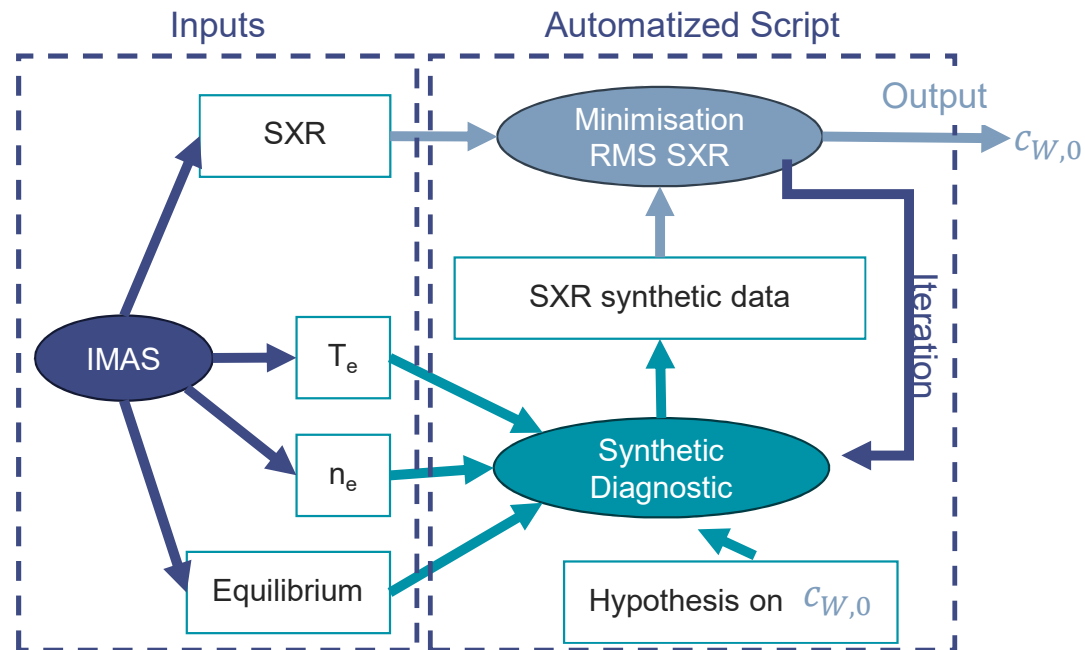


3 ■ Use of synthetic diagnostics



3rd method: synthetic diagnostic

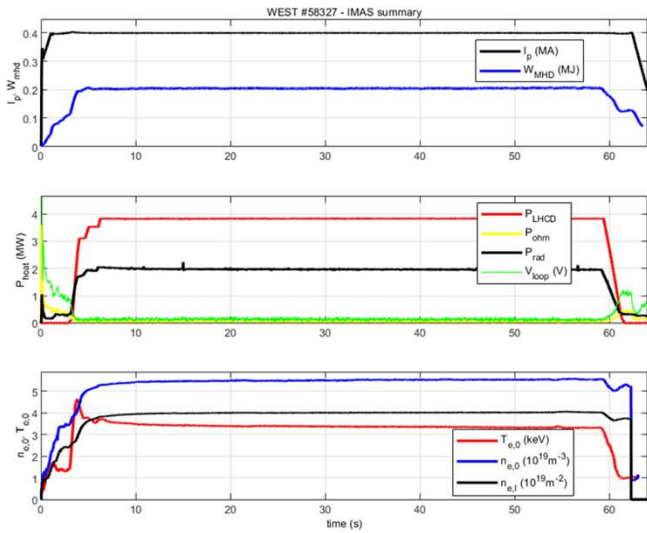
- Valid for $T_e > 2$ keV (sufficient signal) but numerically costly.



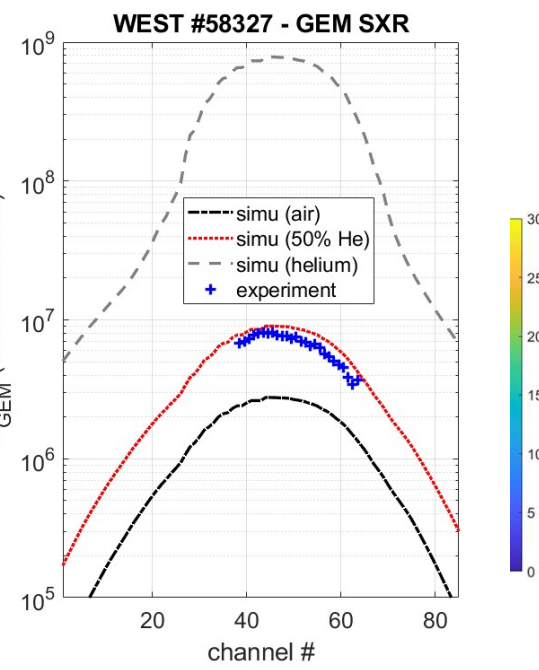
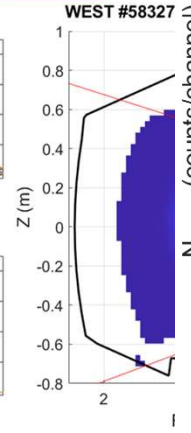
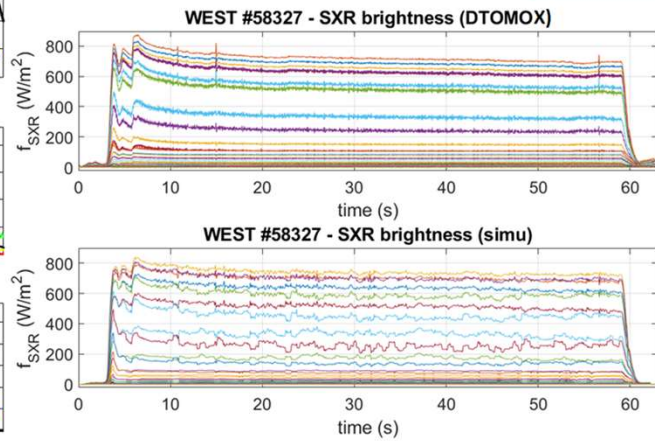


