PUSHING BOUNDARIES OF INTEGRATED MODELING WITH IMPROVED GPU-ENHANCED PERFORMANCE AND VALIDATED GYROKINETIC MODEL IN TRANSP CODE

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1. INTRODUCTION

This paper highlights recent advancements in the TRANSP code [1], focusing on GPU acceleration, integration of high-fidelity gyrokinetic models, and verification and validation for tokamak discharges. TRANSP, a cornerstone of time-dependent transport simulations in the fusion research community, provides a versatile platform for interpretive and predictive modeling of plasma behavior. Supporting a wide range of physics models, synthetic diagnostics, and tools for equilibrium and transport analysis, TRANSP is essential for both operational and research applications. Recent upgrades have significantly enhanced computational efficiency and physics fidelity, including GPU acceleration of key modules and the integration of the high-fidelity gyrokinetic GX turbulence model [2] using the T3D framework [3]. Verification and validation analyses for JET and NSTX discharges confirmed these improvements, with JET studies focusing on verifying the coupling scheme between transport and turbulence models, and NSTX studies focusing on stability analysis of modes that drive anomalous plasma in different plasma regions. These advancements reinforce TRANSP's role as a reliable tool for tackling the challenges of tokamak plasma simulations.

2. GPU OPTIMIZATION FOR HIGH-RESOLUTION NUBEAM ANALYSIS

The NUBEAM module [4], essential for modeling neutral beam injection (NBI) heating and current drive, computes the fast ion distribution function critical for understanding plasma behavior. Recent GPU optimizations have improved performance by over 20x compared to its CPU counterpart, significantly enhancing its utility in between-shot analysis. For example, simulations with 160k Monte Carlo particles, required for stability analysis of energetic particle-driven modes in DIII-D, can now be completed in under 16 seconds. This high-resolution capability supports detailed stability studies and enables rapid adjustments to experimental setups. Performing high-resolution analyses with a large number of Monte Carlo particles in near-real-time signifies a key advancement, establishing TRANSP as an integral tool for modern tokamak experiments.

3. GYROKINETIC INTEGRATION: THE NEXT FRONTIER IN PLASMA TRANSPORT MODELING

The integration of T3D [3] and GX [2] marks a major step in TRANSP's evolution, embedding high-fidelity gyrokinetic turbulence modeling into transport simulations. This advancement addresses the need for turbulence-resolved simulations that remain computationally feasible. Turbulence, a key driver of anomalous transport in magnetized plasmas, affects heat, particle, and momentum fluxes. While traditional models offer efficiency, they lack the precision required for certain predictive applications. Gyrokinetic models like GX resolve this by solving nonlinear equations to capture turbulence dynamics with high fidelity.

T3D employs a transport solver built on TRANSP's PT_SOLVER framework, optimized for seamless integration with gyrokinetic models. This coupling enables self-consistent evolution of sources, equilibrium, and plasma profiles. Rigorous testing, including JET discharge 42982 for coupling validation and NSTX discharge 129041 for comparing turbulence-driven instabilities against the Multi-Mode Model (MMM) [4], has demonstrated the reliability and accuracy of the T3D/GX implementation. From the stability analysis using the GX model, we have demonstrated the ITG contributes to the ion thermal transport in the region $\boldsymbol{\rho}>0.5$, and ETG modes are important for the electron thermal transport (see Fig. 1). Scans with temperature and density gradients as well as plasma $\boldsymbol{\beta}$ are used to identify the instabilities and investigate their sensitivity on plasma parameters.

By combining T3D's modular design with GPU-optimized GX, TRANSP provides a robust solution for turbulence-driven transport, advancing its capacity for detailed stability analysis and scenario development for modern and future tokamak experiments.

