Bayesian inference of tungsten transport coefficients from laser blow-off experiments in ASDEX Upgrade

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INTRODUCTION AND MOTIVATION

1. Low-Z impurities (He, Ne, Ar, N,...) mostly **dilute the main fuel ions**
2. High-Z impurities (W) increase the radiative cooling of the plasma
   a. High-Z ions accumulating on-axis **can trigger a radiative collapse**
   b. Radiation of the W ions can **deteriorate the fusion gain**
3. To infer the **transport coefficients D and V**, we solve an ill-posed inverse problem by inverting the following forward model (Aurora [1,2]):

Trace limit $\frac{n_I Z^2}{n_{D^+}} \ll 1$

Diffusion coefficient ***D***
Convective velocity **V**

$$\frac{\partial n_{I,Z}}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_{I,Z}) + S_{I,Z}$$
$$\Gamma_{I,Z} = -D\frac{\partial n_{I,Z}}{\partial r} + v n_{I,Z}$$

Forward model

Impurity density ***n***

$$\frac{\partial n_w}{\partial t} \neq 0$$

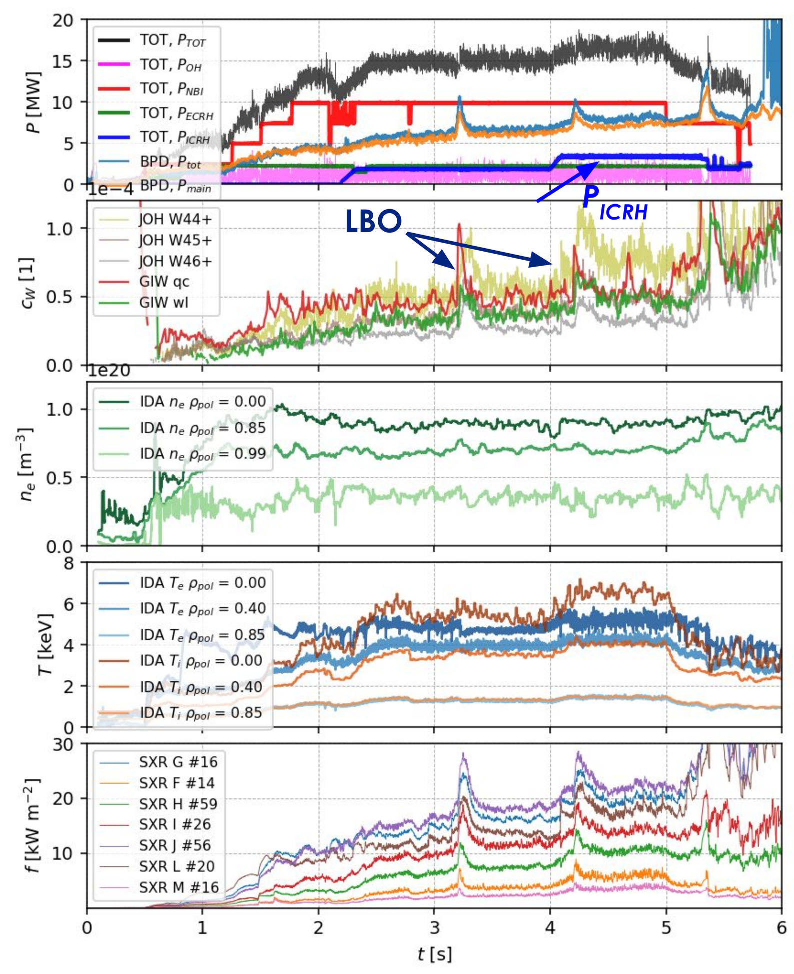
$$\varepsilon_I = n_e n_I L_I(T_e, n_e)$$

