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Bayesian Data Fusion for Enhanced Edge Plasma density profile estimation in KSTAR

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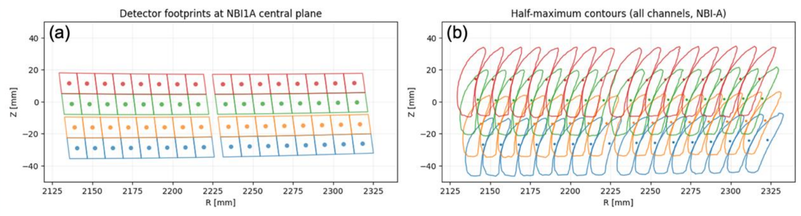
ABSTRACT

- This study introduces a method for accurately determining edge plasma density profiles in the KSTAR tokamak using Bayesian inference and Gaussian process regression.
- A collisional radiative (CR) model, incorporating atomic data, represents D-alpha line intensities as functions of plasma density.
- Measurements from hydrogen beam emission spectroscopy (H-BES), combined with interferometry and Thomson scattering data, enhance the precision of density profile estimations.
- The use of Gaussian process priors and Markov Chain Monte Carlo (MCMC) methods significantly improves the reliability of edge plasma density profiles in the KSTAR tokamak.

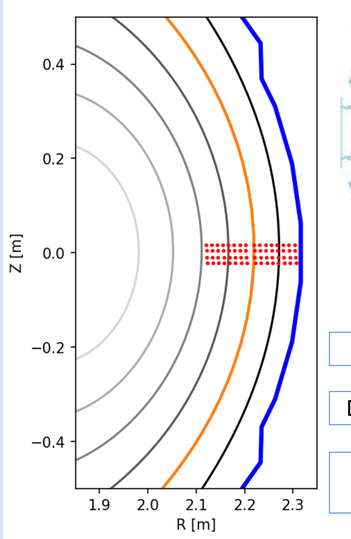
DBES channel footprints and point spread function



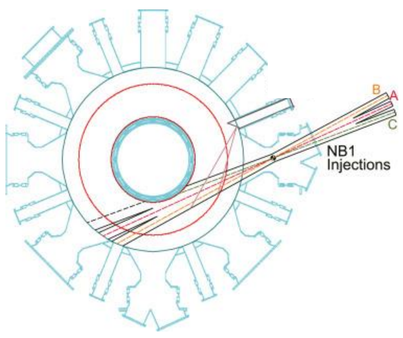
(a) DBES channel footprints in the (R,Z) plane at the NBI-A central plane.

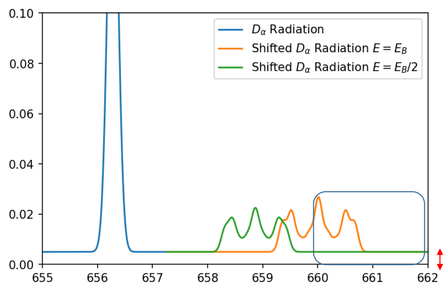
(a) Half-maximum sensitivity contours derived from the footprint extrusion and geometric overlap model.

BACKGROUND



BES detecting position on NBI1-A plane at #28030



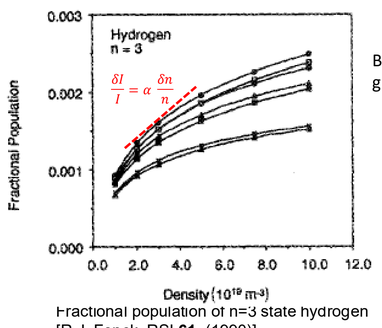


Neutral Beam injected into the plasma

Deuterium atoms react with plasma particles

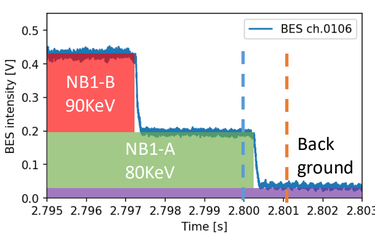
Excitation, ionization, charge exchange, spontaneous emission occurs

Collect Doppler-shifted D_α emission (~660 nm)

