Integrated Modeling of DIII-D Super H-Mode using Improved Pedestal Physics and Integrated Core-Pedestal-Boundary Physics to Optimize Fusion Performance TH

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A comprehensive upgrade of the EPED pedestal model [1], coupled with core and boundary physics, has enabled accurate prediction and optimization of fusion plasma performance. Recent improvements include enhanced kinetic ballooning mode (KBM) constraint calculations through the Ballooning Critical Pedestal (BCP) technique focusing on strongly shaped plasmas, flexible profile configurations near the separatrix, and optimized computational performance. The integrated Core-Edge pedestal-Scrape Off Layer (CESOL) framework based on IPS-FASTRAN [2], combining pedestal (EPED) calculations with core transport (TGLF [3]) and boundary physics (SOLPS-ITER [4]) models, successfully reproduces experimental measurements from DIII-D super H-mode plasmas in Figure 1. While ongoing work continues to improve core transport predictions, the framework provides quantitative understanding of cross-region coupling effects while maintaining high core performance. These advances represent a significant step toward predictive capability for future fusion devices.

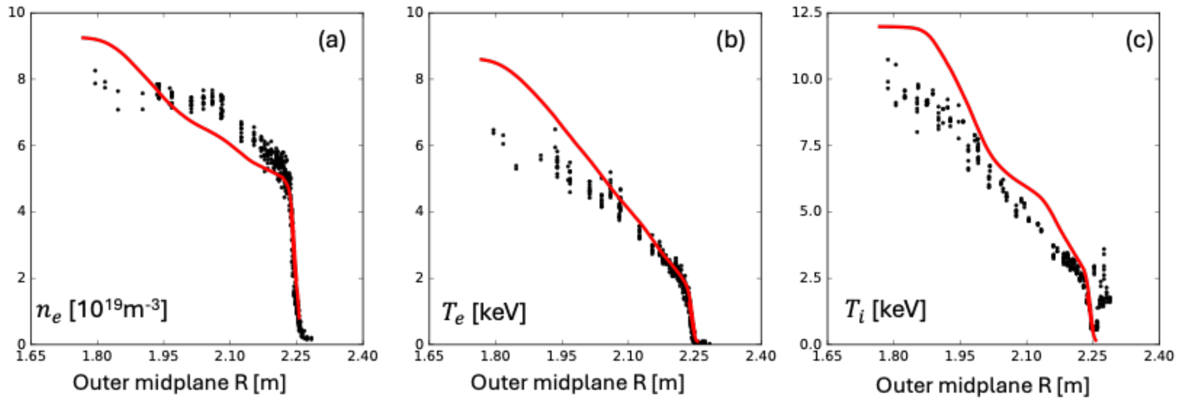

Figure 1 CESOL simulation validated against DIII-D super H-mode discharge (#171322), profiles of (a) electron density, (b) electron temperature, and (c) ion temperature. The black dots are from experimental measurements, and the red line from CESOL predictions

The integrated modeling reveals new insights into pedestal stability behavior. High-resolution profile measurements confirm that the pedestal exhibits strong ballooning characteristics at increased separatrix density ($n_e^{sep}/n_e^{ped} \sim 0.5$), twice that of standard EPED assumption (0.25). This behavior, captured by improved KBM constraint calculations and flexible profile treatments in EPED, demonstrates how enhanced separatrix density modifies pedestal stability through increased collisionality. The framework successfully reproduces these stability transitions across multiple magnetic configurations from experiments with various divertor closure geometries, including upper single null (USN, green in Figure 2), lower single null (LSN, blue in Figure 2), and small angle slot (SAS, red in Figure 2) geometries, validating our understanding of shape effects on stability.