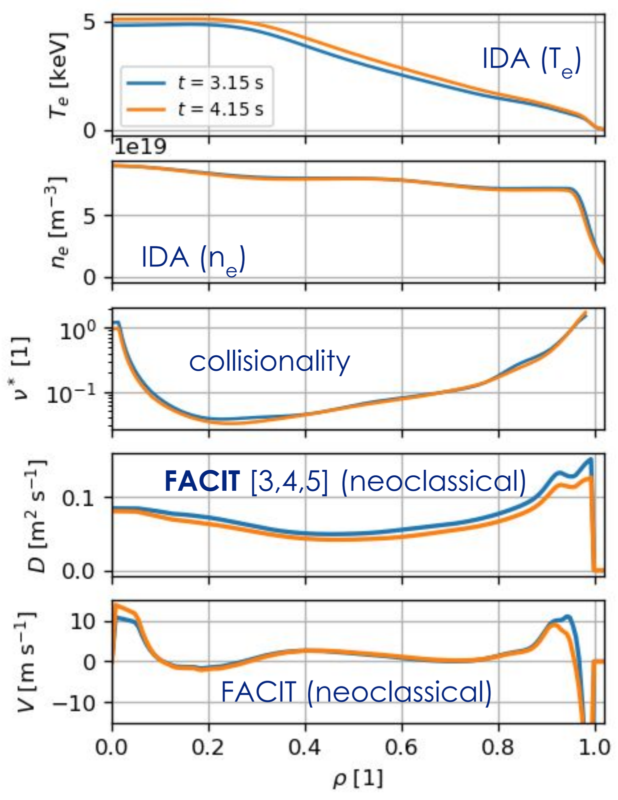
Synthetic diagnostics

EXPERIMENTAL DATA

Two successful LBOs in ASDEX Upgrade discharge #37614

1. at **3.15 s** with P_{ICRH} **= 1.8 MW**
2. at **4.15 s** with P_{ICRH} **= 3.3 MW**

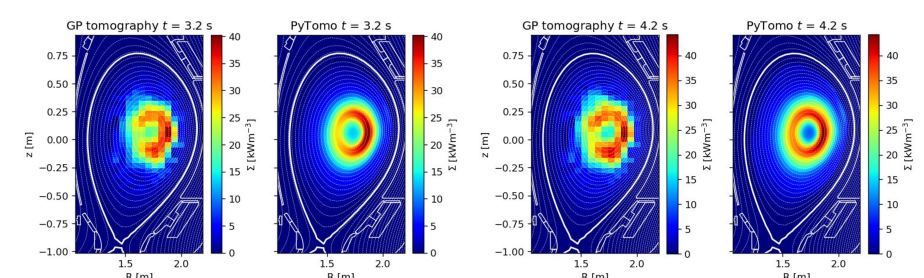


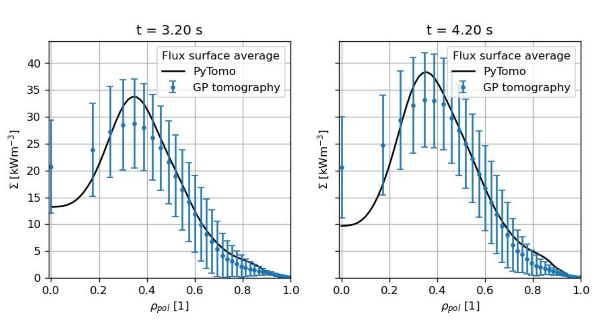


Input data for inference: **soft X-ray camera** data processed using **Gaussian process tomography** [10]

1. Non-stationary Gibbs kernel
2. **Hyperparameters inferred via MCMC sampling**
3. Compared with AUG tomography (PyTomo)

$$\vec{\mu}_{\text{post}} = \vec{\mu}_{\text{prior}} + \left(\Sigma_{\text{prior}}^{-1} + M^\top \Sigma_d^{-1} M\right)^{-1} M^\top \Sigma_d^{-1}\left(\vec{d} - M\vec{\mu}_{\text{prior}}\right)$$
$$\Sigma_{\text{post}} = \left(\Sigma_{\text{prior}}^{-1} + M^\top \Sigma_d^{-1} M\right)^{-1}$$

