FACULTY OF ENGINEERING AND ARCHITECTURE

Research Unit Nuclear Fusion

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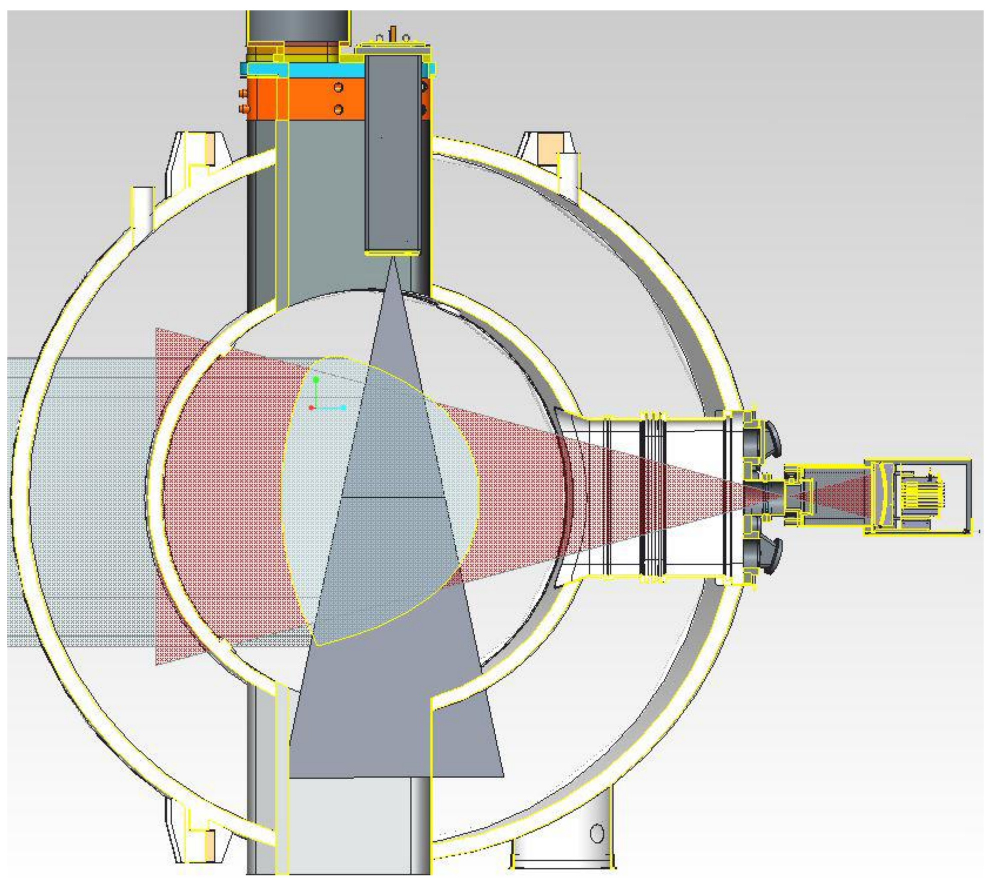
Bayesian integrated estimation of tungsten concentration at WEST using soft X-ray spectroscopy

Background

- ITER: tungsten divertor
- Interaction with plasma → tungsten impurity entering the plasma
- High tungsten concentration in the plasma core → significant **radiative power losses**, even **radiative collapses** [1, 2]
- Reliable tools are required to monitor the central tungsten concentration
- Soft X-ray (SXR) radiation provides information on tungsten concentration

Soft X-ray diagnostic on WEST

- Two sets of GEM-based (gas electron multiplier) 1D cameras located in the same poloidal cross-section
- Two cameras provide horizontal and vertical views, allowing 2D tomographic reconstructions
- Time resolution: ~ 1ms (online) and 10ms (offline)
- Horizontal viewing lines (lines of sight): 128
- Vertical viewing lines: 75



Poloidal view of the WEST soft X-ray tomographic system based on GEM detectors. Horizontal camera is outside the port while vertical camera is inside the vertical port. [1]

- The system measures plasma emissivity ε^{η} $(W \cdot m^{-2})$ integrated along the lines of sight and filtered by the detector spectral response $\eta(h\nu)$:

$$d_j = \int \varepsilon^{\eta} \mathrm{d}l_j$$

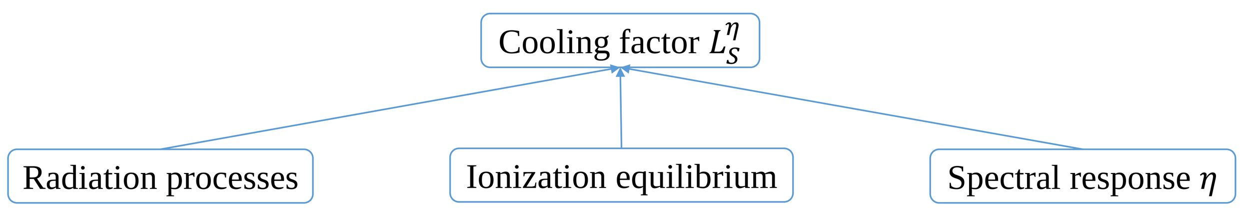
d_j: *line-integrated emissivity along the line of sight* l_j