4. ENHANCING INTEROPERABILITY WITH IMAS

To complement its modeling advancements, TRANSP has integrated the ITER Integrated Modeling & Analysis Suite (IMAS), enhancing interoperability and global collaboration. The IMAS interface provides seamless access to international experimental datasets and incorporates advanced physics models, such as TORBEAM and TORIC-6, for improved accuracy in heating and current drive studies.

A key IMAS-enabled feature is the *make_eqtok* tool, which streamlines equilibrium data preparation by dynamically generating Green's functions and mutual inductance matrices during runtime. This eliminates reliance on precomputed datasets, allowing for greater flexibility and faster configuration of new device geometries. The tool, extracting coil and circuit parameters from IMAS poloidal field active IDS, is particularly useful for conceptual studies and exploring novel tokamak designs. By automating equilibrium preparation, TRANSP accelerates simulation workflows while ensuring consistency across datasets and devices. These advancements strengthen its role in both experimental campaigns and theoretical studies, supporting existing tokamaks and FPP planning.

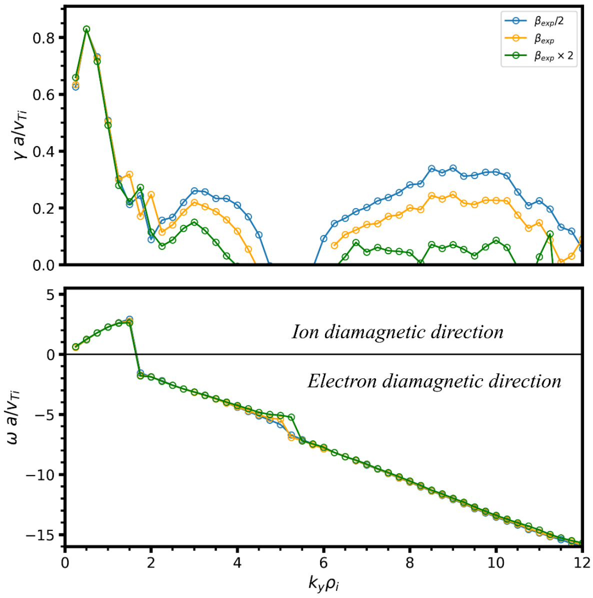

Fig. 1. Growth rates γ and frequencies ω, normalized by a/v_{Ti} (a is the minor radius and v_{Ti} is the ion thermal speed), are plotted against $k_y\rho_i$ for a flux tube at ρ=0.62 in the NSTX discharge 129041. Computations use GX coupled to TRANSP for three plasma beta values. A large-scale mode propagates in the ion diamagnetic direction, while two short-scale modes propagate in the electron diamagnetic direction. Plasma beta has a stabilizing effect on the electron modes.

5. CONCLUSIONS

The integration of gyrokinetic turbulence models via T3D/GX represents a major leap forward in plasma transport simulations, enabling high-fidelity modeling of turbulent dynamics. Combined with GPU-accelerated modules like NUBEAM and the GPU-optimized GX solver, these advancements secure TRANSP's position at the forefront of fusion research. The GPU acceleration of NUBEAM, a critical component for simulating NBI heating and current drive, allows high-resolution, between-shot analyses, transforming experimental workflows and supporting timely decision-making for facilities like DIII-D and SPARC.

T3D/GX further elevates TRANSP's capabilities by embedding turbulence physics into transport simulations. Derived from the TRINITY code, T3D offers modularity and precision, while GX provides advanced gyrokinetic modeling optimized for GPUs. This integration is crucial for capturing turbulence-driven transport and informs both interpretive and predictive studies, particularly for devices like ITER, where resolving turbulence is key to operational success. Alongside these advancements, IMAS compatibility expands TRANSP's utility as a collaborative tool, facilitating data sharing and enabling future enhancements like TORBEAM and TORIC-6. These enhancements to TRANSP highlight its ongoing evolution as a leading platform for high-fidelity fusion simulations.

ACKNOWLEDGEMENTS

This work was supported by the US DOE program under Contract Number DE-AC02-09CH11466.

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