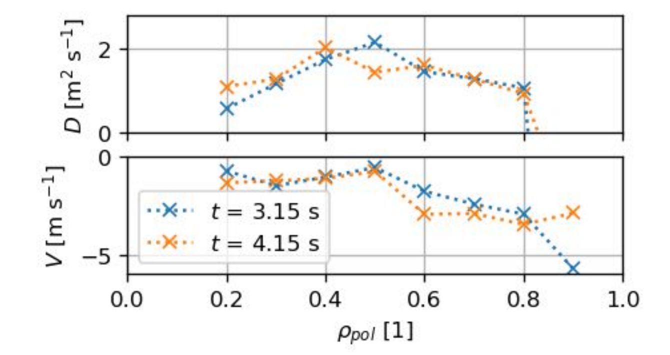




Preliminary anomalous transport - TGLF [6,7] predictions

1. Performed within the **MITIM-PORTALS** [8,9]
2. **SAT2** saturation rule used
3. Power-balance profiles not yet available ⇒ METIS profiles used temporarily

Preliminary TGLF-PORTALS predictions

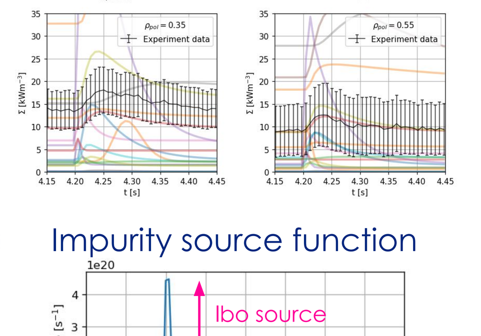


MODEL

$$P(\theta|d_{SXR}, M) \propto P(d_{SXR}|\theta, M)\, P(\theta|M)$$

1. **Gaussian process (GP) prior for D and V profiles** with **stationary RBF** kernel on 5 non-uniformly spaced nodes
2. Infers GP **hyperparameters and latent variables together** in a single run
3. Prior mean defined via a hyperbolic tangent function to describe core/pedestal behavior
4. **Nested sampling** with a slice sampler (UltraNest [11,12]) ⇒ wall-time ~72 hours per run on 36 CPUs

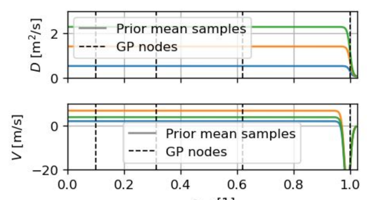
Prior predictive (colors) vs. experimental data (SXR tomography)



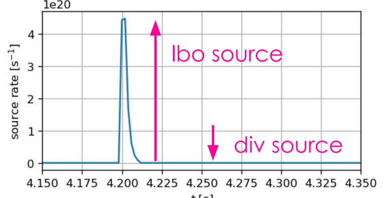
Priors (18 parameters in total):

$$\ln(S_{\text{div}}) \sim \mathcal{N}(\mu,\sigma^2), \quad \ln(S_{\text{LBO}}) \sim \mathcal{N}(\mu,\sigma^2)$$
$$\ln(\theta) \sim \mathcal{N}(\mu,\sigma^2) \ \text{ for } \theta \in \{D_{\text{core}}, \ell_D, \sigma_D, \ell_V, \sigma_V\}$$
$$V_{\text{core}} \sim \mathcal{N}(\mu,\sigma^2)$$
$$\eta_{D,i}, \eta_{V,i} \sim \mathcal{N}(0,1) \quad \text{for } i = 1,\ldots,N_{\text{nodes}}$$

Prior mean profiles (samples)

