Physics-Informed Tomography: Coulomb-Collision Priors and Approximation Error Modeling at DIII-D

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This work resolves three fundamental limitations of Tikhonov regularization, the current standard for fast-ion phase-space tomography: the ad hoc physical choice of regularization parameter, the incomplete treatment of model uncertainties, and the absence of error bounds derived from physics and model uncertainties. Each part is addressed in turn.

While various methods exist for determining the optimal value of the regularization parameter[1], in practice the final choice depends on the researcher's interpretation of what constitutes a physically reasonable solution. To replace this subjective assessment, we propose a Bayesian framework that derives physically motivated priors by sampling Coulomb collision processes, ensuring reconstructed fast-ion distributions remain consistent with fundamental physics without relying on adjustable parameters. We demonstrate this approach using fast-ion D-alpha measurements from DIII-D discharge #132224 during an MHD quiescent phase. Figure 1 illustrates the improved reconstruction quality of our method (c) compared to standard first-order Tikhonov regularization (b), relative to a TRANSP simulation (a).

Furthermore, while model errors from uncertainties in kinetic profiles were previously considered negligible[2, 3], recent results from the ASDEX Upgrade INPA demonstrate significant sensitivity of the reconstructed fast-ion distributions to the electron density[4]. Additional uncertainties arise from detector geometries. Building on our Bayesian framework, we incorporate approximation error modeling to systematically account for plasma parameter and geometry uncertainties directly in the reconstruction process. This approach also provides physically informed error bounds on the reconstructed fast-ion distribution through covariances derived from both collision physics and model uncertainties.

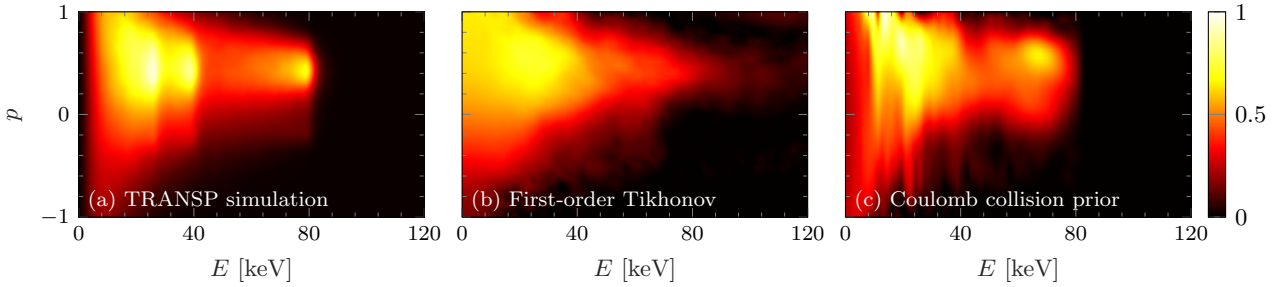

Figure 1. (a) TRANSP simulation for $t = 1985$ ms during discharge #132224 at DIII-D. (b)-(c) Reconstructions obtained using (b) first-order Tikhonov regularization and (c) a Coulomb collision prior.

References

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