Use of Integrated Data Analysis to Maintain Diagnostic Calibrations in a Fusion Reactor

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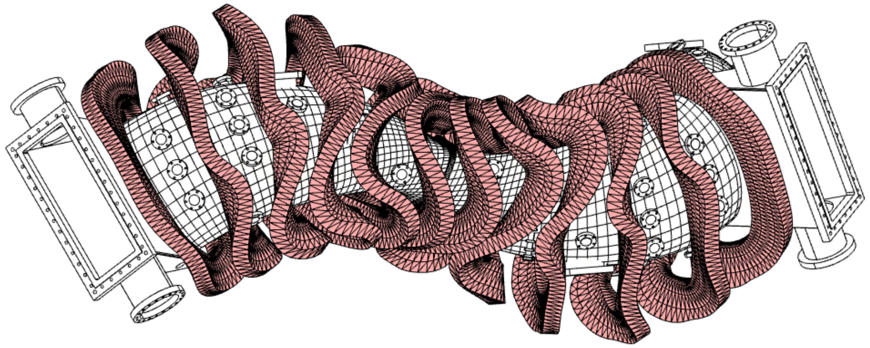
and the HSX team



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Helically Symmetric eXperiment

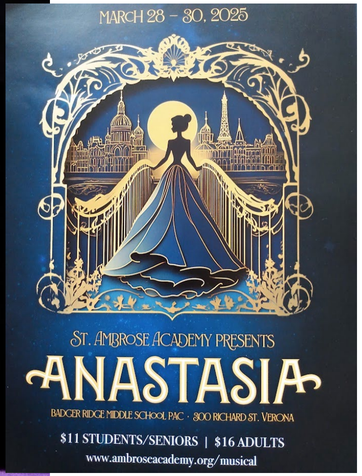
A little bit about myself:

Helically Symmetric eXperiment

My family enjoys camping and kayaking for recreation

We sing in a choir and my youngest son plays the pipe organ

My children perform in a high school musical, and I build the set



Maintaining diagnostic calibrations in a steady-state reactor is a challenge

- Diagnostics will require calibrations (e.g. spatial localization, absolute signal level) which can depend on varying conditions[1]
  - Difficult to maintain absolute calibration of optical systems due to surface erosion, deposition, irradiation
  - Requires deployment of cleaning systems that also change surfaces
- Need for calibration is determined by consistency between multiple measurements
  - E.g. optical & millimeter wave measurements of temperature and density
- Real-time control systems can detect calibration drift through error-correction
  - Possibility of tracking when further calibrations are needed
- Proposal: develop diagnostic forward models that explicitly incorporate calibration information employ Bayesian inference methods

[1]Vayakis, *J. Inst.* **19**, C04013 (2024)