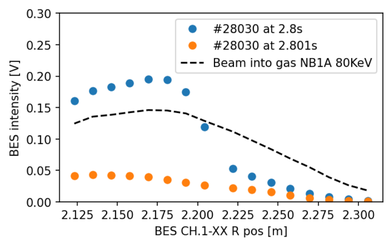


Back ground

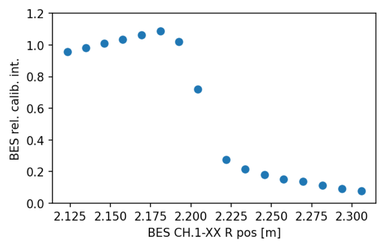
Fractional population of n=3 state hydrogen [R.J. Fonck, RSI **61**, (1990)]



Beam blip for multiple neutral beam injection



BES intensity before post processing



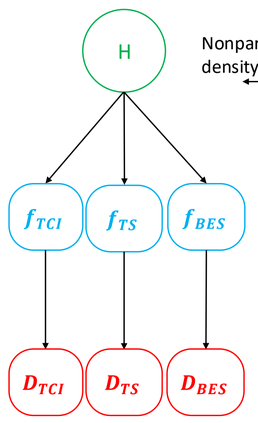
BES intensity after relative calibration

Bayesian inference and Data Fusion

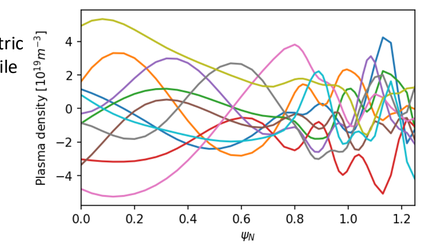
$$P(H|D) = \frac{P(D|H)P(H)}{P(D)}$$

- $P(H|D)$: Posterior
  - The probability that the hypothesis is true with given measured data (Inference)
- $P(D|H)$: Likelihood
  - The probability that the data is generated with given hypothesis
- $P(H)$: Prior
  - The probability that the hypothesis is true
- $P(D)$: Evidence or Marginal likelihood

$$P(H|D_i) \propto \Pi P(D_i|H)P(H)$$

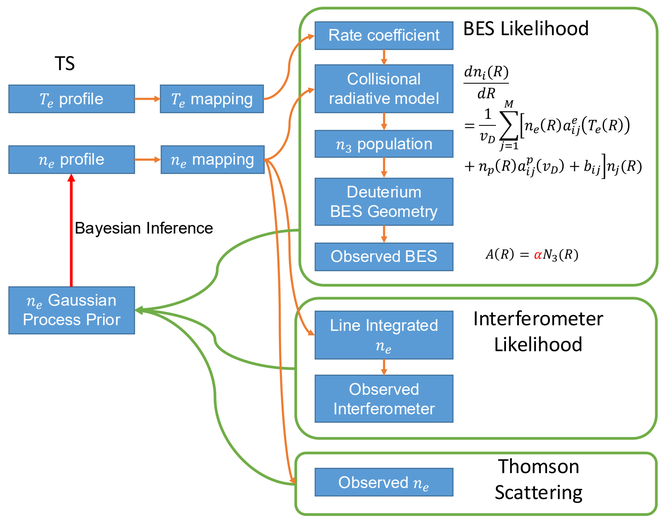


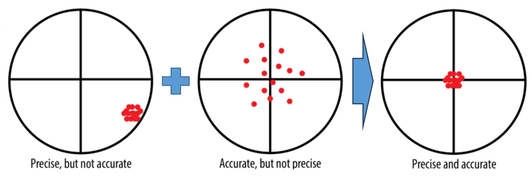
Nonparametric density profile



Density profile samples from Gaussian process (Gibbs kernel)

$$k(\psi,\psi') = \sigma_f^2 \sqrt{\frac{2l(\psi)l(\psi')}{l^2(\psi)+l^2(\psi')}} \exp\left[-\frac{(\psi-\psi')^2}{l^2(\psi)+l^2(\psi')}\right]$$





Main purpose of Hydrogen Beam Emission Spectroscopy (HBES) is edge density fluctuation measurement

◆ Cons: Hard to measure absolute electron density profile

Thomson scattering (TS) is essential diagnostic for electron density and temperature measurement with good accuracy

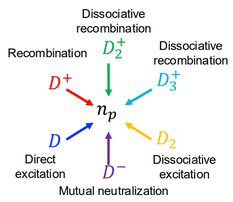
◆ Cons: Low precision at edge & lack of edge channel number

