Validation of a Comprehensive First-Principles-Based Framework for Predicting the Performance of Future Stellarators

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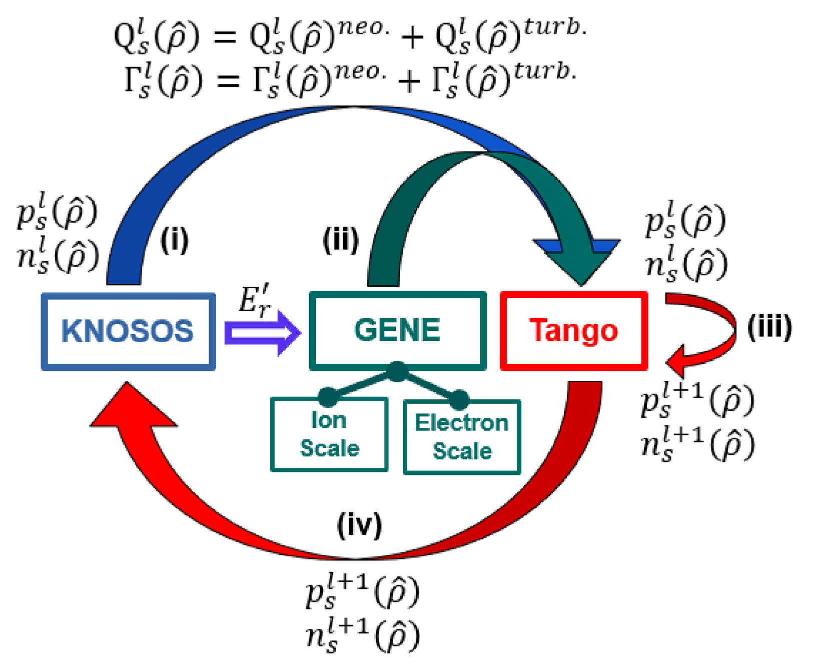
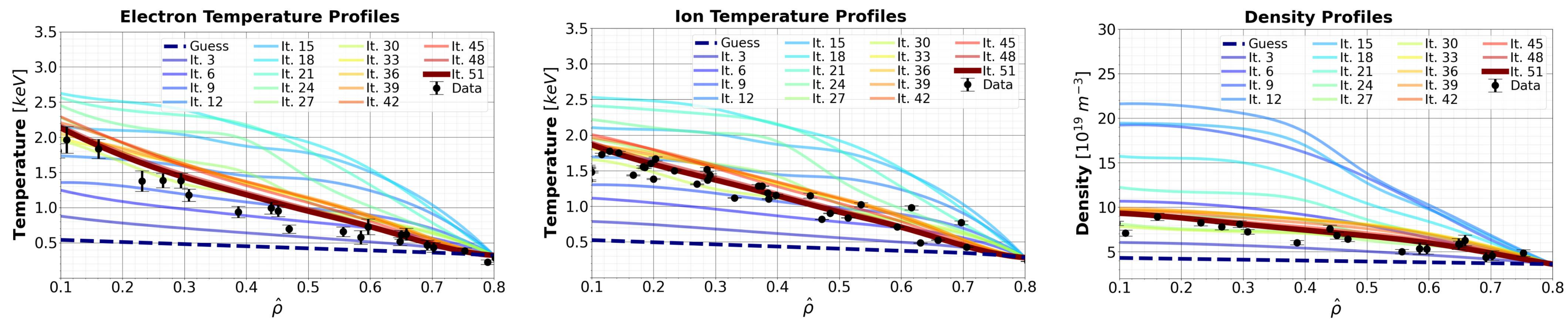
INTRODUCTION

Understanding plasma turbulence is crucial for designing stellarators and advancing reactor development. With the world's most powerful supercomputers, turbulence can be analyzed across the entire plasma volume. To self-consistently evolve plasma profiles and turbulence in a stellarator, we developed the **GENE–KNOSOS–Tango** framework.

