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## **SXR measurement and associated inversion: a crucial tool for controlling fusion performances**

Didier Mazon, Alexandre Jardin, Colette Damien, Geert Verdoolaege, T. Wang, Philippe Malard, M. Walsh, M. Scholz, K. Krol

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# 6th International Conference Frontiers in Diagnostic Technologies (ICFDT6) 19-21.10.2022, Frascati



**SXR measurement and associated  
inversion: a crucial tool for  
controlling fusion performances**

DE LA RECHERCHE À L'INDUSTRIE

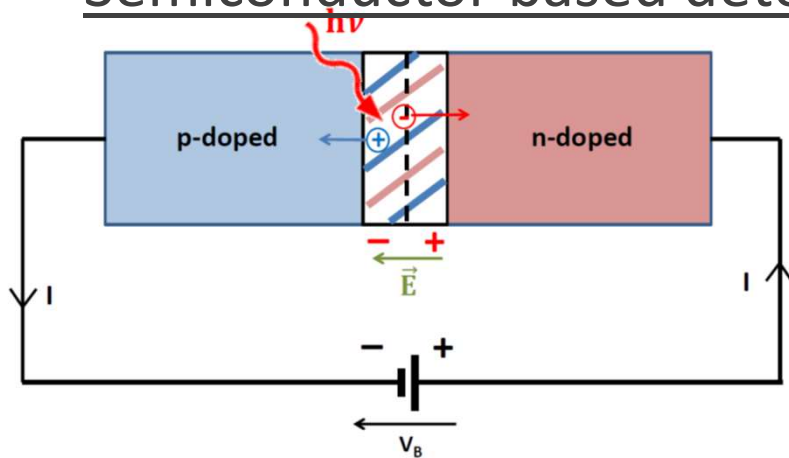
**D. Mazon , A. Jardin, Y. Peysson, D. Colette, T. Wang, G. Verdoolaege, P.  
Malard, M. Walsh, M. Scholz, K. Krol**

Didier Mazon

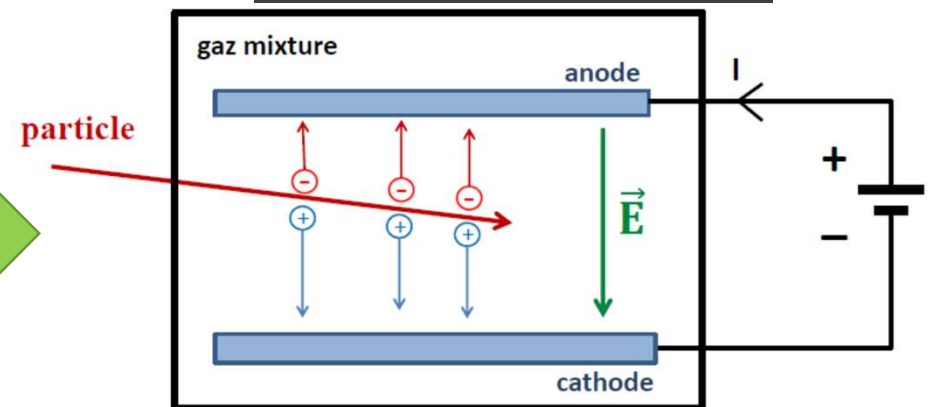


- ❑ Challenges in tokamak: high T, neutrons, gammas...
- ❑ Most common SXR detectors today: **semiconductor diodes**,
- BUT**: ITER, DEMO → too high heat / neutron flux in D-T phase,
- ❑ Neutron resilient technologies essential for ITER [Hu 2017]
- Foreseen techno.: GEM [Mazon 2015], LVIC [Colette 2020], ...

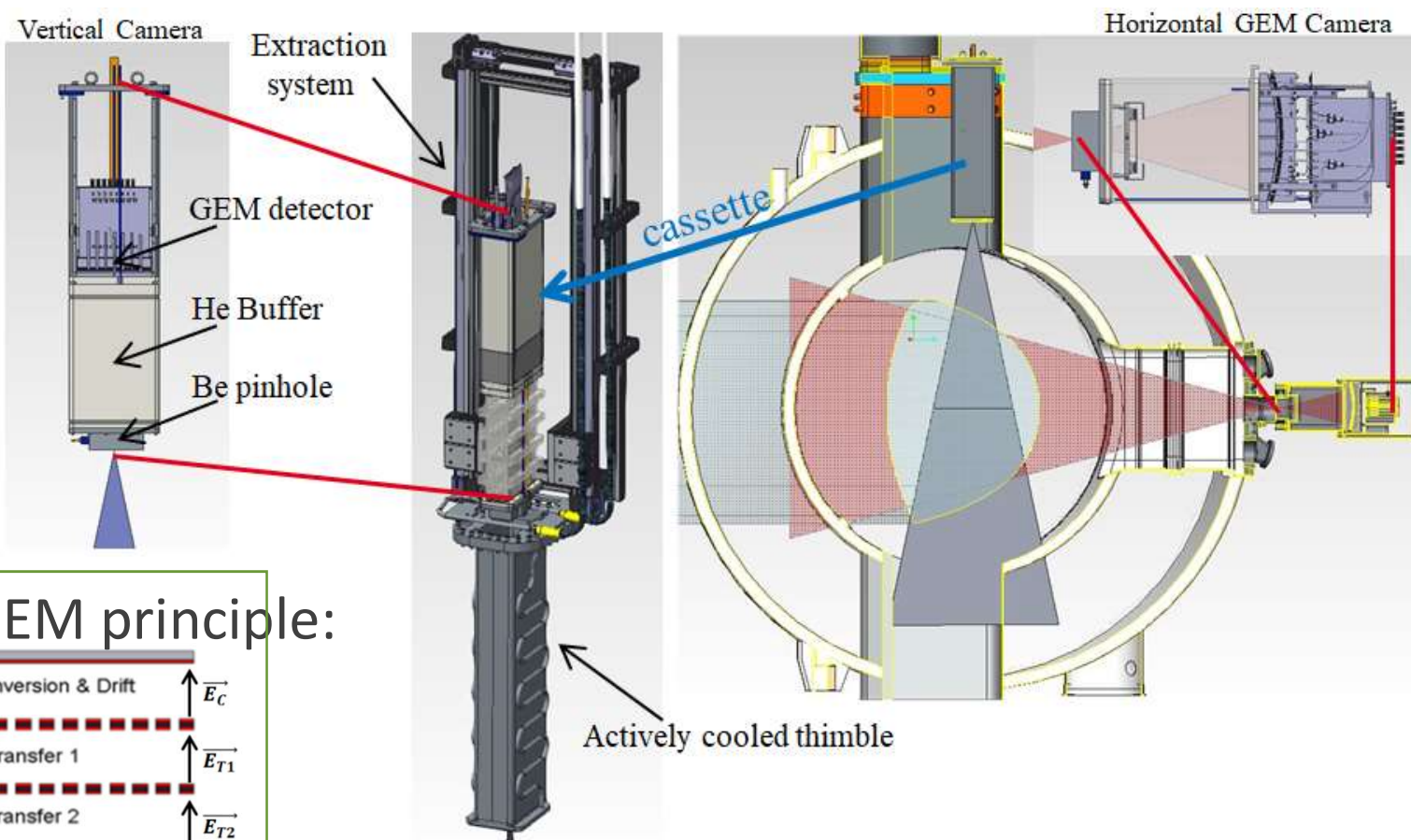
### Semiconductor based detectors:



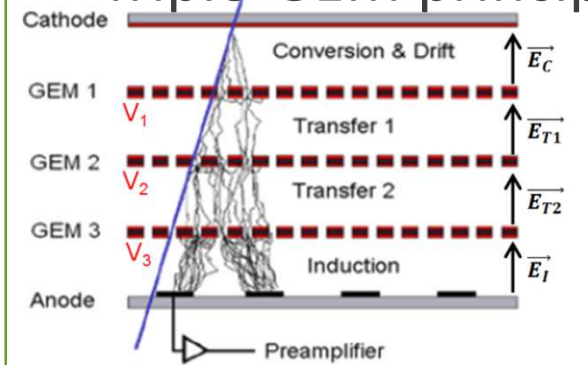
### Gaseous detectors:



### □ GEM-based SXR diagnostic of WEST:

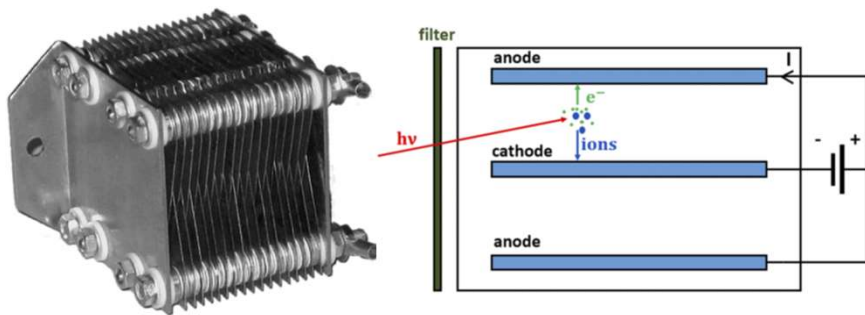


### Triple-GEM principle:



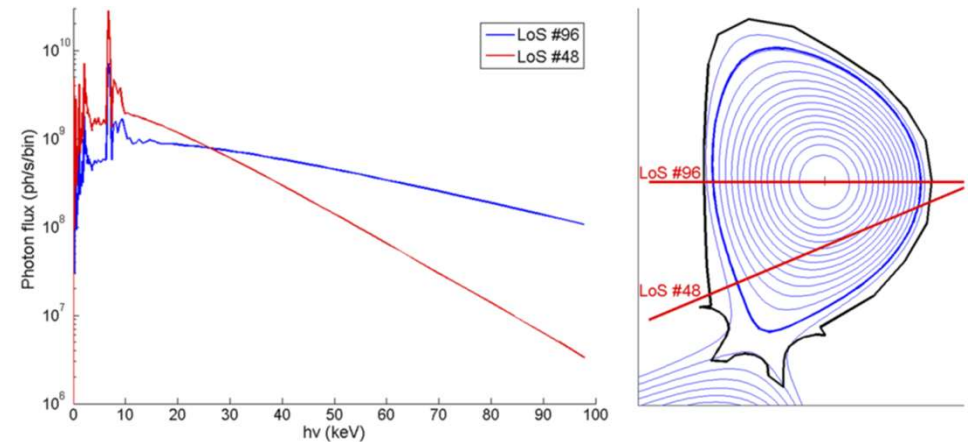
[D. Mazon et al., JINST 2017]

## LVIC concept proposed in [Gott 2009]:

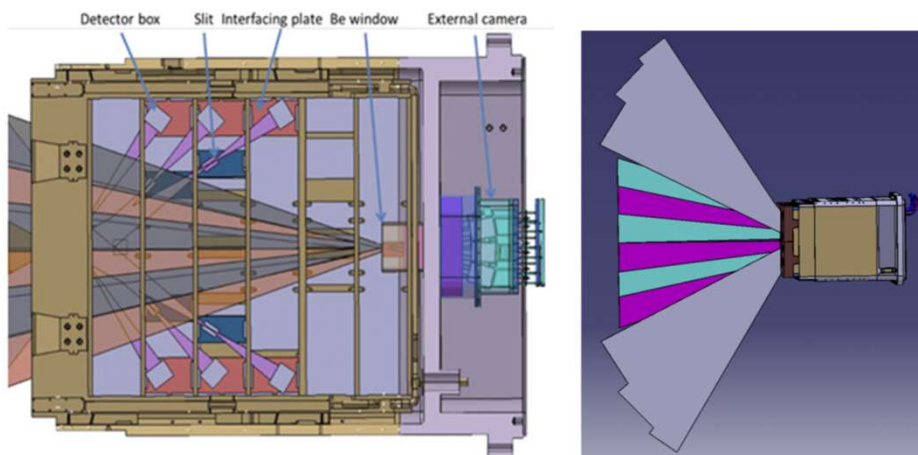


[Y.V. Gott, M.M. Stepanenko, Instrum Exp Tech 52, 260-264 (2009)]

