Next-Generation TRANSP: Enabling High-fidelity Fusion Simulations with IMAS and GPU Optimization

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Introduction: TRANSP [1, 2] is a widely-used computational tool for both interpretive and predictive analysis of tokamak plasmas. Originally developed as an interpretive transport code, TRANSP has evolved into a comprehensive integrated modeling framework that includes NBI and RF physics, equilibrium solvers, and transport models. In recent years, several transformative developments are implemented in TRANSP to enhance its fidelity, efficiency, and interoperability. In particular, three major upgrades are completed: (1) full integration of the IMAS (Integrated Modeling & Analysis Suite) data interface, (2) optimization of the NUBEAM fast-ion Monte Carlo module on modern GPU-based high-performance computers, and (3) coupling of a first-principles gyrokinetic turbulence model GX via the T3D transport solver, enabling embedded turbulence in predictive simulations. Additionally, these new capabilities are applied to perform stability and transport analyses in both existing and proposed spherical tokamak plasmas, benchmarking a high-fidelity gyrokinetic model against reduced transport models. In this paper, we describe each of these developments in detail, and present initial simulation results for NSTX and a next-generation spherical tokamak STAR [3].

IMAS Integration and Global Collaboration: The ITER Integrated Modeling & Analysis Suite (IMAS) has become the international standard for fusion data and modeling interfaces. TRANSP's recent transition to IMAS compliance positions the code as a fully IMAS-enabled analysis tool. The IMAS interface in TRANSP is completed, allowing the code to both fetch experimental inputs and save simulation outputs in the IDS format. In practical terms, TRANSP can now directly initiate runs from an IMAS database entry (for example, using discharge data from devices such as MAST-U or ITER) without ad-hoc preprocessing, and it can write its results back into the IMAS database. This new development opens the opportunity to direct coupling with other physics codes that adhere to the IMAS standard. For instance, several heating and current drive modules are integrated using the IMAS interface: the TORBEAM EC and TORIC-6 IC heating modules are now available in TRANSP via IMAS-based plug-ins. The NUBEAM NBI module now supports IMAS I/O and is ready for coupling with external codes through the IMAS schema.

GPU Optimization of NUBEAM for Between-Shot Analysis: NUBEAM is the Monte Carlo fast-ion simulation model within TRANSP, responsible for modeling neutral beam injection and fast ion slowing-down. It has historically been one of the most computationally intensive components of TRANSP, especially when high numbers of test particles are required for accurate statistical sampling. To enable high-fidelity simulations on faster timescales, NUBEAM is extensively optimized and ported to make use of GPU acceleration. The optimization effort includes NUBEAM refactoring and modernizing (yielding more than an order of magnitude improvement on its own), vectorizing algorithms to exploit advanced CPU architectures (adding roughly another 40% speedup), and finally implementing an OpenMP/OpenACC-based parallelization to offload particle push computations to GPUs. Combined, these improvements achieve a net speedup in excess of $20\times$ compared to the original NUBEAM performance. The GPU-enabled NUBEAM module now provides the capability for between-shot analysis with high fidelity, allowing, for example, rapid evaluation of different NBI configurations or fast ion effect on MHD stability during between-shot-analysis.

Coupling TRANSP with T3D and GX for Embedded Turbulence: While reduced transport models, such as TGLF or MMM, have long been used in TRANSP for predicting anomalous thermal transport, the inclusion of a first-principles gyrokinetic simulation within an integrated modeling workflow marks a new level of fidelity. We have developed an interface in TRANSP to couple to the T3D transport solver with the GPU-optimized gyrokinetic turbulence code GX [4]. In this coupling scheme, TRANSP's native predictive solver PT_SOLVER is effectively replaced with T3D, which evolves the plasma profiles in time using transport fluxes computed by GX. The coupling is achieved through a standardized data exchange: at each time step, TRANSP supplies T3D/GX with the equilibrium and sources, and in return receives the computed plasma profiles. The system advances self-consistently, maintaining consistency between sources, transport, and equilibrium. This "embedded turbulence" approach addresses a long-standing gap by integrating micro-level turbulence physics into a whole-device simulation. We performed a proof-of-concept predictive simulation using the TRANSP+T3D/GX framework for the JET discharge 42982 as a test case. In this initial simulation, only ion scale modes are considered and electrons are treated adiabatically. This test demonstrated that the coupling scheme is stable and that the PT_SOLVER and T3D solvers produce nearly equivalent results in the limit of no turbulent transport. The successful integration of T3D/GX into TRANSP is a milestone that enables high-fidelity predictive simulations including first-principles turbulence effects. It also provides a valuable tool to systematically compare gyrokinetic and reduced transport models under identical conditions within the same framework.