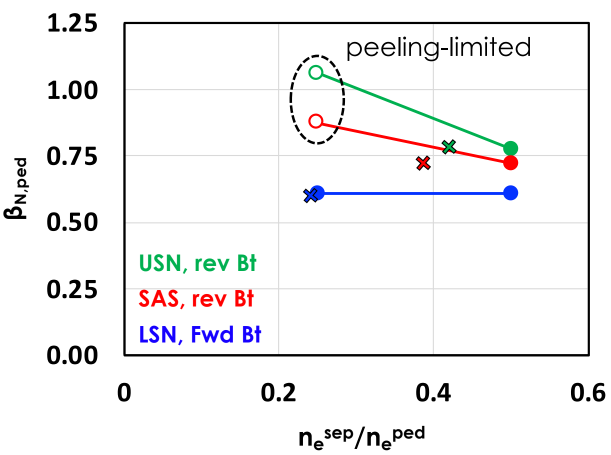

Figure 2 Pedestal stability characteristics showing peeling-to-ballooning transition with increasing separatrix density ratio (The filled circle represents ballooning-limited and the cross marker shows the experimental value)

Recent enhancements to the EPED model's KBM constraint calculations with coefficients properly accounting for R/a dependence have improved accuracy in predicting pedestal width and gradient limitations. While maintaining the fundamental scaling of pedestal width with β_p^{ped}^0.5 , the model implements refined calculations of the bootstrap current profile based on local magnetic geometry at pedestal region. These refinements are particularly important for super H-mode plasmas where strong shaping and low collisionality can lead to second stability access. Additionally, implementation of flexible profile configurations near the separatrix has enabled more accurate representation of edge transport barriers and their coupling to SOL conditions. These improvements, combined with computational optimizations, allow rapid exploration of operating space for scenario development. Enhanced profile flexibility in the EPED model proves essential for capturing experimental behavior. The framework accurately reproduces the observed coupling between separatrix conditions and pedestal structure, with profile diagnostics confirming predicted relationships between pedestal height, width, and separatrix parameters. Measured pedestal pressure shows systematical dependence on separatrix density that matches model predictions, while maintaining consistency with stability constraints. The validation extends across a range of plasma shapes, demonstrating the robustness of the improved physical models in capturing shaping effects on pedestal structure.

The coupling of EPED to SOLPS-ITER represents a major advance in self-consistent boundary modeling. Using a computationally efficient surrogate model based on multiple SOLPS-ITER simulations, the framework determines separatrix conditions by matching global particle and energy balances between core, pedestal and SOL regions. SOLPS-ITER simulations use prescribed profiles from FASTRAN/EPED in the pedestal region as boundary conditions while providing atomic source calculations back to FASTRAN. This bi-directional coupling approach enables accurate prediction of pedestal structure and stability boundaries, showing excellent agreement with experimental operating points in strongly shaped plasmas, including observed transitions between peeling-limited and ballooning-limited regimes. The framework successfully reproduces the measured coupling between separatrix conditions and pedestal structure, with profile diagnostics confirming predicted relationships between pedestal height, width, and separatrix parameters. This coupling has proven particularly important for super H-mode access, where the balance of edge gradients and bootstrap current plays a crucial role in achieving maximum performance.

Integration with core transport models through TGLF, primarily SAT0 model, supplemented with SAT1 and SAT2, provides consistent profile predictions from the magnetic axis through the pedestal region. This capability allows quantitative prediction of global confinement and fusion performance, accounting for the complex interactions between core transport, pedestal stability, and boundary conditions. The framework captures the experimentally observed dependence of core performance on pedestal height while properly accounting for profile stiffness and momentum transport effects.

Comprehensive validations are being performed against new experiment results in theory-motivated Shape and Volume Rise (SVR) experiments on DIII-D, including experiments that appear to access the super H mode regime and achieve the highest pedestal pressure ever recorded on DIII-D. This validation spans multiple operating scenarios with different levels of gas puffing and impurity seeding, demonstrating robust agreement between predicted and measured pedestal structure across different conditions.

The validated framework provides key insights for future devices where managing the trade-off between core performance and boundary control is critical. The demonstrated ability to reproduce experimental measurements across different scenarios, particularly the complicated coupling between stability physics and boundary conditions, establishes confidence in our integrated modeling approach. Ongoing work focuses on extending these capabilities to include additional boundary physics effects, further enhancing predictive capability for next-generation fusion devices.

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