Interferometer have good precision

◆ Cons: Measure line integrated electron density

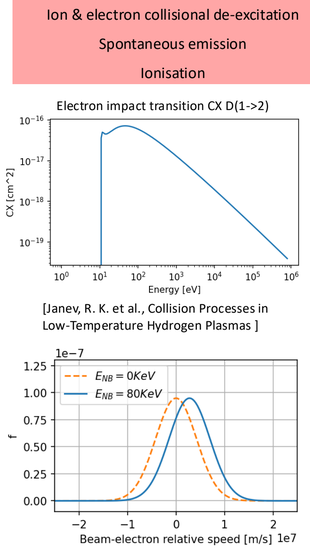
Collisional Radiative model for Beam Emission Spectroscopy

$$\frac{dn_p}{dt} = -\left[\sum_{q\neq p}(n_e X_{pq}^e + n_i X_{pq}^i) + \sum_{q<p} A_{pq}\right] n_p + \left[\sum_{q\neq p}(n_e X_{qp}^e + n_i X_{qp}^i) + \sum_{q>p} A_{qp}\right] n_q + [\alpha_p + \beta_p + \gamma_{d,p}]\, n_i n_e$$

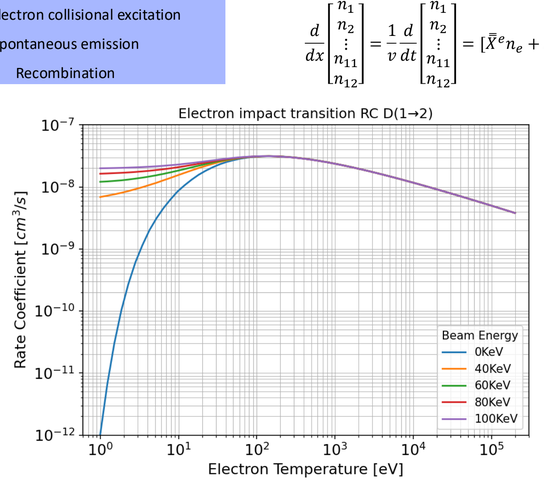


Decreasing population	Increasing population
Ion & electron collisional de-excitation	Ion & electron collisional excitation
Spontaneous emission	Spontaneous emission
Ionisation	Recombination

$$\frac{d}{dx}\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{11} \\ n_{12} \end{bmatrix} = \frac{1}{v}\frac{d}{dt}\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{11} \\ n_{12} \end{bmatrix} = [\bar{\bar{X}}^e n_e + \bar{\bar{X}}^i n_i + \bar{\bar{A}}]\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{11} \\ n_{12} \end{bmatrix}$$



[Janev, R. K. et al., Collision Processes in Low-Temperature Hydrogen Plasmas]



Reaction caused by collision is determined by relative speed between the particles

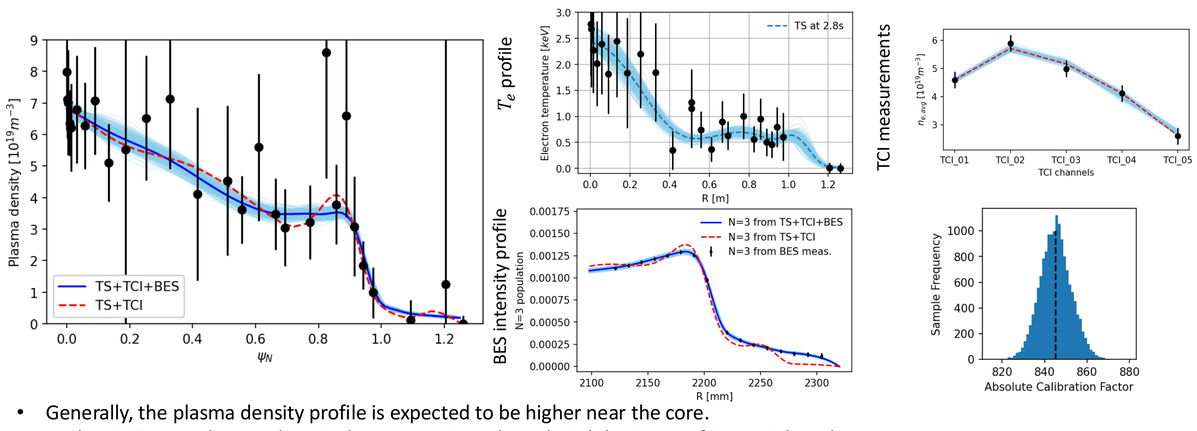
➢ $X^e(E_b, T_e)$ and $X^i(E_b, T_i)$ is function of beam energy and plasma temperature

