ADVANCING PEDESTAL STABILITY PREDICTION THROUGH INTEGRATED EQUILIBRIUM AND RESISTIVE MHD MODELING

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Edge Localized Modes (ELMs) remain a critical challenge for the operation of advanced tokamak devices, threatening both plasma confinement and the integrity of plasma-facing components. The current state-of-the-art models, such as EPED/EUROPED, have been instrumental in forecasting pedestal height and width by constructing a series of equilibrium states and feeding these into the ELITE stability analysis [1]. ELITE, based on the energy principle, offers valuable insights into peeling-ballooning instability thresholds; however, its formulation omits several key physical effects, notably flow shear, resistivity, and diamagnetic effects [2]. These omissions may lead to discrepancies when predicting ELM behavior in regimes where these effects are non-negligible. Hence, there is a growing need for improved predictive models that can account for these multi-faceted influences and offer rapid, yet accurate, design-space explorations for ELM control strategies.

Model Development

We present a newly developed high-accuracy pedestal stability prediction model designed to overcome these limitations. Our approach integrates a self-consistent equilibrium solver with a refined peeling-ballooning (P-B) model implemented within the BOUT++ framework—a magnetohydrodynamic (MHD) code that naturally incorporates boundary effects [3]. The model captures the linear growth rates and nonlinear evolution characteristics associated with edge instabilities, while explicitly resolving the influences of flow shear, resistivity, and diamagnetic effects.

The equilibrium module is constructed by iterating through multiple pedestal configurations, ensuring that each equilibrium satisfies both global force balance and local stability constraints. By sampling a wide range of pedestal parameters, the algorithm identifies the critical thresholds at which peeling-ballooning modes become unstable. For the stability analysis itself, the BOUT++ P-B model is utilized, which solves the full set of resistive MHD equations with the inclusion of advanced corrections to represent flow shear, dynamics and diamagnetic stabilization effects.

The implementation benefits from modern computational techniques that reduce time-to-solution without compromising fidelity. In particular, the integration of our equilibrium solver with BOUT++ allows for a rapid assessment of evolving pedestal parameters. This is crucial for real-time plasma control applications and the development of feedback mechanisms aimed at mitigating the onset of harmful ELMs.

By incorporating these elements, our model provides a more complete physical picture of the pedestal dynamics. The combined influence of these stabilizing mechanisms not only leads to a more reliable prediction of peeling-ballooning thresholds but also establishes a foundation for developing advanced ELM control strategies.

In this work, we first present a new python code-FBGSpy with direct, fixed/free boundary GS solver and show its effectiveness, versatility, and accuracy. The solved equilibriums have good agreements with EFIT. Then a multi-thread code based on hypnotoad-python was developed to generate Clebsch coordinate grids for BOUT++ automatically. Lastly, pedestal height, width are scanned to obtain a stable pedestal condition. In this model, both SOL can be include or exclude using free/fixed boundary solver.

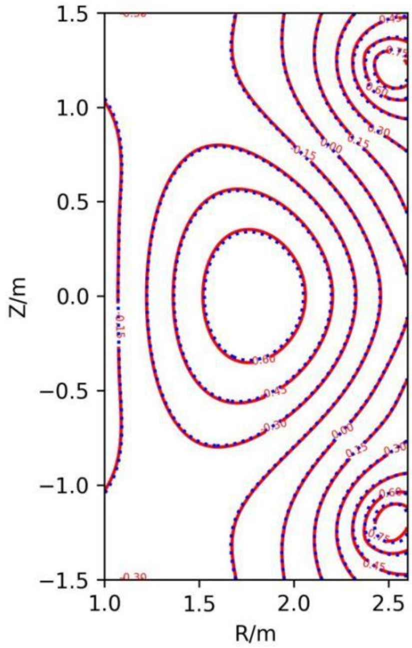

Figure 1： Comparison of FBGSpy (solid) and EFIT's (dashed) results with same J_ϕ

Validation of our model was performed against a set of experimental discharges where detailed measurements of plasma rotation, resistive layers, and pressure profiles were available. In comparisons with the traditional EPED/EUROPED predictions, our model demonstrated enhanced accuracy in predicting the pedestal stability thresholds and the corresponding linear growth rates of peeling-ballooning modes. Particularly, when the profiles exhibited significant flow shear and pronounced diamagnetic effects, our model correctly predicted delayed instability onsets that are consistent with experimental observations.

The predictive capability of our model was also assessed through benchmark simulations. By leveraging an optimized computational architecture and parallelization strategies within the BOUT++ environment, computation times were reduced by nearly an order of magnitude compared to traditional methods. This performance gain is especially promising for its integration into plasma control systems which require near-instantaneous stability assessments.

Beginning with improved physical fidelity, our model shows promise in addressing the significant challenges posed by ELMs in high-performance fusion plasmas. Future work will focus on extending this framework to nonlinear regimes and integrating it within feedback-control loops for experimental verification. The synergy between theoretical developments and experimental implementations holds considerable promise for the realization of continuously stable high-confinement regimes in future fusion reactors.

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