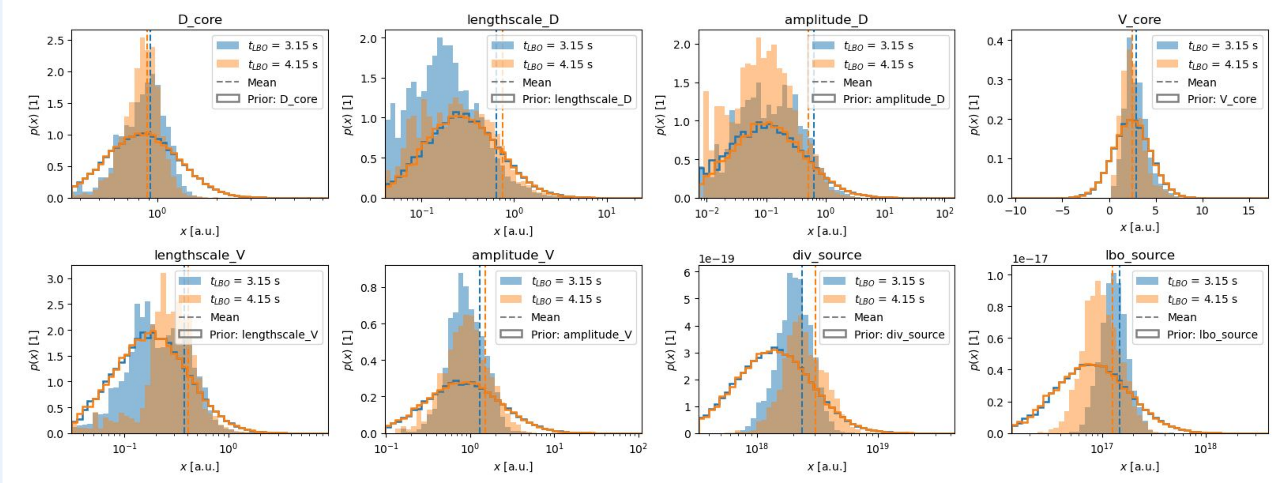


Impurity source function



RESULTS

Marginal posterior distributions (histograms) for both LBOs (at **3.15 s** and **4.15 s**)