Tungsten concentration

- Different **species, ionization states** and **atomic processes** contribute to the measured emissivity
- By solving the ionization equilibrium and considering the spectral response of the detector (η), the total emissivity of species S can be simplified as [3]:

$$\varepsilon_S(T_e) = n_e \cdot n_S \cdot L_S^{\eta}(T_e)$$

T_e: electron temperature
L_S^{η}: filtered cooling factor for species S

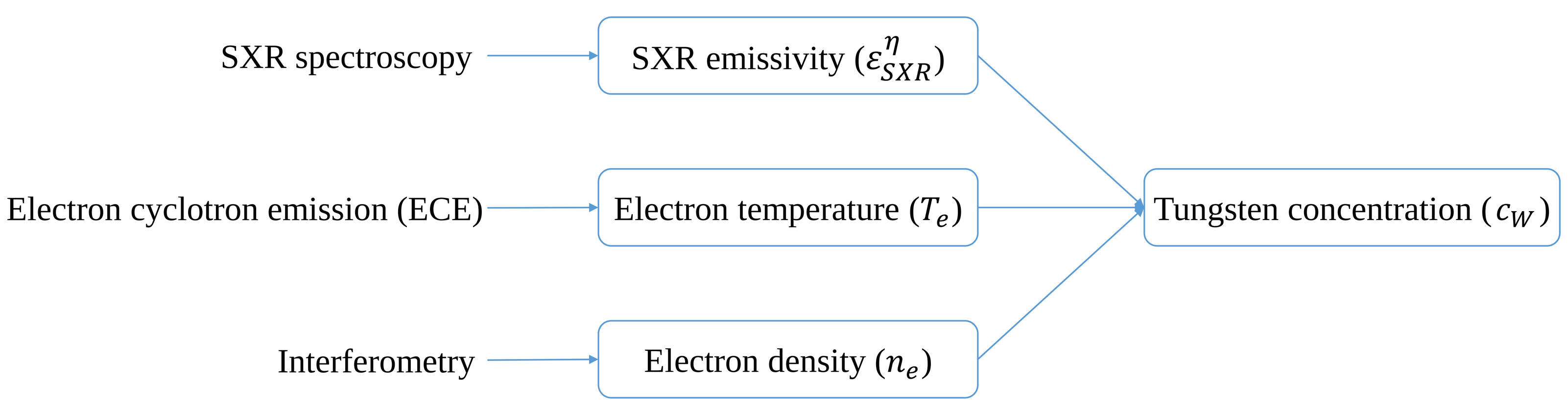


- Considering a hydrogen plasma with dominant tungsten impurities (only 2 species):

