ADVANCING TOKAMAK TRANSPORT SIMULATIONS WITH MMM 9.1: BRIDGING THEORY AND APPLICATION

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The Multi-Mode Module (MMM) is pivotal for modeling and understanding anomalous transport in tokamak plasmas, a critical capability for advancing devices like ITER, the Fusion Pilot Plant, and other next-generation reactors toward sustainable nuclear fusion [1]. As a physics-based model for multi-species, multi-fluid, and multi-mode transport calculations, MMM predicts profiles for electron and ion thermal transport, particle and impurity transport, and momentum transport. These predictions enable modeling of plasma temperatures, densities, and rotations. Known for its strong physics foundation, efficiency, and adaptability, MMM has been extensively verified against gyrokinetic codes [2, 3] and validated across diverse tokamak experiments [4].

The latest version, MMM 9.1, introduces major updates enhancing accuracy, stability, performance, and physics modeling. It incorporates transport mechanisms, including ion temperature gradient (ITG), trapped electron (TE), kinetic ballooning (KB), peeling, high-mode number MHD [5], microtearing (MT), electron temperature gradient (ETG), and drift resistive inertial ballooning (DRIB) modes. Additional improvements include the effects of flow shear, isotopic effects, plasma shaping, unified electron- and ion-scale correlation lengths, impurity dilution, finite Larmor radius effects, and faster solvers. Together, these upgrades deliver over tenfold computational speed improvements while maintaining high fidelity.

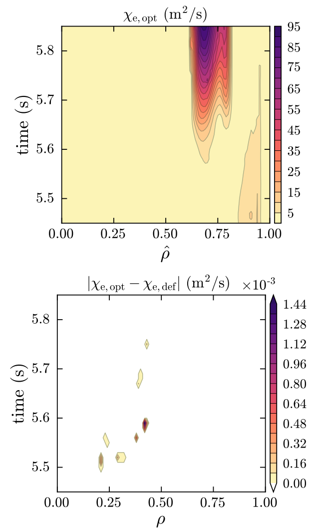

Fig. 1: Optimized (opt) χ_e and absolute differences between optimized (opt) and default (def) profiles. Optimized settings required only 44% as many solver calls as the default.

MMM 9.1 optimizes the ITG/TE mode model by reducing eigenvalue solver calls, significantly decreasing runtime. By focusing on the most unstable mode and excluding less likely modes, solver calls are reduced by 80%, as demonstrated in Fig. 1, using input data from DIII-D discharge 118341 with flow shear effects turned off. This optimization maintains accuracy with negligible error and achieves a more than two-fold improvement in computational efficiency compared to MMM 8.2.

In the MTM model, computational efficiency is improved by replacing linear spacing of $k_y\rho_s$ values with exponential spacing. This refinement prioritizes smaller $k_y\rho_s$ values, which have the greatest impact on diffusivity calculations, significantly reducing solver calls. As shown in Fig. 2, 100 exponentially spaced scans achieve higher precision than 2000 linearly spaced, resulting in substantial runtime reductions.

MMM 9.1 leverages OpenMP parallelization for a fivefold performance boost when compiled with the Intel Fortran Compiler, enabling calculations of all modes, along with thermal, particle, and momentum transport, in just 70 ms per time slice. This efficiency makes MMM well-suited for real-time plasma control, tokamak scenario optimization, and uncertainty quantification in experimental analysis.

Despite these advancements, a limitation arises in the TRANSP code, where the PT-Solver cannot handle negative diffusivities. In TRANSP-MMM predictive simulations, negative diffusivities are disabled, which affects accurate predictions in discharges with significant thermal and momentum pinches. To address this, negative diffusivities are converted into convective velocities, preserving effective particle flux calculations (Fig. 3). These

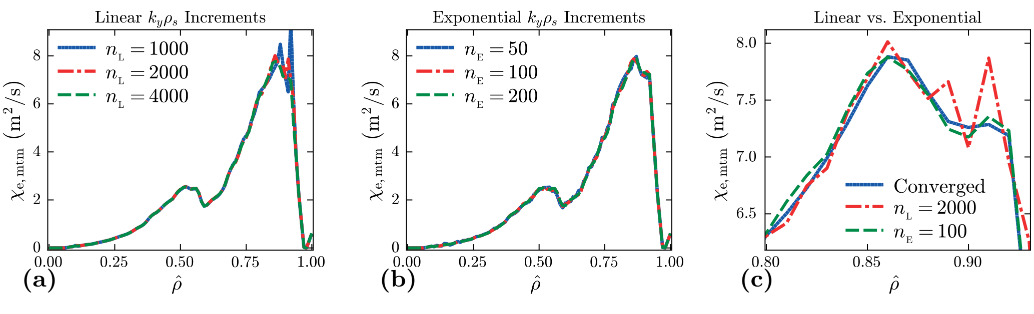

Fig. 2: Convergence comparison of χ_e produced by the MTM model using (a) Linear $k_y\rho_s$ increments using n_L segments, (b) Exponential $k_y\rho_s$ increments using n_E segments, and (c) $n_L = 2000$ linear segments and $n_E = 100$ exponential segments against the converged result (10^6 linear segments). Data from NSTX-U discharge 121123 at $t = 11.8\,s$.