Bayesian inference enables development of integrated data analysis frameworks

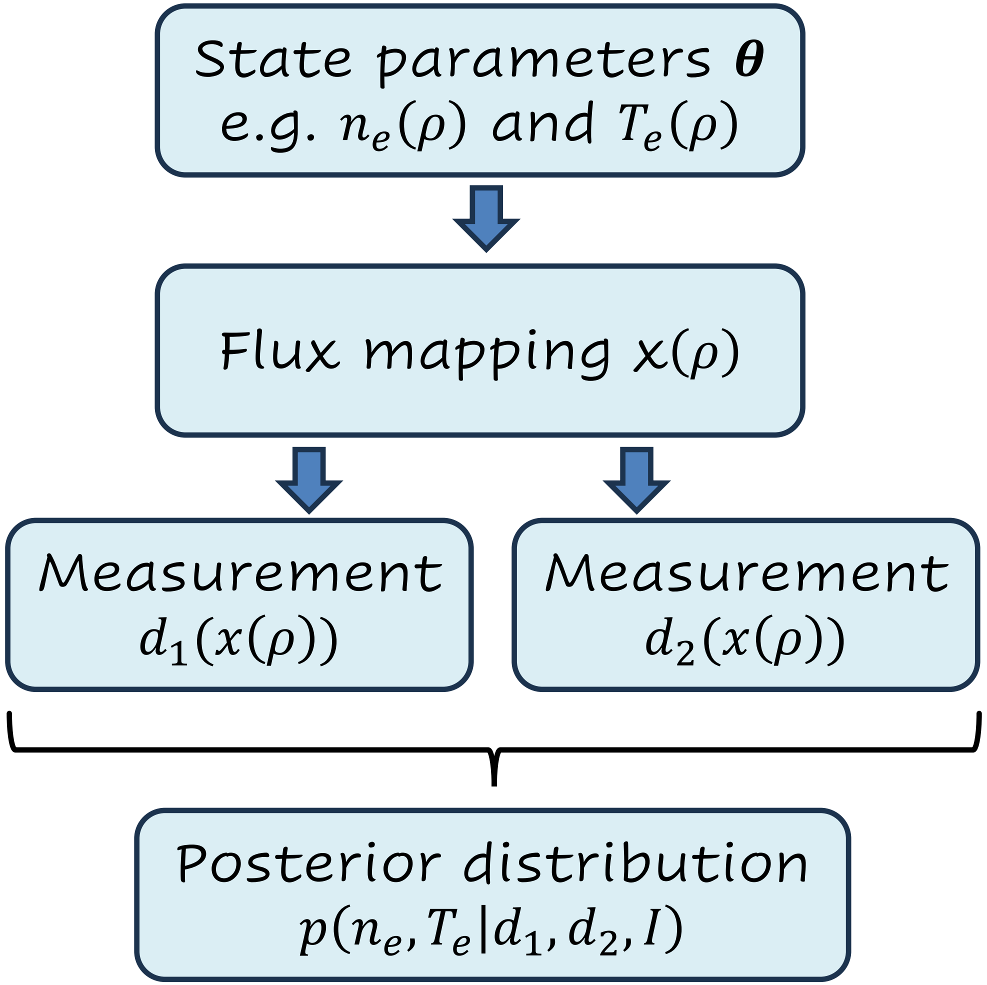
- Conditional probabilities quantify the probability of a plasma state parameter based on the likelihood of various measurements

$$p(\boldsymbol{\theta}|\boldsymbol{d}, I) = \frac{p(\boldsymbol{d}|\boldsymbol{\theta}, I)\, p(\boldsymbol{\theta}|I)}{p(\boldsymbol{d}|I)}$$

- Data from multiple diagnostics are independent so consistent inferences can be made by treating posterior of one measurement as the prior information of another measurement

$$p(\boldsymbol{\theta}|\boldsymbol{d}_1, \boldsymbol{d}_2, I) = \frac{p(\boldsymbol{d}_2|\boldsymbol{\theta}, I)}{p(\boldsymbol{d}_2|I)} p(\boldsymbol{\theta}|\boldsymbol{d}_1, I)$$

- Nuisance parameters (like misalignments) can be introduced to the model and accounted for by marginalization



[2]Fischer, *et al.*, *Fusion Sci. Tech.* **19**, C04013 (2024)