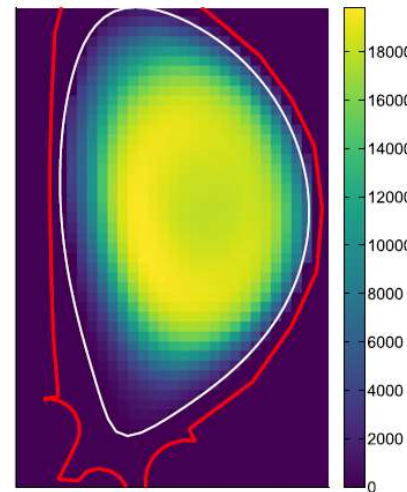
## Modeled line-integrated SXR spectrum



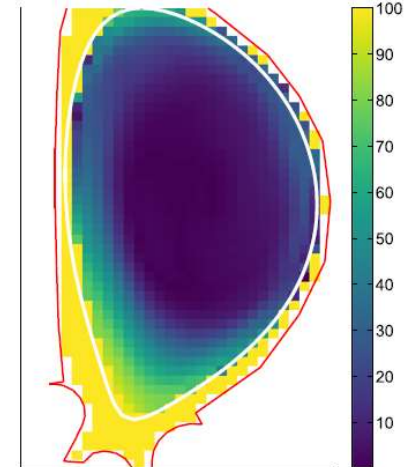
## ITER SXR radial cameras [Colette 2020]



## X-ray tomographic reconstruction ( $W.m^{-3}$ )



## Reconstruction relative error (%)

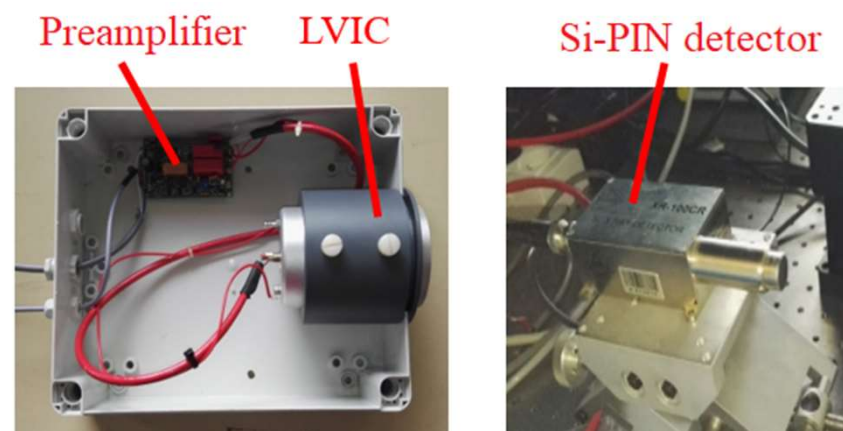
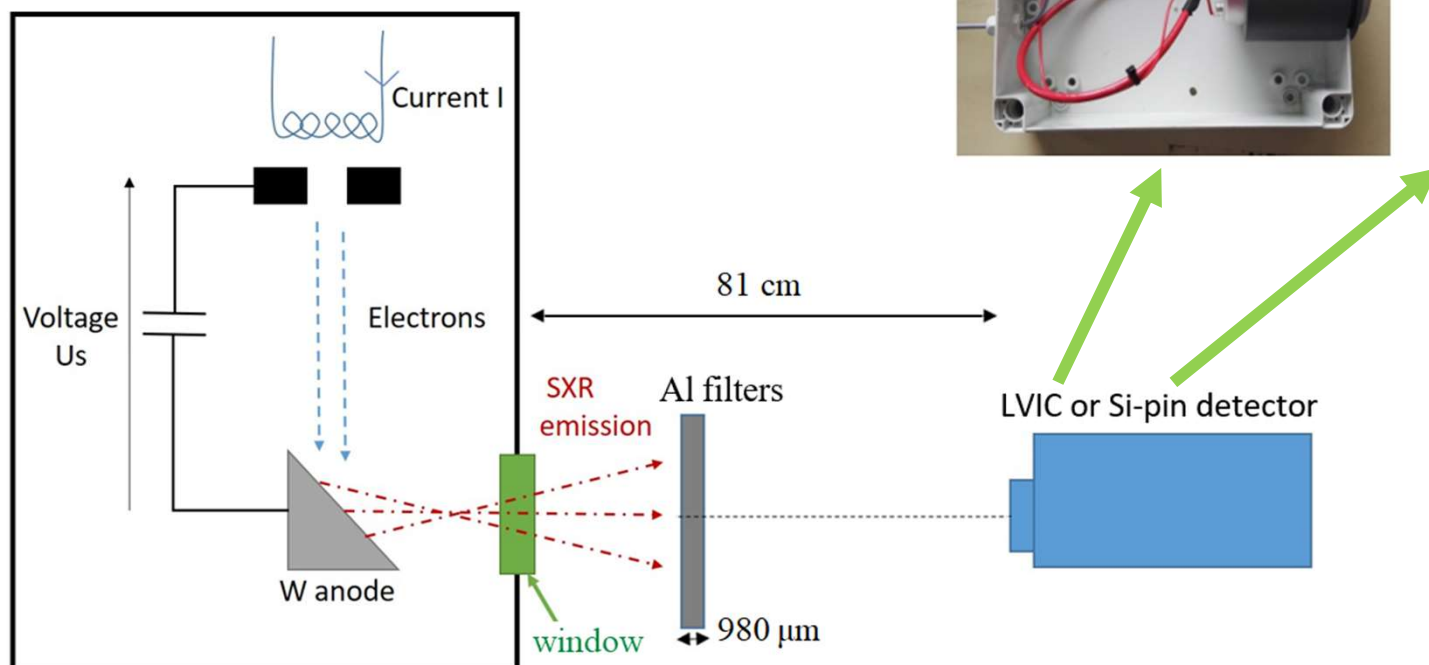


[D. Colette, D. Mazon et al, Rev. Sci. Instrum. 91, 073504 (2020)]



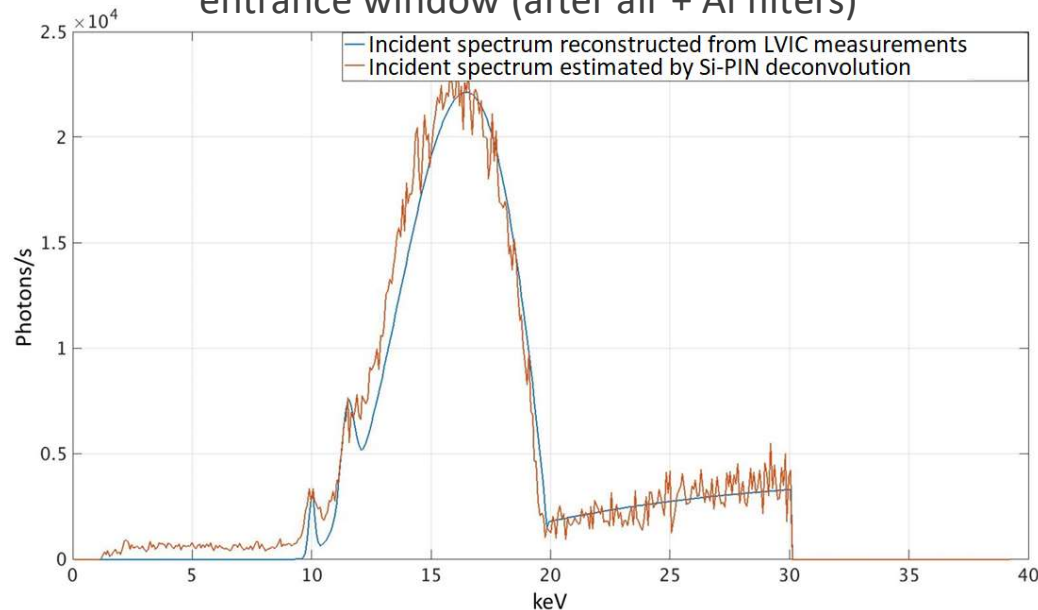
### LVIC prototype tests in lab:

Experimental setup for SXR generation and measurements



[D. Mazon et al., accepted to RSI (2022)]

### Estimated incident spectrum on the LVIC entrance window (after air + Al filters)



- Assumption on the incident SXR spectrum:

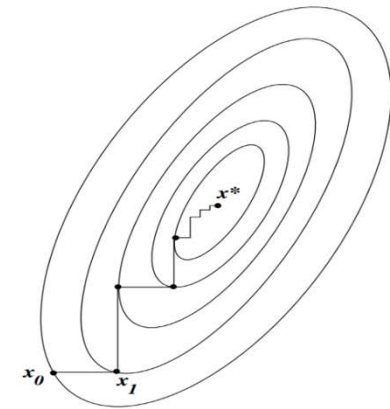
$$\phi(h\nu) = X_1 e^{-\frac{(h\nu - h\nu_1)^2}{2\sigma_1^2}} + X_2 e^{-\frac{(h\nu - h\nu_2)^2}{2\sigma_2^2}} + X_3 - X_4 h\nu$$

$$h\nu_1 = 09.96 \text{ keV (W L}\beta \text{ line),}$$

$$h\nu_2 = 11.42 \text{ keV (W L}\gamma \text{)}$$

Iterative optimization procedure with least-square minimization

$$\{X_i\}_{i=1..5} = \arg \min \|I_{meas} - I_{synt}(\phi(X))\|$$



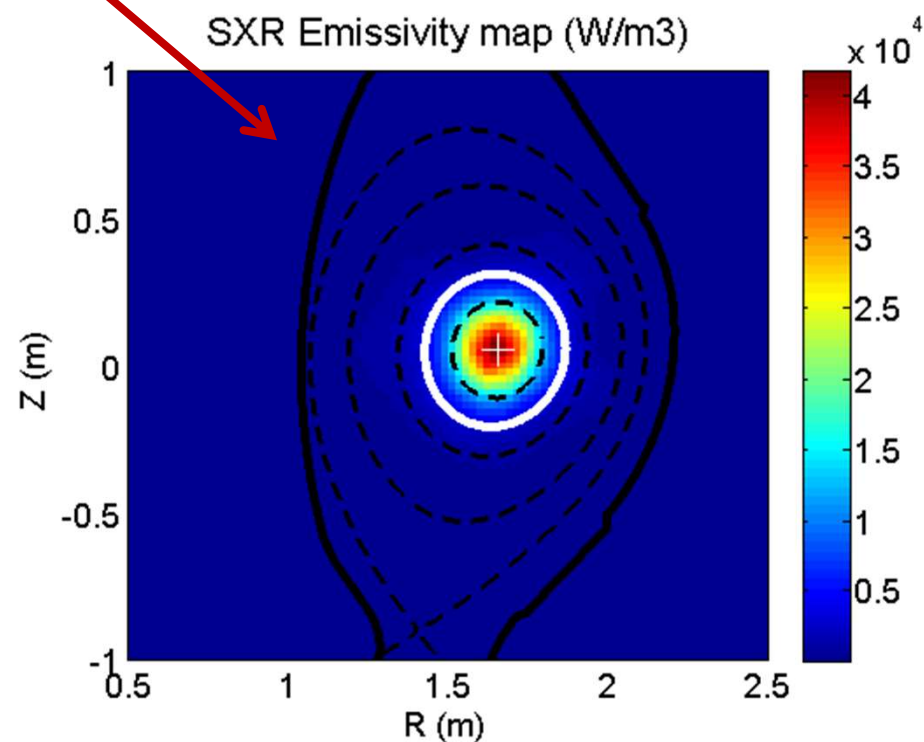
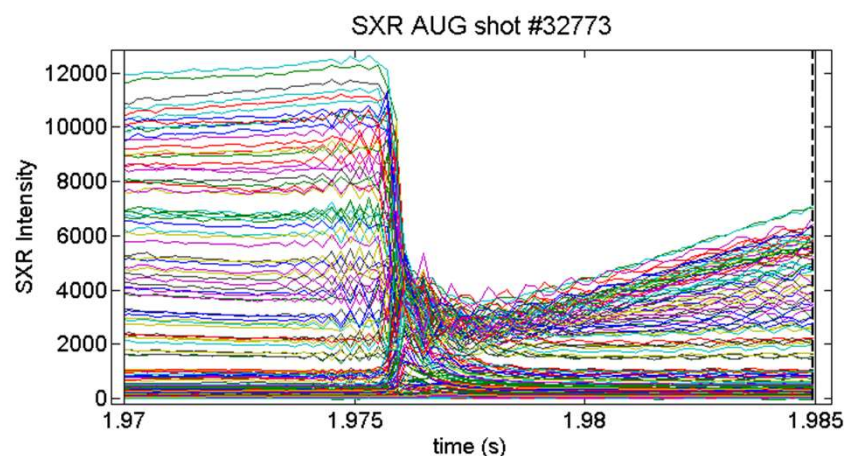
### Experimental results – model validation

Al filter width ( $\mu\text{m}$ )	Measured voltage (mV)	Simulated voltage (mV)	Relative error (%)
969	7.36	7.71	4.5
0	191.22	203.29	5.9

[D. Mazon et al., accepted to RSI (2022)]

- Soft X-rays (SXR) in the energy range 0.1 keV – 20 keV can provide valuable information, through 2D tomography, on:

- Impurity transport,
- Magnetohydrodynamic (MHD) activity, (e.g. sawtooth crash in ASDEX-U)
- Magnetic equilibrium.  
(plasma positioning)





- Impurity force balance equation on a magnetic flux surface:

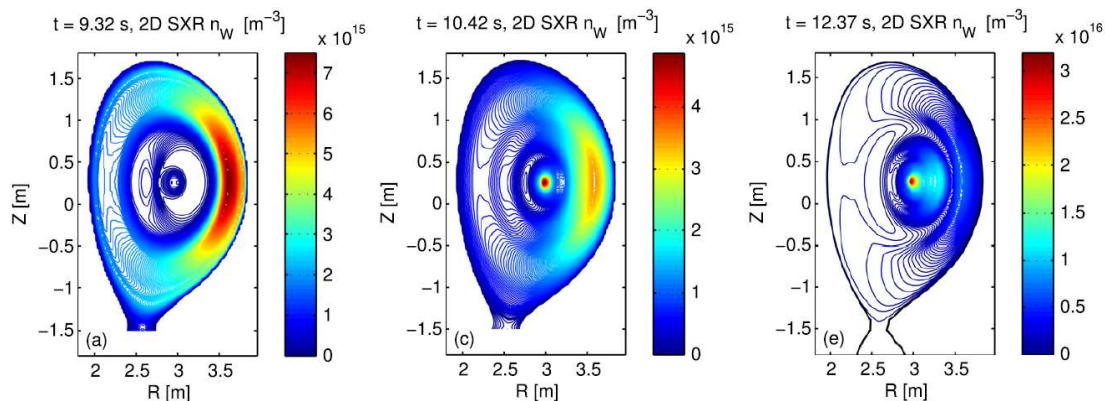
$$\frac{m_z n_z \omega^2}{2} \nabla_{\parallel} R^2 + Z n_z e \nabla_{\parallel} \Phi + T_z \nabla_{\parallel} n_z = R_{z,\parallel}$$

inertia (centrifugal)
electrostatic
pressure
friction

[Reinke PPPL Seminar 2015]

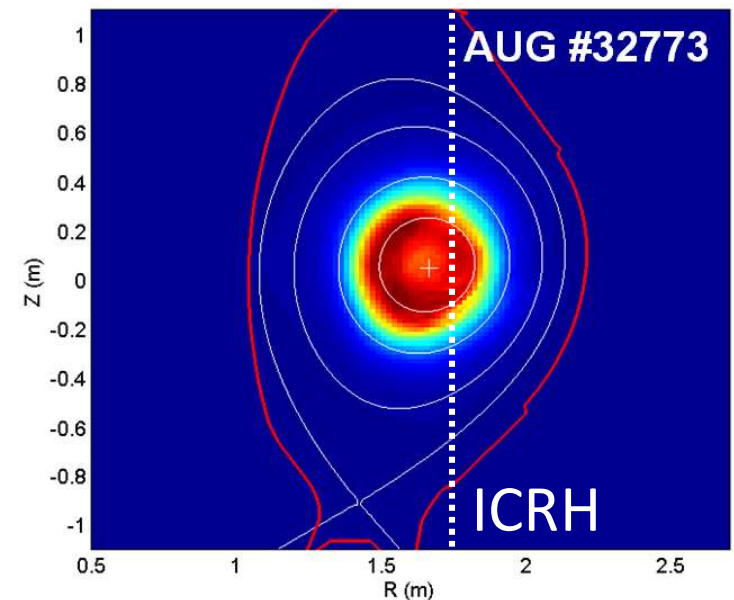
Neutral Beam Injection (NBI):

Ion Cyclotron Resonance Heating (ICRH)



W 2D density distribution evolution with 17 MW of NBI (JET #83351)

[C. Angioni et al., PoP 2015]



❑ Radiated power of impurities:  $P_{rad,Z} = n_e^2 c_Z L_Z(T_e)$

electron density ( $m^{-3}$ )

Impurity concentration

Cooling factor of Z ( $W.m^3$ )

electron temperature (keV)

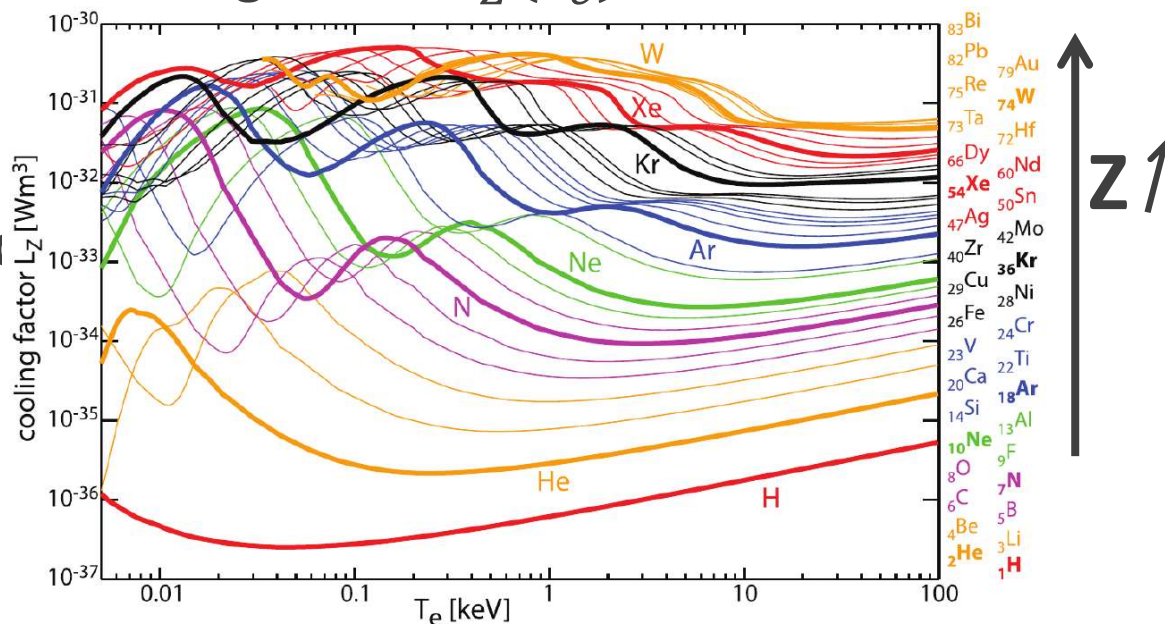
❑ Impurity radiation increases with atomic number Z (high-Z):

Dominant radiation processes:

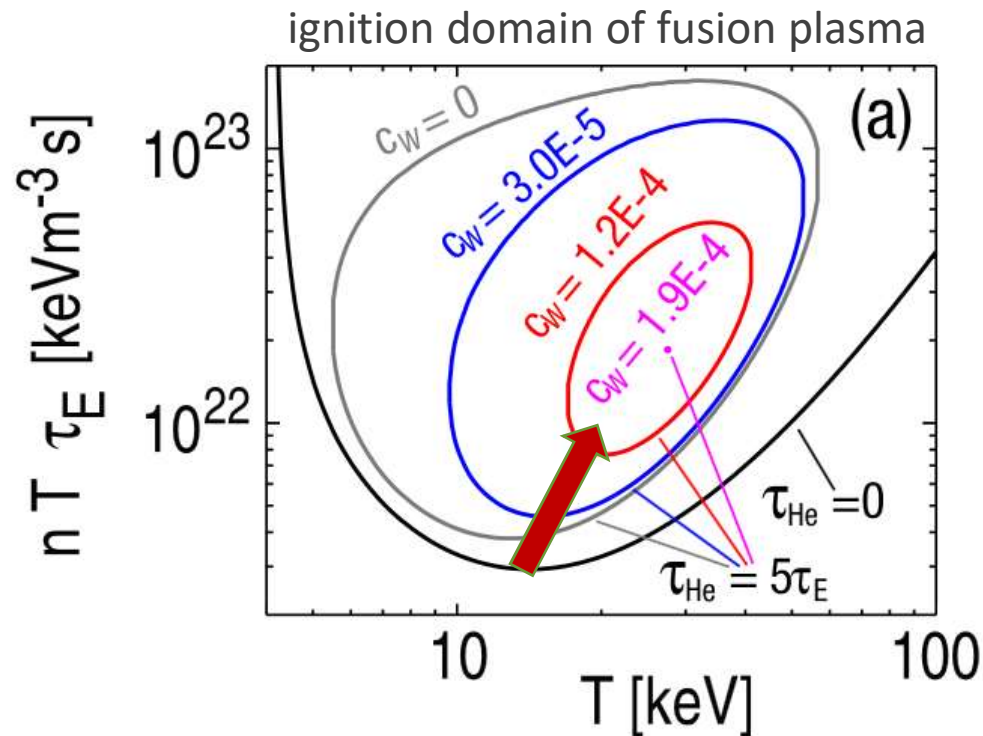
- **Bremsstrahlung**  
(free-free)
- **Radiative recombination**  
(free-bound)
- **Line radiation**  
(bound-bound)

**Soft X-ray range**  
**[0.1 keV – 20 keV]**

Cooling factor  $L_Z(T_e)$  of different elements



[Puetterich NF 2019]



$T$  [keV] – plasma temperature

$n$  [ $1/m^3$ ] – plasma density

$\tau_E$  [s] – energy confinement time

$\tau_{He}$  – Helium confinement time

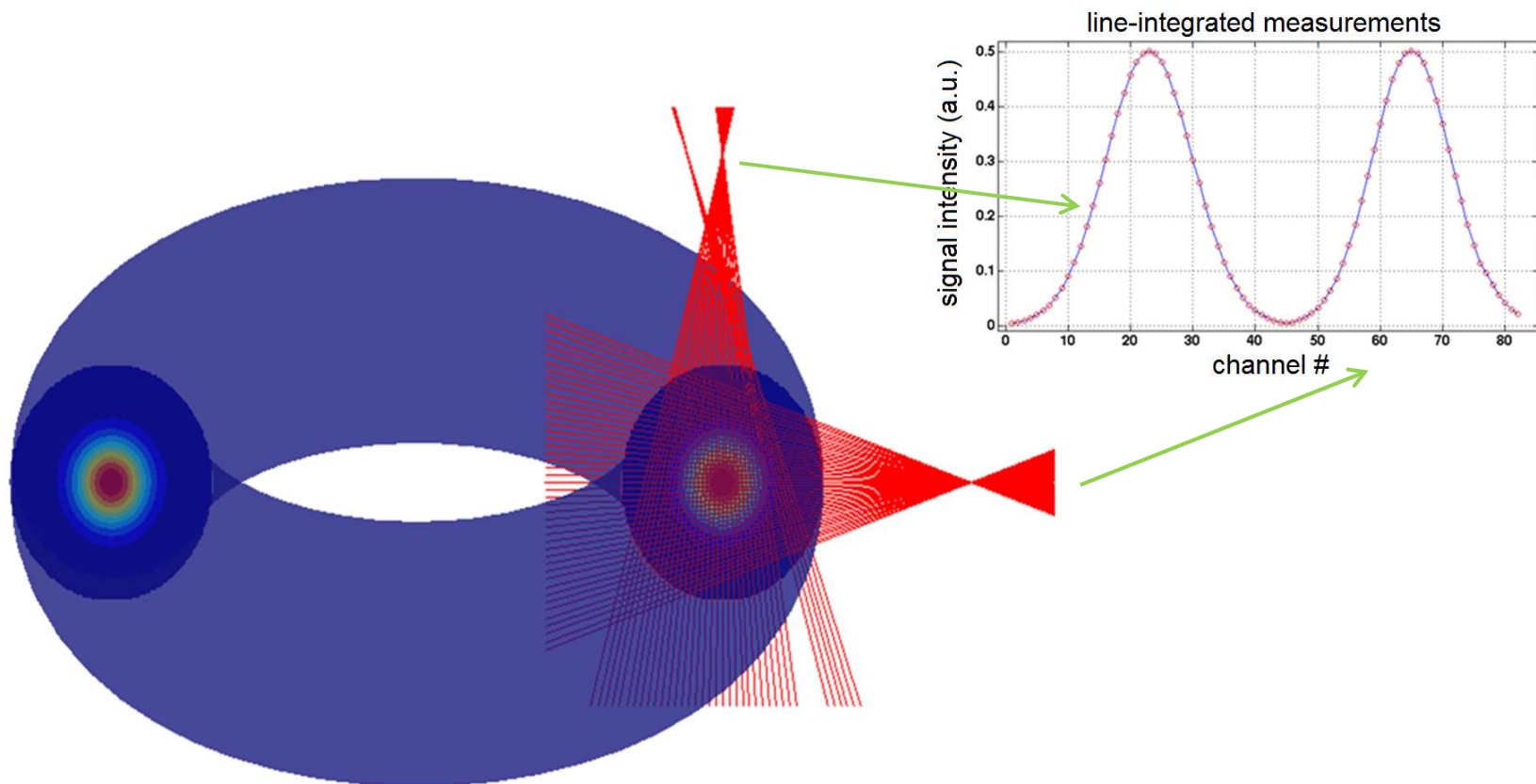
$c_W$  – impurity concentration (W)

[T. Putterich et al., Nuclear Fusion 50 (2), 025012 (2010)]

□ A concentration  $f_W < 0.01\%$  is a requirement for a fusion reactor

→ Diagnostic tools and actuators to control the tungsten core concentration are required!