Stability Assessments with Gyrokinetic vs Reduced Models for NSTX and STAR: The new TRANSP/T3D/GX capability is applied to study turbulent transport stability in both an existing tokamak NSTX and a future high-performance spherical tokamak STAR. In each case, linear and nonlinear gyrokinetic analyses with GX are compared against the predictions of the MMM9.1 reduced transport model [5], which is available within TRANSP.

For NSTX, we use a well-studied high-performance NSTX discharge 129041, an ELM-free lithium-conditioned H-mode from the 2008 campaign [6]. MMM indicated strong instability drive from both ion temperature gradient driven (ITG and TEM) and electron temperature gradient driven modes in this discharge. Using the embedded GX model, we perform linear stability scans to identify the dominant modes. The gyrokinetic analysis reveals that a broad spectrum of modes can be unstable in NSTX, including both ion-directed and electron-directed branches of drift-wave turbulence. The ion temperature gradient scan shows that as the gradient steepens, large-scale ion modes are strongly destabilized, while intermediate-scale electron modes see some growth increase and the smallest electron-scale modes remain largely unaffected. Figure 1 shows the effect of plasma β: in the outer half of the plasma, increasing β has a stabilizing influence on electron modes, consistent with reduced drive for electromagnetic microtearing modes at higher β, whereas in the inner core, higher β can either stabilize or destabilize ion modes, suggesting the presence of KBM thresholds. GX nonlinear simulations of the early flat-top phase of this discharge further indicated that multiple turbulence types coexist; modes propagating in the electron diamagnetic direction such as microtearing or electron-temperature-gradient modes are prevalent along with ion-scale modes. At a later time slice in the discharge, however, the GX analysis finds that only high-k electron modes persisted as unstable, with ion-scale turbulence largely suppressed consistent with a transition to an electron-dominated transport regime. The NSTX case demonstrated reasonable agreement between the gyrokinetic and reduced models on the existence of strong turbulence, but also highlighted the richer detail provided by the first-principles approach in characterizing the mode spectrum and stability boundaries.

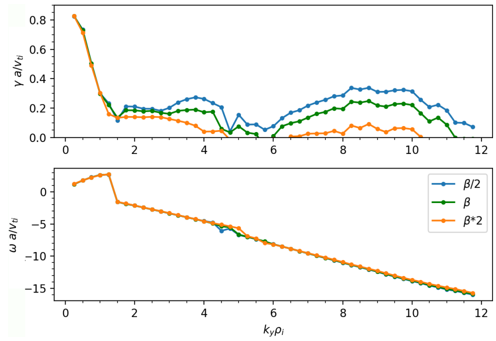

Figure 1: Plasma β scan with linear stability analysis of NSTX discharge 129041 at $\rho = 0.62$ using the GX model in TRANSP. Increased β exerts a stabilizing influence on electron-drift modes (especially in the outer region), and can marginally stabilize or destabilize ion modes in the core suggesting a threshold for kinetic ballooning modes.

For the planned STAR spherical tokamak, which is a high-β steady-state ST with major radius $R \approx 4$ m, $B_T \approx 5$ T, $f_{GW} \approx 0.8$ and significant bootstrap current fraction, we carried out a similar comparative transport stability study. The MMM model predicted a wide range of instabilities contributing to transport in a baseline scenario (20 s quasi-steady state) of STAR. Using profiles consistent with this scenario's equilibrium, linear GX simulations found that no large-scale modes are unstable; instead, unstable modes have relatively short wavelengths with the typical turbulent eddy size decreasing toward the plasma edge. The linear growth rates are sensitive to electron temperature gradient and plasma β. Increasing the T_e gradient or the value of β tends to destabilize modes indicating strong electromagnetic effects. Nonlinear GX simulations for the STAR case are also performed to quantify the turbulence-driven fluxes, as summarized in Fig. 2. The GX