Example of Integrated Data Analysis: Determining Z_{eff}

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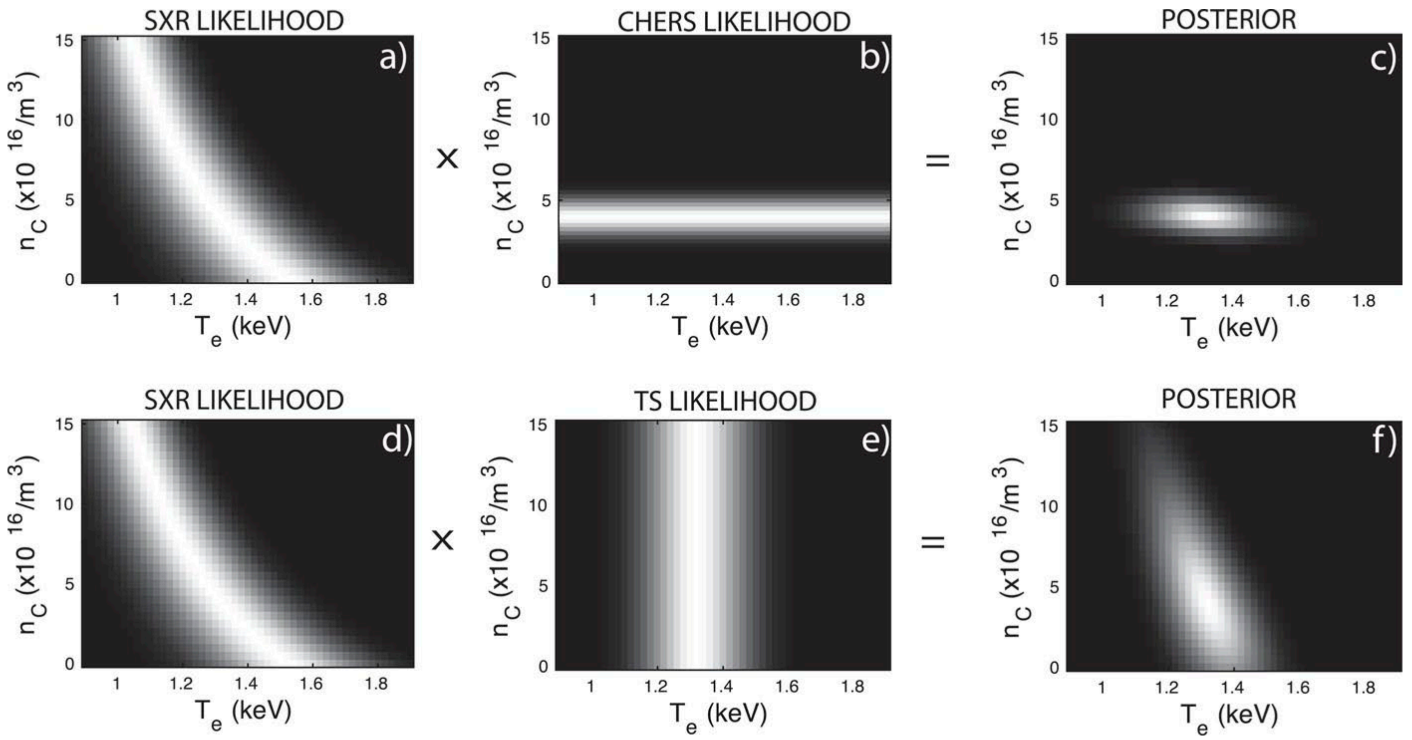
- Soft X-ray emission measurements are sensitive to electron temperature, density, and impurity density

  $$p(\boldsymbol{d}_{SXR}|\boldsymbol{\theta}, I) = f_{SXR}(T_e, n_e, n_z, I)$$

- Thomson Scattering measurements are independent of impurity density

  $$p(\boldsymbol{d}_{TS}|\boldsymbol{\theta}, I) = f_{TS}(T_e, n_e, I)$$

- Their joint likelihood reduces uncertainty in the inference of the impurity density[3] yielding more precision in inferring Z_{eff}