OUTCOME

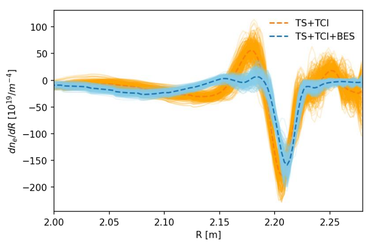
Data Fusion for BES, Thomson scattering and TCI

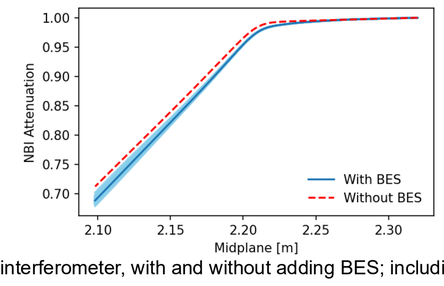
$$P(\bar{n}_e|\bar{d}_{BES}, \bar{d}_{TS}, \bar{d}_{TCI}, \bar{\theta}) \propto P(\bar{n}_e|\bar{\theta})P(\bar{d}_{BES}|\bar{n}_e, \bar{\theta})P(\bar{d}_{TS}|\bar{n}_e, \bar{\theta})\, P(\bar{d}_{TCI}|\bar{n}_e, \bar{\theta})$$

MCMC is used to find distribution



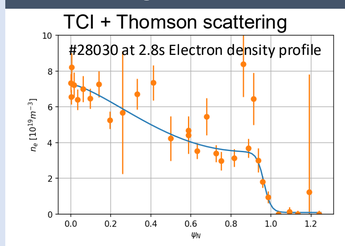
- Generally, the plasma density profile is expected to be higher near the core.
- Without BES, we observe density decrease just inside pedestal due to overfitting at the edge.
- When we combine the three diagnostics with a Gaussian process prior, the sampling results become more plausible.
- The new density profile align well with the TS, TCI, and BES data within their uncertainties.
- It also shows the improved accuracy.

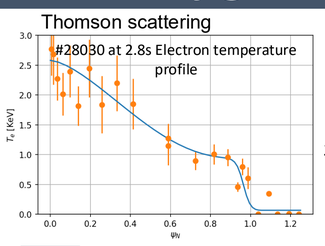




- Density gradient dn_e/dR inferred from Thomson scattering with the interferometer, with and without adding BES; including BES sharpens the edge peak and narrows the uncertainty.
- Cumulative neutral-beam attenuation along the midplane for the same two configurations; including BES yields slightly stronger early attenuation and converges outside the pedestal.

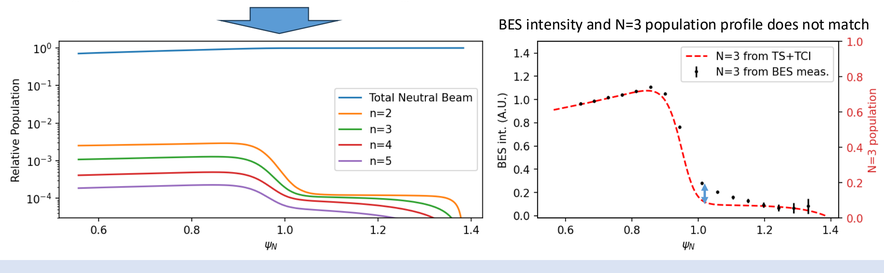
Beam-plasma simulation by given plasma profile





Modified hyperbolic tangent function used in EPED

$$y = \begin{cases} a_1 + a_2\left(\tanh 1 - \tanh\frac{x-1+\frac{a_3}{2}}{\frac{a_3}{2}}\right) + a_4\left(1-\left(\frac{x}{1-a_3}\right)^{a_5}\right)^{a_6} & x < 1.0 \\ a_1 + a_2\left(\tanh 1 - \tanh\frac{x-1+\frac{a_3}{2}}{\frac{a_3}{2}}\right) & x > 1.0 \end{cases}$$



BES intensity and N=3 population profile does not match

Summary & Future work

- We made KSTAR neutral beam plasma interaction simulation based on collisional radiative model.
- We build data fusion model by using Bayesian inference and Gaussian process.
- The estimated density profile are well matched with Thomson scattering, interferometer and beam emission spectroscopy data.
- It can also provide absolute calibration factor of BES.
- The density profile estimation takes a long time with MCMC algorithm, we will make surrogate neural network of data fusion model to speed up the calculation time as a future plan.

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