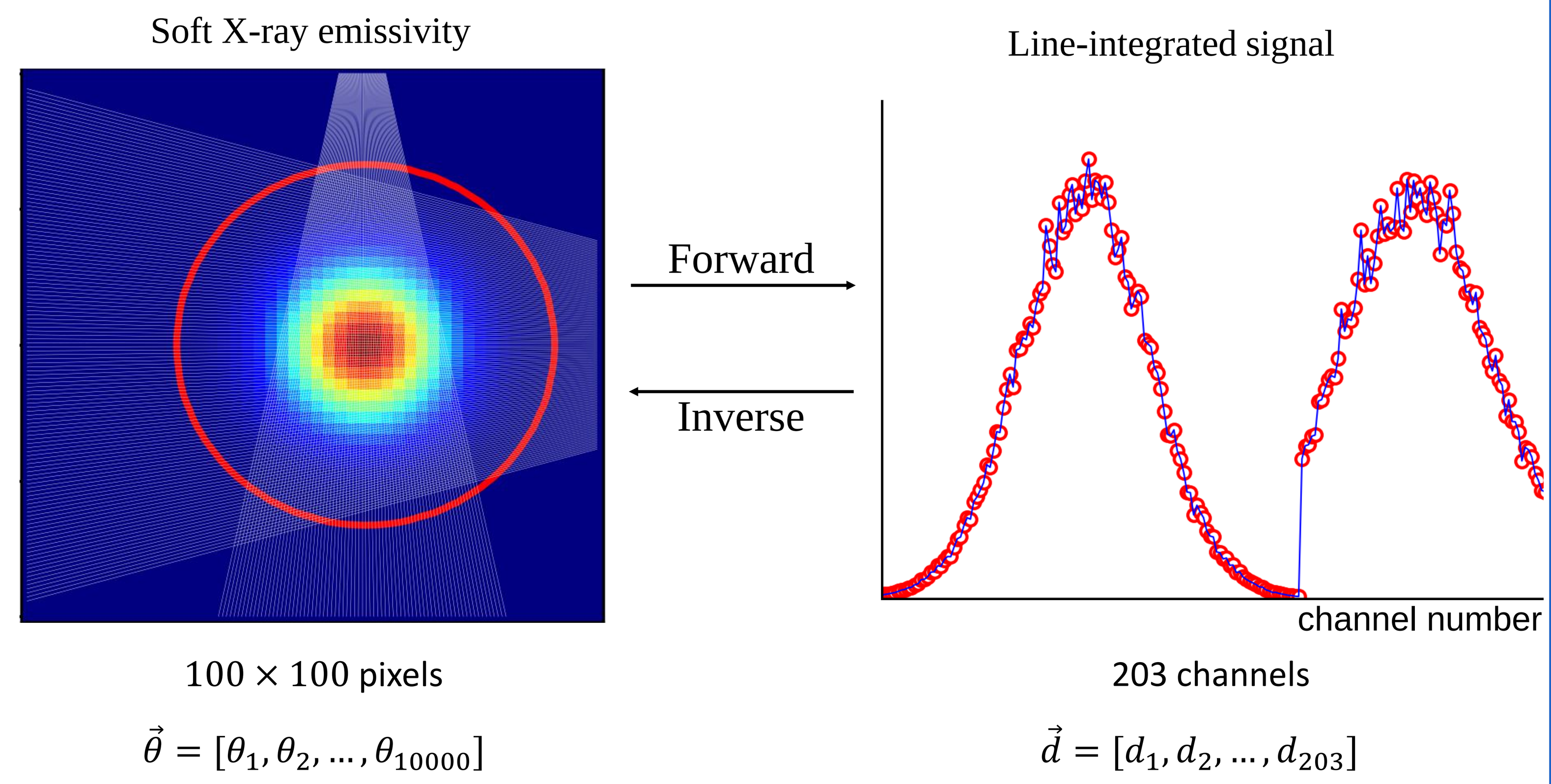
$$\varepsilon_{SXR}^{\eta} \approx n_e^2 \cdot L_H^{\eta}(T_e) + n_e \cdot n_W \cdot L_W^{\eta}(T_e)$$

Then the tungsten concentration $c_W = n_W/n_e$ can be estimated from soft X-ray emissivity [3, 4]:

$$c_W \approx \frac{\varepsilon_{SXR}^{\eta} - n_e^2 \cdot L_H^{\eta}(T_e)}{n_e^2 \cdot L_W^{\eta}(T_e)}$$