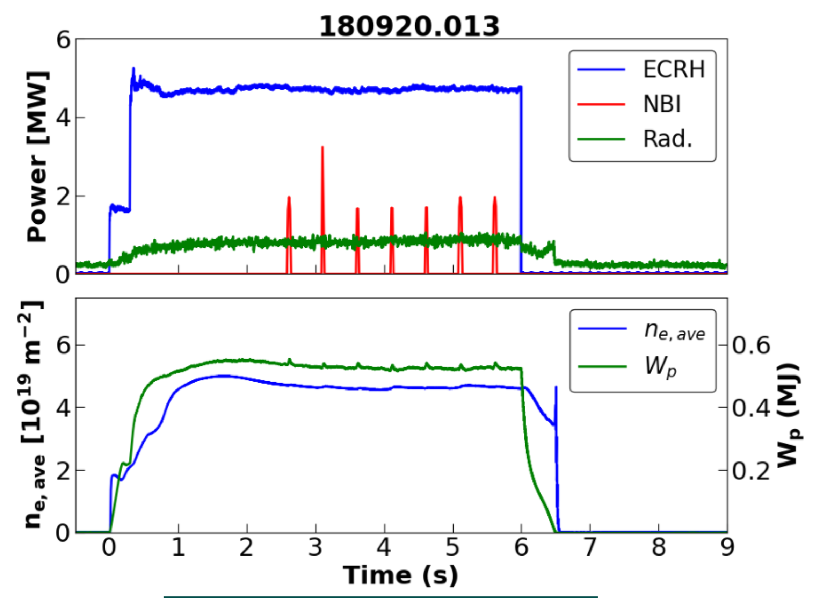




- **KNOSOS:** Computes neoclassical fluxes & E_r **GENE:** Evaluates turbulent transport **Tango:** Modifies profiles based on transport & sources
- Plasma profiles are varied until target fluxes are matched. Convergence is manually determined based on the fulfillment of the radial power and particle balances.
- **The framework's validation is necessary to ensure that simulations reproduce experimental results across a wide range of operating conditions.**

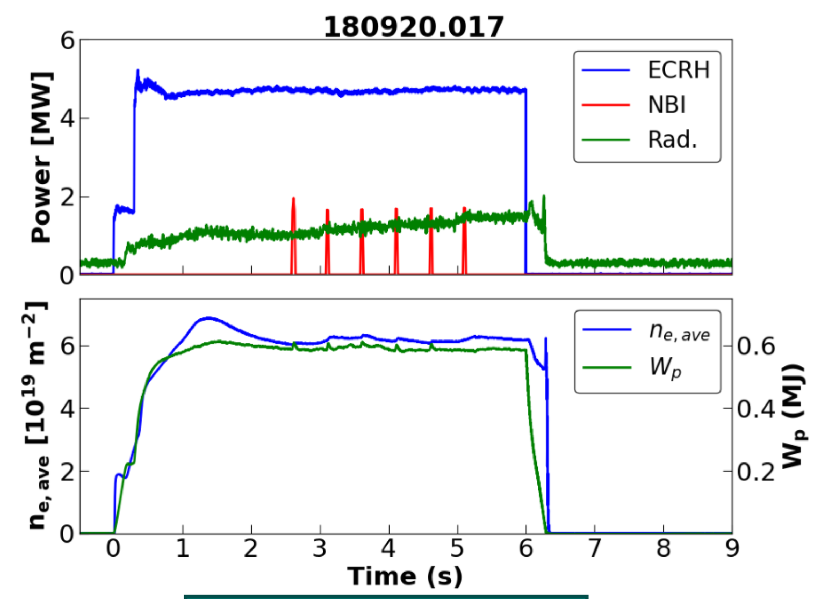
SCENARIOS

3 OP1.2b W7-X discharges [1, 2] were selected for the validation of the **GENE–KNOSOS–Tango** [3–7] simulation suite. The first two scenarios are characterized by a core ion temperature **Ti below 1.5 ± 0.2 keV**, which is typical of W7-X electron-heated plasmas, while the last two exceed this threshold value:



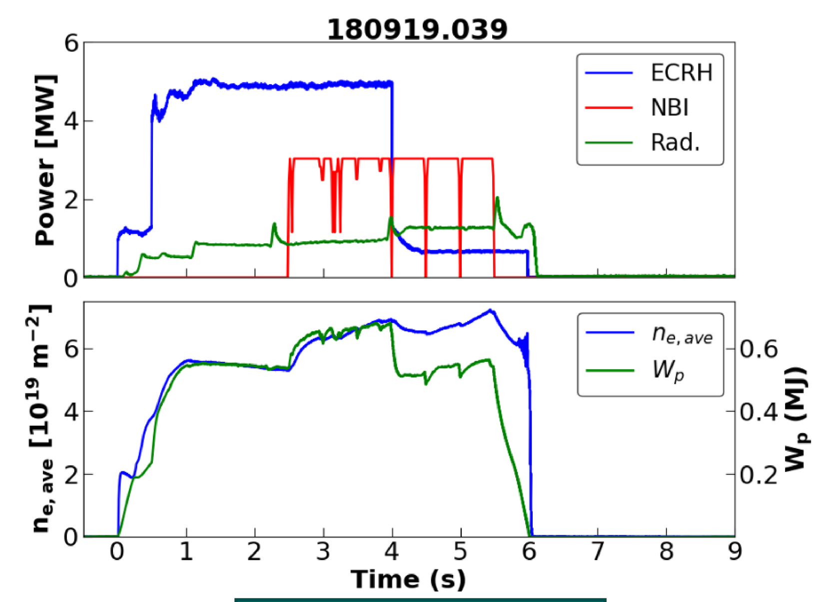
Low-density ECRH

Case 1



High-density ECRH

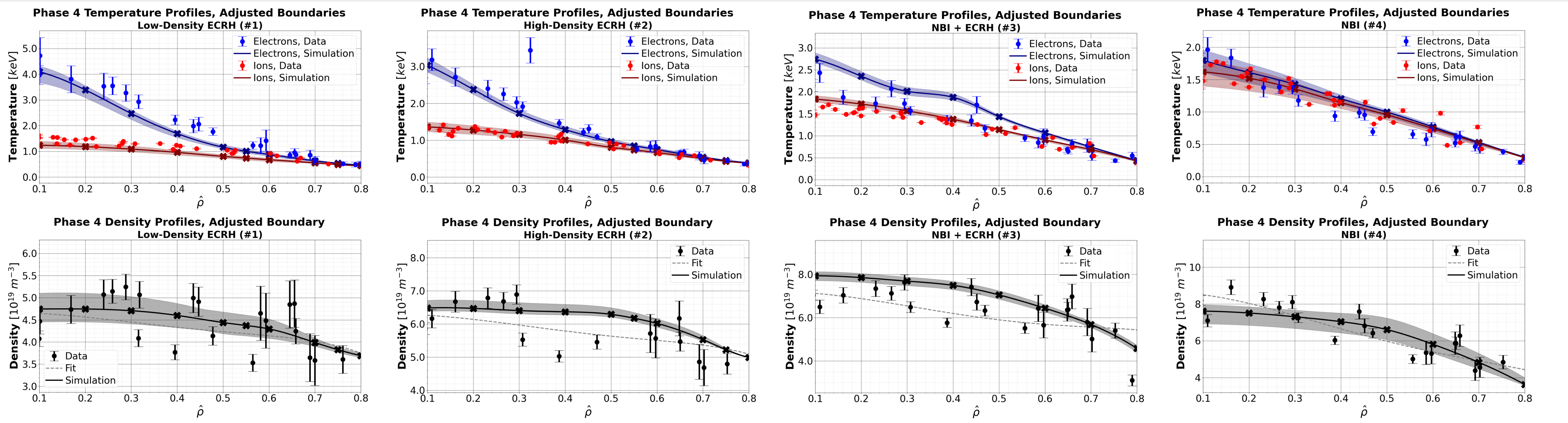
Case 2



NBI (+ECRH)