3rd method: synthetic diagnostic

$$\varepsilon_W^\eta = \int \eta(h\nu) \varepsilon_W(h\nu, T_e) dh\nu = n_e \cdot n_W \cdot L_W^\eta(T_e)$$



$$c_W = 2 \times 10^{-4}$$

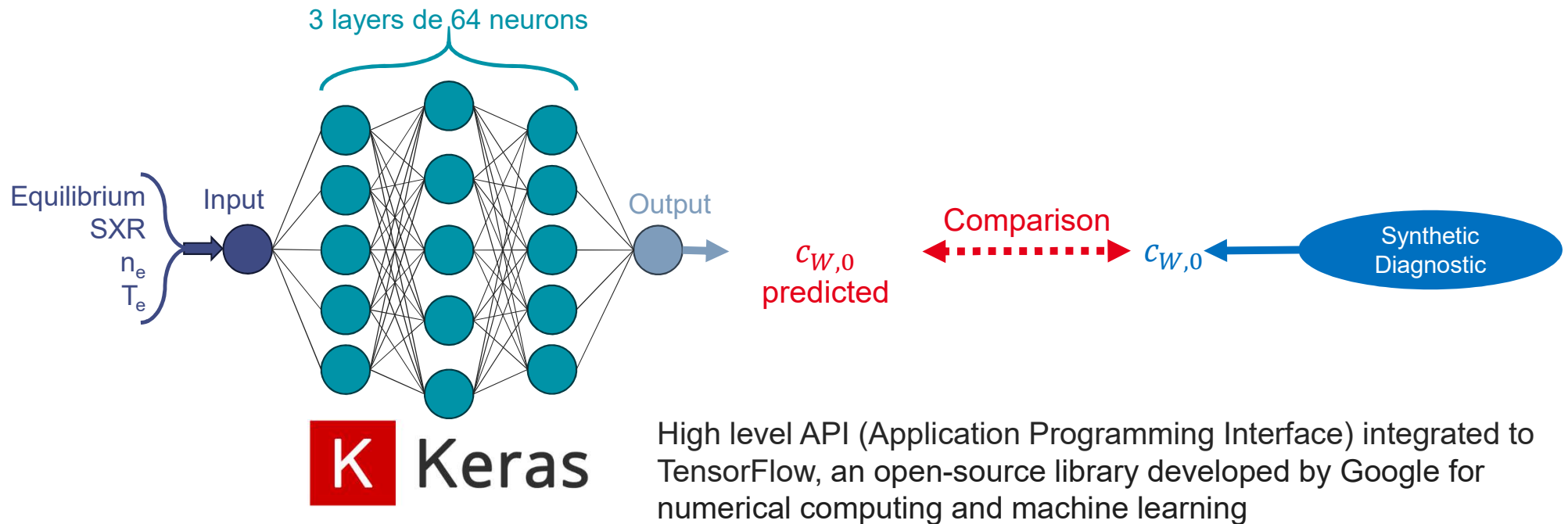


This method makes use of SXR measurement (DTOMOX), Si Diodes detectors absolutely calibrated



4 ■ Neural Network approach: a faster solution

Structure and training of the Neural Network



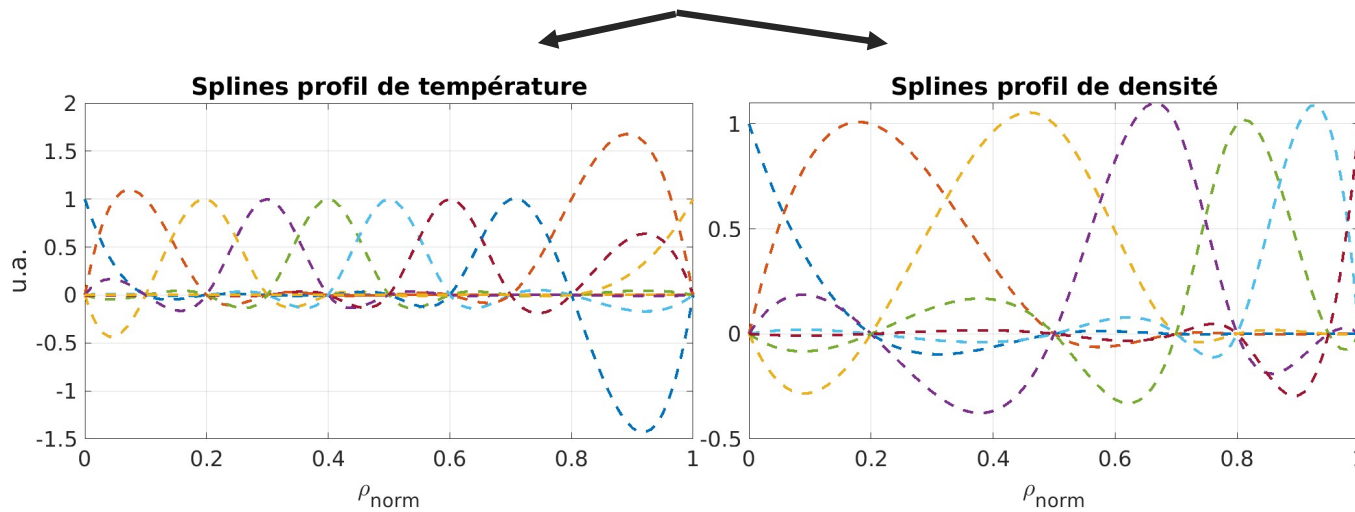
- Training: 611 shots from 2023.
- Validation on 503 shots from 2024.

Parametrisation: reduction of inputs number

Database creation with reduced input numbers for NN training:

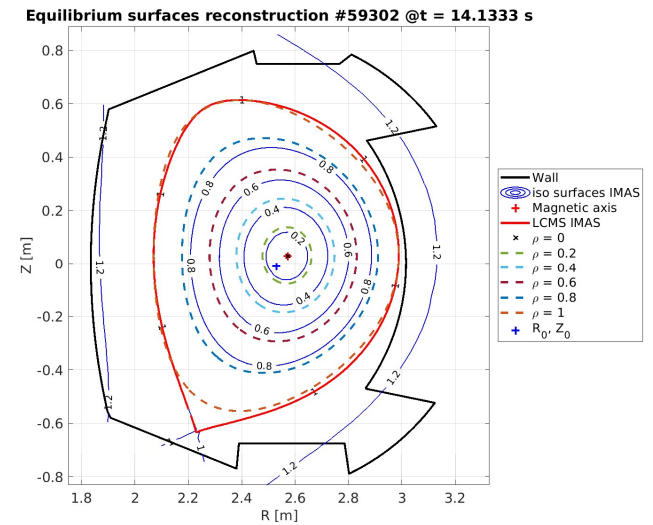
- Equilibrium Parametrisation:

- Splines for profiles parametrisation:



10 splines

7 splines



10 parameters

25



Magnetic surfaces parametrisation

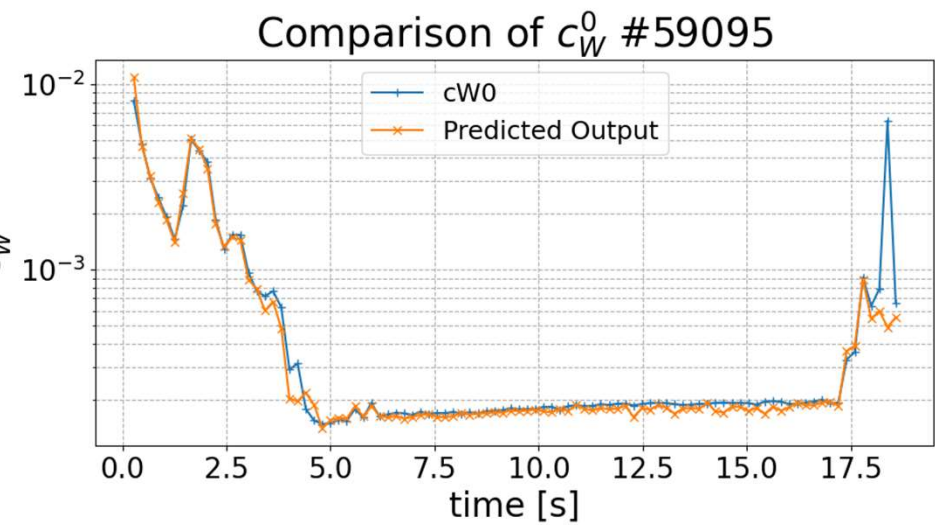
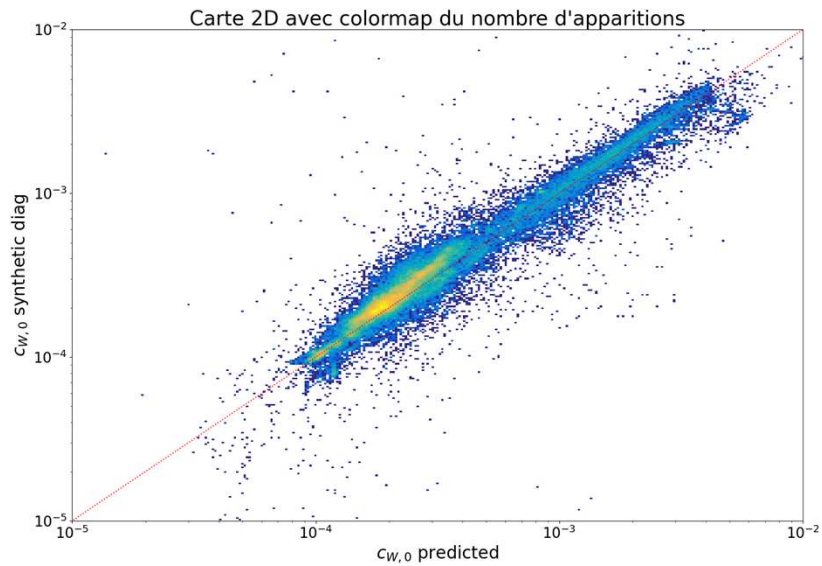
$$\begin{cases} R = R_{axis} + \Delta(\rho) + \rho \cos(\vartheta + \gamma(\rho) \sin \vartheta) \\ Z = Z_{axis} + \rho K(\rho) \sin \vartheta \end{cases} \quad \begin{array}{l} \rho \text{ radial coordinate, } R_{axis} \text{ et } Z_{axis} \text{ magnetic axis} \\ \text{coordinates, } \Delta(\rho) \text{ Shafranov shift } (\Delta < 0), \gamma(\rho) \\ \text{triangularity and } K(\rho) \text{ elongation.} \end{array}$$

The Shafranov shift, elongation and triangularity functions can be assumed to be monotonic and can be expressed by the relations:

$$\Delta(\rho) = \left(\frac{\rho}{\rho_{LCMS}} \right)^\alpha \Delta_{LCMS} \quad \left| \quad K(\rho) = K_{axis} + a_2 \left(\frac{\rho}{\rho_{LCMS}} \right)^2 + a_4 \left(\frac{\rho}{\rho_{LCMS}} \right)^4 \quad \right| \quad \gamma(\rho) = \gamma_{LCMS} \left(\frac{\rho}{\rho_{LCMS}} \right)^\beta$$

With $\Delta_{LCMS} = R_0 - R_{axis}$, R_0 geometrical axis of the LastClosed Magnetic Surface and K_{axis} elongation on axis.

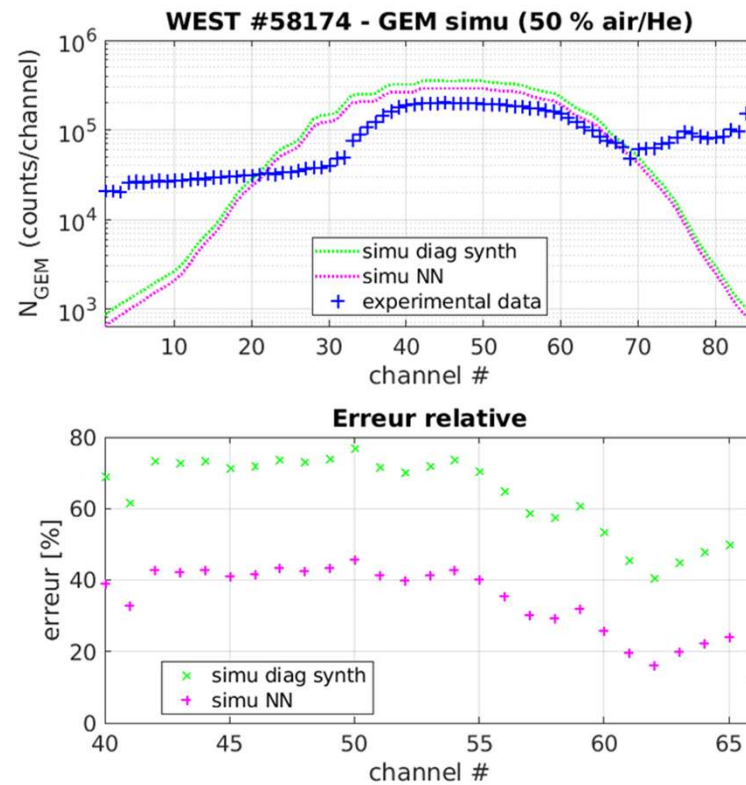
Results



Very good global agreement and also on time evolution.