- Reconstruction of the plasma 2D emissivity from line-integrated measurements, through 2D tomography → **ill-posed problem**



Example: Tore Supra SXR diagnostic



*Andrej Tikhonov*

$$\mathbf{m} = \mathbf{T} \cdot \boldsymbol{\varepsilon} + \tilde{\mathbf{m}}$$

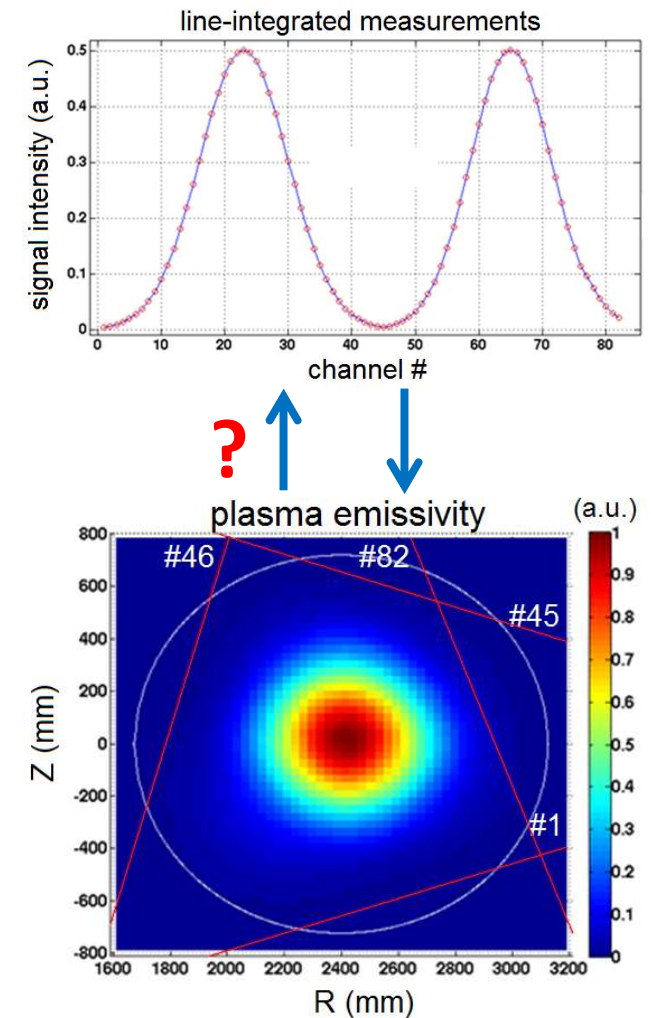
measurements vector  $\mathbf{m}$   
 Transfer matrix  $\mathbf{T}$   
 2D emissivity  $\boldsymbol{\varepsilon}$   
 noise  $\tilde{\mathbf{m}}$

□ Inversion problem: minimization of a functional:

$$\boldsymbol{\varepsilon}_{rec} = \arg \min_{\boldsymbol{\varepsilon}} (\chi^2(\boldsymbol{\varepsilon}) + \lambda \cdot \mathbf{R})$$

- Reconstruction error:  $\chi^2(\boldsymbol{\varepsilon}) = \|\mathbf{m} - \mathbf{T} \cdot \boldsymbol{\varepsilon}\|^2$
- Regularization term:  $\mathbf{R} = {}^t\boldsymbol{\varepsilon} \cdot \mathbf{H} \cdot \boldsymbol{\varepsilon}$
- Regularization param.:  $\lambda$

→ Solution:  $\boldsymbol{\varepsilon}_{rec} = (\mathbf{T} \cdot \mathbf{T} + \lambda \mathbf{H})^{-1} \cdot \mathbf{T} \cdot \mathbf{m}$

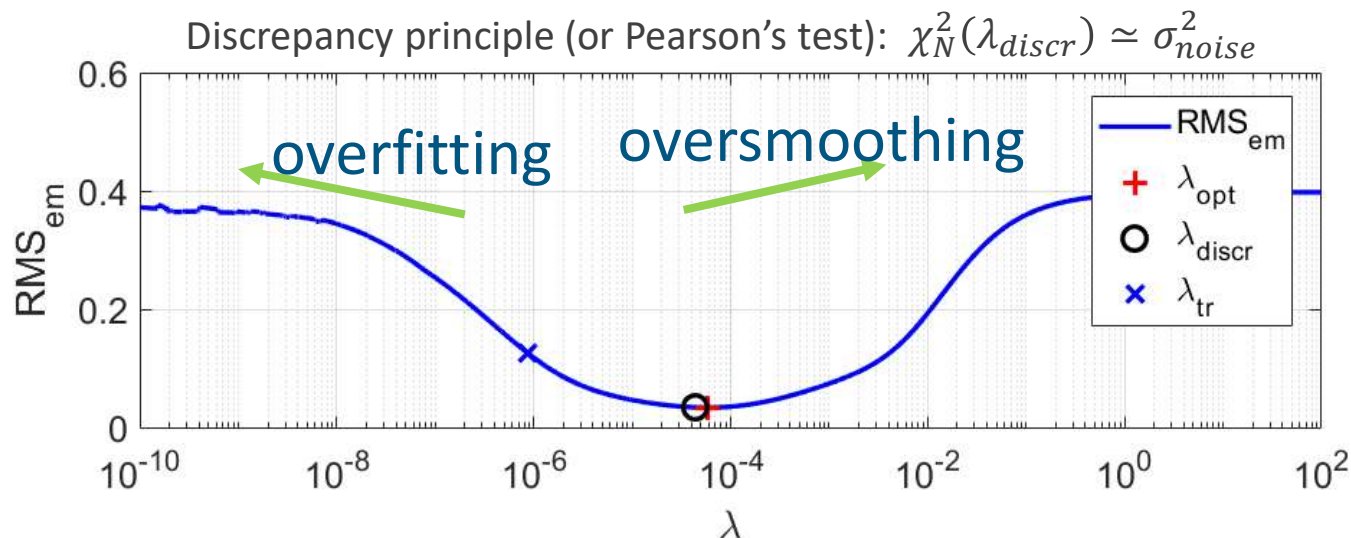
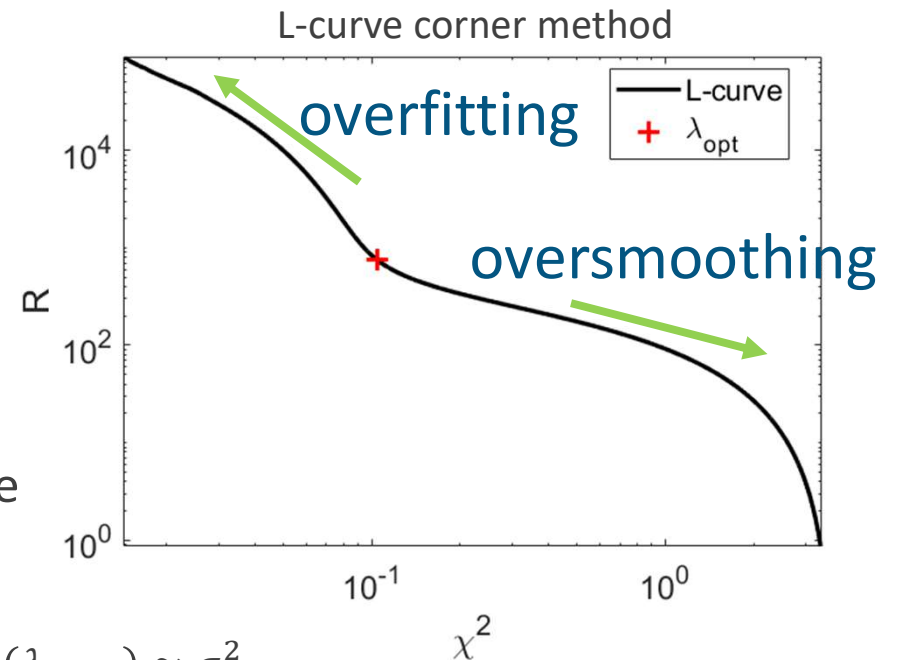




- $\lambda$  acts as a trade-off between smoothing of the solution and fitting of the SXR measurements:

$$\varepsilon_0 = \arg \min_{\varepsilon} (\chi^2(\varepsilon) + \lambda \cdot R(\varepsilon))$$

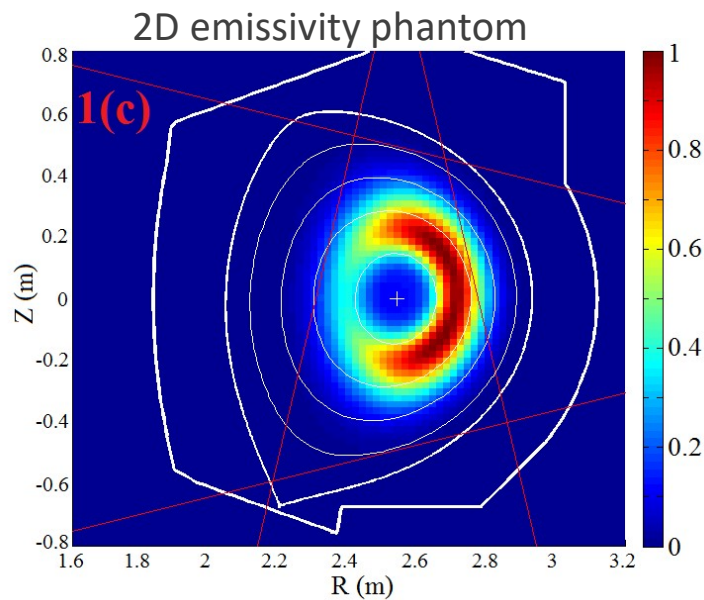
- For example: L-curve, discrepancy principle



- Anisotropic regularization (with magnetic equilibrium) is introduced for the WEST configuration:

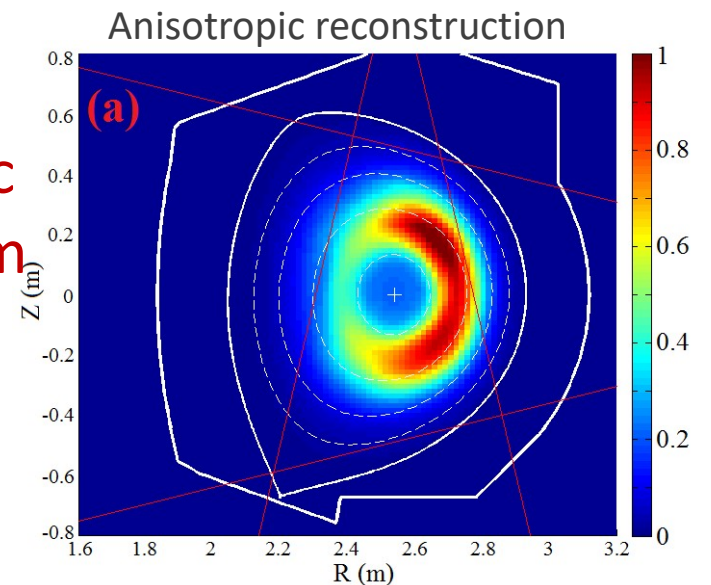
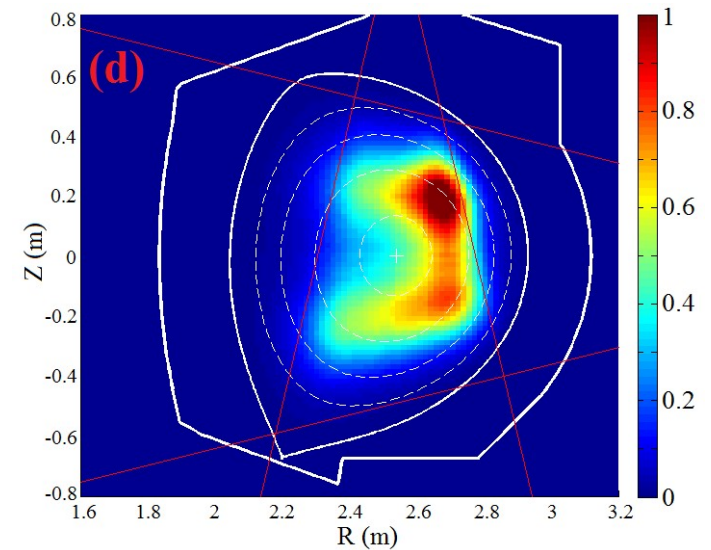
$$\mathbf{H}_{\text{MFI}} = (1 - \tau) {}^t\nabla_{\parallel} \cdot \mathbf{W} \cdot \nabla_{\parallel} + \tau {}^t\nabla_{\perp} \cdot \mathbf{W} \cdot \nabla_{\perp}$$