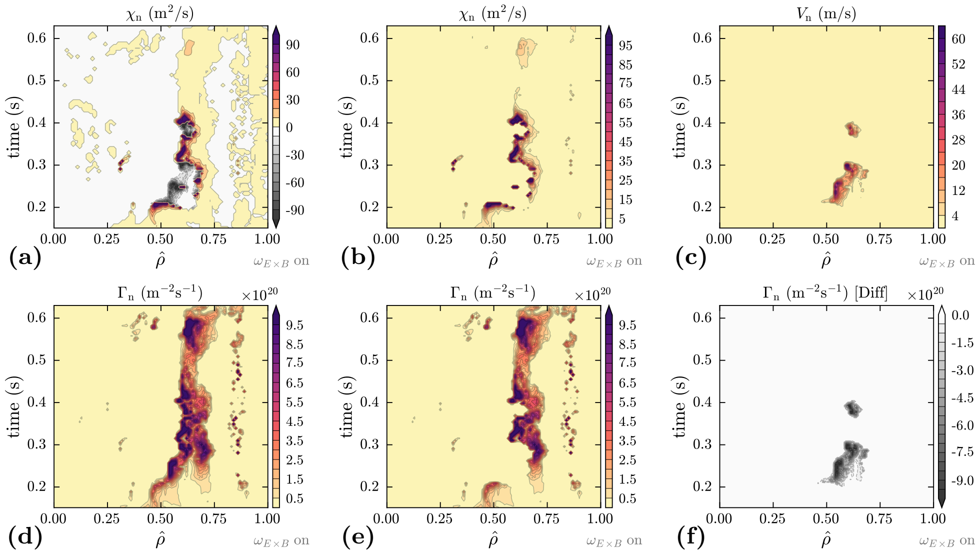

Fig. 3:(a) Particle diffusivity (χ_n) including negative values. (b) Strictly positive χ_n. (c) Convective velocity converted from negative χ_n. (d) Effective flux when negative diffusivity is converted to convective velocity. (e) Effective flux when negative diffusivity is discarded. (f) Difference in flux when negative diffusivity is discarded.

refinements further enhance MMM's capability to capture plasma behavior while maintaining computational efficiency and stability. MMM 9.1 has been extensively validated on conventional tokamaks like EAST, KSTAR, JET, and DIII-D, as well as low aspect ratio devices such as NSTX [2, 4]. Validation spanned a wide range of plasma conditions, including ohmic, L-mode, H-mode, and long-pulse ITB configurations, with variations in density and collisionality. Results showed average RMS deviations of 9.3% for electron temperature and 10.5% for ion temperature, well within experimental error, demonstrating MMM's ability to replicate gyrokinetic simulations while significantly reducing computational demands.

MMM 9.1 effectively captures key plasma behaviors, including internal and edge transport barriers, heating and particle pinches, isotope effects, the Dimits shift, and density limits. A critical factor in these phenomena is resonance broadening, which excludes dissipative kinetic resonance from the energy equation by shifting waves out of particle resonance, thereby eliminating wave-particle interactions. This process reduces viscosity for heavier isotopes (a favorable effect) while increasing it at higher densities (an unfavorable effect). The ITG/TE mode threshold aligns with fluid resonance in the ion energy equation, where viscosity plays a significant role in enhancing the model's sensitivity. Zonal flows, governed by these dynamics, are central to phenomena such as the Dimits shift, L–H transition, isotope scaling, and density limits [6].

MMM 9.1 integrates seamlessly with modeling frameworks such as TRANSP, ASTRA, OMFIT, and IMAS, enabling predictive, time-dependent transport simulations and effective cross-verification with gyrokinetic codes. By bridging theoretical modeling with experimental validation, MMM provides a comprehensive framework for understanding complex plasma interactions and transport processes. By addressing the computational challenges of fully kinetic models, MMM 9.1 uses quasilinear theory to deliver practical yet precise transport predictions in three-dimensional configuration space, avoiding the computational burden of six-dimensional phase space. Our fluid model eliminates the need for three velocity space coordinates and enables a quasilinear description, unlike kinetic models that require a strongly nonlinear approach to capture particle and thermal pinches. These innovations establish MMM 9.1 as an efficient, versatile tool for optimizing plasma performance and supporting the design of next-generation fusion reactors. Its contributions are foundational to theoretical and computational plasma physics, advancing progress toward sustainable fusion energy.

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