Validation with GEM data



Good agreement despite uncertainties in Helium content



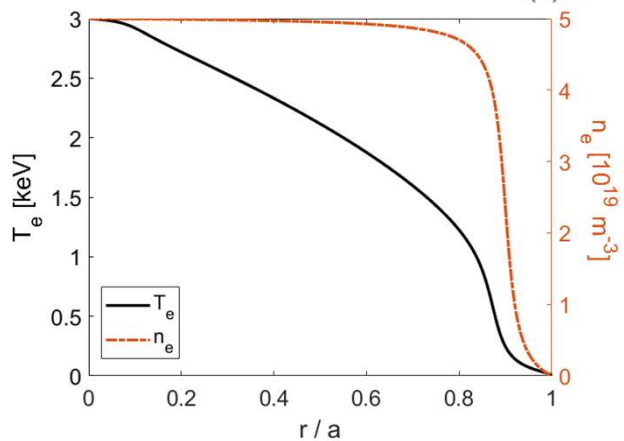
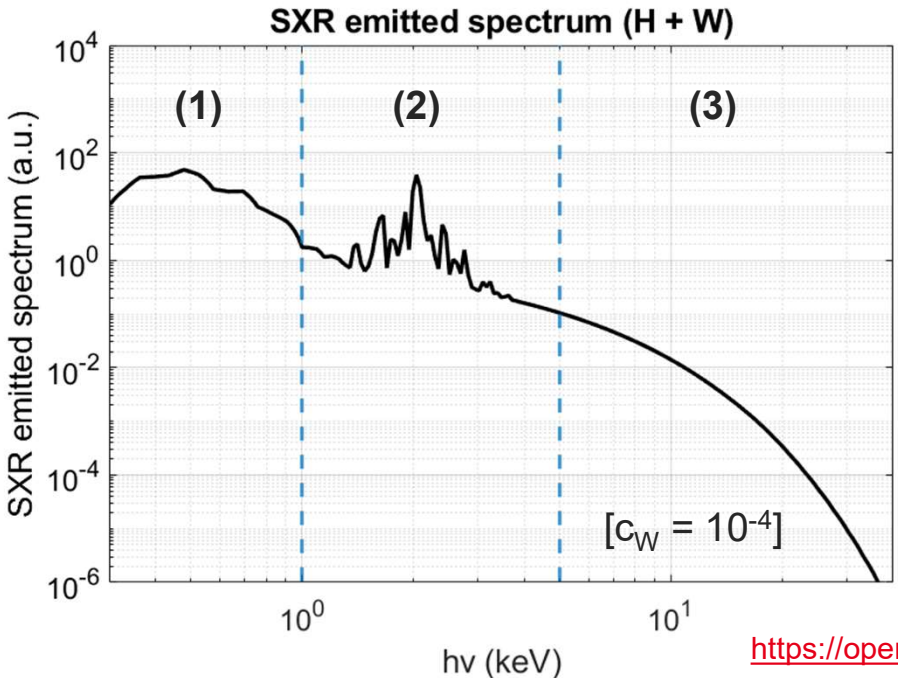
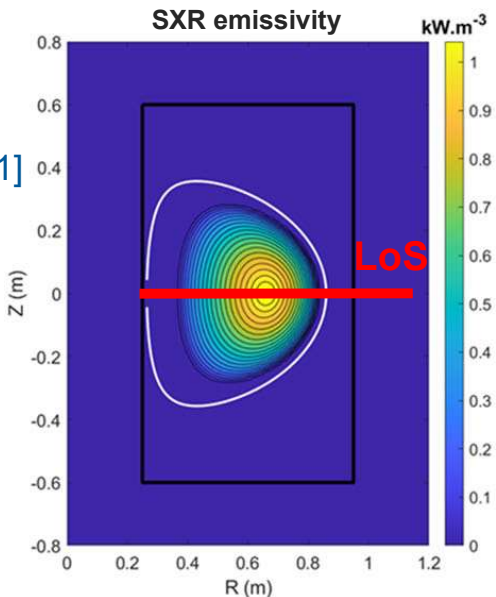
5 ■ Multi-energy line- integrated measurements



4th Method: validation of central T_e and c_W from multi-energy line-integrated measurements

Proof-of-principle with synthetic tools:

- ❑ Tokamak analytical equilibrium with given plasma profile [A. Jardin et al, EPJP 2021]
- ❑ Plasma emission modelled assuming H and W impurities only [open ADAS]
- ❑ 3 spectral ranges of observation: [0.1 – 1 keV], [1 – 5 keV], [5 – 20 keV]



Tomographic system



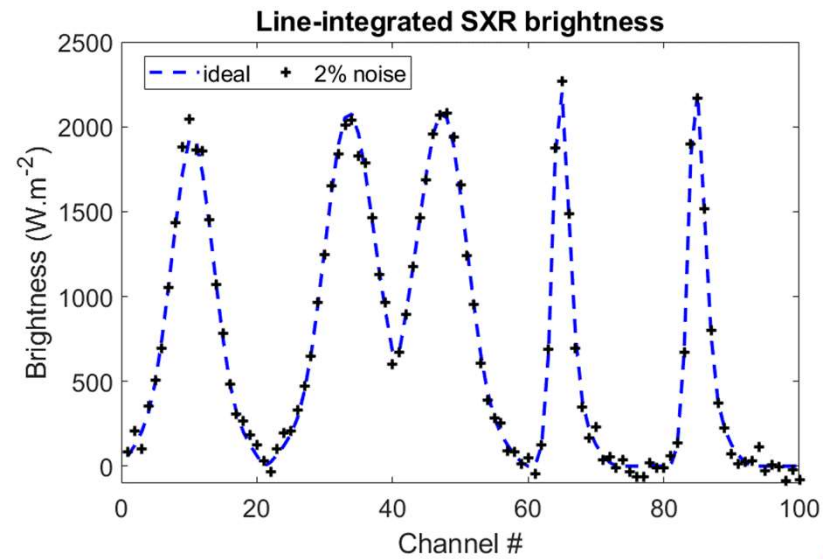
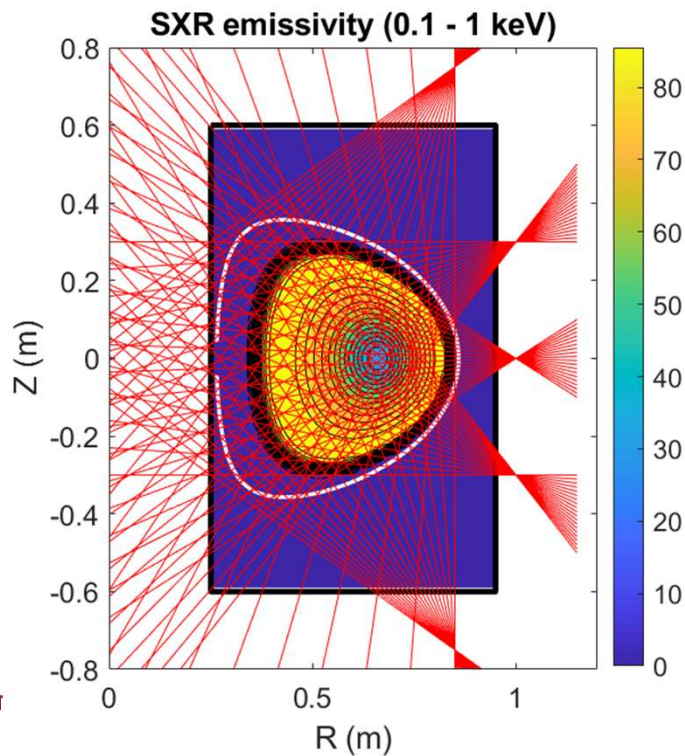
- ❑ Synthetic tomographic system made of five X-ray cameras, 20 LoS each
- ❑ Line-integrated measurements with 2% Gaussian noise

$$f_i^\eta = \int_{LoS} \varepsilon^\eta(R, Z) dr_i + \tilde{f}_i^\eta$$

measurement

emissivity

noise



(c_W , T_e) estimate from multi-energy X-ray measurements



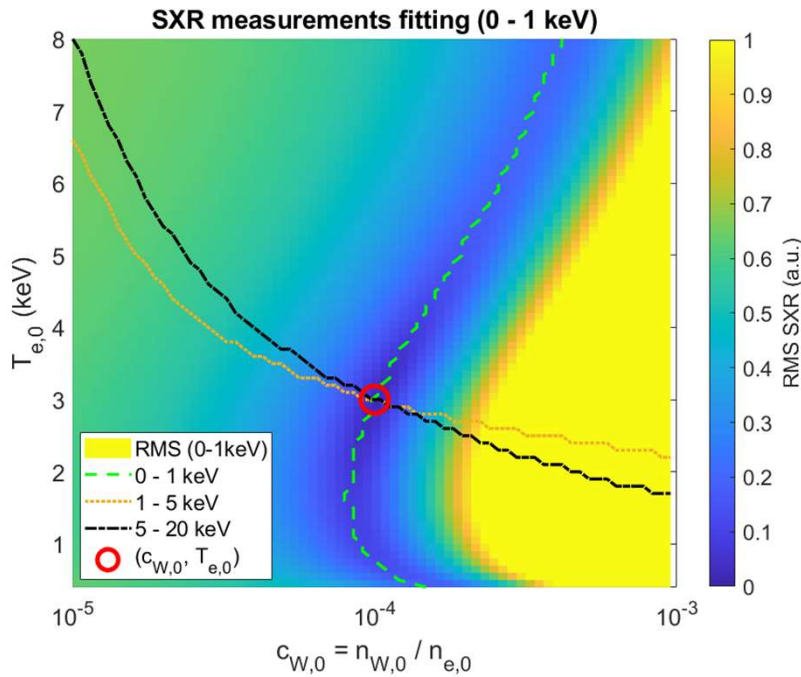
- Proof-of-principle: (c_W , T_e) estimation in the plasma core based on SXR measurement fitting:

$$RMS_{SXR}(c_{W,0}, T_{e,0}) = \frac{1}{\max(f_{i,meas})} \sqrt{\frac{1}{N_f} \sum_{i=1}^{N_f} (f_i(c_{W,0}, T_{e,0}) - f_{i,meas})^2}$$