anisotropy factor:  $0 < \tau < 0.5$



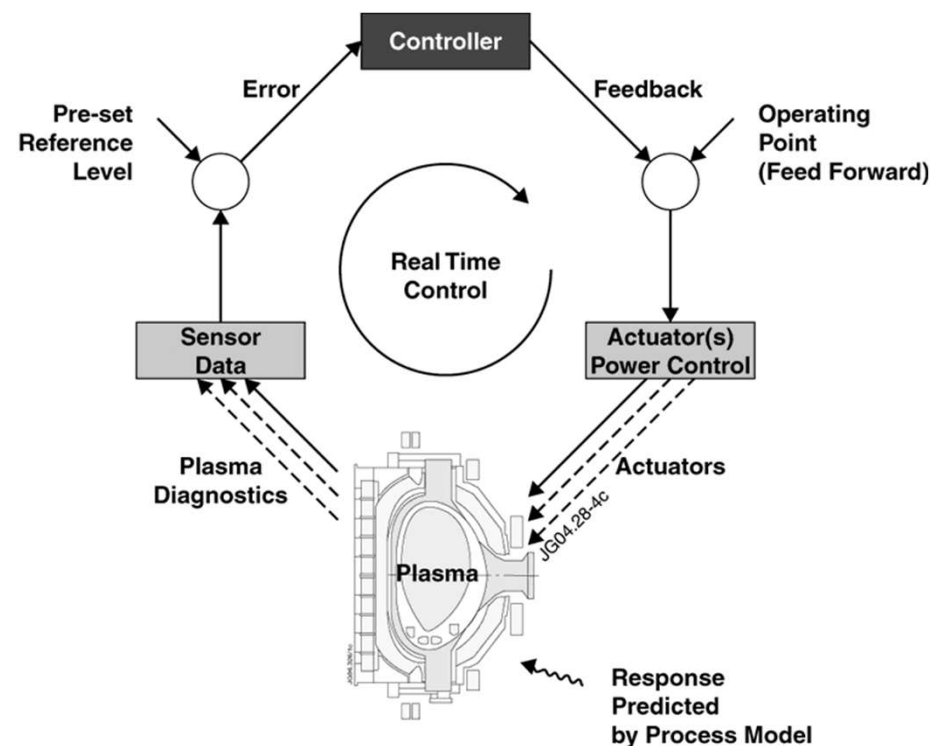
[Jardin et al, JINST 2016]

+ magnetic  
equilibrium



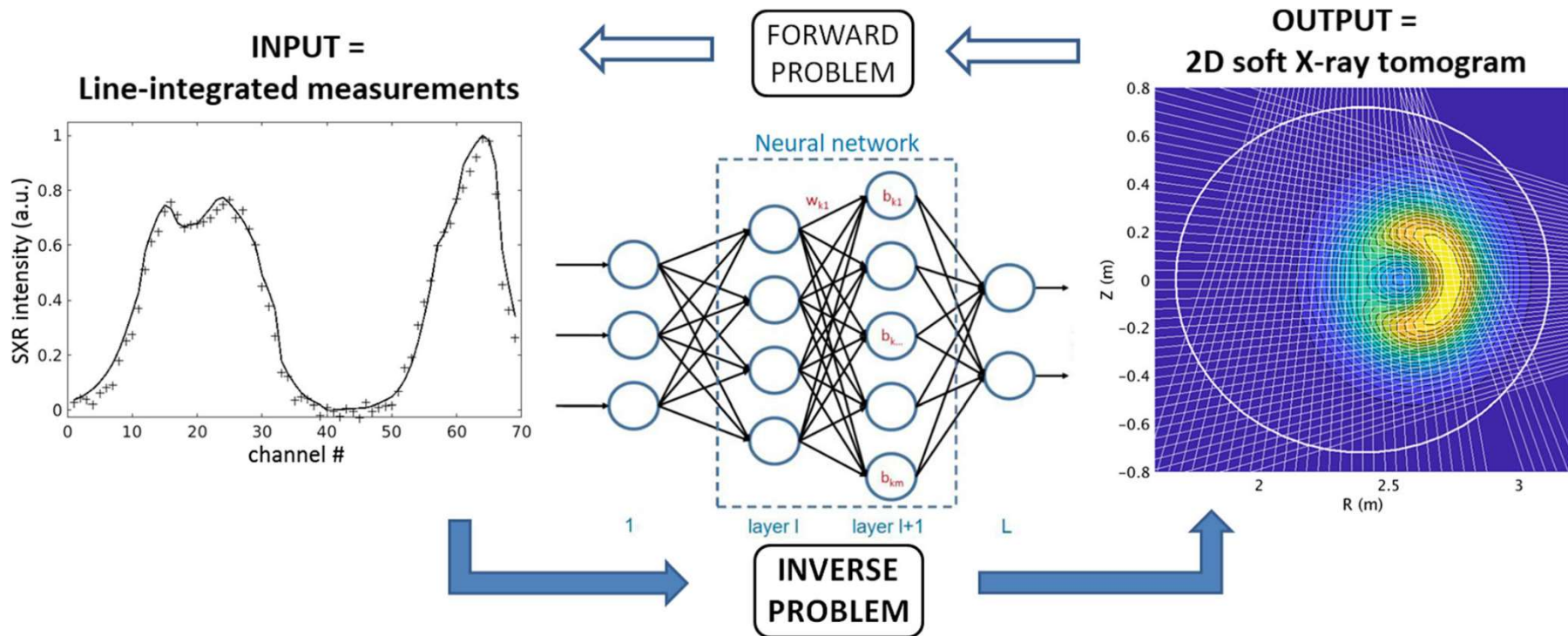
## □ Control of W concentration?

- Reduce W sources (erosion)
- Higher pumping rate
- Avoid strong W poloidal asymmetries
- Central ECRH (pump-out effect)
- Shape plasma profiles: peaked  $T_e$  (temperature screening)
- Trigger mitigating/flushing MHD: sawteeth (core), ELMs (edge)...



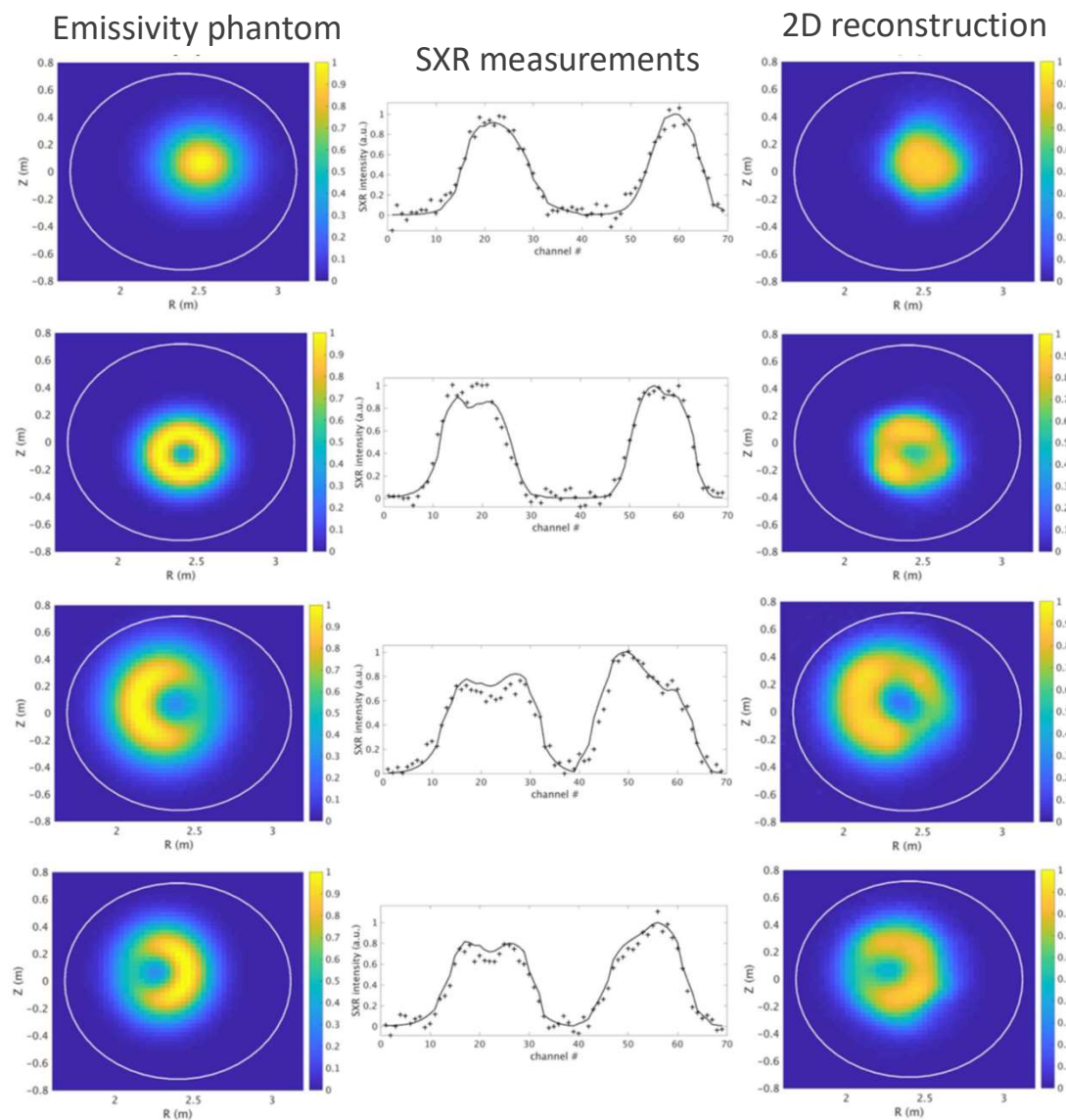
→ Possibility of real-time X-ray tomography?

- ❑ Issue of traditional Tikhonov approach: computing time  $> 0.01 - 10$  s
- ❑ Fast tomography for real-time control  $< 0.1$  ms  $\rightarrow$  Neural networks  
Neural Network: successive neuron layers connecting inputs and outputs.  
Neuron biases and weights are iteratively adjusted by training from a dataset.



[A. Jardin (D. Mazon) et al., Neural networks: from image recognition to tokamak plasma tomography, 2019 *Laser and Particle Beams* 1–5]

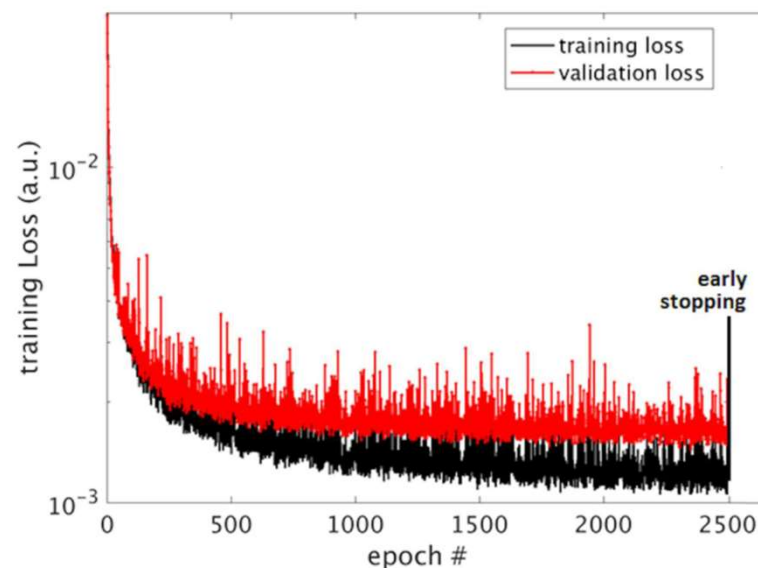




- Large training database to optimize the network parameters  $(\vec{w}, b)$
- Minimization of a Cost Function (MSE) with stochastic gradient-descent method:

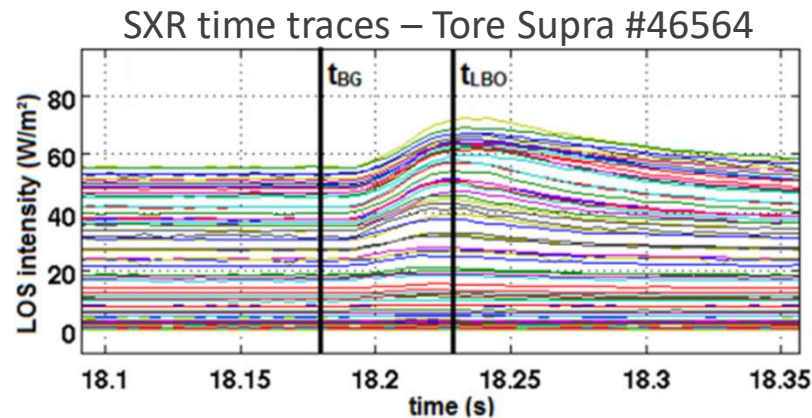
$$C(\vec{w}, b) = \frac{1}{2n} \sum_x [y(x) - a(x, \vec{w}, b)]^2$$

desired output
output from the network

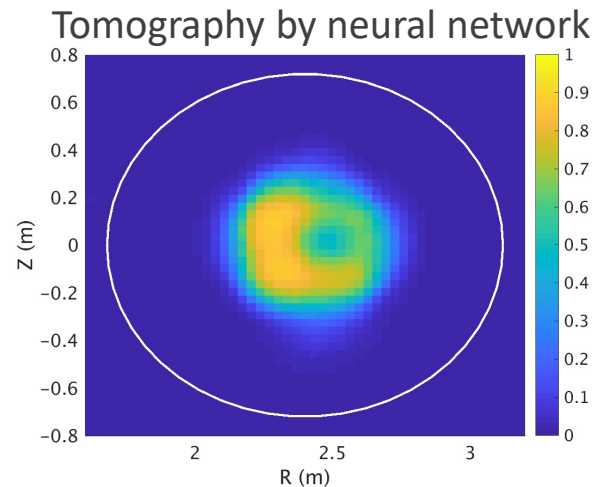
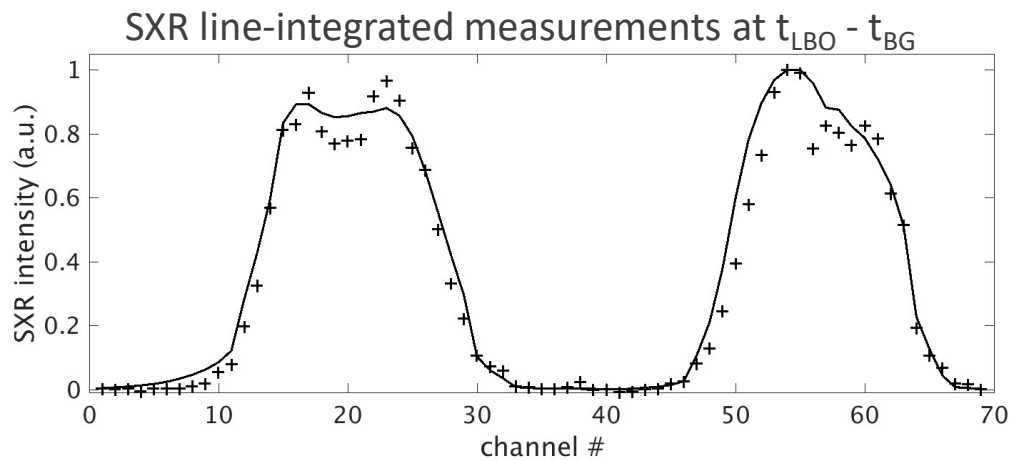




□ Controlled injection of tungsten impurities in Tore Supra:



[A. Jardin (D. Mazon) et al, Acta  
Phys. Pol. A, 138 (2020) 626-631]



→ Consistent with traditional Tikhonov method but fast enough for real-time control ( $< 0.1$  ms)

Posterior information:

- What is the probability distribution of the emissivity, given the measurements?
- What is the most likely emissivity, given the measurements, and how certain are we?



Prior information:

- What are the possible emissivity fields before taking measurements?



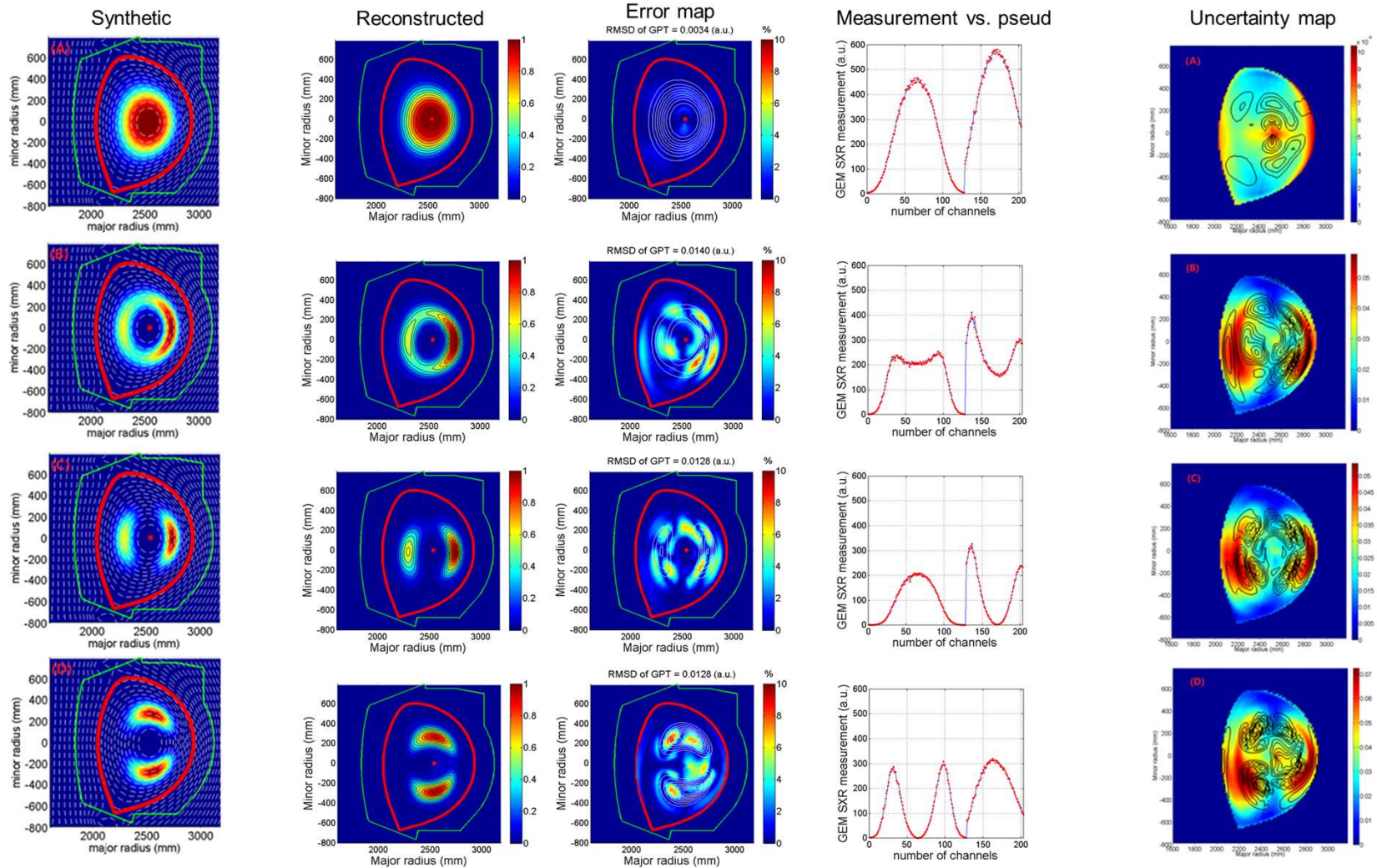
$$p(\text{emissivity} | \text{measurement}) \sim p(\text{measurement} | \text{emissivity}) p(\text{emissivity})$$



Likelihood forward model:

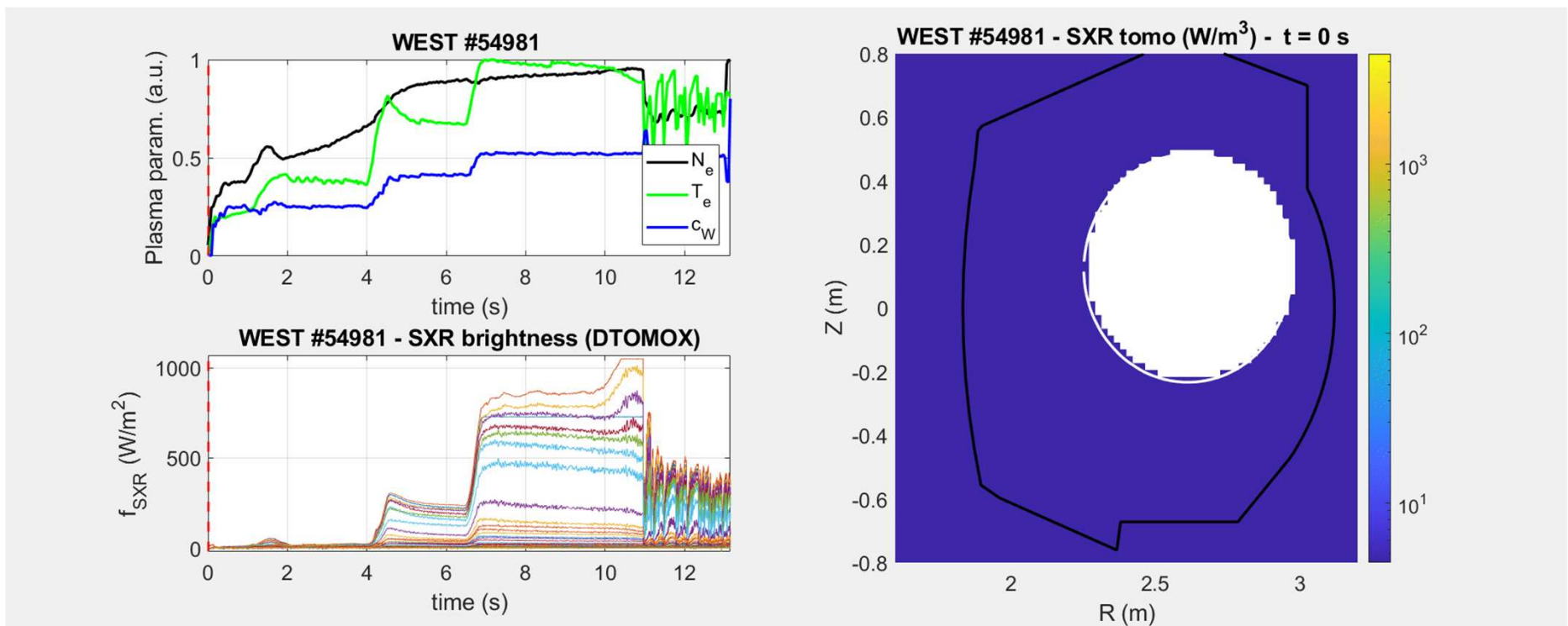
- Suppose we would know the emissivity field, to what measurements would it lead?