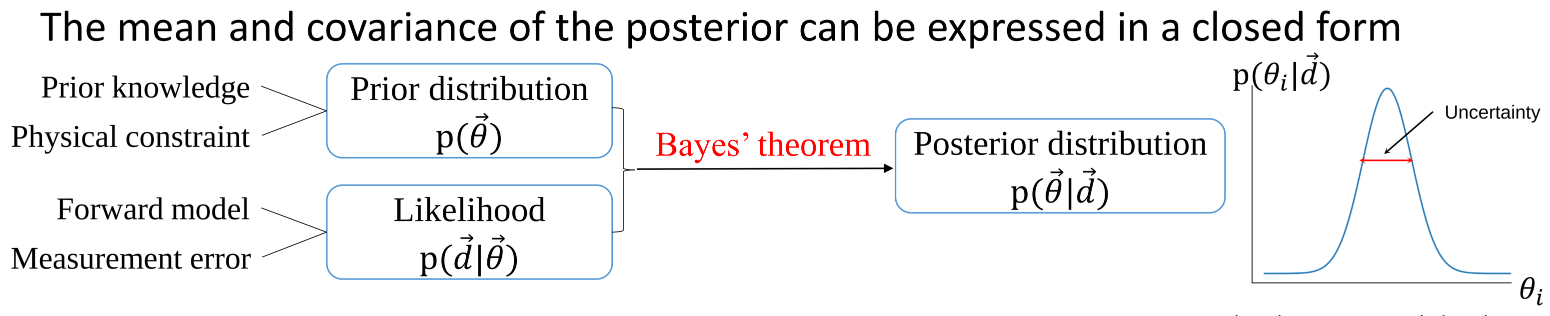
SXR emissivity reconstruction

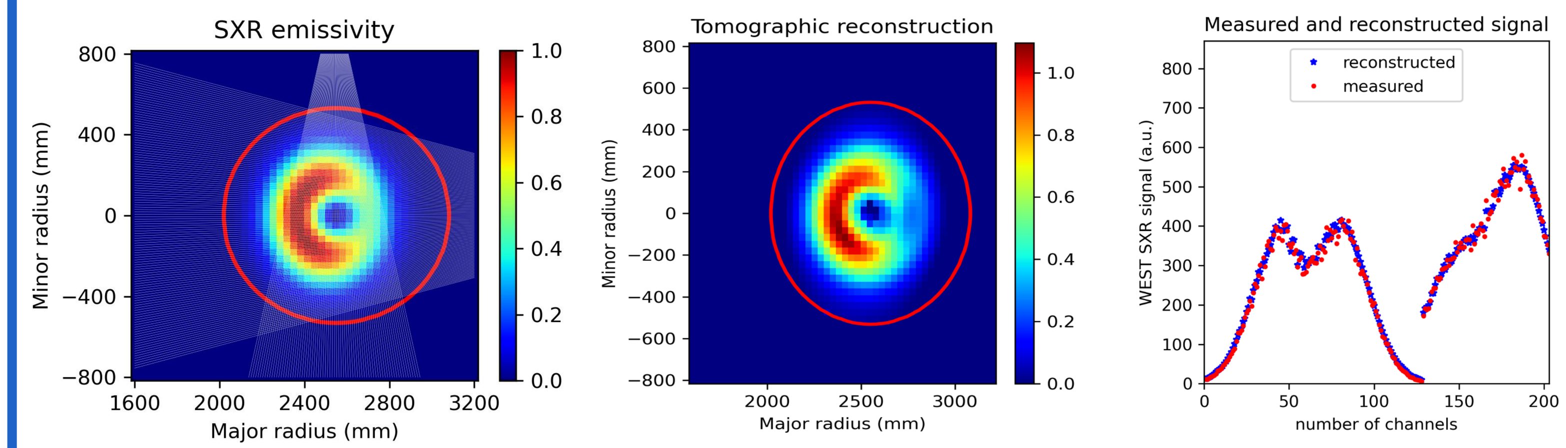


- Highly ill-posed problem: number of pixels ≫ number of channels
- Additional constraints are needed for tomographic reconstruction

Bayesian inference: Gaussian process tomography

- Gaussian process prior: the smoothness of emissivity profile is imposed by correlation between pixels
- Linear forward model (line integrals) and Gaussian likelihood
- Posterior distribution $p(\vec{\theta}|\vec{d})$: multivariate Gaussian distribution
- The mean and covariance of the posterior can be expressed in a closed form





Example result by Gaussian process tomography for synthetic signals. Left - the original synthetic emissivity profile. Middle - the reconstructed emissivity profile. Right - comparison of measured and reconstructed signal

Bayesian integrated estimation of tungsten concentration

Example posterior [4]:

$$p\left(\vec{n}_W, \vec{n}_e, \vec{T}_e \middle| \vec{d}_{SXR}, \vec{d}_{ECE}, \vec{d}_{INT}\right)$$
$$\propto p\left(\vec{d}_{SXR} \middle| \vec{n}_W, \vec{n}_e, \vec{T}_e\right) p\left(\vec{d}_{ECE} \middle| \vec{T}_e\right) p\left(\vec{d}_{INT} \middle| \vec{n}_e\right) p(\vec{n}_W) p(\vec{n}_e) p(\vec{T}_e)$$

- Bayesian modelling for all diagnostic systems
- All sources of uncertainty automatically contribute to the results
- No explicit error propagation
- Complementary or redundant measurements of the same quantity → lower uncertainty

References

[1] Mazon, D., et al. "GEM detectors for WEST and potential application for heavy impurity transport studies," Journal of Instrumentation **11** (2016): C08006.
[2] Mazon, D., et al. "SXR measurement and W transport survey using GEM tomographic system on WEST," Journal of Instrumentation **12** (2017): C11034.
[3] Jardin, A. "Soft X-ray measurements for impurity transport studies in tokamak plasmas," PhD thesis, Aix-Marseille University, 2017.
[4] Wang, T. "Reconstruction of soft X-ray and tungsten concentration profiles in tokamaks using Gaussian process tomography," PhD thesis, Ghent University, 2019.

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