Figure of merit (residual)

prediction

measurement

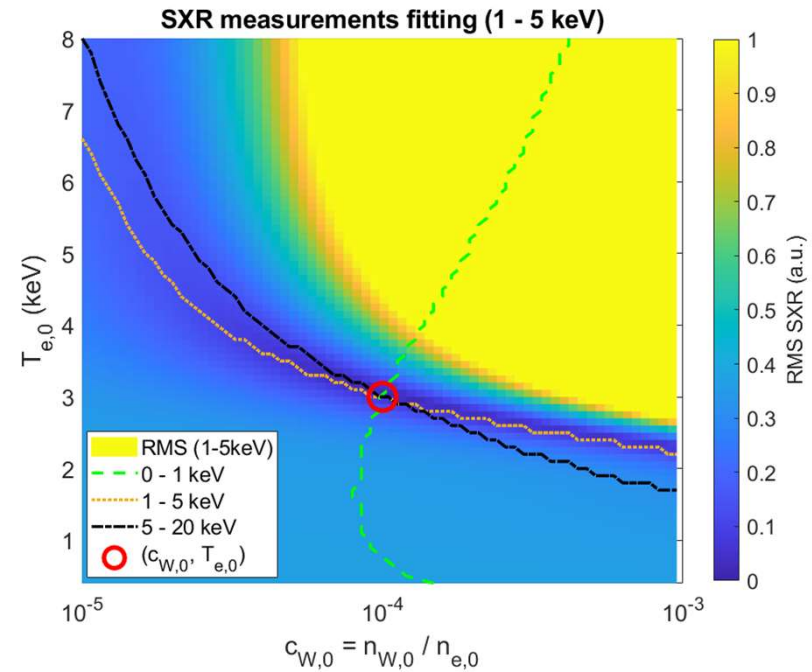
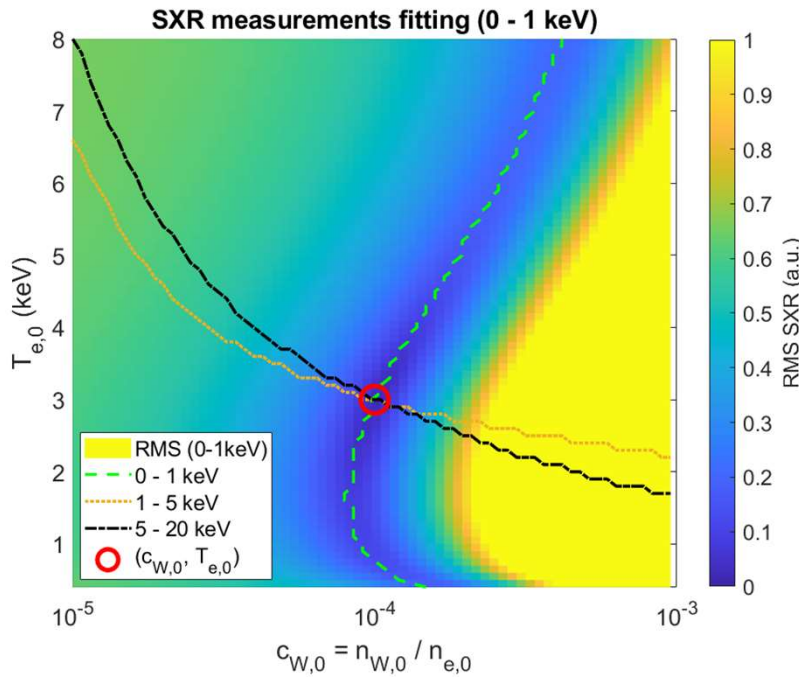


(c_W , T_e) estimate from multi-energy X-ray measurements



- Proof-of-principle: (c_W , T_e) estimation in the plasma core based on SXR measurement fitting:

$$RMS_{SXR}(c_{W,0}, T_{e,0}) = \frac{1}{\max(f_{i,meas})} \sqrt{\frac{1}{N_f} \sum_{i=1}^{N_f} (f_i(c_{W,0}, T_{e,0}) - f_{i,meas})^2}$$



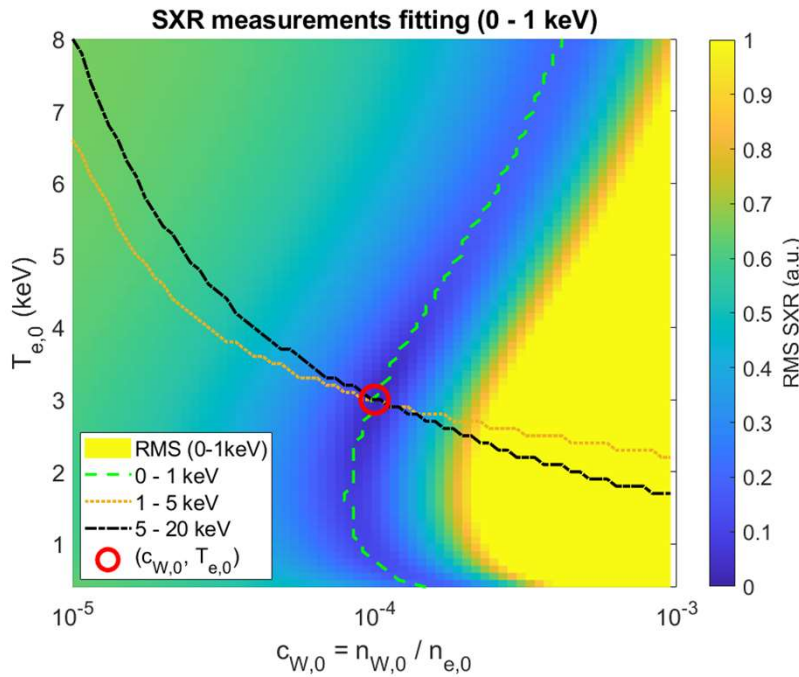
Very promising technique!