*T. Wang, D. Mazon, J. Svensson, D. Li, A. Jardin and G. Verdoolaeye. Gaussian Process tomography for soft X-ray spectroscopy at WEST without equilibrium information. Rev Sci Instrum. 2018 Jun. 89(6).*



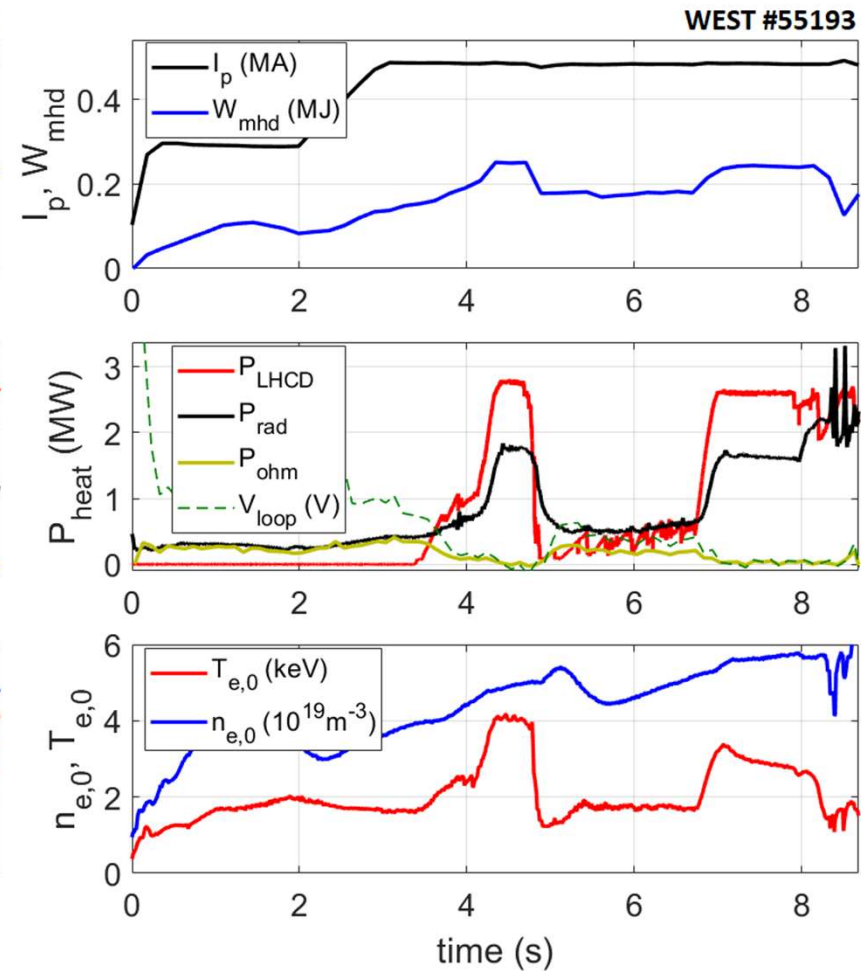
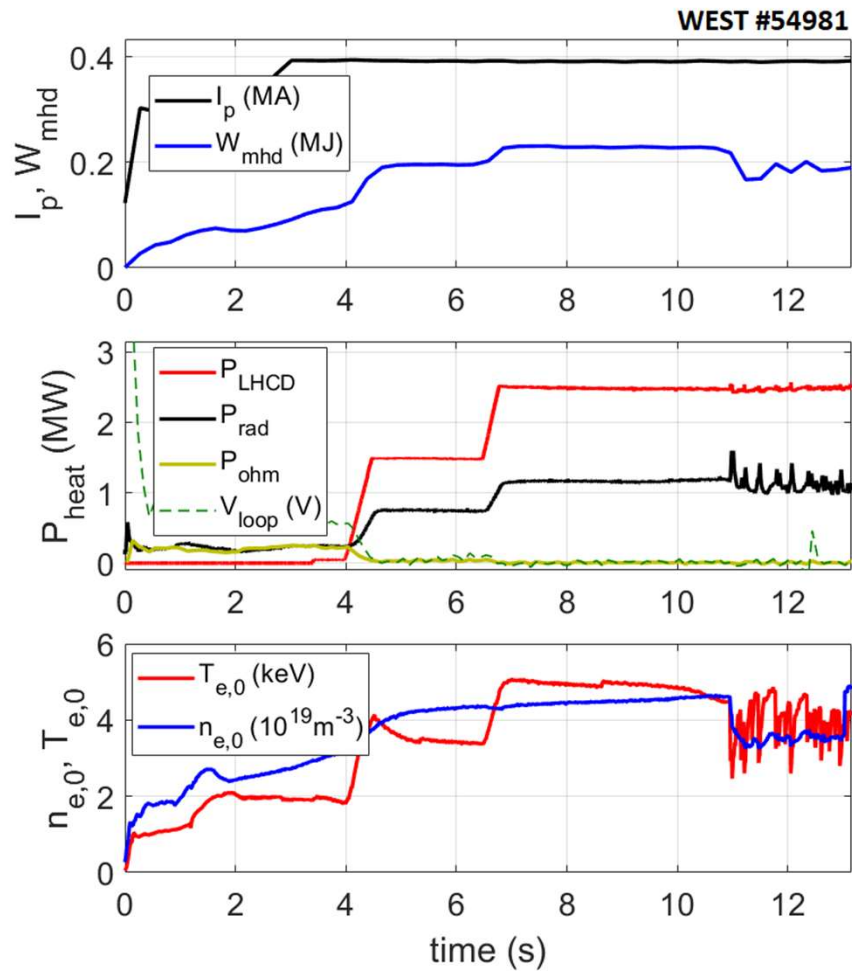
T. Wang, D. Mazon, J. Svensson, D. Li, A. Jardin and G. Verdoolaeg. *Gaussian Process tomography for soft X-ray spectroscopy at WEST without equilibrium information*. *Rev Sci Instrum.* 2018 Jun. 89(6).

- ▶ some recent applications on Tore Supra / WEST (e.g. tomography example, interaction with fast electrons, HXR/SXR integrated approach...)

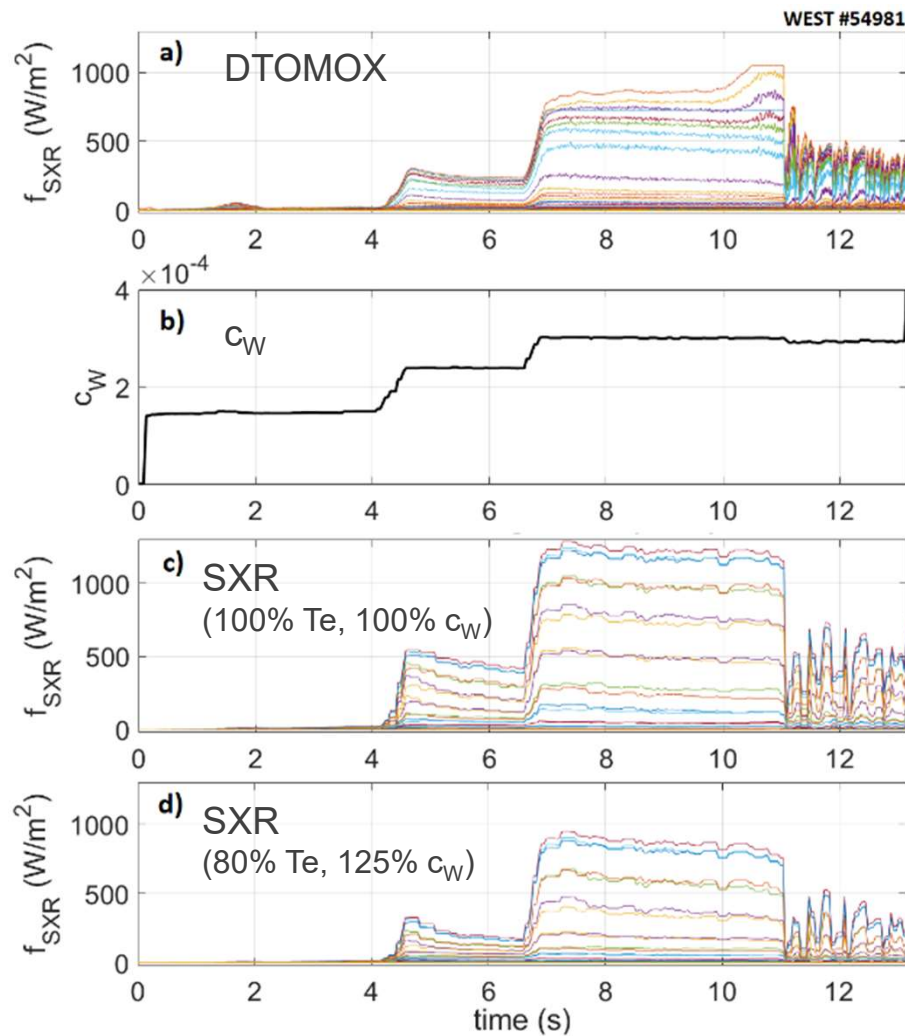




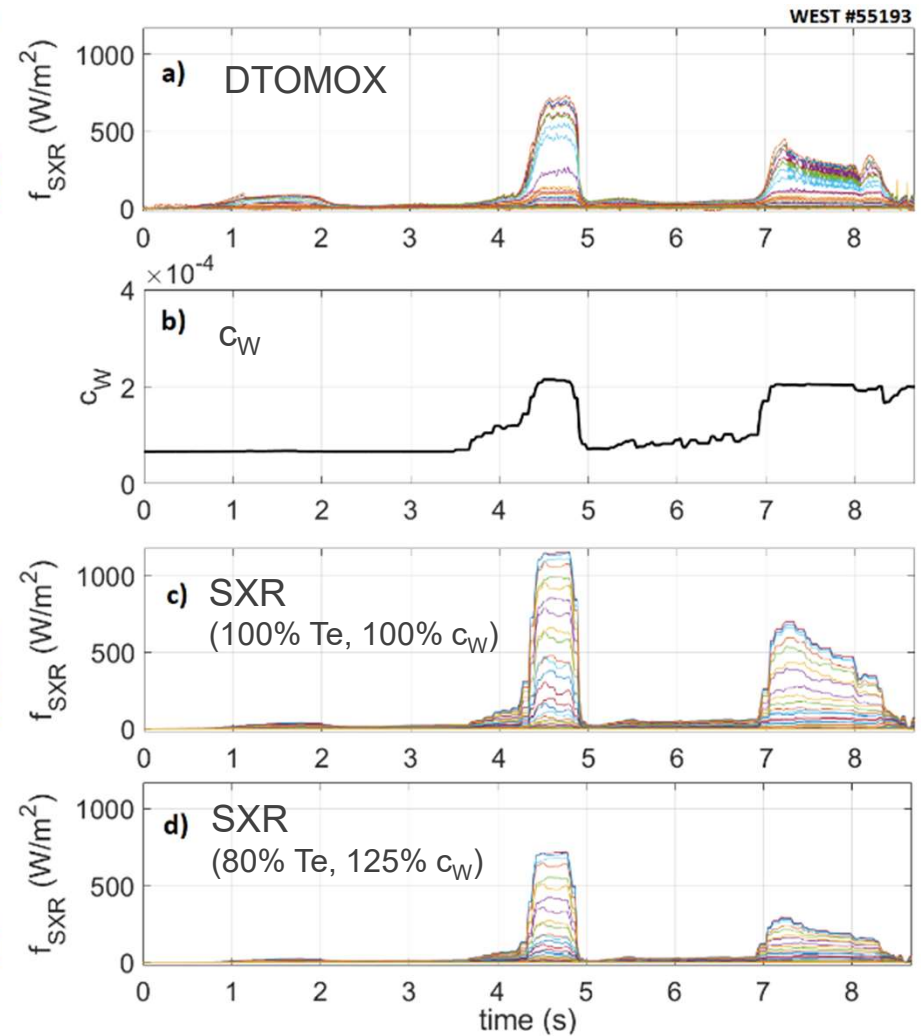
[D. Mazon et al, JINST 17 C01073 (2022)]

