GYROKINETIC REDUCED MODELS FOR PEDESTAL TRANSPORT: VALIDATION AND APPLICATION TO CORE EDGE INTEGRATION

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One of the critical challenges in the development of tokamak-based fusion power plants lies in simultaneously satisfying the requirements of plasma confinement and plasma exhaust. These are often in conflict, arising from the need to reconcile the extremely high fusion temperatures within the core plasma (>10 keV) with conditions that are sustainable for plasma-facing components. This issue of core-edge integration encompasses three interconnected physical domains: divertor/SOL physics, pedestal MHD stability, and pedestal transport. Perhaps the domain with the biggest gap in modeling capabilities is pedestal transport, which is the focus of this work. This presentation describes gyrokinetic reduced models for pedestal transport that are accurate and efficient enough for rigorous validation, predictive modeling, and uncertainty quantification. The models are validated in comparison with several experimental scenarios and applied to answering key questions for core edge integration, notably, the connection between separatrix parameters and confinement.

Nonlinear gyrokinetic simulations in the pedestal are too expensive for routine profile prediction. Hence, we employ a gyrokinetic-based quasilinear mixing length approach. Since the underlying model relies on linear gyrokinetics, this approach captures linear thresholds and dependencies on all relevant parameters, including magnetic shear, Shafranov shift (and other geometric effects), collisionality, impurity effects, and temperature and density gradient scale lengths. Moreover, since instabilities in the pedestal can exhibit complex mode structures, an important feature of this model is that no limiting assumptions are made regarding the eigenmodes. This framework is flexible enough to capture all relevant gyrokinetic instabilities including electron temperature gradient (ETG) modes, microtearing modes (MTM), kinetic ballooning modes (KBM), and ion scale electrostatic instabilities like ion temperature gradient (ITG) instabilities and trapped electron modes (TEM). The effects of ExB shear suppression and some nonlocal effects (via effective ρ^*) are also incorporated into the model. Free parameters in the model are initially tuned to match nonlinear simulations. Subsequent model refinement is carried out in comparison with experimental data employing a Bayesian statistical framework.

The gyrokinetic reduced models for pedestal transport are coupled with the ASTRA integrated modeling framework to evolve pedestal profiles and equilibria in response to experimental heating and particle sources. Particle sources are estimated from interpretive SOLPS simulations. Although linear gyrokinetics is relatively inexpensive in comparison with nonlinear simulations, surrogate models are useful for accelerating the workflow for model development and uncertainty quantification. A variety of surrogate models is exploited for these purposes, starting with simple interpolation schemes for individual discharges and ranging to neural networks trained on larger datasets.

The gyrokinetic reduced models are validated in comparison with data from DIII-D, JET, and NSTX. An example from DIII-D is shown in Fig. 1, which shows a comparison between modeled profiles and experimental profiles in a near-steady-state pre-ELM phase of the discharge. For this scenario, we assume an even split between electrons and ions for the heat flux entering the pedestal. The particle source was estimated from interpretive SOLPS simulations (reported in Refs. [1,2]). Notably, the model recovers both the electron temperature and density profiles accurately for this scenario. Since the relative particle and heat diffusivities are defined by the underlying gyrokinetic eigenmodes, this is a stringent self-consistency test regarding the gyrokinetic instabilities, experimental profiles, and experimental heat and particle sources.

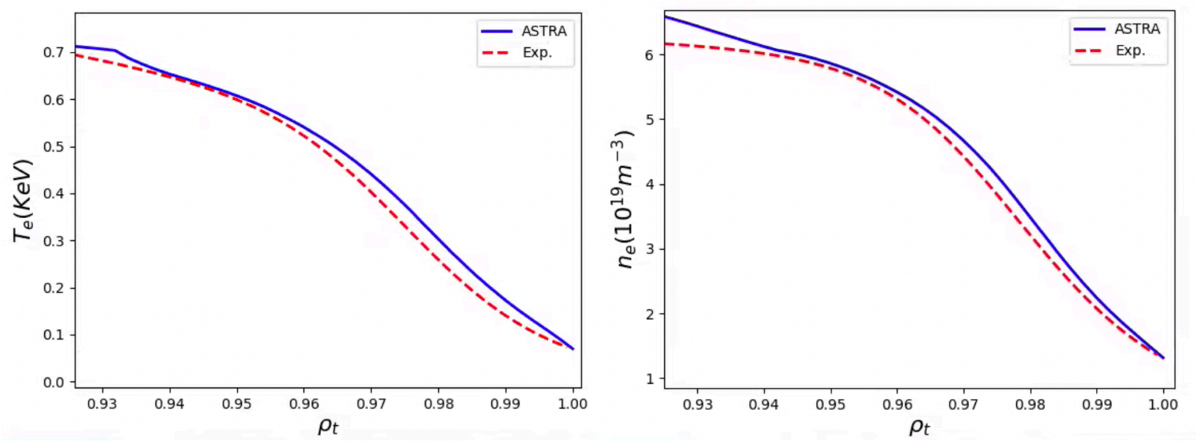

Fig. 1. Comparison between (1) the pre-ELM experimental pedestal profiles from DIII-D discharge 162940 (dashed red) for electron density and temperature and (2) profiles modeled using the gyrokinetic reduced models coupled with ASTRA (blue).

The gyrokinetic reduced models are also applied to key issues of core-edge integration. The predominant trend observed in multiple devices is a degradation of confinement with increasing separatrix density and decreasing separatrix temperature (see, e.g., Refs. [3,4,5,6,7]). Recent analysis of the ITPA confinement database [6] finds a clear trend of decreasing confinement with increasing n_{sep}/n [7]. We investigate this trend using the gyrokinetic reduced models by evolving pedestal profiles for a range of separatrix densities. The gyrokinetic reduced models qualitatively recover the relation between confinement and separatrix density identified in the database. This can be attributed to a strong $\boldsymbol{\eta} = L_n/L_T$ dependence of ETG transport in addition to more complex parameter dependencies of MTM pedestal transport.

Additional ongoing and future work will be discussed including (1) plans for more extensive, statistically rigorous, validation spanning a broader experimental dataset; (2) possible strategies for confinement optimization exploiting tailored density profiles (enabled, e.g., by pellet injection); and (3) the interplay between pedestal transport and MHD stability limits. This work promises to fill a key gap in predictive modeling capabilities for next generation fusion devices.

References

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