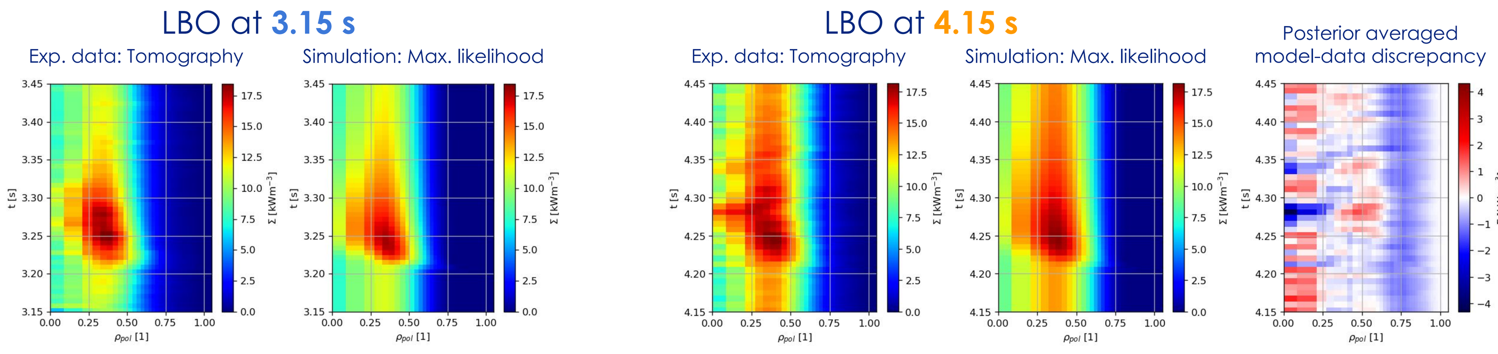


Posterior means

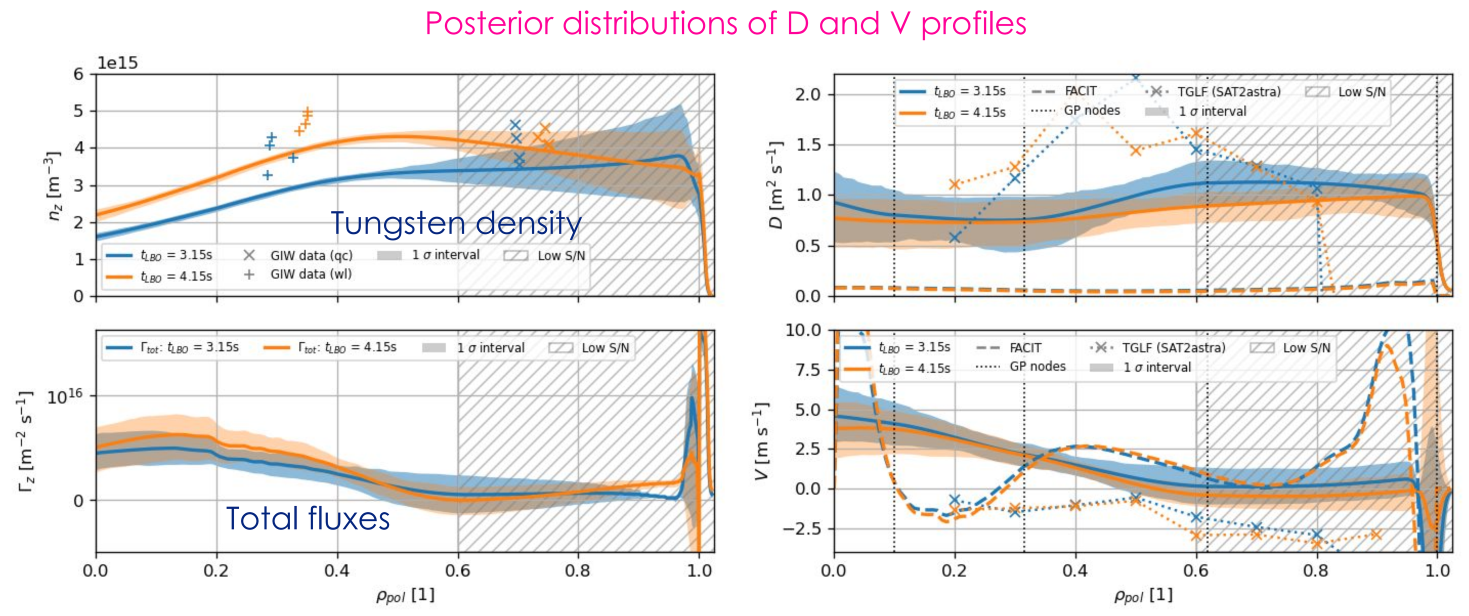
θ	$t = 3.15s$	$t = 4.15s$
D_{core}	0.92	0.88
ℓ_D	0.64	0.75
σ_D	0.64	0.51
V_{core}	2.88	2.49
ℓ_V	0.38	0.41
σ_V	1.30	1.51
S_{div}	2.4×10^{18}	3.1×10^{18}
S_{LBO}	1.5×10^{17}	1.3×10^{17}

Good agreement between the synthetic data (evaluated at maximum likelihood) and the experimental data

