BAYESIAN DATA FUSION FOR ENHANCED EDGE PLASMA DENSITY PROFILE ESTIMATION IN KSTAR

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In KSTAR, an integrated approach has been developed to estimate edge plasma density profiles by combining beam emission spectroscopy (BES) [1], Thomson scattering (TS), and two-color interferometry (TCI). A Bayesian inference framework with a Gaussian process prior is applied to integrate deuterium beam-plasma interaction simulations based on a collisional radiative (CR) model with experimental data from all diagnostics, resulting in an edge density profile that consistently explains the measurements. This approach enables a more accurate determination of edge density profiles while simultaneously providing an absolute calibration factor for BES, which is essential for assessing plasma performance reliably. While lithium BES was originally developed for plasma density profile measurements and has been successfully used for Bayesian inference-based profile estimation in JET [2], KSTAR deuterium BES was designed for density fluctuation measurements. Our work demonstrates that deuterium BES can also be effectively utilized to improve density profile estimates in deuterium plasmas.

The CR model simulates the population dynamics of deuterium atoms excited to the n=3 state along the neutral beam path by solving a set of coupled differential equations that incorporate collisional excitation, de-excitation, and spontaneous emission processes. A central aspect of the model is the calculation of rate coefficients, which depend on both the electron temperature and the beam energy. This simulation framework predicts the intensity of Doppler-shifted D-alpha emission as the beam interacts with plasma particles. The optical system of the BES is simplified to an absolute calibration factor that facilitates a direct comparison between simulated and measured intensities.

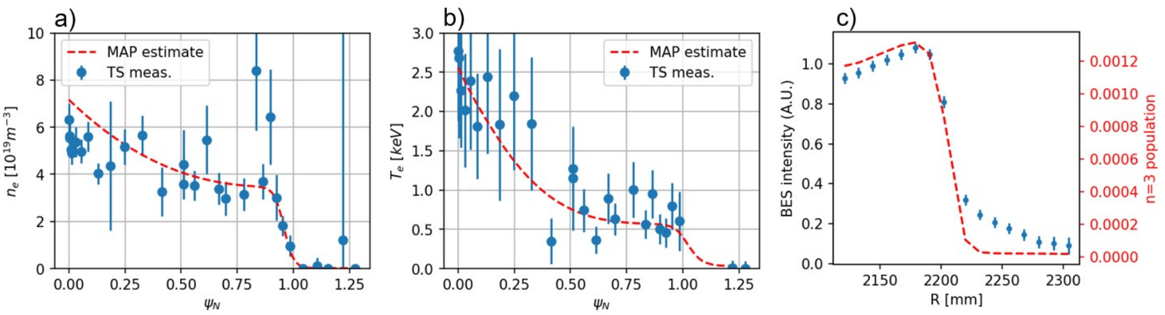

Fig. 1. (a) Fitted electron density profile from TS data using a modified hyperbolic tangent function, with TCI data for consistency. (b) Fitted electron temperature profile from TS data. (c) Comparison of the n=3 population estimated by the CR model from the fitted profiles with the measured BES intensity profile, revealing significant discrepancies.

Measurements from TS and TCI are used to constrain the electron density profile. TS provides high spatial resolution with multiple channels for local density measurements, whereas TCI offers complementary line-integrated data to capture broader density trends. These measurements are incorporated into the plasma equilibrium from EFIT to construct the density distribution across the plasma cross-section. The limitations of conventional profile fitting become evident in Fig. 1. In panel (a), the electron density profile is obtained by fitting a modified hyperbolic tangent function to TS data, with TCI data used to ensure consistency. Panel (b) displays the corresponding electron temperature profile from TS data, and using these fitted profiles, the CR model simulation predicts the n=3 population, which is compared in panel (c) with the measured BES intensity profile. The significant discrepancies—particularly in the edge region where density gradients are steep and measurement uncertainties are larger—demonstrate that the conventional approach struggles to accurately capture the true edge profile. This observation underscores the necessity of a modeling method that not only supports nonparametric fitting but also directly incorporates BES measurements for inferring the density profile.