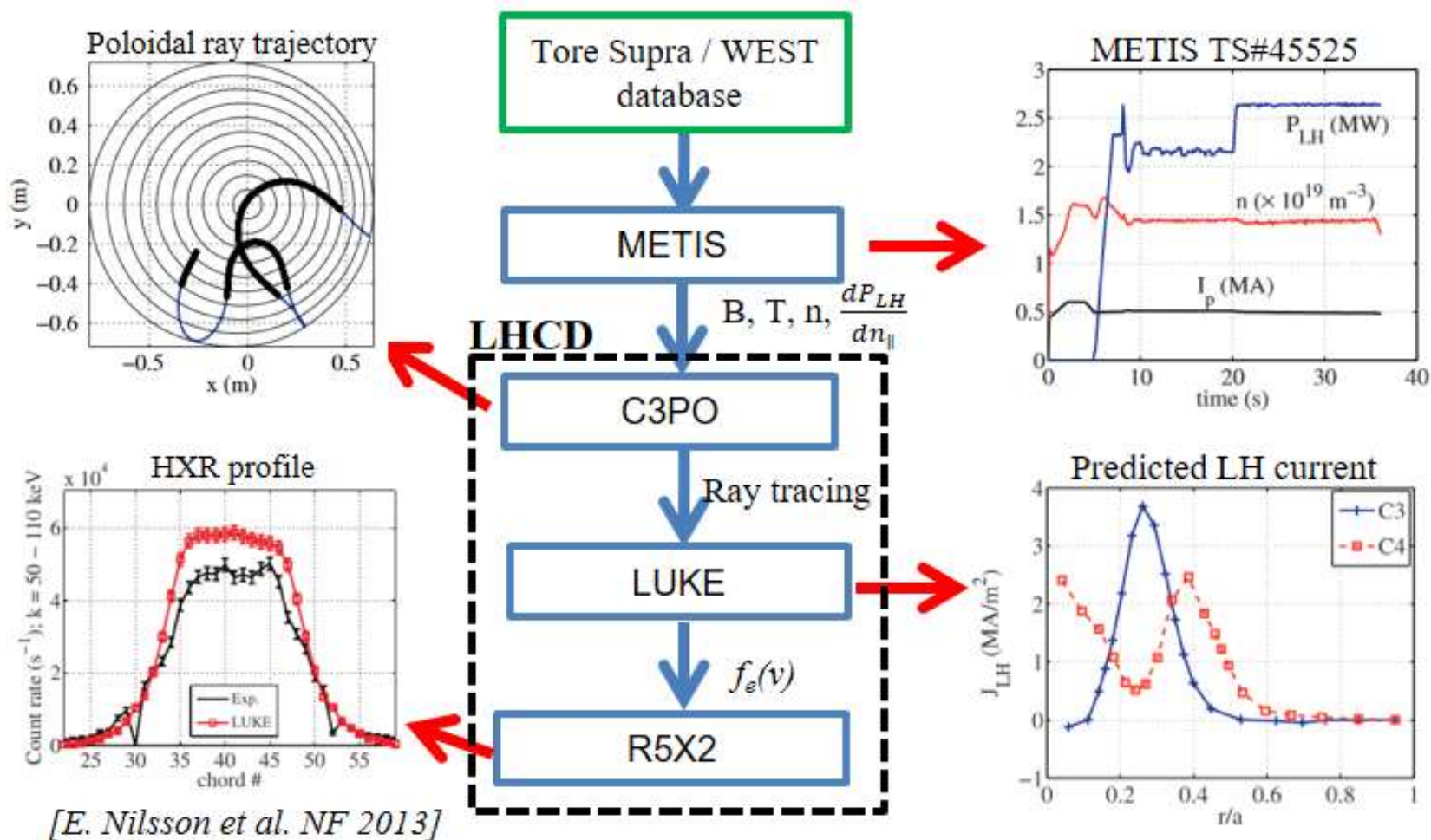




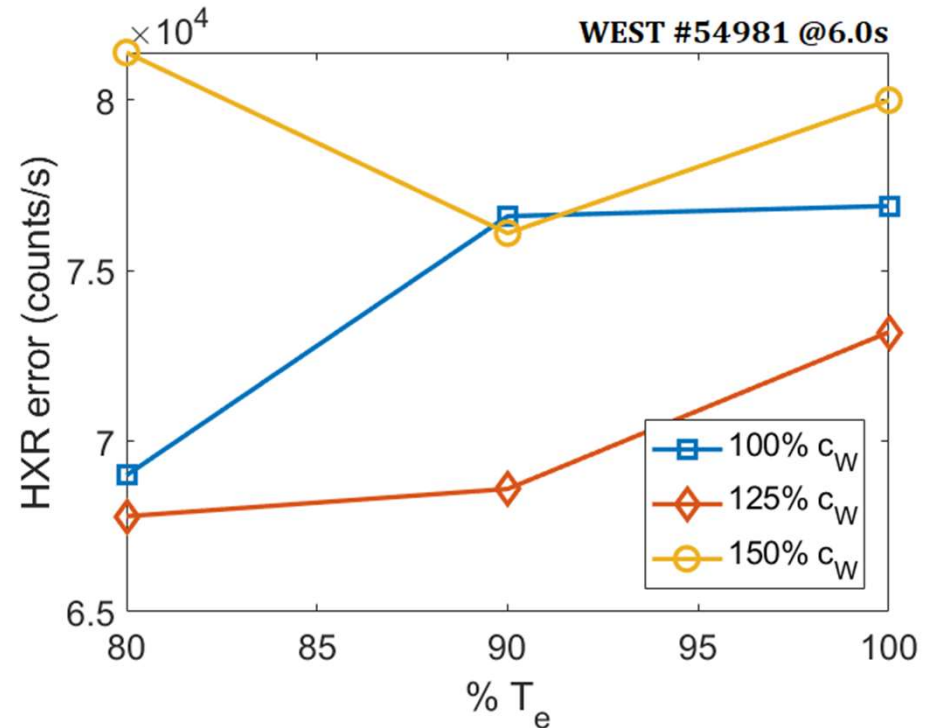
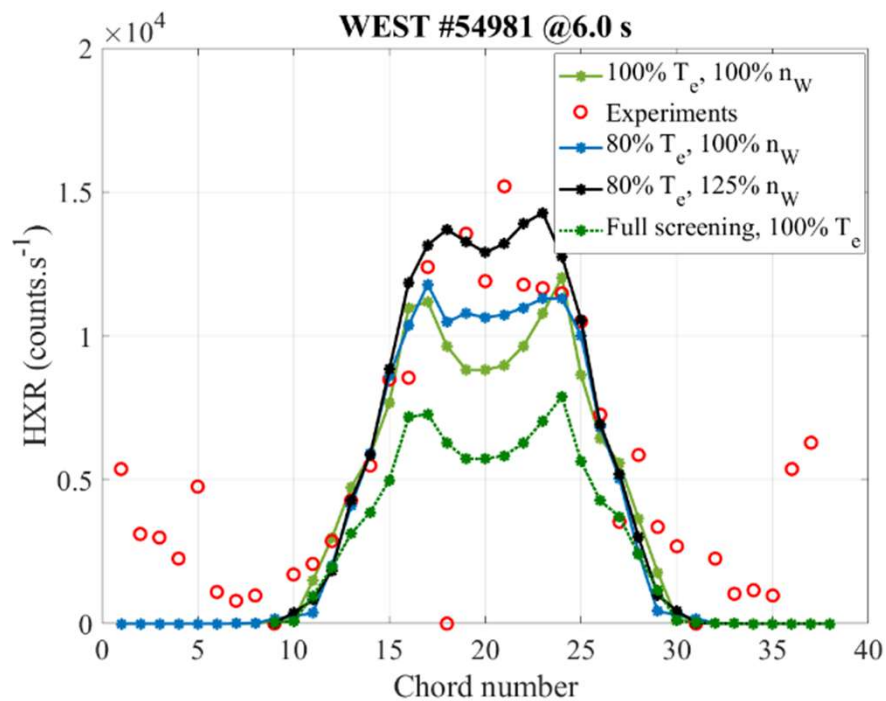


[D. Mazon et al, JINST 17 C01073 (2022)]





□ HXR and SXR modeling give consistent results:



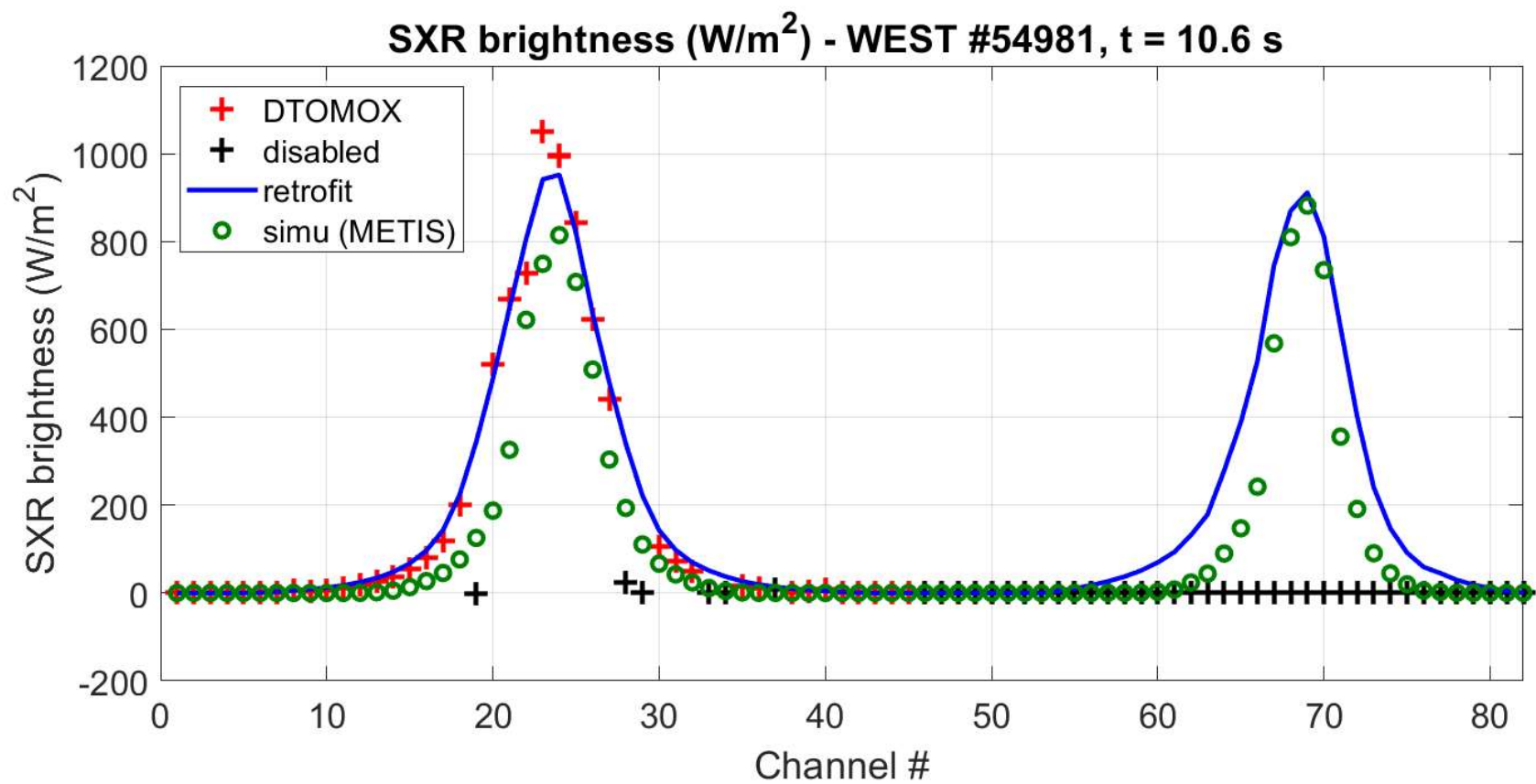
**Figure.** Modelling using METIS LUKE R5X2 suite of codes of HXR measurements in the energy range 60-80 keV for WEST #54981 at 6.0 s. Left: comparison Full screening/partial screening and influence of  $T_e$  and W concentration. Right: Influence of the electron temperature and W concentration on the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

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

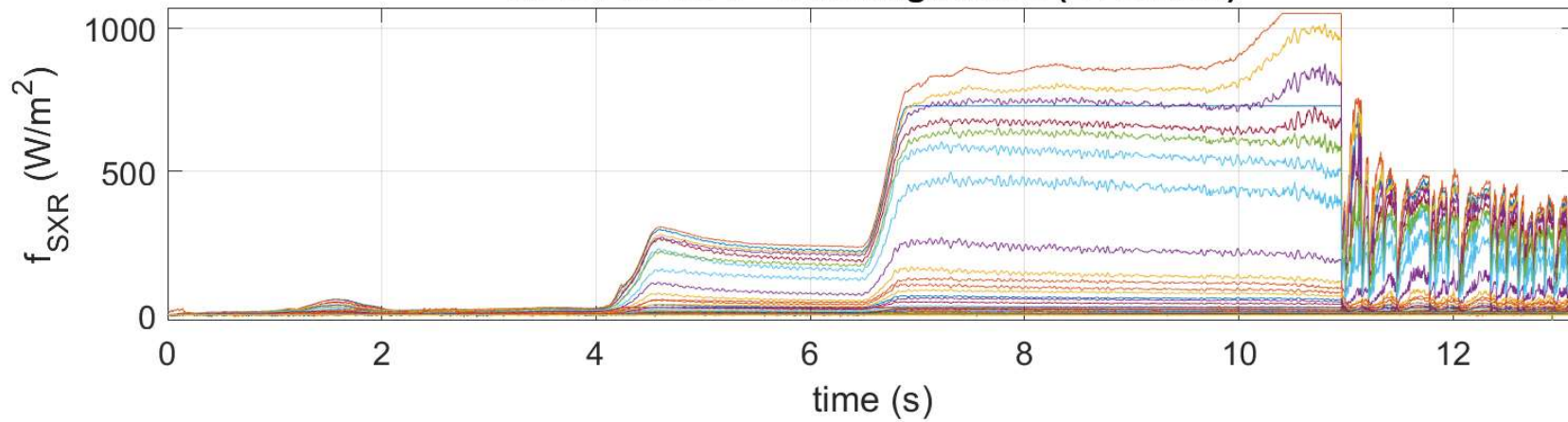
- Several detectors type can deliver proper information from SXR spectrum (Gas detectors)
- Tomographic optimisation is always needed, including magnetic equilibrium
- Not easy anyway to deduce the Cw due principally to the cooling factor dependence on  $T_e$
- HXR/SXR/Modelling integrated approach seems promising

Thanks for your attention!





WEST #54981 - SXR brightness (DTOMOX)



WEST #54981 - SXR brightness (simu)