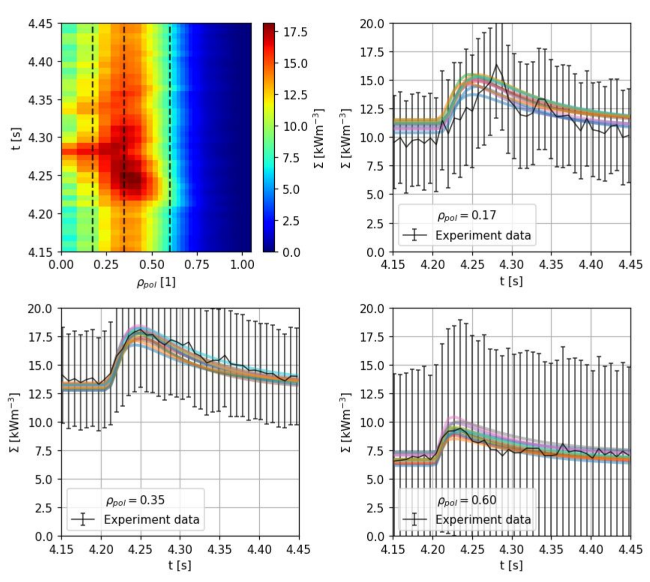
LBO at **3.15 s** — LBO at **4.15 s**



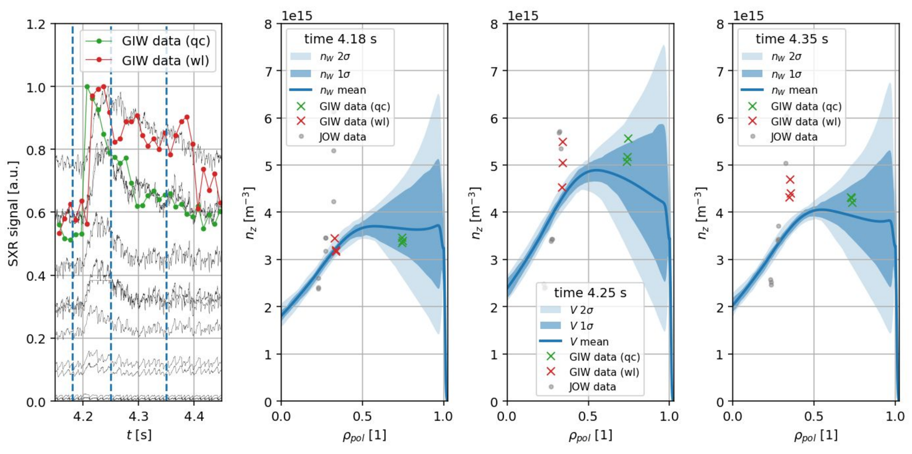
Posterior distributions of D and V profiles



Posterior predictive realizations vs. Experimental data (SXR GP tomography)



Posterior predictive distribution vs. Independent spectroscopy data

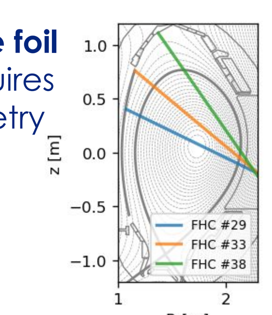


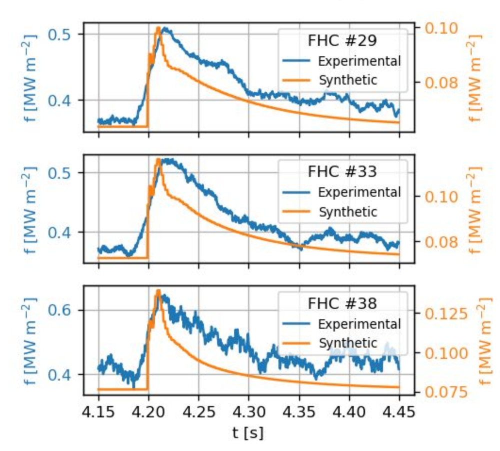
GIW (quasicontinuum/lines) - W Grazing incidence spectroscopy
JOW - Johann W spectrometer

CONCLUSION AND FUTURE PLANS

1. **Developed a tool to infer D and V profiles from LBO experiments**
2. Best performance with GP prior
3. Hyperparameters inferred for subsequent use
4. Good agreement between Aurora simulations and SXR tomography
5. The model remains weakly constrained at the plasma edge ⇒ **additional edge diagnostics**
6. No significant difference observed between experiments in #37614 ⇒ **different shots/experiments**
7. **TGLF results need to be derived from power balance**, work in progress on the integrated modelling

Next step: **include foil bolometry** ⇒ requires raytracing geometry matrix





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