To address these challenges, a Bayesian inference framework is employed to estimate the electron density profile by integrating BES data alongside TS and TCI measurements. A Gaussian process prior is used to provide a flexible, nonparametric representation of the density profile, ensuring consistency across all diagnostics. Likelihood functions for TS and TCI data are formulated as Gaussian distributions and combined with the forward CR model to constrain the BES intensity. Sampling from the posterior distribution via Markov Chain Monte Carlo (MCMC) methods produces an edge density profile that aligns well with TS and TCI measurements and improves the agreement between the predicted and observed BES intensity profiles, as shown in Fig. 2.

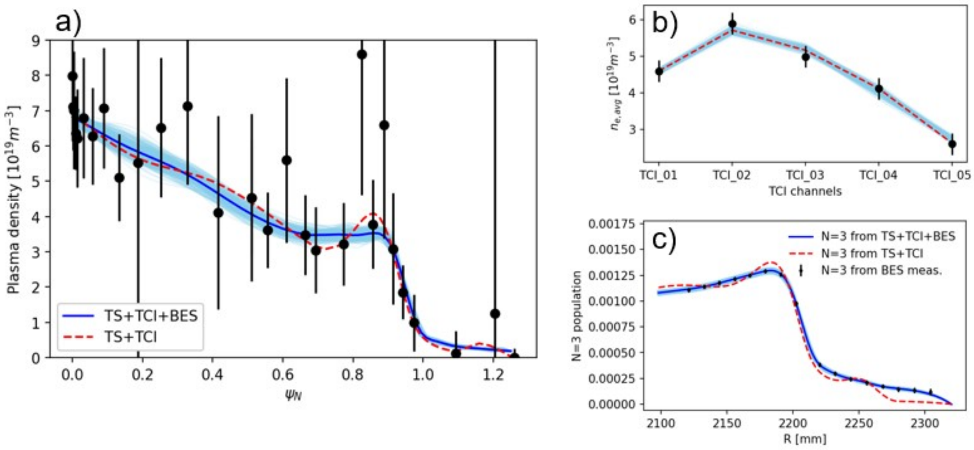

Fig. 2. (a) Estimated electron density profile from Bayesian inference overlaid with TS data. (b) Line-integrated density profile from TCI compared with the inferred profile. (c) Comparison of BES intensity with the n=3 population predicted from the CR model using the inferred density profile, demonstrating improved agreement.

The refined density profile further enables a more accurate estimation of neutral beam attenuation, with simulations showing that the cumulative beam energy deposition is approximately 10% higher when calibrated against the fused density profile. This enhanced simulation capability is critical for understanding energy deposition dynamics along the beam path and improving the overall fidelity of the CR model. Additionally, the method proves effective across diverse plasma operating regimes, including H-mode, L-mode, and plasmas undergoing RMP-induced ELM suppression. In scenarios involving RMP-ELM suppression, the approach captures toroidal variations in the edge density gradient as evidenced by distinct changes in BES intensity profiles corresponding to different RMP phases. These observations provide deeper insight into the interplay between density gradients and turbulence, which is vital for addressing edge instability mechanisms.

The integrated Bayesian data fusion framework including HBES demonstrates significant potential for advancing edge plasma diagnostics in KSTAR. By delivering precise and accurate density profiles, this approach enhances the understanding of plasma behavior and supports the optimization of plasma performance. The method’s capacity to combine high-resolution local measurements with line-integrated data paves the way for comprehensive diagnostics that can adapt to different plasma conditions. Future work will focus on developing a surrogate neural network model to accelerate the computationally intensive MCMC-based inference, thereby enabling near real-time plasma density diagnostics. This improvement will further solidify the framework’s utility in operational scenarios and real-time control applications, ultimately contributing to more efficient and predictive fusion experiments.

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REFERENCES

[1] Y. U. NAM, S. ZOLETNIK, M. LAMPERT, Á. KOVÁCSIK, and H. M. WI, Rev. Sci. Instrum. **85** (2014) 11E434

[2] S. KWAK, J. SVENSSON, M. BRIX, Y.-C. GHIM, and JET CONTRIBUTORS, Nucl. Fusion 57 (2017) 036017