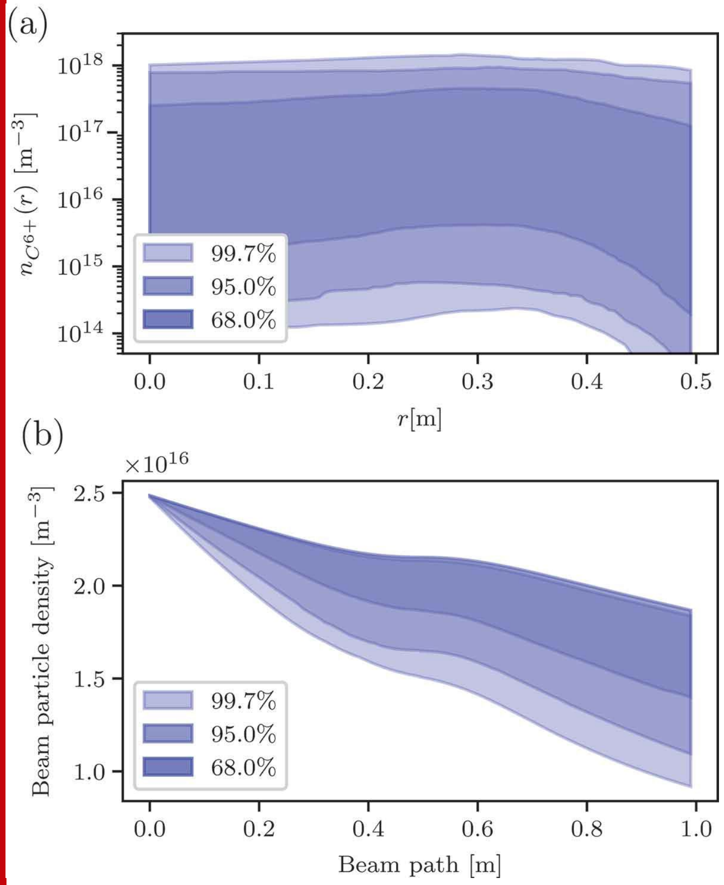


[3]Reusch, *et al.*, *Rev. Sci. Instrum.* **89**, 10K103 (2018)

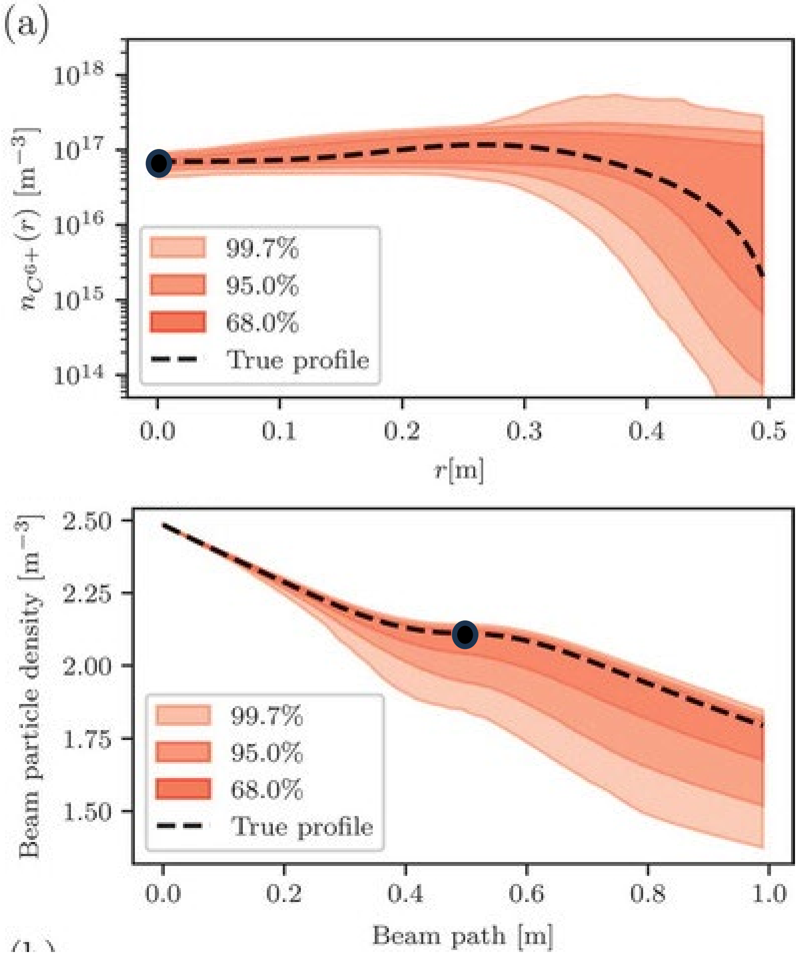
Example of Integrated Data Analysis: Neutral Beam Attenuation

Nornberg, *et al.*, *Fusion Sci. Tech.* **74**, 144 (2018)