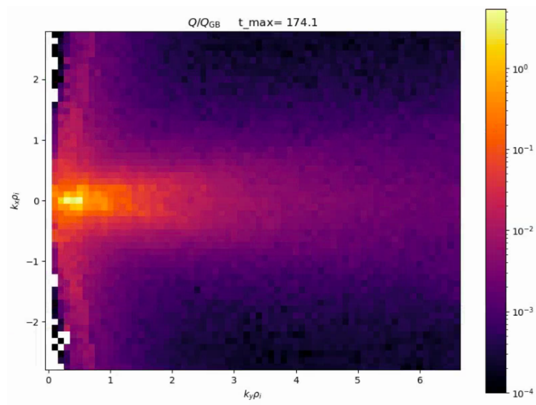

Figure 2: Transport analysis for a high-β STAR spherical tokamak scenario. Nonlinear GX simulation shows larger electron thermal transport compared to the ion thermal transport. Only modes propagating in the electron diamagnetic direction are observed in these linear analyses, implying that electron-driven instabilities dominate in the high-β STAR regime.

results suggest that MTMs and TEMs are the primary drivers of electron thermal transport in this scenario, with smaller contributions from shorter-scale ETG modes. The ion energy transport, by contrast, is found to be largely neoclassical in the STAR conditions with very little ion heat flux from turbulence in GX simulations, similar to observations in NSTX and NSTX-U experiments where electron-channel transport dominates. These findings illustrate how a high-fidelity gyrokinetic approach can provide insight into the nature of turbulence in advanced tokamak concepts, and they offer a benchmark for reduced models, for example, by testing whether MMM can capture the dominance of MTM/TEM-driven electron transport at high β.

Summary and Future Work: Recent upgrades significantly enhance the TRANSP code's capability to perform high-fidelity and timely fusion plasma simulations. The adoption of the IMAS data interface makes TRANSP more accessible and synergistic within the international fusion community, enabling straightforward data exchange and integration with other IMAS-compliant tools. The GPU acceleration of NUBEAM reduces the execution times by an order of magnitude or more, transforming TRANSP into a viable platform for between-shot analysis and scenario optimization on modern supercomputers. The incorporation of embedded turbulence modeling using T3D and GX allows, for the first time, first-principles gyro-kinetic physics to be included in tokamak discharge simulations within TRANSP, opening new opportunities for validating and improving reduced transport models. Initial studies on NSTX and the proposed STAR device using this capability demonstrate the power of the approach in diagnosing and predicting turbulent transport.

Looking forward, efforts are underway to further improve the performance of the coupled TRANSP/T3D/GX simulations through GPU code tuning and exploring multi-scale or reduced-fidelity options that retain accuracy while decreasing runtime. There are also ongoing developments to include initiatives to containerization and distribution TRANSP more broadly (*e.g.*, via Docker) to encourage community contributions. In line with the FAIR principles, the TRANSP development team is continuing to open up the code source and collaborate with researchers worldwide. With these next-generation capabilities, TRANSP can serve not only as a post-experiment analysis code, but also as a high-fidelity predictive tool for optimizing future fusion plasma scenarios in devices like ITER and beyond.

References

[1] J. Breslau, *et al.*, "TRANSP code" DOI: 10.11578/dc.20180627.4 (2018).

[2] A. Y. Pankin, *et al.*, *Computer Physics Communications*, **312**, 109611 (2025).

[3] J. E. Menard, *et al.*, Proc. 29th IAEA Fusion Energy Conf. (2023).

[4] N. R. Mandell, *et al.*, *J. Plasma Phys.* **90**, 905900402 (2024).

[5] T. Rafiq, *et al.*, *Phys. Plasmas* **20**, 032506 (2013).

[6] W. Guttenfelder, *et al.*, Proc. 24th IAEA Fusion Energy Conf. (2012).

The research described here was conducted at the Princeton Plasma Physics Laboratory, a national laboratory operated by Princeton University for the United States Department of Energy under Prime Contract No. DE-AC02-09CH11466.