(c_W , T_e) estimate from multi-energy X-ray measurements



- Proof-of-principle: (c_W , T_e) estimation in the plasma core based on SXR measurement fitting:

$$RMS_{SXR}(c_{W,0}, T_{e,0}) = \frac{1}{\max(f_{i,meas})} \sqrt{\frac{1}{N_f} \sum_{i=1}^{N_f} (f_i(c_{W,0}, T_{e,0}) - f_{i,meas})^2}$$



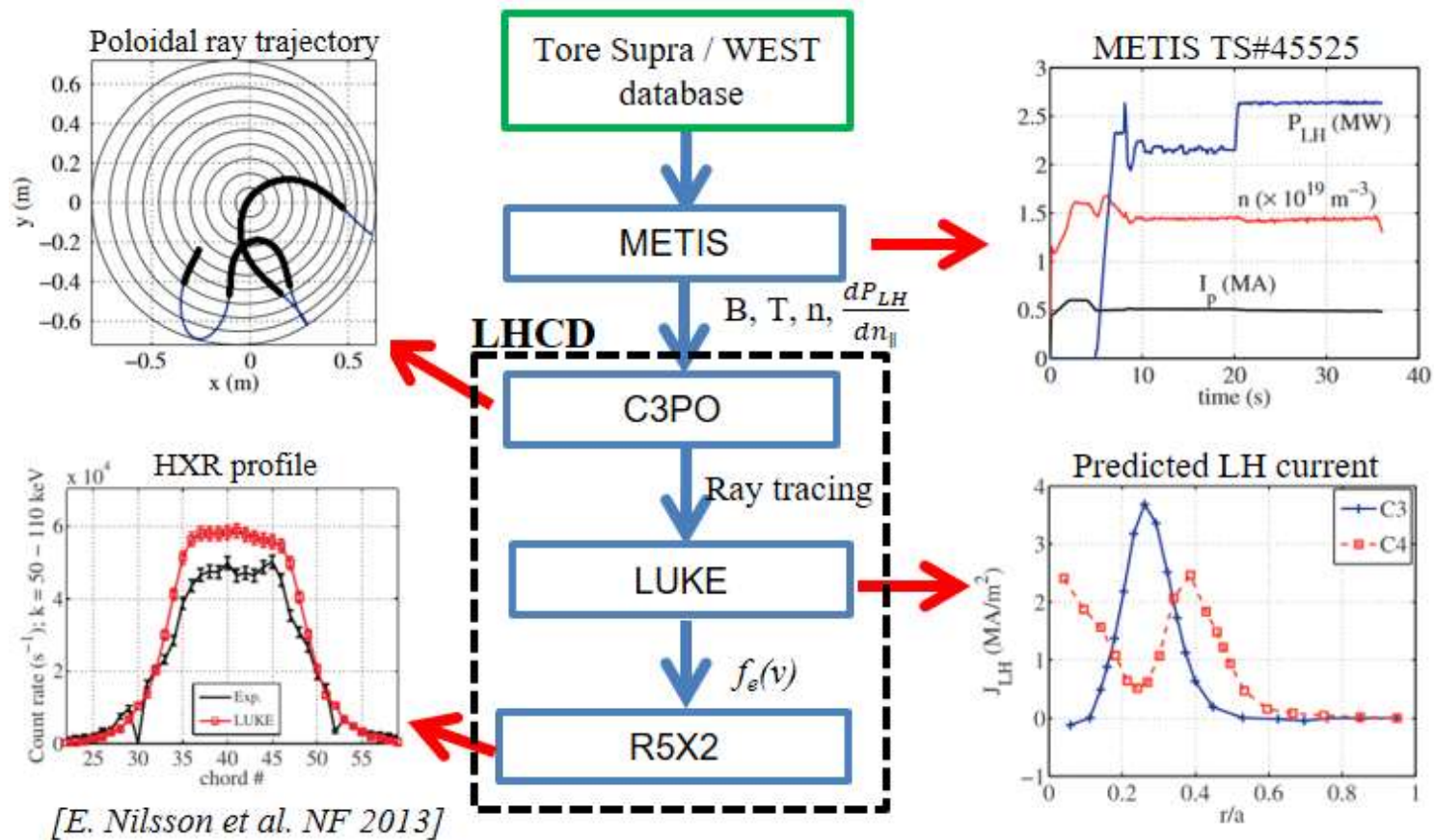
- 0 – 1 keV / 1 – 20 keV → Bolometry / SXR [P. Manas et al, 2023]
- 1 – 5 keV / 5 – 20 keV → multi-energy SXR → GEM [D. Mazon et al, JINST 2022]
- 1 – 20 keV / > 20 keV → SXR / HXR [D. Mazon et al, EPS 2023]

→ Requires Hard X-ray (HXR) modelling



6 ■ **LHCD / HXR modeling:** **T_e and c_w validation**

LHCD / HXR modeling



W impurities and suprathermal electrons

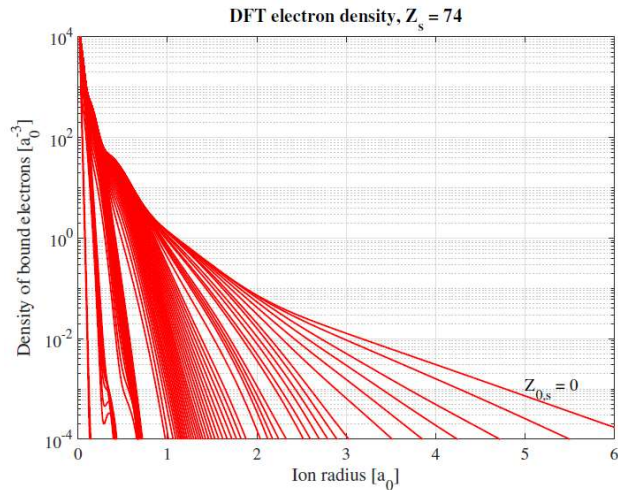
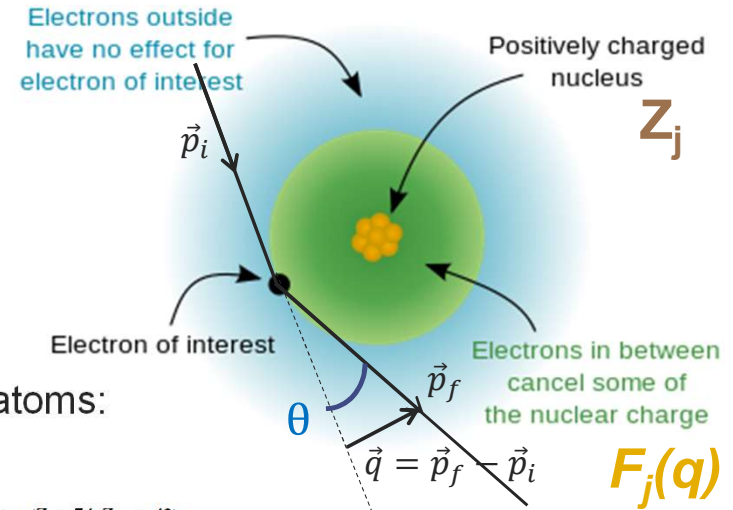


Impact of W on fast electron dynamics:

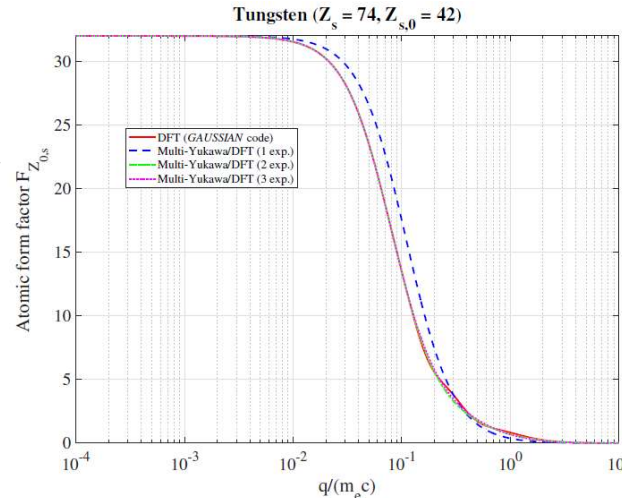
- Elastic e-i collisions [Peysson et al NF 2023]
- Inelastic collisions: mean excitation energy [Walkowiak et al PoP 2022]
- Fast Electron Bremsstrahlung [Peysson et al FEC IAEA 2023]

□ Cross-sections include the partial screening effect $\frac{d\sigma}{d\Omega} \sim |Z_j - F_j(q)|^2$

□ Central quantity to update these quantities for non-fully ionized impurity atoms: density of bound electrons \rightarrow atomic form factor $F_j(q)$



$$F_j(q) = \int \rho_{e,j}(\vec{r}) e^{-i\vec{q}\cdot\vec{r}/a_0} d\vec{r}$$



\vec{q} : Transferred momentum

Effective ion charge:

$$Z = Z_j - F_j(q)$$



LHCD / HXR modeling: T_e and c_W validation

□ HXR and SXR modeling give consistent results:

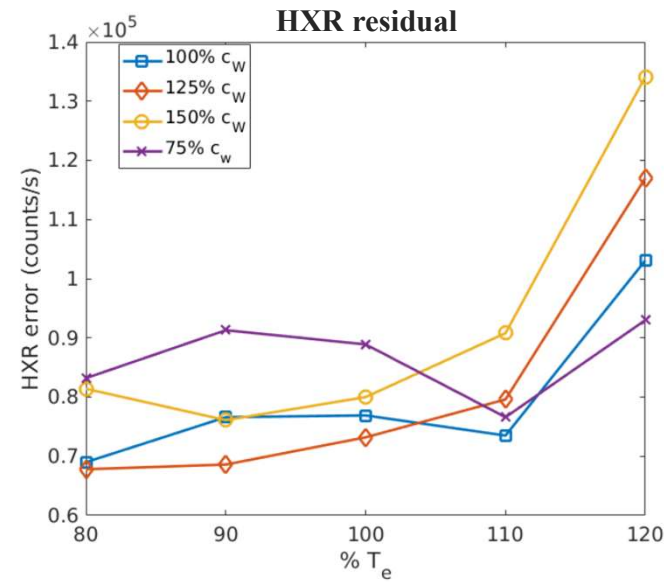
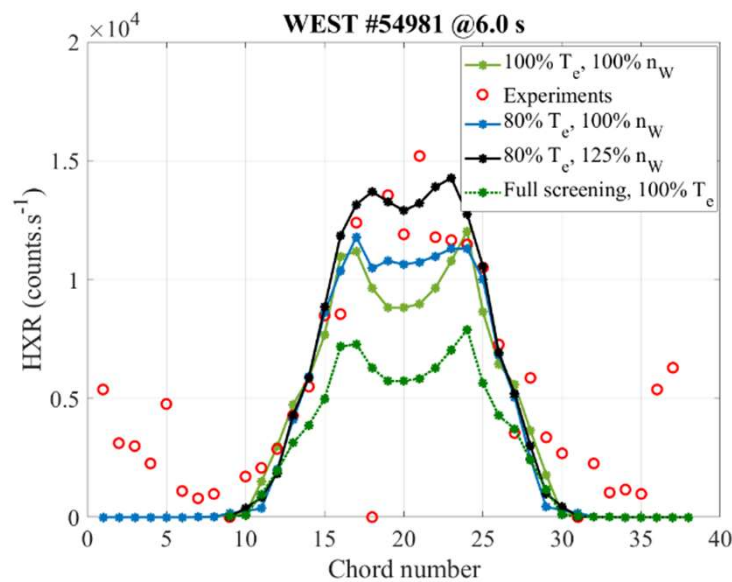
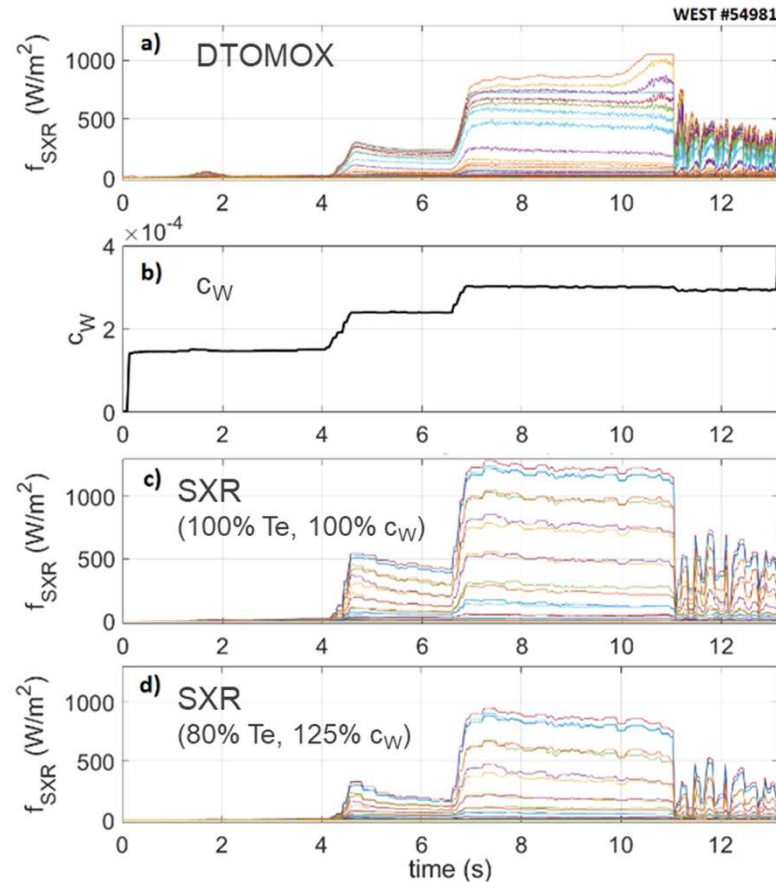
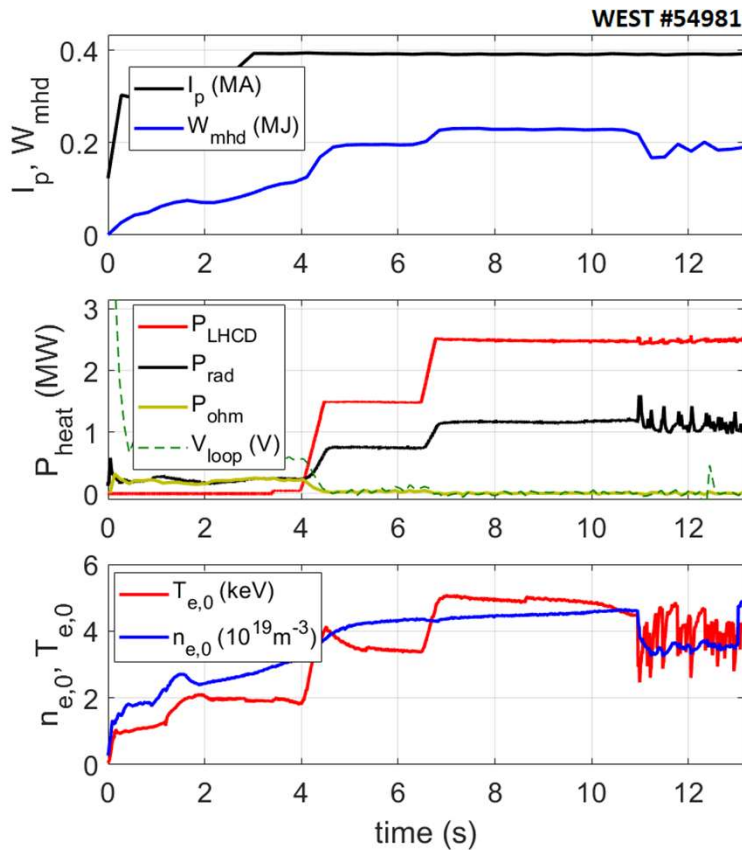