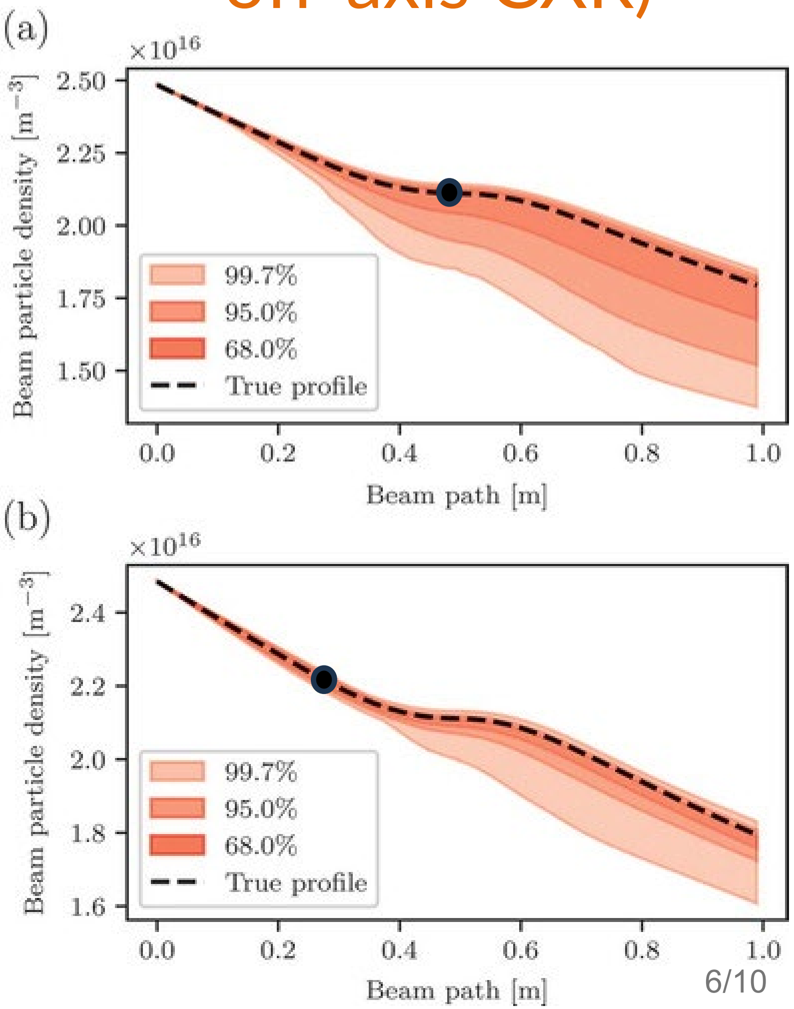
Prior



Posterior (on-axis CXR)



Posterior (on-axis vs. off-axis CXR)



Key approaches to getting the most from IDA

- Develop prior probability distributions based on uncertainties in physical model
    - Example: Establish bounds on diffusive particle transport for impurity transport modelling
        - Range from classical diffusion to Bohm diffusion
    - Example: Bounds on likely impurity density in a plasma for inferring neutral beam attenuation
        - Range from concentrations too low to affect radiative losses up to radiative collapse
- Data is data: treat data acquired from plasma and calibrations on equal basis
    - Example: Neutral beam emission analysis for Zeff measurement

Proposal: Develop an integrated model of plasma density and temperature measurements on HSX

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- Develop forward models of interferometry, reflectometry, ECE, and Thomson Scattering
  - Differing dependencies help constrain state parameter inferences
  - Include nuisance parameters in model to account for changes to calibration values[5]
    Examples:

$$p(\boldsymbol{d}_{TS}|\boldsymbol{\theta}, I) = f_{TS}(T_e, n_e) + \delta_{\mathrm{err}}(\boldsymbol{x}_{\mathrm{align}})$$

$$p(\boldsymbol{d}_{ECE}|\boldsymbol{\theta}, I) = f_{ECE}(T_e) + \delta_{err}(n_e, T_e, \Gamma_{\mathrm{reflect}}, \boldsymbol{x}_{\mathrm{align}})$$

