Database of Gyrokinetic Transport Simulations and Comparison To a New Comprehensive Theory-based Transport Model*†

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A transport database has been created with over 300 nonlinear gyrokinetic simulations obtained using the GYRO code [1, 2]. The database is comprised of a wide variety of parameter scans used to systematically study the effects of $E \times B$ shear, plasma shaping, magnetic shear, safety factor q, T_i/T_e, ν_*, and plasma β, on turbulent energy, particle, and momentum transport due to Ion Temperature Gradient (ITG) and Trapped Electron Modes (TEM) in toroidal geometry. The goal of this work is to increase our understanding of turbulent transport and advance our predictive capabilities. There are two motivating factors. First, we need to expand our knowledge of transport in the presence of kinetic electrons and plasma shaping. Previous work has tended to focus on studying ITG modes with adiabatic electrons for a single reference case in shifted circle geometry. Second, there is a need for a broad, publicly available, nonlinear database for benchmarking and transport model development. Here, we describe some of the key results from the nonlinear simulations and then compare the diffusivities from a recently developed trapped gyro-Landau-fluid based transport model (TGLF) [3] against the simulations.

We first report on several key results from the GYRO transport database focusing on the effects of plasma shaping on long wavelength ITG/TEM transport and on extending the $E \times B$ shear quench rule to realistic geometry. To date, our best theory-based transport models including the GLF23 [4] model and the driftwave piece of the MM95 [5] model, are only valid for shifted circle geometry. In an effort to extend predictive transport models to shaping geometry we have used nonlinear gyrokinetic simulations to study the effects of plasma shaping on turbulent transport in toroidal geometry using the GYRO code. Systematics scans have been performed around several reference cases in the local, electrostatic, colllisionless limit. Using a parameterized local equilibrium model for shaped geometry, simulations show that the GYRO normalized energy diffusivities exhibit an inverse linear dependence on elongation κ at fixed midplane minor radius. This translates to a scaling of $\chi \propto \kappa^{-3}$ using the ITER definition for the diffusivities which is close to the empirical factor of κ^{-4} used in the MM95 model. This result is very robust and has proven to be valid for a wide range of safety factor and magnetic shear values.

The $E \times B$ shear quench rule was originally deduced from adiabatic electron ITG simulations and is an important ingredient in transport models such as GLF23 and MM95. We have verified that the effect of $E \times B$ shear stabilization in electrostatic flux-tube simulations is well modeled by a simple quench rule with the turbulent diffusivity scaling like $(\gamma_E/\gamma_{\max})$ where γ_E is the $E \times B$ shear rate and $\gamma_{\max}$ is maximum linear growth rate without $E \times B$ shear. We find it also applies in the presence of kinetic electrons for ITG/TEM transport with weak and physically relevant values for the Kelvin-Helmholtz drive (parallel velocity shear). In shifted circle geometry without parallel velocity shear, we find that the quench point is robustly at $\gamma_E/\gamma_{\max} = 2 \pm 0.5$ for both adiabatic and kinetic electron scans around several reference cases including peaked density cases where the unstable modes are primarily in the electron direction. For real geometry, kinetic electron simulations show that the quench point varies systematically with elongation κ and aspect ratio A. A new version of the quench rule is shown that captures the effects of κ and A on the quench point.

Finally, we describe the physics contained in the newly developed TGLF transport model. The TGLF model is the successor to the GLF23 model and contains comprehensive physics including the effects of general toroidal geometry, particle trapping, collisions, and finite beta. The model is based on a set of newly derived trapped-gyro-Landau-fluid equations which provide a fast and accurate approximation to the linear eigenmodes of drift-wave instabilities ranging from long to intermediate wavelength ITG/TEM modes to short wavelength Electron Temperature Gradient (ETG) modes. The linear eigenmodes have been extensively benchmarked against a large database of linear gyrokinetic runs yielding an average deviation between the gyrokinetic and TGLF linear growth rates of 11.4% in shifted circle geometry. These linear benchmarks show that the TGLF model is more accurate than the original GLF23 model over a broader range of parameters including parameter relevant to reversed shear and the H-mode pedestal. Using the TGLF eigenmodes, we compute quasilinear particle and energy fluxes using a turbulence saturation model which is fit to a large set of nonlinear GYRO simulations. The quality of the fit to the GYRO simulations will be shown.

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