Figure. Modelling using METIS LUKE R5X2 suite of codes of HXR measurements in the energy range 60-80 keV for WEST #54981 at 6.0 s. Left: comparison Full screening/partial screening and influence of T_e and W concentration. Right: Influence of the electron temperature and W concentration on the discrepancy between R5X2 and HXR measurements.

[D. Mazon et al, JINST 17 C01073 (2022)]



SXR modeling consistent with HXR



SXR
Measurement

c_W by METIS

SXR model with
METIS data

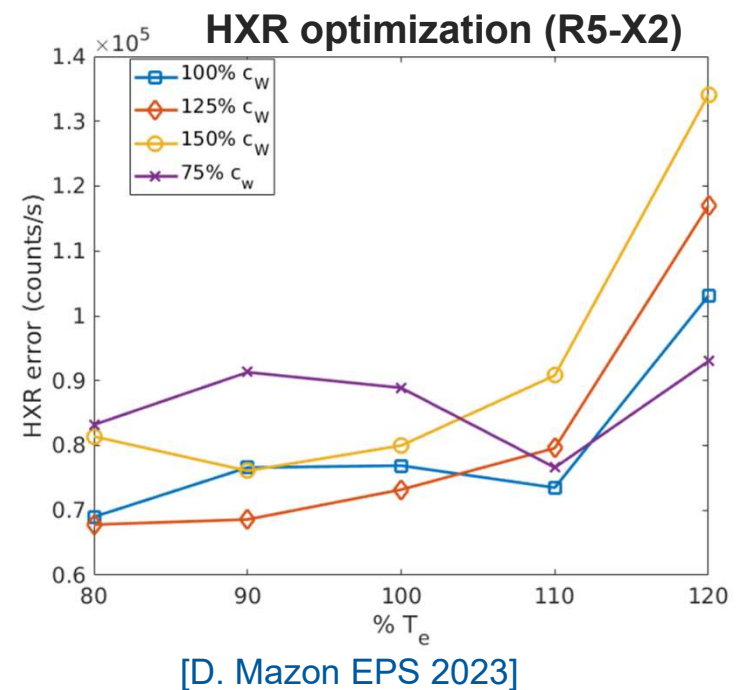
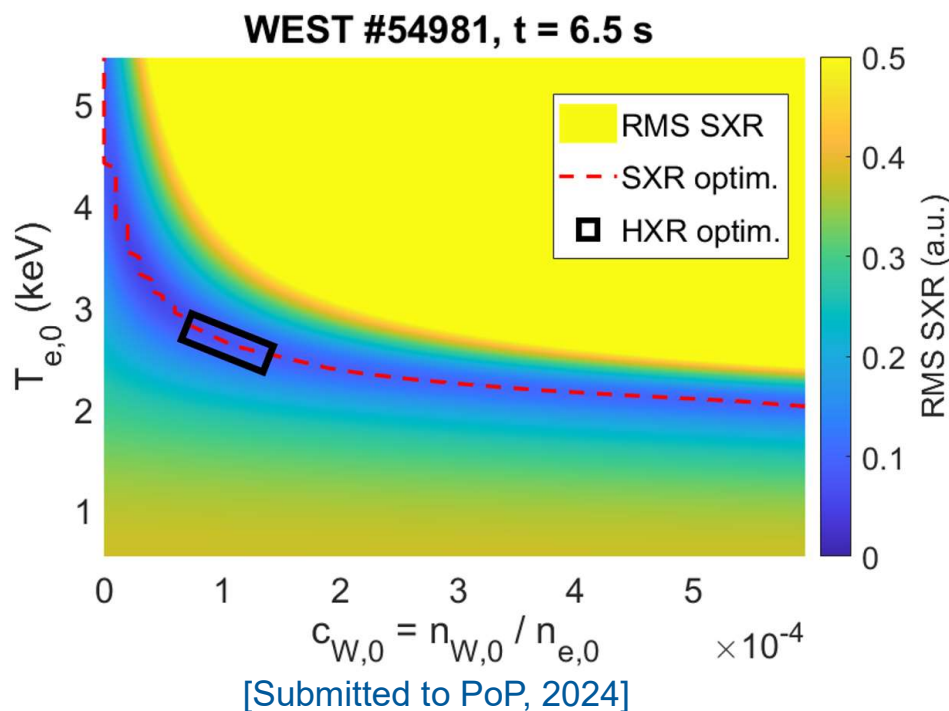
SXR model with the
same values found
by LUKE

-> good agreement



(c_W, T_e) estimate from SXR + HXR on WEST

□ Experimental test on WEST tokamak with SXR DTOMOX (Si diodes) + HXR (CdTe) diagnostics:



Perspective: extend with tomography in energy bands to recover radial profile → GEM applications

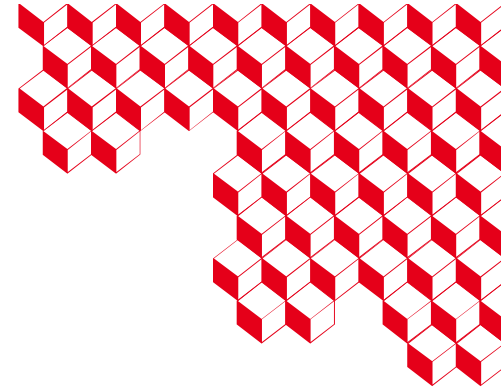


Conclusions and perspectives

- Soft-X Ray emission can provide a lot of plasma information including Tungsten distribution
- This requires very good calibration, different set of diagnostics, modelling
- Several techniques to reconstruct the W distribution give coherent results
- Gas detectors seem very promising for ITER and future reactors, resilient to neutrons
- Other techniques (Bayesian, Artificial Intelligence...) are also potential interesting candidates.



irfm



Many thanks for your attention!

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