  - Treat calibration data on same level as data acquired from plasma discharges

- Take advantage of differences in measurement spatial localization, time resolution, and modelling uncertainties to reduce overall systematic uncertainty

- Determine whether loss of a diagnostic (like TS) can be compensated by treating it as a calibration measurement for the millimeter wave systems

[5] *van Milligen, Rev. Sci. Instrum.* **82**, 073503 (2011)

Possible uses of IDA within Data Assimilation systems

Can diagnostic calibration drift be accounted in real-time data assimilation controllers[6,7] like ASTI?

Data assimilation entails employing physics-based simulations to create an evolving state vector correlated with the observations

- Can we model calibration drift as an increasing observation noise?
- Can the controller supply information to the diagnostic forward models on likely calibration shifts?
- Can the controller determine when calibration is necessary?

Physics Simulation

State vector

System Noise

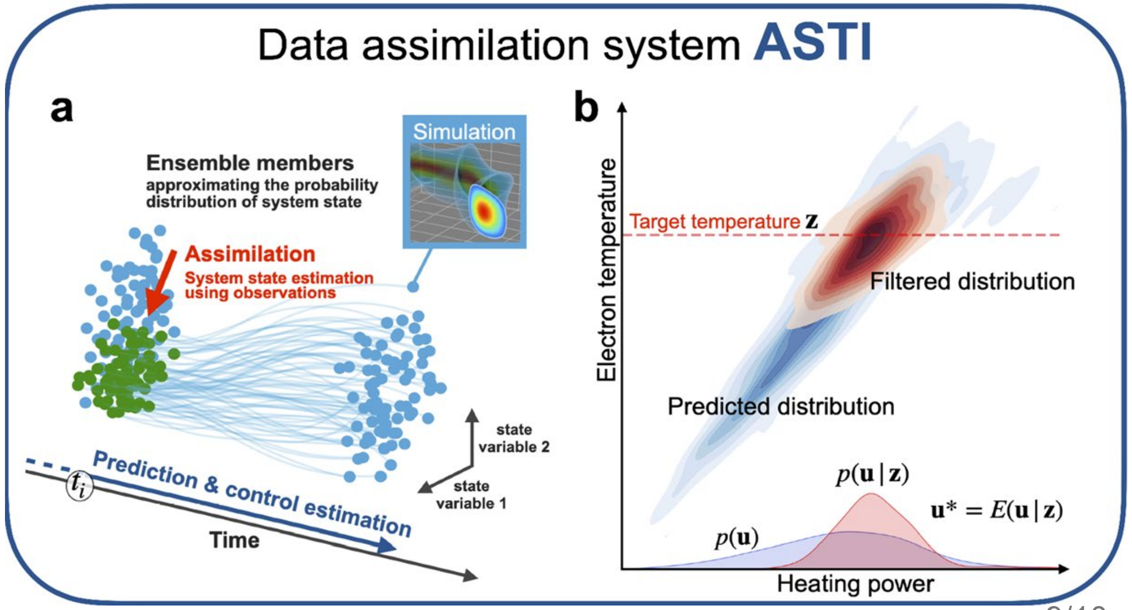
$$\boldsymbol{x}_t = f_t(\boldsymbol{x}_{t-1}, \boldsymbol{v}_t)$$

$$\boldsymbol{y}_t = H_t \boldsymbol{x}_{t-1} + \boldsymbol{w}_t$$

Observables

Observation Model

Observation Noise



[6]Morishita, *et al.*, *Sci Rep* **14**, 137 (2024)
[7]Morishita, *et al.*, *Comp. Phys. Comm.* **274**, 108287 (2022)

Summary and discussion

- Maintaining diagnostic calibrations in steady-state reactors is a challenge
- Real-time controllers must be aware of calibration drift
- IDA techniques could be employed to track calibration drift to:
    - Determine when a maintenance shutdown is required
    - Identify which calibrations would be sufficient to restart