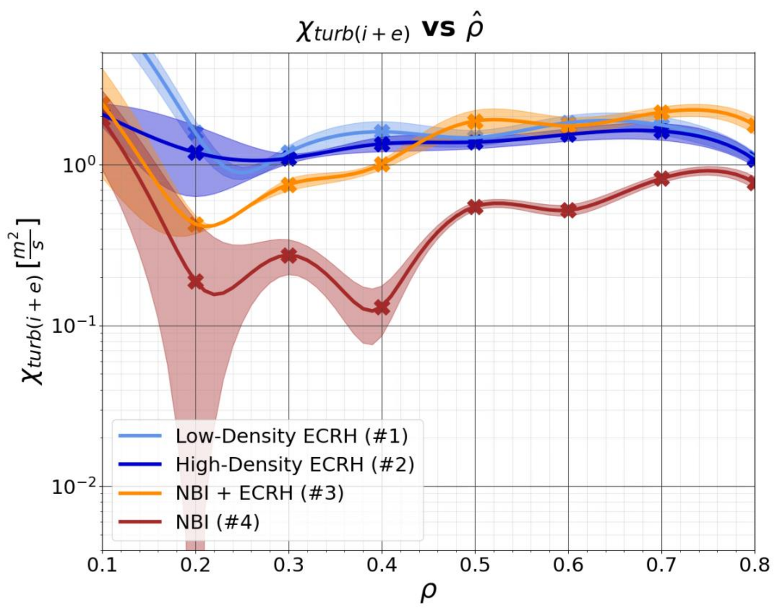
Cases 3 & 4

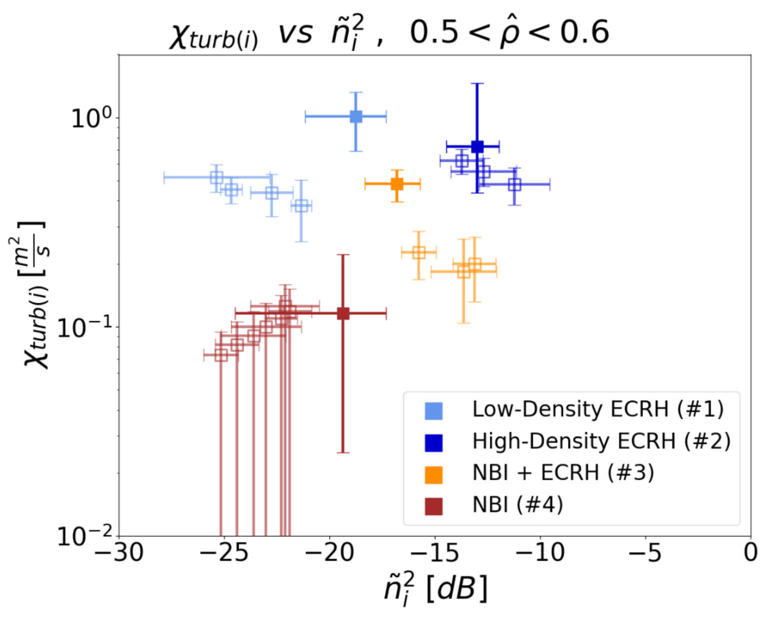
RESULTS – PROFILES

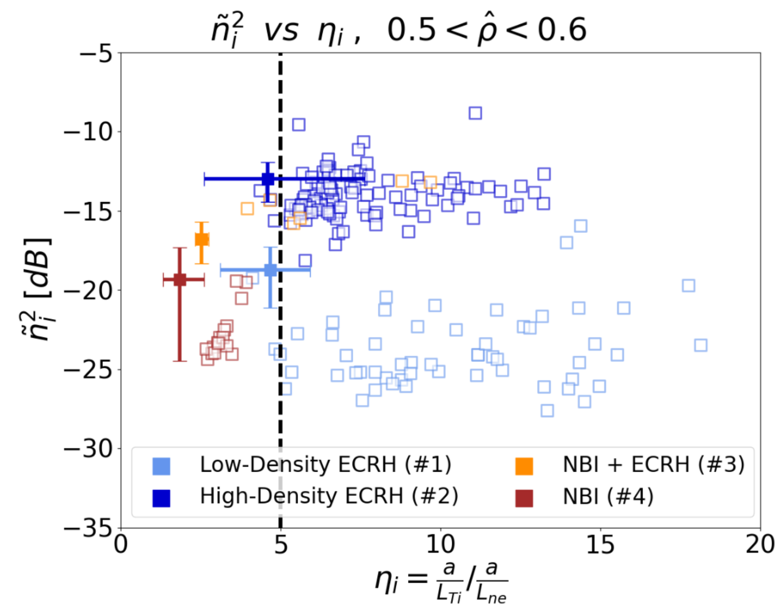


- Small adjustments on the profile boundaries within the error bars allow for better matching of the experimental data points and compliance of power and particle balances.
- This emphasizes the **importance of plasma edge** modeling, which is unfortunately beyond the scope of this study.

RESULTS – TURBULENCE PROPERTIES







- Simulation results (**solid**) show good qualitative agreement with experimental data (**hollow**).
- The NBI scenario (**case #4**) has the lowest turbulent transport among the four cases.
- Varying the **collisionality** (**cases #1 and #2**) can have a negligible impact on turbulent transport.
- Reducing $\boldsymbol{\eta_i}$ (**cases #2, #3, and #4**) decreases the fluctuation amplitude arising from ITG turbulence.

CONCLUSION & OUTLOOK

The validation of the GENE–KNOSOS–Tango framework enables credible predictions of physical phenomena in stellarators and reactor performance based on a given set of edge parameters. Future work will focus on adding global effects to the framework through GENE-3D, understanding multi-scale effects, and simulating other W7-X discharges, such as high-performance pellet fueling and high-beta scenarios.

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